

BEFORE THE IOWA UTILITIES BOARD  
DEPARTMENT OF COMMERCE  
STATE OF IOWA

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IN RE:

INTERSTATE  
POWER AND LIGHT  
COMPANY



DOCKET NO. GCU-07-01

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**DIRECT TESTIMONY OF DR. JAMES E. HANSEN**

1 **Q. Please state your name and business address.**

2 A. My name is James E. Hansen. My business address is 2880 Broadway, New York, New  
3 York 10025.

4 **Q. By whom are you presently employed and in what capacity?**

5 A. I am employed by the National Aeronautics and Space Administration (NASA) Goddard  
6 Space Flight Center (GSFC), which has its home base in Greenbelt, Maryland. I am the  
7 director of the Goddard Institute for Space Studies (GISS), which is a division of GSFC  
8 located in New York City. I am also a senior scientist in the Columbia University Earth  
9 Institute and an Adjunct Professor of Earth and Environmental Sciences at Columbia. I  
10 am responsible for defining the research direction of the Goddard Institute, obtaining  
11 research support for the Institute, carrying out original scientific research directed  
12 principally toward understanding global change, and providing relevant information to  
13 the public. I am testifying here as a private citizen, a resident of Kintnersville,  
14 Pennsylvania on behalf of the planet, of life on Earth, including all species.

15 **Q. What is your educational background?**

16 A. I was trained in physics and astronomy at the University of Iowa in the space science  
17 program of Professor James Van Allen. I have a bachelor's degree in physics and

18 mathematics, a master's degree in astronomy, and a Ph.D. in physics, all from the  
19 University of Iowa. I also did research as a graduate student at the Universities of Kyoto  
20 and Tokyo, and I was a post-doctoral fellow of the United States National Science  
21 Foundation studying at the Sterrewacht, Leiden University, Netherlands, under Prof.  
22 Henk van de Hulst.

23 **Q. Please describe your professional experience.**

24 A. Upon graduating from the University of Iowa in February 1967 I joined the Goddard  
25 Institute for Space Studies, where I have worked ever since, except for 1969 when I was a  
26 post-doctoral fellow in the Netherlands. In my first ten years at the Goddard Institute I  
27 focused on planetary research. I was Principal Investigator for an experiment on the  
28 Pioneer Venus spacecraft to study the clouds of Venus and I was involved in other  
29 planetary missions. In the mid-1970s, as evidence of human-made effects on Earth's  
30 atmosphere and climate became apparent, I began to spend most of my time in research  
31 on the Earth's climate. I became director of the Goddard Institute in 1981, focusing the  
32 Institute's program on global change, while maintaining a broad perspective from  
33 planetary studies and the Earth's history.

34 **Q: Are you sponsoring any exhibits as part of your testimony?**

35 A: Yes. All the figures referenced in my testimony are included as Exhibit \_\_\_\_ (JEH-1)  
36 Schedule A. A 2007 article authored by myself and five colleagues, entitled "Climate  
37 change and trace gases", is included as Exhibit \_\_\_\_ (JEH-1) Schedule B.

38 **Q. What is the purpose of your testimony?**

39 A. My aim is to present clear scientific evidence describing the impact that coal-fired power  
40 plants (without carbon capture and storage) will have on the Earth's climate, and thus on

41 the well-being of today's and future generations of people and on all creatures and species  
42 of creation.

43 Burning of fossil fuels, primarily coal, oil and gas, increases the amount of carbon  
44 dioxide (CO<sub>2</sub>) and other gases and particles in the air. These gases and particles affect  
45 the Earth's energy balance, changing both the amount of sunlight absorbed by the planet  
46 and the emission of heat (long wave or thermal radiation) to space. The net effect is a  
47 global warming that has become substantial during the past three decades.

48 Global warming from continued burning of more and more fossil fuels poses clear  
49 dangers for the planet and for the planet's present and future inhabitants. Coal is the  
50 largest contributor to the human-made increase of CO<sub>2</sub> in the air. Saving the planet and  
51 creation surely requires phase-out of coal use except where the CO<sub>2</sub> is captured and  
52 sequestered (stored in one of several possible ways).

53 **Q. Coal is only one of the fossil fuels. Can such a strong statement specifically against**  
54 **coal be justified, given still-developing understanding of climate change?**

55 A. Yes. Coal reserves contain much more carbon than do oil and natural gas reserves, and it  
56 is impractical to capture CO<sub>2</sub> emissions from the tailpipes of vehicles. Nor is there any  
57 prospect that Saudi Arabia, Russia, the United States and other major oil-producers will  
58 decide to leave their oil in the ground. Thus unavoidable CO<sub>2</sub> emissions from oil and gas  
59 in the next few decades will take atmospheric CO<sub>2</sub> amounts close to, if not beyond, the  
60 level needed to cause dangerous climate change. The only practical way to prevent CO<sub>2</sub>  
61 levels from going far into the dangerous range, with disastrous effects for humanity and  
62 other inhabitants of the planet, is to phase out use of coal except at power plants where  
63 the CO<sub>2</sub> is captured and sequestered.

64 **Q. But why focus on a coal plant in Iowa? Coal-fired power plants are being built at a**  
65 **much faster rate in China.**

66 A. The United States is responsible for more than three times as much of the excess CO<sub>2</sub> in  
67 the air than any other country. The United States and Europe together are responsible for  
68 well over half of the increase from the pre-industrial CO<sub>2</sub> amount (280 ppm, ppm = parts  
69 per million) to the present-day CO<sub>2</sub> amount (about 385 ppm). The United States will  
70 continue to be most responsible for the human-made CO<sub>2</sub> increase for the next few  
71 decades, even though China's ongoing emissions will exceed those of the United States.  
72 Although a portion of human-made CO<sub>2</sub> emissions is taken up by the ocean, there it  
73 exerts a 'back pressure' on the atmosphere, so that, in effect, a substantial fraction of past  
74 emissions remains in the air for many centuries, until it is incorporated into ocean  
75 sediments. Furthermore, even as China's emissions today approximately equal those of  
76 the United States, China's per capita CO<sub>2</sub> emissions are only about 20% of those in the  
77 United States.

78 China, India and other developing countries must be part of the solution to global  
79 warming, and surely they will be, if developed countries take the appropriate first steps.  
80 China and India have the most to lose from uncontrolled climate change, as they have  
81 huge populations living near sea level, and they have the most to gain from reduced local  
82 air pollution. Analogous to the approach of the Montreal Protocol, developing countries,  
83 with technical assistance, will need to reduce their emissions soon after the developed  
84 world reduces its emissions.

85 Furthermore, it makes economic sense for the United States to begin strong actions now  
86 to reduce emissions. Required technology developments in efficiency, renewable

87 energies, truly clean coal, biofuels, and advanced nuclear power will produce good high-  
88 tech jobs and provide a basis for international trade that allows recovery of some of the  
89 wealth that the country has been hemorrhaging to China.

90 **Q. How can one power plant in Iowa be of any significance in comparison with many**  
91 **power-plants in China?**

92 A. The Iowa power plant can make an important difference because of tipping points in the  
93 climate system, tipping points in life systems, and tipping points in social behavior. A  
94 tipping point occurs in a system with positive feedbacks. When forcing toward a change,  
95 and change itself, become large enough, positive feedbacks can cause a sudden  
96 acceleration of change with very little, if any, additional forcing.

97 Arctic sea ice is an example of a tipping point in the climate system. As the warming  
98 global ocean transports more heat into the Arctic, sea ice cover recedes and the darker  
99 open ocean surface absorbs more sunlight. The ocean stores the added heat, winter sea  
100 ice is thinner, and thus increased melting can occur in following summers, even though  
101 year-to-year variations in sea ice area will occur with fluctuations of weather patterns and  
102 ocean heat transport.

103 Arctic sea ice loss can pass a tipping point and proceed rapidly. Indeed, the Arctic sea  
104 ice tipping point has been reached. However, the feedbacks driving further change are  
105 not 'runaway' feedbacks that proceed to loss of all sea ice without continued forcing.  
106 Furthermore, sea ice loss is reversible. If human-made forcing of the climate system is  
107 reduced, such that the planetary energy imbalance becomes negative, positive feedbacks  
108 will work in the opposite sense and sea ice can increase rapidly, just as sea ice decreased  
109 rapidly when the planetary energy imbalance was positive.

110 Planetary energy imbalance can be discussed quantitatively later, including all of the  
111 factors that contribute to it. However, it is worth noting here that the single most  
112 important action needed to decrease the present large planetary imbalance driving climate  
113 change is curtailment of CO<sub>2</sub> emissions from coal burning. Unless emissions from coal  
114 burning are reduced, actions to reduce other climate forcings cannot stabilize climate.

115 The most threatening tipping point in the climate system is the potential instability of  
116 large ice sheets, especially West Antarctica and Greenland. If disintegration of these ice  
117 sheets passes their tipping points, dynamical collapse of the West Antarctic ice sheet and  
118 part of the Greenland ice sheet could proceed out of our control. The ice sheet tipping  
119 point is especially dangerous because West Antarctica alone contains enough water to  
120 cause about 20 feet (6 meters) of sea level rise.

121 Hundreds of millions of people live less than 20 feet above sea level. Thus the number of  
122 people affected would be 1000 times greater than in the New Orleans Katrina disaster.  
123 Although Iowa would not be directly affected by sea level rise, repercussions would be  
124 worldwide.

125 Ice sheet tipping points and disintegration necessarily unfold more slowly than tipping  
126 points for sea ice, on time scales of decades to centuries, because of the greater inertia of  
127 thick ice sheets. But that inertia is not our friend, as it also makes ice sheet disintegration  
128 more difficult to halt once it gets rolling. Moreover, unlike sea ice cover, ice sheet  
129 disintegration is practically irreversible. Nature requires thousands of years to rebuild an  
130 ice sheet. Even a single millennium, about 30 generations for humans, is beyond the time  
131 scale of interest or comprehension to most people.

132 Because of the danger of passing the ice sheet tipping point, even the emissions from one  
133 Iowa coal plant, with emissions of 5,900,000 tons of CO<sub>2</sub> per year and 297,000,000 over  
134 50 years could be important as “the straw on the camel’s back”. The Iowa power plant  
135 also contributes to tipping points in life systems and human behavior.

136 **Q. How can Iowa contribute to tipping points in life systems and human behavior?**

137 There are millions of species of plants and animals on Earth. These species depend upon  
138 each other in a tangled web of interactions that humans are only beginning to fathom.  
139 Each species lives, and can survive, only within a specific climatic zone. When climate  
140 changes, species migrate in an attempt to stay within their climatic niche. However,  
141 large rapid climate change can drive most of the species on the planet to extinction.  
142 Geologic records indicate that mass extinctions, with loss of more than half of existing  
143 species, occurred several times in the Earth’s history. New species developed, but that  
144 process required hundreds of thousands, even millions, of years. If we destroy a large  
145 portion of the species of creation, those that have existed on Earth in recent millennia, the  
146 Earth will be a far more desolate planet for as many generations of humanity as we can  
147 imagine.

148 Today, as global temperature is increasing at a rate of about 0.2°C (0.36°F) per decade,  
149 isotherms (a line of a given average temperature) are moving poleward at a rate of about  
150 50-60 km (35 miles) per decade. Some species are moving, but many can move only  
151 slowly, pathways may be blocked as humans have taken over much of the planet, and  
152 species must deal with other stresses that humans are causing. If the rate of warming  
153 continues to accelerate, the cumulative effect this century may result in the loss of a  
154 majority of existing species.

155 The biologist E.O. Wilson explains that the 21<sup>st</sup> century is a “bottleneck” for species,  
156 because of extreme stresses they will experience, most of all because of climate change.  
157 He foresees a brighter future beyond the fossil fuel era, beyond the human population  
158 peak that will occur if developing countries follow the path of developed countries and  
159 China to lower fertility rates. Air and water can be clean and we can learn to live with  
160 other species of creation in a sustainable way, using renewable energy. The question is:  
161 how many species will survive the pressures of the 21<sup>st</sup> century bottleneck?  
162 Interdependencies among species, some less mobile than others, can lead to collapse of  
163 ecosystems and rapid nonlinear loss of species, if climate change continues to increase.  
164 Coal will determine whether we continue to increase climate change or slow the human  
165 impact. Increased fossil fuel CO<sub>2</sub> in the air today, compared to the pre-industrial  
166 atmosphere, is due 50% to coal, 35% to oil and 15% to gas. As oil resources peak, coal  
167 will determine future CO<sub>2</sub> levels. Recently, after giving a high school commencement  
168 talk in my hometown, Denison, Iowa, I drove from Denison to Dunlap, where my parents  
169 are buried. For most of 20 miles there were trains parked, engine to caboose, half of the  
170 cars being filled with coal. If we cannot stop the building of more coal-fired power  
171 plants, those coal trains will be death trains – no less gruesome than if they were boxcars  
172 headed to crematoria, loaded with uncountable irreplaceable species.  
173 So, how many of the exterminated species should be blamed on the 297,000,000 tons of  
174 CO<sub>2</sub> that will be produced in 50 years by the proposed Sutherland Generating Station  
175 Unit 4 power plant? If the United States and the rest of the world continue with  
176 “business-as-usual” increases in CO<sub>2</sub> emissions, a large fraction of the millions of species  
177 on Earth will be lost and it will be fair to assign a handful of those to Sutherland



178 Generating Station Unit 4, even though we cannot assign responsibility for specific  
179 species. Moreover, the effect of halting construction of this power plant potentially could  
180 be much greater, because of the possibility of positive feedbacks among people.

181 **Q. What tipping points in human behavior are you referring to?**

182 A. As the reality of climate change becomes more apparent, as the long-term consequences  
183 of further climate change are realized, and as the central role of coal in determining future  
184 atmospheric CO<sub>2</sub> is understood, the pressures to use coal only at power plants where the  
185 CO<sub>2</sub> is captured and sequestered will increase. If the public begins to stand up in a few  
186 places and successfully opposes the construction of power plants that burn coal without  
187 capturing the CO<sub>2</sub>, this may begin to have a snowball effect, helping utilities and  
188 politicians to realize that the public prefers a different path, one that respects all life on  
189 the planet.

190 The changes in behavior will need to run much broader and deeper than simply blocking  
191 new dirty coal plants. Energy is essential to our way of life. We will have to find ways  
192 to use energy more efficiently and develop renewable and other forms of energy that  
193 produce little if any greenhouse gases. The reward structure for utilities needs to be  
194 changed such that their profits increase not in proportion to the amount of energy sold,  
195 but rather as they help us achieve greater energy and carbon efficiency. As people begin  
196 to realize that life beyond the fossil fuel era promises to be very attractive, with a clean  
197 atmosphere and water, and as we encourage the development of the technologies needed  
198 to get us there, we should be able to move rapidly toward that goal. But we need tipping  
199 points to get us rolling in that direction.

200 Iowa, and this specific case, can be a tipping point, leading to a new direction. A  
201 message that ‘old-fashioned’ power plants, i.e., those without carbon capture and  
202 sequestration, are no longer acceptable, would be a message of leadership, one that would  
203 be heard across Iowa and beyond the state’s borders.

204 **Q. Alleged implications of continued coal burning without carbon capture are**  
205 **profound and thus require proof of a causal relationship between climate change**  
206 **and CO<sub>2</sub> emissions. What is the nature of recent global temperature change?**

207 A. **Figure 1(a)** shows global mean surface temperature change over the period during which  
208 instrumental measurements are available for most regions of the globe. The warming  
209 since the beginning of the 20<sup>th</sup> century has been about 0.8°C (1.4°F), with three-quarters  
210 of that warming occurring in the past 30 years.

211 **Q. Warming of 0.8°C (1.4°F) does not seem very large. It is much smaller than day to**  
212 **day weather fluctuations. Is such a small warming significant?**

213 A. Yes, and it is important. Chaotic weather fluctuations make it difficult for people to  
214 notice changes of underlying climate (the average weather, including statistics of extreme  
215 fluctuations), but it does not diminish the impact of long-term climate change.

216 First, we must recognize that global mean temperature changes of even a few degrees or  
217 less can cause large climate impacts. Some of these impacts are associated with climate  
218 tipping points, in which large regional climate response happens rapidly as warming  
219 reaches critical levels. Already today’s global temperature is near the level that will  
220 cause loss of all Arctic sea ice. Evidence suggests that we are also nearing the global  
221 temperature level that will cause the West Antarctic ice sheet and portions of the  
222 Greenland ice sheet to become unstable, with potential for very large sea level rise.

223 Second, we must recognize that there is more global warming “in the pipeline” due to  
224 gases humans have already added to the air. The climate system has large thermal  
225 inertia, mainly due to the ocean, which averages 4 km (about 2.5 miles) in depth.  
226 Because of the ocean’s inertia, the planet warms up slowly in response to gases that  
227 humans are adding to the atmosphere. If atmospheric CO<sub>2</sub> and other gases stabilized at  
228 present amounts, the planet would still warm about 0.5°C (about 1°F) over the next  
229 century or two. In addition, there are more gases “in the pipeline” due to existing  
230 infrastructure such as power plants and vehicles on the road. Even as the world begins to  
231 address global warming with improved technologies, the old infrastructure will add more  
232 gases, with still further warming on the order of another 1°F.

233 Third, eventual temperature increases will be much larger in critical high latitude regions  
234 than they are on average for the planet. High latitudes take longer to reach their  
235 equilibrium (long-term) response because the ocean mixes more deeply at high latitudes  
236 and because positive feedbacks increase the response time there. Amplification of high  
237 latitude warming is already beginning to show up in the Northern Hemisphere. **Figure**  
238 **1(b)** is the geographical pattern of mean temperature anomalies for the first six years of  
239 the 21<sup>st</sup> century, relative to the 1951-1980 base period. Note that warming over land  
240 areas is larger than global mean warming, an expected consequence of the large ocean  
241 thermal inertia. Warming is larger at high latitudes than low latitudes, primarily because  
242 of the ice/snow albedo feedback. Warming is larger in the Northern Hemisphere than in  
243 the Southern Hemisphere, primarily because of greater ocean area in the Southern  
244 Hemisphere, and the fact that the entire Southern Ocean surface around Antarctica is  
245 cooled by deep mixing. Also human-caused depletion of stratospheric ozone, a

246 greenhouse gas, has reduced warming over most of Antarctica. This ozone depletion and  
247 CO<sub>2</sub> increase have cooled the stratosphere, increased zonal winds around Antarctica, and  
248 thus warmed the Antarctic Peninsula while limiting warming of most of the Antarctic  
249 continent.

250 Until the past several years, warming has also been limited in Southern Greenland and  
251 the North Atlantic Ocean just southeast of Greenland, an expected effect of deep ocean  
252 mixing in that vicinity. However, recent warming on Greenland is approaching that of  
253 other landmasses at similar latitudes in the Northern Hemisphere. On the long run,  
254 warming on the ice sheets is expected to be at least twice as large as global warming.  
255 Amplification of warming at high latitudes has practical consequences for the entire  
256 globe, especially via effects on ice sheets and sea level. High latitude amplification of  
257 warming is expected on theoretical grounds, it is found in climate models, and it is  
258 confirmed in paleoclimate (ancient climate) records.

259 **Q. But those paleoclimate records show that the Earth's climate has changed by very**  
260 **large amounts many times in the past. For that reason, the NASA Administrator**  
261 **has suggested that we may not need to "wrestle" with human-made climate change.**  
262 **How do you reach a contrary conclusion?**

263 **A.** Paleoclimate data, indeed, reveal large climate changes. But that history of ancient  
264 climate changes shows that modest forcing factors can produce large climate change. In  
265 fact, paleoclimate data provide our most accurate and certain measure of how sensitive  
266 global climate is to climate forcings, including human-made climate forcings.

267 **Q. What is a climate forcing?**

268 A. A climate forcing is an imposed perturbation to the Earth's energy balance, which would  
269 tend to alter the planet's temperature. For example, if the sun were to become 1%  
270 brighter, that would be a forcing somewhat more than  $+2 \text{ W/m}^2$ , because the Earth  
271 absorbs about  $238 \text{ W/m}^2$  of energy from the sun. An increase of greenhouse gases, which  
272 absorb terrestrial heat radiation and thus warm the Earth's surface, is also a positive  
273 forcing. Doubling the amount of atmospheric  $\text{CO}_2$  is a forcing of about  $+4 \text{ W/m}^2$ .

274 Q. **How large are natural climate variations?**

275 A. That depends on the time scale. A useful time scale to examine is the past several  
276 hundred thousand years. There is good data for the temperature, changes of atmospheric  
277 composition, and the most important changes on the Earth's surface. Specifically, we  
278 know the amount of long-lived greenhouse gases,  $\text{CO}_2$ ,  $\text{CH}_4$  and  $\text{N}_2\text{O}$ , as a function of  
279 time from air bubbles in the ice sheets. Ice sheets are formed by snowfall that piles up  
280 year by year and compresses into ice as the weight of snow above increases. The date  
281 when the snow fell is known accurately for about the past 15,000 years from counting  
282 annual layers marked by summer crusting. Annual layers can be clearly distinguished in  
283 the upper part of the ice sheet. Less precise ways of dating ice layers are available for the  
284 entire depth of the ice sheets. The temperature when the snowflakes fell is inferred from  
285 the isotopic composition of the ice.

286 **Figure 2** shows the temperature on the Antarctic ice sheet for the past 425,000 years.  
287 Similar curves are found from Greenland and from alpine ice cores, as well as from ocean  
288 sediment cores. Layered ocean sediments contain the shells of microscopic animals that  
289 lived in the ocean, the proportion of elements in these microscopic shells providing a  
290 measure of the ocean temperature at the time the animals lived. Swings of temperature

291 from warm interglacial periods to ice ages occur worldwide, with the glacial-interglacial  
292 temperature range being typically 3-4°C in the tropics, about 10°C at the poles, and about  
293 5°C on global average.

294 We live today in a warm interglacial period, the Holocene, now almost 12,000 years in  
295 duration. The last ice age peaked about 20,000 years ago. Global mean temperature was  
296 about 5°C colder than today, with an ice sheet more than a mile thick covering Canada  
297 and reaching into the United States, covering the present sites of Seattle, Minneapolis,  
298 and New York. So much water was locked in this ice sheet, and other smaller ice sheets,  
299 that sea level was 110-130 meters (about 350-400 feet) lower during the ice age, thus  
300 exposing large areas of continental shelves.

301 **Figure 3** shows that large changes of sea level are the norm as climate changes. Global  
302 sea level, global temperature, and atmospheric greenhouse gas amounts are obviously  
303 very highly correlated.

304 **Q. The sea level changes are enormous. Is sea level always changing? What have the**  
305 **consequences been?**

306 A. On millennial time scales resolvable in this graph, sea level, CO<sub>2</sub> and global temperature  
307 change together. However, close examination shows that sea level has been stable for  
308 about the past 7000 years. In that period the planet has been warm enough to prevent an  
309 ice sheet from forming on North America, but cool enough for the Greenland and  
310 Antarctic ice sheets to be stable. The fact that the Earth cooled slightly over the past  
311 8000 years probably helped to stop further sea level rise.

312 Sea level stability played a role in the emergence of complex societies. When sea level  
313 was rising at the rate of 1 meter per century or faster biological productivity of coastal

314 waters was limited. Thus it is not surprising that when the world's human population  
315 abandoned mobile hunting and gathering in the Neolithic (12,000-7000 years ago) they  
316 gathered in small villages in foothills and mountains. Day et al. note that within 1000  
317 years of sea level stabilization, urban (>2500 people) societies developed at many places  
318 around the world (**Figure 4**). With the exception of Jericho, on the Jordan River, all of  
319 these first urban sites were coastal, where high protein food sources aided development of  
320 complex civilizations with class distinctions.

321 Modern societies have constructed enormous infrastructure on today's coastlines. More  
322 than a billion people live within 25 meter elevation of sea level. This includes practically  
323 the entire nation of Bangladesh, almost 300 million Chinese, and large populations in  
324 India and Egypt, as well as many historical cities in the developed world, including major  
325 European cities, many cities in the Far East, all major East Coast cities in the United  
326 States, among hundreds of other cities in the world.

327 **Q. How much will sea level rise if global temperature increases several degrees?**

328 A. Our best guide for the eventual long-term sea level change is the Earth's history. The last  
329 time the Earth was 2-3°C warmer than today, about 3 million years ago, sea level was  
330 about 25 meters higher. The last time the planet was 5°C warmer, just prior to the  
331 glaciation of Antarctica about 35 million years ago, there were no large ice sheets on the  
332 planet. Given today's ocean basins, if the ice sheets melt entirely, sea level will rise  
333 about 70 meters (about 230 feet).

334 The main uncertainty about future sea level is the rate at which ice sheets melt. This is a  
335 "nonlinear" problem in which positive feedbacks allow the possibility of sudden ice sheet  
336 collapse and rapid sea level rise. Initial ice sheet response to global warming is

337 necessarily slow, and it is inherently difficult to predict when rapid change would begin.  
338 I have argued that a “business-as-usual” growth of greenhouse gases would yield a sea  
339 level rise this century of more than a meter, probably several meters, because practically  
340 the entire West Antarctic and Greenland ice sheets would be bathed in meltwater during  
341 an extended summer melt season.

342 The Intergovernmental Panel on Climate Change calculated a sea level rise of only 21-51  
343 cm by 2095 for “business-as-usual” scenarios A2 and A1B, but their calculation included  
344 only thermal expansion of the ocean and melting of alpine glaciers, thus omitting the  
345 most critical component of sea level change, that from ice sheets. IPCC noted the  
346 omission of this component in its sea level projections, because it was unable to reach a  
347 consensus on the magnitude of likely ice sheet disintegration. However, much of the  
348 media failed to note this caveat in the IPCC report.

349 Earth’s history reveals many cases when sea level rose several meters per century, in  
350 response to forcings much weaker than present human-made climate forcings. Iceberg  
351 discharge from Greenland and West Antarctica has recently accelerated. It is difficult to  
352 say how fast ice sheet disintegration will proceed, but this issue provides strong incentive  
353 for policy makers to slow down the human-made experiment with our planet.

354 Knowledge of climate sensitivity has improved markedly based on improving  
355 paleoclimate data. The information on climate sensitivity, combined with knowledge of  
356 how sea level responded to past global warming, has increased concern that we could will  
357 to our children a situation in which future sea level change is out of their control.

358 **Q. How can the paleoclimate data reveal the climate sensitivity to forcings?**



359 A. We compare different climate states in the Earth's history, thus obtaining a measure of  
360 how much climate responded to climate forcings in the past. In doing this, we must  
361 define climate forcings and climate feedbacks clearly. Alternative choices for forcings  
362 and feedbacks are appropriate, depending on the time scale of interest.

363 A famous definition of climate sensitivity is from the 'Charney' problem, in which it is  
364 assumed that the distributions of ice sheets and vegetation on the Earth's surface are fixed  
365 and the question is asked: how much will global temperature increase if the amount of  
366 CO<sub>2</sub> in the air is doubled? The Charney climate sensitivity is most relevant to climate  
367 change on the decadal time scale, because ice sheets and forest cover would not be  
368 expected to change much in a few decades or less. However, the Charney climate  
369 sensitivity must be recognized as a theoretical construct. Because of the large thermal  
370 inertia of the ocean, it would require several centuries for the Earth to achieve its  
371 equilibrium response to doubled CO<sub>2</sub>, and during that time changes of ice sheets and  
372 vegetation could occur as 'feedbacks', i.e., as responses of the climate system that  
373 engender further climate change. Feedbacks can either magnify or diminish climate  
374 changes, these effects being defined as positive and negative feedbacks, respectively.

375 Climate feedbacks include changes of atmospheric gases and aerosols (fine particles in  
376 the air). Gases that change in response to climate change include water vapor, but also  
377 the long-lived greenhouse gases, CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O.

378 **Q. Is water vapor not a stronger greenhouse gas than these others?**

379 A. Yes, and that is sometimes a source of confusion. Water vapor readily evaporates into  
380 and condenses out of the atmosphere. The amount of H<sub>2</sub>O in the air is a function of the  
381 climate, primarily a function of temperature. The air holds more water vapor in the

382 summer than in winter, for example. Water vapor is a prime example of what we call  
383 ‘fast’ feedbacks, those feedbacks that respond promptly to changes of climate. Because  
384 H<sub>2</sub>O causes a strong greenhouse effect, and tropospheric H<sub>2</sub>O increases with temperature,  
385 it provides a positive feedback.

386 The Charney climate sensitivity includes the effects of fast feedbacks such as changes of  
387 water vapor and clouds, but it excludes slow feedbacks such as ice sheets. We obtain an  
388 empirical measure of the equilibrium Charney climate sensitivity by comparing  
389 conditions on Earth during the last ice age, about 20,000 years ago with the conditions in  
390 the present interglacial period prior to major human-made effects. Averaged over a  
391 period of say 1000 years, the planet in each of these two states, glacial and interglacial,  
392 had to be in energy balance with space within a small fraction of 1 W/m<sup>2</sup>. Because the  
393 amount of incoming sunlight was practically the same in both periods, the 5°C difference  
394 in global temperature between the ice age and the interglacial period had to be maintained  
395 by changes of atmospheric composition and changes of surface conditions. Both of these  
396 are well known.

397 **Figure 5** shows that there was a lesser amount of long-lived greenhouse gases in the air  
398 during the last ice age. These gases affect the amount of thermal radiation to space, and  
399 they have a small impact on the amount of absorbed solar energy. We can compute the  
400 climate forcing due to the glacial-interglacial change of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O with high  
401 accuracy. The effective climate forcing, including the indirect effect of CH<sub>4</sub> on other  
402 gases, is  $3 \pm 0.5$  W/m<sup>2</sup>.

403 Changes on the Earth’s surface also alter the energy balance with space. The greatest  
404 change is due to the large ice sheets during the last ice age, whose high albedo

405 ('whiteness' or reflectivity) caused the planet to absorb less solar radiation. Smaller  
406 effects were caused by the altered vegetation distribution and altered shorelines due to  
407 lower sea level during the ice age. The climate forcing due to all these surface changes is  
408  $3.5 \pm 1 \text{ W/m}^2$ .

409 Thus the glacial-interglacial climate change of  $5^\circ\text{C}$  was maintained by a forcing of about  
410  $6.5 \text{ W/m}^2$ , implying a climate sensitivity of about  $\frac{3}{4}^\circ\text{C}$  per  $\text{W/m}^2$ . This empirical climate  
411 sensitivity includes all fast feedbacks that exist in the real world, including changes of  
412 water vapor, clouds, aerosols, and sea ice. Doubled  $\text{CO}_2$  is a forcing of  $4 \text{ W/m}^2$ , so the  
413 Charney climate sensitivity is  $3 \pm 1^\circ\text{C}$  for doubled  $\text{CO}_2$ . Climate models yield a similar  
414 value for climate sensitivity, but the empirical result is more precise and it surely includes  
415 all real world processes with 'correct' physics.

416 **Q. This climate sensitivity was derived from two specific points in time. How general is**  
417 **the conclusion?**

418 A. We can check climate sensitivity for the entire past 425,000 years. Ice cores (**Figure 5**)  
419 provide a detailed record of long-lived greenhouse gases. A measure of surface  
420 conditions is provided by sediment cores from the Red Sea and other places, which yield  
421 a record of sea level change (**Figure 6a**). Sea level tells us how large the ice sheets were,  
422 because water that was not in the ocean was locked in the ice sheets. Greenhouse gas and  
423 sea level records allow us to compute the climate forcings due to both atmospheric and  
424 surface changes for the entire 425,000 years.

425 When the sum of greenhouse gas and surface albedo forcings (**Figure 6b**) is multiplied  
426 by the presumed climate sensitivity of  $\frac{3}{4}^\circ\text{C}$  per  $\text{W/m}^2$  the result is in remarkably good  
427 agreement with 'observed' global temperature change (**Figure 6c**) implied by Antarctic

428 temperature change. Therefore this climate sensitivity has general validity for this long  
429 period. This is the Charney climate sensitivity, which includes fast feedback processes  
430 but specifies changes of greenhouse gases and surface conditions.

431 It is important to note that these changing boundary conditions (the long-lived  
432 greenhouse gases and surface albedo) are themselves feedbacks on long time scales. The  
433 cyclical climate changes from glacial to interglacial times are driven by very small  
434 forcings, primarily by minor perturbations of the Earth's orbit about the sun and by the  
435 tilt of the Earth's spin axis relative to the plane of the orbit.

436 **Q. Can you clarify cause and effect for these natural climate changes?**

437 A. **Figure 7** is useful for that purpose. It compares temperature change in Antarctica with  
438 the greenhouse gas forcing. Temperature and greenhouse gas amounts are obtained from  
439 the same ice core, which reduces uncertainty in their sequencing despite substantial  
440 uncertainty in absolute dating. There is still error in dating temperature change relative to  
441 greenhouse gas change, because of the time needed for ice core bubble closure.  
442 However, that error is small enough that we can infer, as shown in **Figure 7b**, that the  
443 temperature change tends to slightly precede (by several hundred years) the greenhouse  
444 gas changes. Similarly, although the relative dating of sea level and temperature changes  
445 are less accurate, it is clear that warming usually precedes ice melt and sea level rise.

446 These sequencings are not surprising. They show that greenhouse gas changes and ice  
447 sheet area changes act as feedbacks that amplify the very weak forcings due to Earth  
448 orbital changes. The climate changes are practically coincident with the induced changes  
449 of the feedbacks (**Figure 7**). The important point is that the mechanisms for the climate  
450 changes, the mechanisms substantially affecting the planet's radiation balance and thus

451 the temperature, are the atmospheric greenhouse gases and the surface albedo. Earth  
452 orbital changes induce these mechanisms to change, for example, as the tilt of the spin  
453 axis increases both poles are exposed to increased sunlight. Changed insolation affects  
454 the melting of ice and, directly and indirectly, the uptake and release of greenhouse gases.

455 **Q. What is the implication for the present era and the role of humans in climate?**

456 A. The chief implication is that humans have taken control of global climate. This follows  
457 from **Figure 8**, which extends records of the principal greenhouse gases to the present.  
458 CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O (not shown) are far outside their range of the past 800,000 years for  
459 which ice core records of atmospheric composition are available.

460 **Q. Yet the global warming also shown in Figure 8 does not seem to be commensurate**  
461 **with the greenhouse gas increases, if we were to use the paleoclimate as a guide.**

462 **Can you explain that?**

463 A. Yes. Observed warming is in excellent agreement with climate model calculations for  
464 observed greenhouse gas changes. Two factors must be recognized.

465 First, the climate system has not had enough time to fully respond to the human-made  
466 climate forcings. The time scale after 1850 is greatly expanded in **Figure 8**. The  
467 paleoclimate portion of the graph shows the near-equilibrium (~1000 year) response to  
468 slowly changing forcings. In the modern era, most of the net human-made forcing was  
469 added in the past 30 years, so the ocean has not had time to fully respond and the ice  
470 sheets are just beginning to respond to the present forcing.

471 Second, the climate system responds to the net forcing, which is only about half as large  
472 as the greenhouse gas forcing. The net forcing is reduced by negative forcings, especially  
473 human-made aerosols (fine particles).

474 **Q. But is not the natural system driving the Earth toward colder climates?**

475 A. If there were no humans on the planet, the long term trend would be toward colder  
476 climate. However, the two principal mechanisms for attaining colder climate would be  
477 reduced greenhouse gas amounts and increased ice cover. The feeble natural processes  
478 that would push these mechanisms in that direction (toward less greenhouse gases and  
479 larger ice cover) are totally overwhelmed by human forcings. Greenhouse gas amounts  
480 are skyrocketing out of the normal range and ice is melting all over the planet. Humans  
481 now control global climate, for better or worse.

482 Another ice age cannot occur unless humans go extinct, or unless humans decide that  
483 they want an ice age. However, ‘achieving’ an ice age would be a huge task. In contrast,  
484 prevention of an ice age is a trivial task for humans, requiring only a ‘thimbleful’ of  
485 CFCs (chlorofluorocarbons), for example. The problem is rather the opposite, humans  
486 have already added enough greenhouse gases to the atmosphere to drive global  
487 temperature well above any level in the Holocene.

488 **Q. How much warmer will the Earth become for the present level of greenhouse gases?**

489 A. That depends on how long we wait. The Charney climate sensitivity (3°C global  
490 warming for doubled CO<sub>2</sub>) does not include slow feedbacks, principally disintegration of  
491 ice sheets and poleward movement of vegetation as the planet warms. When the long-  
492 lived greenhouse gases are changed arbitrarily, as humans are now doing, this change  
493 becomes the predominant forcing, and ice sheet and vegetation changes must be included  
494 as part of the response in determining long-term climate sensitivity.

495 It follows from **Figure 7** that equilibrium climate sensitivity is 6°C for doubled CO<sub>2</sub>  
496 (forcing of 4 W/m<sup>2</sup>) when greenhouse gases are the forcing, not 3°C. (Note: the

497 Antarctic temperature change, shown in **Figure 7**, is about twice the global mean  
498 change.) To achieve this full response we must wait until ice sheets have had time to  
499 melt and forests have had time to migrate. This may require hundreds of years, perhaps  
500 thousands of years. However, elsewhere we have discussed evidence that forests are  
501 already moving and ice sheet albedos are already responding to global warming, so  
502 climate sensitivity is already partially affected by these processes.

503 Thus the relevant equilibrium climate sensitivity on the century time scale falls  
504 somewhere between 3°C and 6°C for doubled CO<sub>2</sub>. The expected temperature change in  
505 the 21<sup>st</sup> century cannot be obtained by simply multiplying the forcing by the sensitivity,  
506 as we could in the paleoclimate case, because a century is not long enough to achieve the  
507 equilibrium response. Instead we must make computations with a model that includes the  
508 ocean thermal inertia, as is done in climate model simulations. However, these models  
509 do not include realistically all of the slow feedbacks, such as ice sheet and forest  
510 dynamics.

511 **Q. The huge climate changes over the past few hundred thousand years show the**  
512 **dramatic effects accompanying global temperature change of only a few degrees.**  
513 **And you infer climate sensitivity from the documented climate variations. Yet the**  
514 **climate changes and mechanisms are intricate, and it is difficult for the lay person to**  
515 **grasp the details of these analyses. Is there other evidence supporting the conclusion**  
516 **that burning of the fossil fuels will have dramatic effects upon life on Earth?**

517 A. Yes. Climate fluctuations in the Pleistocene (past 1.8 million years) are intricate, as  
518 small forcings are amplified by feedbacks, including ‘carbon cycle’ feedbacks.  
519 Atmospheric CO<sub>2</sub> varies a lot because carbon is exchanged among its surface reservoirs:

520 the atmosphere, ocean, soil, and biosphere. For example, the solubility of CO<sub>2</sub> in the  
521 ocean decreases as the ocean warms, a positive feedback causing much of the  
522 atmospheric CO<sub>2</sub> increase with global warming. That feedback is simple, but the full  
523 story of how weak forcings create large climate change is indeed complex.

524 A useful complement to Pleistocene climate fluctuations is provided by longer time  
525 scales with larger CO<sub>2</sub> changes than those caused by orbital oscillations. Larger CO<sub>2</sub>  
526 changes occur on long time scales because of transfer of carbon between the solid earth  
527 and the surface reservoirs. The large CO<sub>2</sub> changes on these long time scales allow the  
528 Earth orbital climate oscillations to be viewed as 'noise'. Thus long time scales help  
529 provide a broader overview of the effect of changing atmospheric composition on  
530 climate.

531 A difficulty with long time scales is that knowledge of atmospheric composition changes  
532 is not as good. Samples of ancient air preserved in ice cores exist for only about one  
533 million years. But there are indirect ways of measuring ancient CO<sub>2</sub> levels to better than  
534 a factor of two beyond one million years ago. Atmospheric composition and other  
535 climate forcings are known well enough for the combination of Pleistocene climate  
536 variations and longer-term climate change to provide an informative overview of climate  
537 sensitivity and a powerful way to assess the role of humans in altering global climate.

538 **Q. What determines the amount of CO<sub>2</sub> in the air on long time scales?**

539 On long (geologic) time scales CO<sub>2</sub> is exchanged between the surface reservoirs  
540 (atmosphere, ocean, soil and biosphere) and the solid Earth. Two processes take CO<sub>2</sub> out  
541 of the surface reservoirs: (1) chemical weathering of silicate rocks, which results in the  
542 deposition of (calcium and magnesium) carbonates on the ocean floor, and (2) burial of



543 organic matter, some of which eventually forms fossil fuels. Weathering is the more  
544 dominant process, accounting for ~80% of carbon removal from surface reservoirs.  
545 CO<sub>2</sub> is returned to the atmosphere principally via subduction of oceanic crustal plates  
546 beneath continents. When a continental plate overrides carbonate-rich ocean crust, the  
547 subducted ocean crust experiences high temperatures and pressures. Resulting  
548 metamorphism of the subducted crust into various rock types releases CO<sub>2</sub>, which makes  
549 its way to the atmosphere via volcanic eruptions or related phenomena such as ‘seltzer’  
550 spring water. This return of CO<sub>2</sub> to the atmosphere is called ‘outgassing’.

551 Outgassing and burial of CO<sub>2</sub>, via weathering and organic deposits, are not in general  
552 balanced at any given time. Depending on the movement of continental plates, the  
553 locations of carbonate-rich ocean crust, rates of mountain-building (orogeny), and other  
554 factors, at any given time there can be substantial imbalance between outgassing and  
555 burial. As a result, atmospheric CO<sub>2</sub> changes by large amounts on geologic time scales.

556 **Q. How much do these geologic processes change atmospheric CO<sub>2</sub>?**

557 A. Rates of outgassing and burial of CO<sub>2</sub> are each typically  $2-4 \times 10^{12}$  mol C/year. An  
558 imbalance between outgassing and burial of say  $2 \times 10^{12}$  mol C/year, if confined  
559 entirely to the atmosphere, would correspond to ~0.01 ppm CO<sub>2</sub> per year. However, the  
560 atmosphere contains only of order  $10^{-2}$ , i.e., about 1%, of the total CO<sub>2</sub> in the surface  
561 carbon reservoirs (atmosphere, ocean, soil, biosphere), so the rate of geologic changes to  
562 atmospheric CO<sub>2</sub> is only about 0.0001 ppm CO<sub>2</sub> per year. This compares to the present  
563 human-made atmospheric CO<sub>2</sub> increase of ~2 ppm per year. Fossil fuels burned now by  
564 humans in one year contain the amount of carbon buried in organic sediments in  
565 approximately 100,000 years.

566 The contribution of geologic processes to atmospheric CO<sub>2</sub> change is negligible  
567 compared to measured human-made changes today. However, in one million years a  
568 geologic imbalance of 0.0001 ppm CO<sub>2</sub> per year yields a CO<sub>2</sub> change of 100 ppm. Thus  
569 geologic changes over tens of millions of years can include huge changes of atmospheric  
570 CO<sub>2</sub>, of the order of 1000 ppm of CO<sub>2</sub>. As a result, examination of climate changes on  
571 the time scale of tens of millions of years has the potential to yield a valuable perspective  
572 on how climate changes with atmospheric composition.

573 **Q. What is the most useful geologic era to consider for that purpose?**

574 A. The Cenozoic era, the past 65 million years, is particularly valuable for several reasons.  
575 First, we have the most complete and most accurate climate data for the most recent era.  
576 Second, climate changes in that era are large enough to include ice-free conditions.  
577 Third, we know that atmospheric greenhouse gases were the principal global forcing  
578 driving climate change in that era.

579 **Q. How do you know that greenhouse climate forcing was dominant in the Cenozoic?**

580 A. Climate forcings, perturbations of the planet's energy balance, must arise from either  
581 changes in the incoming energy, changes that alter the planetary surface, or changes  
582 within the atmosphere. Let us examine these three in turn.

583 Solar luminosity is growing on long time scales, at a rate such that the sun was ~0.5%  
584 dimmer than today in the early Cenozoic. Because the Earth absorbs about 240 W/m<sup>2</sup> of  
585 solar energy, the solar climate forcing at the beginning of the Cenozoic was about -1  
586 W/m<sup>2</sup> relative to today. This small growth of solar forcing through the Cenozoic era, as  
587 we will see, is practically negligible.

588 Changing size and location of continents can be an important climate forcing, as the  
589 albedo of the Earth's surface depends on whether the surface is land or water and on the  
590 angle at which the sun's rays strike the surface. A quarter of a billion years ago the major  
591 continents were clumped together (**Figure 9**) in the super-continent Pangea centered on  
592 the equator. However, by the beginning of the Cenozoic (65 million years before present,  
593 65 My BP, the same as the end of the Cretaceous) the continents were close to their  
594 present latitudes. The direct (radiative) climate forcing due to this continental drift is no  
595 more than  $\sim 1 \text{ W/m}^2$ .

596 In contrast, atmospheric  $\text{CO}_2$  reached levels of 1000-2000 ppm in the early Cenozoic,  
597 compared with values as low as  $\sim 180$  ppm during recent ice ages. This range of  $\text{CO}_2$   
598 encompasses about three  $\text{CO}_2$  doublings and thus a climate forcing more than  $10 \text{ W/m}^2$ .  
599 So it is clear that changing greenhouse gases provided the dominant global climate  
600 forcing through the Cenozoic era.

601 We are not neglecting the fact that dynamical changes of ocean and atmospheric currents  
602 can affect global mean climate. Climate variations in the Cenozoic are too large to be  
603 accounted for by such dynamical hypotheses.

604 **Q. What caused atmospheric  $\text{CO}_2$  amount to change?**

605 A. At the beginning of the Cenozoic era, 65 My BP, India was just south of the Equator  
606 (**Figure 9**), but moving north rapidly, at about 15 cm/year. The Tethys Ocean, separating  
607 Eurasia from India and Africa, was closing rapidly. The Tethys Ocean had long been a  
608 depocenter for carbonate sediments. Thus prior to the collision of the Indian and African  
609 plates with the Eurasian plate, subduction of carbonate-rich oceanic crust caused  
610 outgassing to exceed weathering, and atmospheric  $\text{CO}_2$  increased.

611 The Indo-Asian collision at ~50 My BP initiated massive uplift of the Himalayas and the  
612 Tibetan Plateau, and subsequently drawdown of atmospheric CO<sub>2</sub> by weathering has  
613 generally exceeded CO<sub>2</sub> outgassing. Although less important, the Alps were formed in  
614 the same time frame, as the African continental plate pushed against Eurasia. With the  
615 closing of the Tethys Ocean, the major depocenters for carbonate sediments became the  
616 Indian and Atlantic oceans, because the major rivers of the world empty into those basins.  
617 For the past 50 million years and continuing today, regions of subduction of carbonate  
618 rich ocean crust have been limited. Thus, while the oceans have been a strong sink for  
619 carbonate sediments, little carbonate is being subducted and returned to the atmosphere  
620 as CO<sub>2</sub>. As a result, over the past 50 million years there has been a long-term decline of  
621 greenhouse gases and global temperature.

622 **Q. Can you illustrate this long-term cooling trend?**

623 A. Yes. **Figure 10a** shows a quantity,  $\delta^{18}\text{O}$ , that provides an indirect measure of global  
624 temperature over the Cenozoic era, with a caveat defined below.  $\delta^{18}\text{O}$  defines the amount  
625 of the heavy oxygen isotope <sup>18</sup>O found in the shells of microscopic animals  
626 (foraminifera) that lived in the ocean and were deposited in ocean sediments. By taking  
627 ocean cores of the sediments we can sample shells deposited over time far into the past.  
628 **Figure 10a** shows the average result from many ocean cores around the world obtained  
629 in deep sea drilling programs.

630 The proportion of  $\delta^{18}\text{O}$  in the foraminifera shell depends on the ocean water temperature  
631 at the time the shell was formed, and thus  $\delta^{18}\text{O}$  provides a proxy measure of temperature.  
632 However, an ice sheet forming on the Earth's surface has an excess of <sup>16</sup>O in its H<sub>2</sub>O  
633 molecules, because <sup>16</sup>O evaporates from the ocean more readily than <sup>18</sup>O, leaving behind

634 a relative excess of  $^{18}\text{O}$  in the ocean. As long as the Earth was so warm that little ice  
635 existed on the planet, as was the case between 65 My BP and 35 My BP,  $^{18}\text{O}$  yields a  
636 direct measure of temperature, as indicated by the red curve and the temperature scale on  
637 the left side of **Figure 10a**.

638 The sharp change of  $\delta^{18}\text{O}$  at about 34 My BP was due to rapid glaciation of the Antarctic  
639 continent. From 34 My BP to the present,  $\delta^{18}\text{O}$  changes reflect both ice volume and  
640 ocean temperature changes. We cannot separate the contributions of these two processes,  
641 but both increasing ice volume and decreasing temperature change  $\delta^{18}\text{O}$  in the same  
642 sense, so the  $\delta^{18}\text{O}$  curve continues to be a qualitative measure of changing global  
643 temperature, chronicling the continuing long-term cooling trend of the planet over the  
644 past 50 million years.

645 The black curve in **Figure 10a** shows the rapid glacial-interglacial temperature  
646 oscillations, which are smoothed out in the mean (red and blue) curves. **Figure 10b**  
647 expands the time scale for the most recent 3.5 million years, so that the glacial-  
648 interglacial fluctuations are clearer. **Figure 10c** further expands the most recent 425,000  
649 years, showing the familiar Pleistocene ice ages punctuated by brief interglacial periods.  
650 Note that the period of civilization within the Holocene is invisibly brief with the  
651 resolution in **Figure 10a**. *Homo sapiens* have been present for about 200,000 years, and  
652 the predecessor species, *Homo erectus*, for about 2 million years, still rather brief on the  
653 time scale of **Figure 10a**.

654 **Q. Can you explain the nature of the global climate change illustrated in Figure 10?**

655 A. The long-term cooling from 50 My BP to the present must be due primarily to decreasing  
656 greenhouse gases, primarily  $\text{CO}_2$ , which fell from 1000-2000 ppm 50 My BP to 180-280

657 ppm in recent glacial-interglacial periods. Full glaciation of Antarctica, at about 34 My  
658 BP, occurred when CO<sub>2</sub> fell to 500 ±150 ppm.

659 Between 34 and 15 My BP global temperature fluctuated, with Antarctica losing most of  
660 its ice at about 27 My BP. Antarctica did not become fully glaciated again until about 15  
661 My BP. Deglaciation of Antarctica was associated with increased atmospheric CO<sub>2</sub>,  
662 perhaps due to the negative feedback caused by reduction of weathering as ice and snow  
663 covered Antarctica as well as the higher reaches of the Himalayas and the Alps.

664 Cooling and ice growth resumed at about 15 My BP continuing up to the current  
665 Pleistocene ice age. During the past 15 My CO<sub>2</sub> was at a low level, about 200-400 ppm  
666 and its proxy measures are too crude to determine whether it had a long-term trend. Thus  
667 it has been suggested that the cooling trend may have been due to a reduction of poleward  
668 ocean heat transports, perhaps caused by the closing of the Isthmus of Panama at about  
669 12 My BP or the steady widening of the oceanic passageway between South America and  
670 Antarctica.

671 We suggest that the global cooling trend after 15 My BP may due to continued drawdown  
672 of atmospheric CO<sub>2</sub> of a degree beneath the detection limit of proxy measures. Little  
673 additional drawdown would be needed, because the increasing ice cover on the planet  
674 makes climate sensitivity extremely high, and the logarithmic nature of CO<sub>2</sub> forcing  
675 makes a small CO<sub>2</sub> change very effective at low CO<sub>2</sub> amounts. There are reasons to  
676 expect CO<sub>2</sub> drawdown in this period: the Andes were rising rapidly in this period, at a  
677 rate of about 1 mm per year (1 km per My). The mass of the Andes increased so much as  
678 to slow down the convergence of the Nazca and South American plates by 30% in the  
679 past 3.2 My. Increased weathering and reduced subduction both contribute to drawdown

680 of atmospheric CO<sub>2</sub>. Finally, a suggestion that CO<sub>2</sub> has been declining over the relevant  
681 period is provided by the increase of C4 plants relative to C3 plants that occurred  
682 between 8 and 5 My BP; C4 plants are more resilient to low atmospheric CO<sub>2</sub> levels (C4  
683 and C3 photosynthesis are alternative biochemical pathways for fixing carbon, the C4  
684 path requiring more energy but being more tolerant of low CO<sub>2</sub> and drought conditions).  
685 However, given the high climate sensitivity with large ice cover, other small forcings  
686 could have been responsible for the cooling trend without additional CO<sub>2</sub> decline.

687 In summary, there are many uncertainties about details of climate change during the  
688 Cenozoic era. Yet important conclusions emerge, as summarized in **Figure 11**. The  
689 dominant forcing that caused global cooling, from an ice free planet to the present world  
690 with large ice sheets on two continents, was a decrease in atmospheric CO<sub>2</sub>. Human-  
691 made rates of change of climate forcings, including CO<sub>2</sub>, now dwarf the natural rates.

692 **Q. Is this relevant to the question of whether we need to “wrestle” with climate change?**

693 A. Yes, it may help resolve the conundrum sensed by some lay persons based on realization  
694 that the natural world has undergone huge climate variations in the past. That is true, but  
695 those climate variations produced a different planet. If we follow “business as usual”  
696 greenhouse gas emissions, putting back into the air a large fraction of the carbon that was  
697 stored in the ground over millions of years, we surely will set in motion large climate  
698 changes with dramatic consequences for humans and other species.

699 **Q. Why are climate fluctuations in the past few million years (Figure 10b) so regular?**

700 A. The instigator is the distribution of sunlight on the Earth, which continuously changes by  
701 a small amount because of the gravitational pull of other planets, especially Jupiter and  
702 Saturn, because they are heavy, and Venus, because it comes close. The most important

703 effect is on the tilt of the Earth's spin axis relative to the plane of the Earth's orbit  
704 (**Figure 12**). The tilt varies by about  $2^\circ$  with a regular periodicity of about 41 Ky (41,000  
705 years). When the tilt is larger it exposes both polar regions to increased sunlight at 6-  
706 month intervals. The increased heating of the polar regions melts ice in both  
707 hemispheres.

708 The 41 Ky climate variability is apparent in **Figure 10b** and is present in almost all  
709 climate records. However, glacial-interglacial climate variations became more complex  
710 in the most recent 1.2 My, with large variations at  $\sim 100$  Ky periodicity, as well as  $\sim 41$  Ky  
711 and  $\sim 23$  Ky periods. As the planet became steadily colder over the past several million  
712 years, the amplitude of glacial-interglacial climate swings increased (**Figure 10b**) as ice  
713 sheet area increased. Ice sheets on Northern Hemisphere continents, especially North  
714 America, extended as far south as  $45^\circ\text{N}$  latitude. Similar ice sheets were not possible in  
715 the Southern Hemisphere, which lacked land at relevant latitudes.

716 Hemispheric asymmetry in ice sheet area allows two additional Earth orbital parameters,  
717 which work in concert, to come into play. Gravitational tugs of the planets cause the  
718 eccentricity of the Earth's orbit about the sun to vary from near zero (circular) to an  
719 eccentricity of about 0.06. When the orbit is significantly non-circular, this allows  
720 another orbital parameter, axial precession, to become important. Precession, which  
721 determines the date in the year at which the Earth in its elliptical orbit is closest to the  
722 sun, varies with a periodicity of ca. 23 Ky. When the Earth is closest to the sun in  
723 Northern Hemisphere winter, thus furthest from the sun in summer, ice sheet growth in  
724 the Northern Hemisphere is encouraged by increased winter snowfall and cool summers.  
725 The effect of eccentricity + precession on ice sheet growth is opposite in the two



726 hemispheres, so the effect is important only when the area of high albedo ice and snow is  
727 much different in the two hemispheres, as it has been in the past million years. Climate  
728 variations then include all three periodicities, ~23 Ky precession, ~41 Ky tilt, and ~100  
729 Ky eccentricity, as has been demonstrated for the recent ice age cycles.

730 **Q. What are the current Earth orbital parameters?**

731 A. Precession has the Earth closest to the sun in January, furthest in July, which would favor  
732 growth of Northern Hemisphere ice. But eccentricity is small, about 0.016, so the  
733 precession effect is not large. Tilt is about midway between its extremes headed toward  
734 smaller tilt, the next minimum tilt occurring in ~10 Ky. Smaller tilt favors ice sheet  
735 growth, so, if it were not for humans, we might expect a trend toward the next ice age.  
736 But the trend may have been weak, because, by the time tilt reaches its minimum, the sun  
737 will be closest to the sun in Northern Hemisphere summer. Thus in this particular cycle  
738 the two mechanisms, tilt and eccentricity + precession, will be working against each  
739 other, rather than reinforcing each other. In any event, this natural tendency has become  
740 practically irrelevant in the age of fossil-fuel-burning humans.

741 **Q. Why is the natural glacial-interglacial cycle irrelevant?**

742 A. Earth orbital changes were only pacemakers for glacial-interglacial climate change,  
743 inducing changes of ice area and greenhouse gases. Changes of surface albedo and  
744 greenhouse gases were the mechanisms for climate change, providing the immediate  
745 causes of the climate changes. We showed in **Figure 6** that these two mechanisms  
746 account for the glacial-interglacial climate variations.

747 Now humans are responsible for changes of these climate mechanisms. Greenhouse  
748 gases are increasing far outside the range of natural glacial-interglacial variations (**Figure**

749 **8)** and ice is melting all over the planet. The weak effect of slow orbital changes is  
750 overwhelmed by the far larger and faster human-made changes.

751 Humans are now entirely responsible for long-term climate change (**Figure 13**).  
752 However, it would be misleading to say that humans are “in control”. Indeed, there is  
753 great danger that humans could set in motion future changes that are impossible to  
754 control, because of climate system inertia, positive feedback, and tipping points.

755 **Q. Can we finally finish with this paleoclimate discussion?**

756 A. Please allow one final comment. For the record, since I could only estimate broad ranges  
757 for CO<sub>2</sub> in the Cenozoic era, I should show at least one estimate from the proxy CO<sub>2</sub> data.  
758 **Figure 14A** shows estimated CO<sub>2</sub> for the entire Phanerozoic eon, the past 540 million  
759 years. I show this longer time interval, because it includes CO<sub>2</sub> changes so large as to  
760 make the errors in the proxies less in a relative sense.

761 Geologic evidence for ice ages and cool periods on this long time frame (**Figure 14B**)  
762 shows a strong correlation of climate with CO<sub>2</sub>. Climate variations were huge, ranging  
763 from ice ages with ice sheets as far equatorward as 30 degrees latitude to a much warmer  
764 planet without ice. Although other factors were also involved in these climate changes,  
765 greenhouse gases were a major factor.

766 **Q. Are climate models consistent with paleoclimate estimates of high climate sensitivity  
767 and with observed global warming in the past century?**

768 A. Yes. Climate models yield equilibrium sensitivity (the response after several centuries)  
769 of typically about 3°C for doubled CO<sub>2</sub>. **Figure 15B** shows the resulting global warming  
770 when such a climate model (one with ~3°C sensitivity for doubled CO<sub>2</sub>) is driven by  
771 climate forcings measured or estimated for the period 1880-2003 (**Figure 15A**). The

772 calculated and observed warmings are similar. Good agreement might also be obtained  
773 using a model with higher sensitivity and a smaller forcing or using a model with lower  
774 sensitivity and a larger forcing. But the sensitivity of this model agrees well with the  
775 empirical sensitivity defined by paleoclimate data.

776 **Q. I am confused. Did you not say earlier that climate sensitivity is about 6°C for**  
777 **doubled CO<sub>2</sub>?**

778 A. Yes. That is an important point that needs to be recognized. We showed that the real  
779 world climate sensitivity is 6°C for doubled CO<sub>2</sub>, when both fast and slow feedback  
780 processes are included, based on data that covered climate states ranging from  
781 interglacial periods 1°C warmer than today to ice ages 5°C cooler than today. That 6°C  
782 sensitivity is also the appropriate estimate for the range of warmer climates up to the  
783 point at which all ice sheets are melted and high latitudes are fully vegetated.

784 This higher climate sensitivity, 6°C for doubled CO<sub>2</sub>, is the appropriate sensitivity for  
785 long time scales, when greenhouse gases are the specified forcing mechanism and all  
786 other slow feedbacks are allowed to fully respond to the climate change. The substantial  
787 relevant slow feedbacks are changes of ice sheets and surface vegetation.

788 **Q. Yet you employed a climate model with 3°C sensitivity, a model excluding these slow**  
789 **feedbacks. Does this cause a significant error?**

790 A. No, not in simulations of the 20<sup>th</sup> century climate change as in **Figure 15**. Feedbacks  
791 come into play not in response to climate forcing but in response to climate change.  
792 Ocean thermal inertia introduces a lag, shown by the climate response function in **Figure**  
793 **15c**. The response function is the fraction of the equilibrium surface response that is  
794 achieved at a given time subsequent to introduction of the forcing. About half of the

795 equilibrium response occurs within a quarter century, but further response at the Earth's  
796 surface is slowed by mixing of water between the ocean surface layer and the deeper  
797 ocean. Nearly full response requires several centuries.

798 Furthermore, the response time to a climate forcing increases in proportion to the square  
799 of climate sensitivity, so the response time for 6°C climate sensitivity is about four times  
800 greater than that shown in **Figure 15c**. The explanation for this strong dependence of  
801 response time on climate sensitivity is simple: the rate of heating is fixed, so to warm the  
802 ocean mixed layer would take twice as long for 6°C sensitivity as for 3°C sensitivity. But  
803 this additional time allows more mixing of heat into the deeper ocean. For diffusive  
804 mixing it follows analytically, as shown in the referenced paper, that the response time  
805 goes as the square of climate sensitivity.

806 In addition, some climate feedback processes can increase response time above that  
807 associated with ocean thermal inertia alone. A fast feedback such as atmospheric water  
808 vapor amount occurs almost instantly with temperature change. However, ice sheets  
809 require time to disintegrate or grow, and vegetation migration in response to shifting  
810 climate zones also may require substantial time.

811 Ice sheet and vegetation responses were not important factors affecting the magnitude of  
812 20<sup>th</sup> century global warming, so simulations of 20<sup>th</sup> century global temperature change  
813 were not compromised by exclusion of those feedbacks. However, with a substantial and  
814 almost monotonic global warming now in place (**Figure 1A**), the ice sheet and vegetation  
815 feedbacks should begin to contribute significantly to climate change in the 21<sup>st</sup> century.  
816 Ice sheet and vegetation changes will continue to alter the planetary energy balance over  
817 century time scales and must be accounted for in projecting future climate change.

818 **Q. Can we move on from this technical discussion of feedbacks and response time?**

819 A. Please allow one final comment. The 6°C sensitivity (for doubled CO<sub>2</sub>) is valid for a  
820 specified change of greenhouse gases as the climate forcing. That is relevant for human-  
821 made change of atmospheric composition, and this sensitivity yields the correct answer  
822 for long-term climate change if actual greenhouse gas changes are used as the forcing  
823 mechanism. However, climate model scenarios for the future usually incorporate human-  
824 made emissions of greenhouse gases. Atmospheric greenhouse gas amounts may be  
825 affected by feedbacks, which thus alter expected climate change.

826 Greenhouse gas feedbacks are not idle speculation. Paleoclimate records reveal times in  
827 the Earth's history when global warming resulted in release of large amounts of methane  
828 to the atmosphere. Potential sources of methane include methane hydrates 'frozen' in  
829 ocean sediments and tundra, which release methane in thawing. Recent Arctic warming  
830 is causing release of methane from permafrost, but not to a degree that has prevented near  
831 stabilization of atmospheric methane amount over the past several years.

832 Paleoclimate records show that the positive feedbacks that occur for all major long-lived  
833 greenhouse gases (carbon dioxide, methane, and nitrous oxide) are moderate for global  
834 warming less than 1°C. However, no such constraints exist for still larger global  
835 warming, because there are no recent interglacial periods with global warming greater  
836 than about 1°C. Based on other metrics (avoiding large sea level rise, extermination of  
837 species, and large regional climate disruption) we argue that we must aim to keep  
838 additional global warming, above the level in 2000, less than 1°C. Such a limit should  
839 also avert massive release of frozen methane.

840 **Q. Observed (and modeled) global warming of 0.8°C in the past century seems small in**  
841 **view of the large changes of greenhouse gases shown in Figure 8. Why is that?**

842 A. There are two reasons.

843 First, there is the large thermal inertia of the ocean. It takes a few decades to achieve just  
844 half of the global warming with climate sensitivity of 3°C for doubled CO<sub>2</sub>, as shown in  
845 **Figure 15C**. And the slow feedbacks that contribute half of the paleoclimate change are  
846 now just beginning to come into play.

847 Second, the greenhouse gases are not the only climate forcing. Human-made  
848 tropospheric aerosols, **Figure 15A**, are estimated to cause a negative forcing about half as  
849 large as the greenhouse forcing, but opposite in sign.

850 **Q. There must be some uncertainty in the climate forcings, especially the aerosol**  
851 **forcing. Can you verify that the estimated forcings are realistic?**

852 A. Yes. The aerosol forcing is difficult to verify directly, but there is an exceedingly  
853 valuable diagnostic that relates to the net climate forcing. Given that the greenhouse gas  
854 forcing is known accurately, the constraint on net forcing has implications for the aerosol  
855 forcing, because other forcings are either small or well-measured (**Figure 15A**). The  
856 diagnostic that I refer to is the planetary energy imbalance.

857 The Earth's energy imbalance, averaged over several years, is a critical metric for several  
858 reasons. First and foremost, it is a direct measure of the reduction of climate forcings  
859 required to stabilize climate. The planetary energy imbalance measures the climate  
860 forcing that has not yet been responded to, i.e., multiplication of the energy imbalance by  
861 climate sensitivity defines global warming still "in the pipeline".

862 A good period to evaluate the Earth's energy imbalance is the eleven-year period 1995-  
863 2005, because this covers one solar cycle from solar minimum to solar minimum. A  
864 climate model with sensitivity  $\sim 3^{\circ}\text{C}$  for doubled  $\text{CO}_2$ , driven by the climate forcings in  
865 **Figure 15A**, yields an imbalance of  $0.75 \pm 0.15 \text{ W/m}^2$  for 1995-2005. Observations of  
866 heat gain in measured portions of the upper 700 m of the ocean yield a global heat gain of  
867  $\sim 0.5 \text{ W/m}^2$ . Measured or estimated heat used in sea ice and land ice melt, warming of  
868 ground and air, and ocean warming in polar regions and at depths below 700 m yield a  
869 total estimated heat gain of  $0.75 \pm 0.25 \text{ W/m}^2$ .

870 The observed planetary energy imbalance thus supports the estimated climate forcings  
871 used in the climate simulations of **Figure 15**. This check is not an absolute verification,  
872 because the results also depend upon climate sensitivity, but the model's sensitivity is  
873 consistent with paleoclimate data. Indeed, the existence of a substantial planetary energy  
874 imbalance provides confirmation that climate sensitivity is high. Climate response time  
875 varies as the square of climate sensitivity, so if climate sensitivity were much smaller, say  
876 half as large as indicated by paleoclimate data, it would not be possible for realistic  
877 climate forcings to yield such a large planetary energy imbalance.

878 Comment: The planetary energy imbalance is the single most critical metric for the state  
879 of the Earth's climate. Ocean heat storage is the largest term in this imbalance; it needs  
880 to be measured more accurately, present problems being incomplete coverage of data in  
881 depth and latitude, and poor inter-calibration among different instruments. The other  
882 essential measurement for tracking the energy imbalance is continued precise monitoring  
883 of the ice sheets via gravity satellite measurements.

884 **Q. How much is global warming expected to increase in the present century, and how**  
885 **does this depend upon assumptions about fossil fuel use?**

886 A. We can project future global warming with reasonable confidence, for different assumed  
887 scenarios of greenhouse gases, by extending the climate model simulations that matched  
888 well the observed global temperature change in the past century. **Figure 16** shows such a  
889 projection based on the GISS global climate model, which has climate sensitivity close to  
890 3°C for doubled CO<sub>2</sub>. The model excludes slow climate feedbacks such as changes of ice  
891 sheet area and global vegetation distributions, but the effects of those slow feedbacks on  
892 global mean temperature should be small during the next several decades.

893 ‘Business-as-Usual’ climate scenarios, such as IPCC scenarios A1B and A2, yield  
894 additional global warming of at least 2°C in the 21<sup>st</sup> century. Actual warming for  
895 ‘business-as-usual’ climate forcing could be larger because: (1) slow climate feedbacks  
896 such as ice sheet disintegration, vegetation migration, and methane release from melting  
897 permafrost are not included, (2) atmospheric aerosols (small particles, especially sulfates)  
898 that have a cooling effect are kept fixed, but it is expected that they could decrease this  
899 century, (3) CO<sub>2</sub> emissions as high as in business-as-usual scenarios may have climate  
900 effects large enough to alter the ability of the biosphere to take up the assumed proportion  
901 of CO<sub>2</sub> emissions.

902 The ‘alternative scenario’ is defined with the aim of keeping additional global warming,  
903 beyond that of 2000, less than 1°C. This requires that additional climate forcing be kept  
904 less than about 1.5 W/m<sup>2</sup>, assuming a climate sensitivity of about 3°C for doubled CO<sub>2</sub>,  
905 and in turn this requires that CO<sub>2</sub> be kept from exceeding about 450 ppm, with the exact  
906 limit depending upon how well other climate forcings are constrained, especially



907 methane. **Figure 16** shows that additional global warming in the alternative scenario is  
908 about 0.8°C by 2100, and it remains less than 1°C under the assumption that a slow  
909 decrease in greenhouse gas forcing occurs after 2100.

910 **Q. How do these levels of global warming relate to dangerous climate change?**

911 A. That is the fundamental issue, because practically all nations, including the United States,  
912 have signed the Framework Convention on Climate Change, agreeing to stabilize  
913 greenhouse gas emissions at a level that prevents “dangerous” anthropogenic interference  
914 with the climate system (**Figure 17**). In just the past few years it has become clear that  
915 atmospheric composition is already close to, if not slightly beyond, the dangerous level of  
916 greenhouse gases. In order to understand this situation, it is necessary to define key  
917 metrics for what constitutes “danger”, to examine the Earth’s history for levels of climate  
918 forcing associated with these metrics, and to recognize changes that are already  
919 beginning to appear in the physics of the climate system.

920 Principal metrics defining dangerous include: (1) ice sheet disintegration and sea level  
921 raise, (2) extermination of species, and (3) regional climate disruptions (**Figure 18**). Ice  
922 sheet disintegration and species extinction proceed slowly at first but have the potential  
923 for disastrous non-linear collapse later in the century. The consequences of ice sheet  
924 disintegration and species extinction could not be reversed on any time scale of interest to  
925 humanity. If humans cause multi-meter sea level rise and exterminate a large fraction of  
926 species on Earth, they will, in effect, have destroyed creation, the planet on which  
927 civilization developed over the past several thousand years.

928 Regional climate disruptions also deserve attention. Global warming intensifies the  
929 extremes of the hydrologic cycle. On the one hand, it increases the intensity of heavy

930 rain and floods, as well as the maximum intensity of storms driven by latent heat,  
931 including thunderstorms, tornados and tropical storms. At the other extreme, at times and  
932 places where it is dry, global warming will lead to increased drought intensity, higher  
933 temperatures, and more and stronger forest fires. Subtropical regions such as the  
934 American West, the Mediterranean region, Australia and parts of Africa are expected to  
935 be particularly hard hit by global warming. Because of earlier spring snowmelt and  
936 retreat of glaciers, fresh water supplies will fail in many locations, as summers will be  
937 longer and hotter.

938 **Q. Is it possible to say how close we are to deleterious climate impacts?**

939 A. Yes. I will argue that we are near the dangerous levels for all three of these metrics.

940 In the case of sea level, this conclusion is based on both observations of what is  
941 happening on the ice sheets today and the history of the Earth, which shows how fast ice  
942 sheets can disintegrate and the level of warming that is needed to spark large change.

943 **Figure 19** shows that the area on the Greenland ice sheet with summer melt has been  
944 increasing over the period of satellite observations, the satellite view being essential to  
945 map this region. The area with summer melt is also increasing on West Antarctica.

946 **Figure 20** shows summer meltwater on Greenland. The meltwater does not in general  
947 make it to the edge of the ice sheet. Rather it runs to a relative low spot or crevasse on  
948 the ice sheet, and there burrows a hole all the way to the base of the ice sheet. The  
949 meltwater then serves as lubrication between the ice sheet and the ground, thus speeding  
950 the discharge of giant icebergs to the ocean (**Figure 21**).

951 **Q. Is it not true that global warming also increases the snowfall rate, thus causing ice**  
952 **sheets to grow faster?**

953 A. The first half of that assertion is correct. The inference drawn by ‘contrarians’, that  
954 global warming will cause ice sheets to become bigger, defies common sense as well as  
955 abundant paleoclimate evidence. The Earth’s history shows that when the planet gets  
956 warmer, ice sheets melt and sea level increases. Ice sheet size would not necessarily need  
957 to decrease on short time scales in response to human-made perturbations. However, we  
958 now have spectacular data from a gravity satellite mission that allows us to evaluate ice  
959 sheet response to global warming.

960 The gravity satellite measures the Earth’s gravitational field with sufficient precision to  
961 detect changes in the mass of the Greenland and Antarctic ice sheets. As shown by  
962 **Figure 22**, the mass of the ice sheet increases during the winter and decreases during the  
963 melting season. However, the net effect is a downward trend of the ice sheet mass. In  
964 the past few years Greenland and West Antarctica have each lost mass at a rate of the  
965 order of 150 cubic kilometers per year.

966 **Q. Is sea level increasing at a significant rate?**

967 A. Sea level is now increasing at a rate of about 3.5 cm per decade or 35 cm per century,  
968 with thermal expansion of the ocean, melting of alpine glaciers, and the Greenland and  
969 West Antarctic ice sheets all contributing to this sea level rise. That is double the rate of  
970 20 years ago, and that in turn was faster than the rate a century earlier. Previously sea  
971 level had been quite stable for the past several millennia.

972 **Q. Is the current level of sea level rise dangerous?**

973 A. This rate of sea level rise is more than a nuisance, as it increases beach erosion, salt water  
974 intrusion into water supplies, and damage from storm surges. However, the real danger is

975 the possibility that the rate of sea level rise will continue to accelerate. Indeed, it surely  
976 will accelerate, if we follow business-as-usual growth of greenhouse gas emissions.

977 **Q. How fast can sea level rise and when would rapid changes be expected?**

978 A. Those questions are inherently difficult to answer for a non-linear process such as ice  
979 sheet disintegration. Unlike ice sheet growth, which is a dry process limited by the rate  
980 of snowfall, ice sheet disintegration is a wet process that can proceed rapidly and  
981 catastrophically once it gets well underway.

982 Some guidance is provided by the Earth's history. When the Laurentide ice sheet, which  
983 covered Canada and reached into the northern edges of the United States, disintegrated  
984 following the last ice age, there were times when sea level rose several meters per  
985 century. The Greenland and West Antarctic ice sheets are at somewhat higher latitudes  
986 than the Laurentide ice sheet, but West Antarctica seems at least as vulnerable to rapid  
987 disintegration because it rests on bedrock below sea level. Thus the West Antarctic ice  
988 sheet is vulnerable to melting by warming ocean water at its edge as well as surface melt.  
989 In addition, if we follow business-as-usual, the human-made climate forcing will be far  
990 larger and more rapid than the climate forcings that drove earlier deglaciations.

991 I have argued that business-as-usual greenhouse gas growth almost surely will cause  
992 multi-meter sea level rise within a century. High latitude amplification of global  
993 warming would result in practically the entire West Antarctic and Greenland ice sheets  
994 being bathed in meltwater for a lengthened melt season. A warmer ocean and summer  
995 rainfall could speed flushing of the ice sheets. If we wait until rapid disintegration  
996 begins, it will be impossible to stop.

997 **Q. What consequences would be expected with multi-meter sea level rise?**

998 A. Most of the world's large cities are on coast lines (**Figure 23**). The last time that global  
999 mean temperature was 2-3°C warmer than now was in the Pliocene, when sea level was  
1000 about 25 meters higher than today. About one billion people live within 25-meter  
1001 elevation of sea level. As shown by **Figure 24**, most East Coast cities in the United  
1002 States would be under water with a sea level rise that large, almost the entire nation of  
1003 Bangladesh, the State of Florida, and an area in China that presently contains about 300  
1004 million people. There are historical coastal cities in most countries. A sea level rise of 5-  
1005 7 meters, which could be provided by West Antarctica alone, is enough to displace a few  
1006 hundred million people.

1007 **Q. Does sea level provide a precise specification of 'dangerous' warming?**

1008 A. I suggest that it is useful to look at prior interglacial periods, some of which were warmer  
1009 than our current interglacial period. In some of these periods, e.g., the interglacials ~125  
1010 and ~425 thousand years ago, sea level was higher than today by as much as a few  
1011 meters, but sea level did not approach the level in the Pliocene. Although we do not have  
1012 accurate measurements of global mean temperature for the earlier interglacial periods, we  
1013 do have local measurements at places of special relevance.

1014 **Figure 25a** is the temperature in the Western Pacific Warm Pool, the warmest ocean  
1015 region on the planet, a region of special importance because it strongly affects transport  
1016 of heat to higher latitudes via both the atmosphere and ocean. **Figure 26b** is the  
1017 temperature in the Indian Ocean, the place that has the highest correlation with global  
1018 mean temperature during the period of instrumental data, the period when an accurate  
1019 global mean temperature can be calculated. **Figure 25** concatenates modern instrumental  
1020 temperatures with proxy paleo measures. In both of these regions it appears that the

1021 warming of recent decades has brought recent temperatures to within about 1°C or less of  
1022 the warmest interglacial periods.

1023 Tropical ocean temperature change is only moderately smaller than global mean  
1024 temperature change in both recent times and glacial-interglacial climate change. For this  
1025 reason, I assert that it would be foolhardy for humanity to allow additional global  
1026 warming to exceed about 1°C.

1027 **Q. But if additional global warming is kept less than 1°C that does not seem to**  
1028 **guarantee that sea level rise of a few meters would not occur, given the changes that**  
1029 **occurred in the previous interglacial periods, does it?**

1030 A. You are right, and I am not recommending that the world should aim for additional global  
1031 warming of 1°C. Indeed, because of potential sea level rise, as well as the other critical  
1032 metrics that I will discuss, I infer that it is desirable to avoid any further global warming.  
1033 However, I also note that there is an enormous difference between global warming less  
1034 than 1°C and global warming of 2-3C. The latter warming would have the global climate  
1035 system pointed toward an eventual sea level rise measured in the tens of meters. In that  
1036 case we should expect multi-meter sea level rise this century and initiation of ice sheet  
1037 disintegration out of our control with a continually rising sea level and repeated coastal  
1038 disasters unfolding for centuries. Economic and social consequences are difficult to  
1039 fathom.

1040 With global warming less than 1°C it is possible that sea level rise this century would be  
1041 less than 1 meter. Ice sheet changes would likely unfold much more slowly than with 2-  
1042 3°C global warming. If the maximum global warming is kept less than 1°C, it may be  
1043 practical to achieve moderate adjustments of global climate forcings that would avert the

1044 occurrence of large sea level change. Human-made gases in the air will decrease when  
1045 sources are reduced sufficiently, so as events unfold and understanding improves, it may  
1046 prove necessary to set goals that yield a declining global temperature beyond the human-  
1047 induced maximum temperature. However, considering the 1000-year lifetime of much of  
1048 the CO<sub>2</sub>, if the additional warming is 2-3°C, it will be impractical to avoid disastrous  
1049 consequences.

1050 **Q. What other ghosts of climate future can be seen?**

1051 A. Another potential consequence that would be irreversible is extermination of species.  
1052 Animal and plant species can survive only within certain climatic zones. As climate  
1053 changes, animals and plants can migrate, and in general they deal successfully with  
1054 fluctuating climate. However, large climate changes have caused mass extinctions in the  
1055 past. Several times in the Earth's history global warming of five degrees Celsius or more  
1056 led to extinction of a majority of species on the planet. Of course other species came into  
1057 being over many thousands of years. But mass extinctions now would leave a far more  
1058 desolate planet for as long as we can imagine.

1059 Global warming of 0.6°C in the past three decades has initiated a systematic movement  
1060 of climatic zones, with isotherms moving poleward at a rate of typically 50-60 km per  
1061 decade. As this movement continues, and as it would accelerate with business-as-usual  
1062 increases of fossil fuel use, it will add a strong climatic stress to the other stresses that  
1063 humans have placed on many species. Species at high latitudes (**Figure 26**) and high  
1064 altitudes (**Figure 27**) are in danger of, in effect, being pushed off the planet by global  
1065 warming. Many other species will be threatened as the total movement of climatic zones

1066 increases, because some species are less mobile than others. Interdependencies of species  
1067 leave entire ecosystems vulnerable to collapse.

1068 It can be argued, as E.O. Wilson has suggested, that the world beyond the 21<sup>st</sup> century,  
1069 post fossil fuel domination and post the human population peak, could have an  
1070 environment that is more tolerant of all species. It is difficult to project how many of the  
1071 species of creation will survive the bottleneck in the 21<sup>st</sup> century (**Figure 28**), but surely  
1072 the number will be much smaller if the stresses include business-as-usual climate change.  
1073 Realization that we are already near ‘dangerous’ climate change, for sea level rise and  
1074 other effects, has a bright side. It means that we must curtail atmospheric CO<sub>2</sub> and other  
1075 climate forcings more sharply than has generally been assumed. Thus various problems  
1076 that had begun to seem almost inevitable, such as acidification of the ocean, cannot  
1077 proceed much further, if we are to avoid other catastrophes. If the needed actions are  
1078 taken, we may preserve most species.

1079 **Q. Are there other criteria, besides sea level and species extinction, for “danger”?**

1080 A. There are many regional effects of global warming. Large natural weather and climate  
1081 fluctuations make it difficult to identify global warming effects, but they are beginning to  
1082 emerge. If we follow business-as-usual, the southernmost parts of our country are likely  
1083 to have much less tolerable climate. Fresh water shortages could become a frequent  
1084 problem in parts of the country, especially those dependent on snowpack runoff, as spring  
1085 comes earlier and summers are longer, hotter and drier, and forest fires will be an  
1086 increasing problem. Other parts of the country, and in some cases the same places, will  
1087 experience heavier rain, when it occurs, and greater floods. The tier of semi-arid states,  
1088 from West Texas through the Dakotas, is subject to the same expected increase of



1089 hydrologic extremes, but overall they are likely to become drier and less suited for  
1090 agriculture, if we follow business-as-usual and large global warming ensues.

1091 Given that effects of global warming on regional climate are already beginning to  
1092 emerge, the regional climate criterion also implies that further global warming much  
1093 above the present level is likely to be deleterious.

1094 **Q. Is it still possible to avoid dangerous climate change?**

1095 A. It is possible, but just barely. Most climate forcings are increasing at a rate consistent  
1096 with, or even more favorable (slower), than the ‘alternative scenario’ which keeps  
1097 warming less than 1°C. CO<sub>2</sub> is the one climate forcing that is increasing much more  
1098 rapidly than in the alternative scenario, and if CO<sub>2</sub> emissions continues on their current  
1099 path CO<sub>2</sub> threatens to become so dominant that it will be implausible to get the net  
1100 climate forcing onto a path consistent with the alternative scenario. Furthermore, as I  
1101 have discussed, there are reasons to believe that even the smaller warming of the  
1102 alternative scenario may take us into the dangerous range of climate change. It is likely  
1103 that we will need to aim for global warming even less than 1°C.

1104 **Q. Why are CO<sub>2</sub> and coal the focus of climate concerns?**

1105 A. **Figure 29a** shows one crucial fact. When a pulse of CO<sub>2</sub> is added to the atmosphere by  
1106 burning fossil fuels, half of the CO<sub>2</sub> disappears from the air within about 25 years, being  
1107 taken up by carbon sinks, principally the ocean. However, uptake then slows as the CO<sub>2</sub>  
1108 added to the ocean exerts a ‘back pressure’ that inhibits further uptake. About one-fifth  
1109 of the initial increase is still present in the atmosphere after 1000 years. Complete  
1110 removal of the pulse depends upon formation of carbonate sediments on the ocean floor,

1111 a very slow process. It is this long atmospheric lifetime that makes CO<sub>2</sub>, on the long run,  
1112 the principal climate forcing for human-made climate change.

1113 **Q. Why do you focus especially on coal?**

1114 A. Part of the reason is the size of the coal carbon reservoir, shown in **Figure 29b**. The coal  
1115 reservoir is larger than either oil or gas. The amount of CO<sub>2</sub> already emitted to the  
1116 atmosphere, shown by the purple portions of the bar graphs, is about 50% from coal, 35%  
1117 from oil and 15% from gas. On the long run, coal will be even much more important.

1118 Proven and estimated reserves of these fossil fuels are uncertain, and the amounts shown  
1119 in **Figure 29b** for oil and coal both could be substantially over-estimated. Many experts  
1120 believe that we are already at a point of having used approximately half of the  
1121 economically recoverable reserves of oil. In that case we are already at approximately  
1122 the point of ‘peak oil’ production and oil use will soon begin to noticeably decline  
1123 because of resource constraints.

1124 Uncertainties in the oil and gas reserves have little qualitative effect on the climate  
1125 discussion, however. The reasons are, first, that remaining oil and gas, used at any  
1126 feasible rate, can at most only take atmospheric CO<sub>2</sub> to approximately 450 ppm. Second,  
1127 it is impractical to avoid the use of readily extractable oil and gas, and most of the CO<sub>2</sub>  
1128 resulting from that oil and gas will be emitted to the atmosphere, because it is emitted by  
1129 small sources where it is impractical to capture the CO<sub>2</sub>.

1130 Coal reserves are also uncertain and it is likely that the estimates in **Figure 29b**, even the  
1131 smaller estimate of EIA (Energy Information Agency), are too high. Nevertheless, there  
1132 is more CO<sub>2</sub> in coal than in the other conventional fossil fuels. Indeed, there is enough

1133 CO<sub>2</sub> in coal to take the Earth far into the ‘dangerous’ zone of climate change, to doubled  
1134 atmospheric CO<sub>2</sub> and even beyond.

1135 The second critical fact about coal is that it is possible to imagine coal being used only at  
1136 power plants to generate electricity, with the CO<sub>2</sub> emissions captured and sequestered,  
1137 with the carbon put back underground where it came from. Indeed, the elementary  
1138 carbon cycle facts summarized in **Figure 29** dictate the solution to the global warming  
1139 problem.

1140 **Q. Can a solution to global warming be defined?**

1141 A. An outline of a practical solution can be defined readily (**Figure 30**). By far the most  
1142 important element in this solution, indeed 80% of the solution, is phase-out of coal use  
1143 except at power plants where the CO<sub>2</sub> is captured and sequestered. This requirement is  
1144 dictated by the fundamental facts of the carbon cycle summarized in **Figure 29**.

1145 The steps needed to achieve termination of CO<sub>2</sub> emissions from coal use are: (1) a  
1146 moratorium in developed countries on construction of new coal-fired power plants until  
1147 the technology is ready for carbon-capture and sequestration, (2) a similar subsequent  
1148 moratorium in developing countries, (3) a phase-out over the next several decades of  
1149 existing old-technology coal plants, with replacement by coal-fired plants that capture  
1150 and sequester the CO<sub>2</sub>, energy efficiencies, renewable energies, or other sources of  
1151 energy that do not emit CO<sub>2</sub>.

1152 **Figure 31** defines a specific scenario: developed countries halt construction by 2012 of  
1153 any coal-fired power plants that do not capture and sequester CO<sub>2</sub>, developing countries  
1154 halt such construction by 2022, and all existing coal-fired power plants without  
1155 sequestration are ‘bull-dozed’ by 2050 (linear decrease of their emissions between 2025

1156 and 2050). The 10-year delay of the moratorium for developing countries is analogous to  
1157 that allowed by the Montreal Protocol in chlorofluorocarbon phase-out and it is justified  
1158 by the primary responsibility of developed countries for the current excess of greenhouse  
1159 gases in the atmosphere as well as by the much higher per capita emissions in developed  
1160 countries.

1161 **Figure 32** shows that continued business-as-usual emission of CO<sub>2</sub> will more than double  
1162 the pre-industrial amount of CO<sub>2</sub> (280 ppm) in the air, even though we have neglected  
1163 feedbacks that would likely accompany such large emissions and we have included no  
1164 emissions from unconventional fossil fuels (tar shale, tar sand, heavy oil, etc.). **Figure**  
1165 **33** shows that this specified phase-out of coal emissions keeps the maximum future  
1166 atmospheric CO<sub>2</sub> level at about 450 ppm.

1167 **Q. Is it plausible for coal-fired power plants without carbon capture to be phased out?**

1168 A. The time scale for action used in calculations for **Figures 32 and 33**, with moratoriums in  
1169 developed countries by 2012 and in developing countries by 2022, are conservative, our  
1170 aim being to show that it is practical to keep CO<sub>2</sub> below 450 ppm. However, because it is  
1171 becoming increasingly likely that an additional 1°C global warming will cause substantial  
1172 climate impacts, it is highly desirable to take action sooner.

1173 I believe that the plausibility of obtaining actions in time depends upon whether citizens  
1174 become informed and place pressure on the decision-making process. It seems highly  
1175 unlikely that national governments, which are under the strong influence of fossil fuel  
1176 special interests, will exercise the required leadership. Even Germany, among the  
1177 ‘greenest’ of all nations, is making plans to build coal-fired power plants without carbon

1178 capture. Clearly decision-makers do not yet ‘get it’. The public must become more  
1179 involved, if they hope to preserve creation.

1180 Those who argue that it is implausible to ‘bulldoze’ old technology power plants, while  
1181 energy efficiency and clean energy sources are expanded, might compare the task with  
1182 the efforts put into World War II. It is a feasible undertaking.

1183 **Q. If coal is 80% of the solution, what is the other 20%?**

1184 A. There must be a gradually increasing price on carbon emissions. A carbon price is  
1185 essential to wean us off of our fossil fuel addiction. Without such a phased withdrawal  
1186 we will soon begin to exhibit the behavior of a desperate addict, attempting to squeeze  
1187 carbon fuels out of unconventional or remote sources, e.g., ‘cooking’ the Rocky  
1188 Mountains to drip oil out of tar shale and traveling to extreme environments such as the  
1189 Arctic National Wildlife Refuge to extract every last drop of oil from the ground.  
1190 The irrationality of this behavior is apparent from the realization that fossil fuels are  
1191 finite. We must learn to live without them as they dwindle. If we begin sooner, we can  
1192 live with cleaner air and water, preserve creation, and pass on to our children a healthy  
1193 planet with almost all of the species that we found when we arrived.

1194 **Q. A carbon price? Does that mean a tax?**

1195 A. It could be a tax, but there are various options, and it does not need to increase the  
1196 amount of money extracted from citizens by the government. It might include rations  
1197 that could be bought and sold, cap and trade emission quotas for industries, and other  
1198 alternatives that stimulate energy and carbon efficiencies, including renewable energies  
1199 and other forms of energy that do not produce greenhouse gases. This price can start  
1200 small, the key requirement being certainty that it will continue to rise, because this is the

1201 stimulus that the business community needs to make the essential long-term investments.  
1202 The price must promise to be large enough that it stimulates technology development, but  
1203 it must not be so large or rise so rapidly that it harms the economy.

1204 It is a truism that a strong economy is needed to afford the investments needed for a clean  
1205 environment and stable climate. It is desirable to separate the decisions on altering the  
1206 carbon price from short-term political considerations. One way to achieve this would be  
1207 via a “Carbon Tsar”, analogous to the Chairman of the Federal Reserve, who would  
1208 carefully adjust the carbon price so as to optimize economic and environmental gain.

1209 **Q. Can coal phase-out and a gradually rising carbon price solve the climate problem?**

1210 A. These would need to be accompanied by sensible actions. A gradually rising price is not  
1211 sufficient for the demand reductions that will be needed to phase off the fossil fuel  
1212 addiction fast enough. There need to be improved efficiency standards on buildings,  
1213 vehicles, appliances, lighting, electronic devices, etc. Regulations on utilities need to be  
1214 modified so that profits grow when the utilities help consumers waste less energy, rather  
1215 than profits being in proportion to amount of energy sold. The government should be  
1216 supporting more energy research and development, and more effectively, than it is now.  
1217 However, the coal phase-out and carbon price are the essential underpinnings. Without  
1218 these, other actions are nearly fruitless, only yielding a modest slowing of emissions  
1219 growth.

1220 **Q. But are even these enough, if we are so close to a dangerous greenhouse gas level?**

1221 A. There are additional actions that could close the gap between where we are and where we  
1222 need to be to stabilize climate, even if we are slightly overshooting the dangerous level.  
1223 However, these other actions can close the gap only if we get onto a path to stabilize CO<sub>2</sub>

1224 in the near future. Without getting onto a downward path of CO<sub>2</sub> emissions, these other  
1225 actions provide little respite.

1226 The planet is now out of energy balance by something between 0.5 and 1 W/m<sup>2</sup>. If we  
1227 reduced human-made climate forcings by that amount, the warming ‘in-the-pipeline’  
1228 would be eliminated, the forcing leading to a continual warming tendency would be  
1229 eliminated. **Figure 35** shows that there is a large enough climate forcing in pollutant  
1230 forcings, specifically, tropospheric ozone, especially its precursor methane, and black  
1231 soot, to offset the present planetary energy imbalance, if we should make major  
1232 reductions of these pollutants.

1233 Some of these non-CO<sub>2</sub> forcings are particularly effective in the Arctic, so it may even be  
1234 possible to save the Arctic from further ice loss by means of special efforts to reduce  
1235 these forcings, coupled with stabilization of atmospheric CO<sub>2</sub>. There are other benefits of  
1236 such an effort: these pollutants are harmful to human health, being a primary cause of  
1237 asthma and other respiratory and cardiovascular problems, and they reduce agricultural  
1238 productivity.

1239 **Q. Even if these forcings are reduced, will not the benefits soon be erased by inevitable**  
1240 **increases of CO<sub>2</sub>? It is said that even a 450 ppm limit on CO<sub>2</sub> is inconceivable.**

1241 A. It is said by whom? Fossil fuel companies, and government energy departments, take it  
1242 as a god-given fact that all fossil fuels will be burned because they are there. That may  
1243 almost be true for the readily mined oil and gas. However, we have shown above that  
1244 even with generous estimates for undiscovered oil and gas reserves, CO<sub>2</sub> never exceeds  
1245 450 ppm if coal use is phased out except at power plants that capture and sequester the  
1246 CO<sub>2</sub>. Old technology coal-fired power plants must be replaced by 2050, but the pressure

1247 for doing so will mount as climate change and its consequences become more apparent,  
1248 especially the consequences for China, India and Bangladesh.

1249 **Q. But CO<sub>2</sub> is already 385 ppm and increasing about 2 ppm per year. Does not simple**  
1250 **arithmetic say that we will pass 450 ppm within a few decades?**

1251 A. Yes, if we keep increasing fossil fuel CO<sub>2</sub> emissions. But that is not a god-given fact.

1252 **Q. But even if emissions from coal use are reduced, today's oil plus gas emissions**  
1253 **exceed coal emissions. How can coal be so important?**

1254 A. Phasing out coal emissions will reduce the annual growth rate of atmospheric CO<sub>2</sub>.  
1255 Today, and for the period of accurate CO<sub>2</sub> data, the annual increase of CO<sub>2</sub> in the air  
1256 averages 57% of the fossil fuel emissions (**Figure 36**), despite the fact that we (the world)  
1257 have not done a good job of limiting deforestation and we have not done a good job of  
1258 encouraging agricultural practices that would sequester CO<sub>2</sub> in the soil. If we reduce CO<sub>2</sub>  
1259 emissions from coal, the airborne fraction of CO<sub>2</sub> will decrease in the near and medium  
1260 term, so there would be a more than proportionate decrease of the annual growth in  
1261 atmospheric CO<sub>2</sub>.

1262 **Q. But will not a decrease in emissions of CO<sub>2</sub> from coal be offset by a continuing**  
1263 **increase in emissions of CO<sub>2</sub> from oil?**

1264 A. On the contrary, oil production is going to peak and CO<sub>2</sub> emissions from oil will  
1265 inevitably decline, if not now then surely within the next few decades. And there is  
1266 considerable potential, via improved forestry and agricultural practices, to do much better  
1267 at sequestering CO<sub>2</sub> in soil and in forests, as opposed to the loss (emission) of CO<sub>2</sub> from  
1268 forests and soils in the past.



1269 **Q. But you admit that we are likely to pass the dangerous level of CO<sub>2</sub>. Is there**  
1270 **anything that can be done in that case?**

1271 A. In the short-term we only have to reduce CO<sub>2</sub> emissions by more than 57% for  
1272 atmospheric CO<sub>2</sub> to begin to decline (in the long run the reduction must be larger).  
1273 However, there is at least one feasible way to draw CO<sub>2</sub> from the atmosphere. As  
1274 summarized in **Figure 37**, if biofuels were burned in power plants, with the CO<sub>2</sub> captured  
1275 and sequestered, atmospheric CO<sub>2</sub> could be drawn down. The growing vegetation would  
1276 take in CO<sub>2</sub> from fossil fuel-elevated atmospheric levels, and this CO<sub>2</sub> would then be  
1277 captured at the power plant. In effect, fossil fuel CO<sub>2</sub> would be put back underground,  
1278 where it had come from.

1279 The biofuels should be extracted from natural grasses or other cellulosic fibers farmed in  
1280 a way that promotes soil conservation and carbon storage in the soil. Such an approach  
1281 contrasts with production of corn-based ethanol, which in net is ineffective at reducing  
1282 atmospheric CO<sub>2</sub>.

1283 **Q. Rather than go to this trouble, can we not adapt to the impacts of climate change?**

1284 A. Yes, leaving aside the effects of large changes in regional climate extremes and the  
1285 extermination of species, we could deal with a one meter rise of sea level by making a  
1286 lake large enough to hold that much water. Two hundred meter dams at the locations  
1287 indicated in **Figure 38** could hold that much water. A large number of people would be  
1288 displaced by this lake. It may require difficult negotiations with Canada. And if we  
1289 allow ice sheets to disintegrate to the point of one meter sea level rise, we can be quite  
1290 sure that another meter is on the way.

1291 **Q. Is there not a good place for another lake?**

1292 A. Yes, it would require higher dams (242 meters), but one meter of sea level could be  
1293 stored in Russia (**Figure 39**). This also displaces a large number of people. And if we let  
1294 the ice sheets go that far, there is probably two more meters of sea level on the way.  
1295 There are no remaining geological candidates for storing that much water. So the historic  
1296 coastal cities are sunk. It seems that the adaptation path is a lot like appeasement; it just  
1297 gets you into deeper trouble.

1298 **Q. Well then, is there still time to avoid the climate problems?**

1299 A. Yes, there is still time (**Figure 40**). As shown above, we can just barely still avoid 450  
1300 ppm by phasing out coal use except at power plants that capture and sequester CO<sub>2</sub>. It  
1301 requires an almost immediate moratorium on new coal-fired power plants in the West,  
1302 and, within a decade later, a moratorium in the developing world.

1303 **Q. Isn't this going to cause energy shortages and blackouts?**

1304 A. Not if we exploit the potentials in energy efficiency, renewable energies, nuclear power,  
1305 or other energy sources that do not produce greenhouse gases. We are going to have to  
1306 learn to do that someday anyhow, and it is an enormous economic advantage to us if we  
1307 learn it sooner rather than later. Others, including China, will need better technologies.  
1308 If we get there first, we will have something to sell them. We might get some of the  
1309 money back that we have been sending over there.

1310 **Q. Why take the first step? Why not demand that China act at the same time?**

1311 A. I already mentioned the economic reason. In addition, we are responsible for the  
1312 problem. China has just passed us in current emissions, but the climate change is due to  
1313 cumulative emissions, not current emissions. The United States is responsible for more  
1314 than three times as much of cumulative CO<sub>2</sub> emissions as any other country, and we will

1315 continue to be most responsible for decades. Even with China's high current emissions,  
1316 our per capita emissions are five times as great as China's.

1317 **Q. Is there any evidence that such an approach would work?**

1318 A. Certainly. The prior global atmospheric threat, destruction of the ozone layer, was solved  
1319 with just such an approach. When the science suggested that chlorofluorocarbons (CFCs)  
1320 had the potential to destroy the stratospheric ozone layer, there was an immediate  
1321 moratorium on building of more CFC factories. Consumers played a big role in reducing  
1322 demand, and immediately annual CFC production stabilized (**Figure 43**). Later, when  
1323 the Antarctic Ozone hole was discovered, the Montreal Protocol was adopted and later  
1324 strengthened several times, phasing out production of these chemicals. A key aspect of  
1325 this protocol was that developing countries should have an extra ten years to implement  
1326 the phase-out, and they should be provided with technical assistance to achieve it.

1327 The ozone story was a success story (**Figure 44**), as scientists transmitted a clear  
1328 message, the media informed the public, the public responded in a positive way, and the  
1329 United States government exercised strong leadership. Special interests, the chemical  
1330 companies producing CFCs, denied the science for several years, but they cooperated  
1331 once it became clear that they could make money producing substitute chemicals.

1332 **Q. Why has the global warming story not followed a similar path?**

1333 A. The blame can be spread around. I believe that we scientists have not done as good a job  
1334 in making clear the threat to the planet and creation. Special interests have been  
1335 extremely effective in casting doubt on the science. Moreover, they have managed to  
1336 have a great impact on the media, demanding that the story be presented as "fair and  
1337 balanced" even when the evidence became "clear and unambiguous". I also infer, based

1338 on numerous observations, that special interests have had undue influence (exceeding the  
1339 one person one vote concept) on governments, especially in Washington.

1340 Although the responsibility can be spread widely (**Figure 46**), the consequences of our  
1341 profligate use of resources will be borne primarily by young people, today's children and  
1342 grandchildren, and later generations.

1343 **Q. Are you saying that the blame belongs on past generations?**

1344 A. No. They can genuinely say "we did not know". The blame will fall squarely on today's  
1345 adults, if we do not act. We can no longer feign ignorance. Scientific consensus has  
1346 been reached. If we stay on the business-as-usual course that our energy departments  
1347 take for granted, when climate events unfold in the future it is not likely that our children  
1348 and grandchildren will look back on our generation with equanimity, not should they. If  
1349 we allow climate to deteriorate and creation to be destroyed, we will be the generation  
1350 that knew enough and still had time, but for selfish reasons declined to take actions.  
1351 Instead, we built more coal-fired power plants. In that event, rather than the "greatest  
1352 generation", how will our epitaph read?

1353 **Q. I am the one asking questions. Is there still time?**

1354 A. There is still time (**Figure 47**). However, it is clear that Congress does not 'get it'. They  
1355 stand ready to set a goal of 60% reductions, 80%, 90%! Horse manure. Those are  
1356 meaningless numbers, serving nothing but their campaign purposes. Before you cast a  
1357 vote for a politician ask whether they will support actions that can actually solve the  
1358 problem. Specifically, I suggest that you ask them whether they will support the  
1359 Declaration of Stewardship (**Figure 48**).

1360 The most important question, by far, is the moratorium on new coal-fired power plants in  
1361 the United States and Europe, the places that have created the climate problem. Until we  
1362 take that action, we have no basis for a successful discussion with China, India, and other  
1363 developing countries.

1364 **Q. So you think that replacing some people in congress can solve the problem?**

1365 A. It is important to replace members of Congress who place the profits of special interests  
1366 above the future of our children and grandchildren, but even with personnel changes I  
1367 would not expect Congress to solve the climate crisis without more direct help from the  
1368 public. Strong specific messages are needed. Rejection of a coal-fired power plant that  
1369 does not capture CO<sub>2</sub> is such a message.

1370 Of course such an action then places obligations on various parties. Steps must be taken  
1371 to promote greater energy efficiency and acquisition of alternative energy sources. These  
1372 are challenges that can be met and that will yield benefits in the future.

1373 **Q. Do you see reason for optimism if such steps are taken?**

1374 A. Yes. CO<sub>2</sub> is the main problem. **Figure 49d** shows that the growth of CH<sub>4</sub> is falling  
1375 below even the alternative scenario, far below all IPCC scenarios. **Figure 49e** shows that  
1376 the growth of N<sub>2</sub>O is close to the alternative scenario and below most IPCC scenarios.  
1377 **Figure 49f** shows that the growth of Montreal Protocol trace gases and other trace gases  
1378 is falling below all IPCC scenarios and is approaching the alternative scenario. So the  
1379 growth of the non-CO<sub>2</sub> climate forcings is encouraging.

1380 Indeed, if we look at the growth rate of the sum of all long-lived greenhouse gases  
1381 (**Figure 50**), we see that it is falling between the IPCC scenarios and the alternative  
1382 scenario. The reason that the net forcing is higher than in the alternative scenario is that

1383 the actual CO<sub>2</sub> growth rate has exceeded the growth rate for CO<sub>2</sub> assumed in the  
1384 alternative scenario. Actual recent CO<sub>2</sub> increases have averaged close to 2 ppm per year,  
1385 while the alternative scenario requires the growth rate of the late 1990s (1.7 ppm) to  
1386 decline to ~1.3 ppm per year by mid century. (If it turns out that 1°C additional global  
1387 warming is dangerous, then an even steeper decline may be needed.)

1388 Clearly a much more promising future than in IPCC business-as-usual scenarios is  
1389 possible. The issue is CO<sub>2</sub> and more specifically it is coal. It is still possible to get on the  
1390 alternative scenario track, and even do better than that scenario, but only if coal emissions  
1391 begin to decline. Once the CO<sub>2</sub> emissions are in the air we cannot get them back – a  
1392 large fraction will stay in the air more than 1000 years.

1393 **Q. Can you summarize the status of the matter?**

1394 **A. Figures 51 and 52** are my summary and my personal observations, my personal opinion.  
1395 The climate surely is approaching tipping points, with the potential for us to lose control  
1396 of the consequences. A solution is feasible and the required actions would have many  
1397 side benefits. Opposition, it seems to me, stems primarily from short-term special  
1398 financial interests, whose effective misinformation campaigns make the struggle to  
1399 inform difficult.

1400 This is a matter which should unite those of conservative and liberal bents. The core  
1401 issue is one of generational inequity. Younger people can help by making clear that they  
1402 recognize the difference between words and deeds. Stalling and misinformation may  
1403 help keep short-term profits flowing, but the legacy that it leaves on the planet will not be  
1404 erased or forgotten.

1405 **Q. Do you have any final comment for the Board?**

1406 A. Yes. I would like to express my gratitude to the State of Iowa, which has always been so  
1407 generous in providing educational opportunities to its people, even as many graduates go  
1408 on to careers in other states across the nation. I was extremely fortunate to be able to  
1409 attend the University of Iowa, and especially to learn in the Department of Physics and  
1410 Astronomy of Prof. James Van Allen. I thank Bruce Johansen and Ines Horovitz for  
1411 comments on this testimony, and Makiko Sato for technical scientific assistance and my  
1412 wife Anniek for her tolerance of inordinate obsessions.

1413 **Q. Does this conclude your prepared Direct Testimony?**

1414 A. Yes.