On April 20 Dr. Scott Denning presented a talk on climate change," Simple, Serious, Solvable" at the Colorado Scientific Society. Dr. Denning is the Director of Education at the Department of Atmospheric Science at Colorado State University.

Climate change can be thought of with regard to conservation of energy and the first law of thermodynamics. When more heat is added to something than is removed, warming occurs and the reverse is true. While local weather may be explained by discussing that weather fronts advance to replace existing ones, for the earth as a whole, the only way to change the enthalpy of the planet is through the top of the atmosphere. There is no conduction to a vacuum and no convection of heat into space. The heat that comes in as radiation from the sun must pass through the air, which is composed of 99 percent oxygen and nitrogen molecules. These are both diatomic molecules with shared electrons. In the interaction between the gas molecules and photons, the energy of the molecules can be affected by photons of infrared radiation to a limited degree. Carbon dioxide and water molecules are shaped differently, with two atoms of oxygen to one cation. These are the most abundant gases in our atmosphere that have more than two atoms. The shape of the molecules translates to a greater number of ways of vibration of the atomic bonds, which then means that these molecules will absorb a different wavelength of radiation, a slightly different energy level of photon. What makes CO_2 into a greenhouse gas are these three atoms with more degrees of freedom of vibration, and more ways of rearranging the geometry of that molecule so that it can interact with a broad spectrum of different energy level photons.

When the sun beats down on the earth, the radiation is reflected back by the earth's albedo. The radiation that doesn't reflect back becomes absorbed and warms up the planet. Only about 6 percent of the infrared radiation can be directly emitted to space; the rest interacts with the gas molecules and cloud droplets and then is radiated back down. An infrared camera can measure radiation coming down from the sky at night at 340 watts/sq meter with not a photon coming from the sun. A calculation for the entire earth at night results in twice as much energy as is received directly from the sun. Roughly 420 watts is emitted from every sq meter of land in the evening. Without the heat reflected from the atmospheric molecules, the temperature in the morning would be -78 degrees F. The strongest evidence of the greenhouse effect is that we can survive night. Roughly 2/3 of the energy hitting the earth's surface is actually emitted from the molecules in the air. This counteracts the radiation leaving the earth's surface. Doubling the CO_2 in the atmosphere would be equivalent to adding 4 watts to every sq m of earth continuously.

The story of global warming is more than extrapolation. Climate scientists use the terms forcing and response, or cause and effect. Climate forcing is measured in watts/sq m. Response is measured in degrees. response/forcing = sensitivity, or how sensitive the earth's climate is to an imbalance of radiation at the top of the atmosphere. The difference between the watts entering at the top of the atmosphere and the watts exiting at the top of the atmosphere is the forcing. The temperature will adjust if there is an imbalance. Climate sensitivity can be estimated for the past if there is a means to calculate the numerator and denominator, i.e. estimate the warming or cooling effect and the watts per sq meter added and subtracted.

Climate sensitivity can be estimated from the last glacial maximum. The location of ice was known, as is the albedo of glacial ice and sea ice. Temperatures can be reconstructed from fossils in sea cores. CO_2 disappears during ice ages, which is known from the ice cores in Antarctica. This drawdown occurs in about 100,000 years but it then reappears quickly. The concentration for interglacial peaks is between 275 and 300 ppm, and in glacial valleys at 175-200 ppm. This has consequences for the radiation balance as well. Given the ingredients--the maps of the ice and snow, the reconstructed maps of temperature, and the reconstructed time series of CO_2 and other gases that are in these cores-- the climate forcing difference can be reconstructed between the last glacial maximum and today. The albedo effect is about 3.5 watts/sq m; greenhouse gases are 6.5 watts/sq m change from full on glacial and full on interglacial; and there is a global mean temperature change of about 5 degrees C, with more change where ice was. The tropics showed very little temperature change.

Sensitivity is response / forcing. 5/6.5 = 3/4 degree/ watt, from full-on glacial to full-on interglacial over a period of 10,000 yrs. That much heat could be added in this century in what took 100 centuries before, from 18,000 years ago to 8000 years ago.

There was 6.5 watts/sq m at the end of the ice age. The Little Ice Age is harder to reconstruct , but maybe there was a watt/sq m, maybe .8 watt/sq m, which is believed to do with a gradual change in the solar output and volcanoes, which is recorded in tree rings and also in beryllium isotopes in Antarctica. There has been a 2 watt/sq m ramp in the energy balance for the planet since industrialization due to greenhouse gases. If nothing is done about global warming, if there is no policy, if China, India and Africa all build modern industrial economies based on coal oil and gas, 12 watts/sq m will be added eventually to the energy balance of the planet, which is nearly twice the amount from deglaciation.

With strong policy the warming of 1.5 -2 degrees could occur by the end of the century. Without strong policy there may be 4 degrees of warming. The problem is that the heavy lifting must be done now to avoid that trajectory, but the payoff is not seen immediately, in fact maybe not until two or three generations.

The patterns are as follows: land warms up more quickly than oceans; the northern hemisphere warms faster than the southern (which does not include as much land); snowy places warm more quickly because of the albedo effect. With a 5-10 degrees warming in the middle half of NA, it would be comparable to moving from Illinois to Mississippi and from Colorado to Texas. Therefore, it is not just polar bears that are affected, but crops and real estate.

83 percent of Colorado water is used to irrigate farmland. 75 million people live in the arid West. These situations can exist because of mountains and snowpack. Reservoirs don't compare to snowpack. If the climate is warmed to that of Texas, the snowpack will be eliminated, with water-limited snowpack buildup and photon-limited snowpack loss. The melting season moves earlier, and as a result of earlier snowpack melt, there is less peak snow water equivalent. There is much variability year to year with Colorado snowpack. But if a regression line is run through a graph of the data, there is seen to be about

20 percent less snowpack than 50 yrs ago with less than 2 degrees F of warming in our part of the world, not the projected 10 degrees.

Transpiration is affected. Drought is not just a measure of water in, but actually the running sum of water out-water in. Even if nothing affects the precipitation, if the evaporative losses increase, drought increases over time. 10 degrees warmer climate equates to more evaporative demand, as has been documented in tree rings. In the year 1000-1200 there were megadroughts that were believed to contribute to the collapse of the Anasazi civilization. Closer to Colorado there was the dust bowl back in the 30s. The droughts in the 20th and 21st century are worse than anything documented in the last 1000 yrs.

Fire risk is increased. Increased temperature increases evaporative demand exponentially, that is, the amount of water that the air can hold increases exponentially with temperature. There are also longer warmer seasons, where water begins evaporating from the soils in April instead of May, and keeps evaporating until September or October instead of August. The trees run out of water earlier and they become drought stressed. Also, out-of-control fires occur more often in a hot summer than otherwise. For all of these reasons, there is more fire danger with higher temperature. The Natural Research Council study shows a 700 percent increase in wildfire in Colorado under a moderate climate change.

Storm surges cause almost all loss of life in hurricanes. The most destructive force is storm surge plus waves. The real problem is not the creeping sea level, but coastal flooding. When the 100-yr flood becomes the 10-yr flood, infrastructure may require significant fixes every 10 yrs.

Climate change is not just caused by the US but by global economic prosperity. Shanghai contains more people in the city proper than any other city in the world, with 22 million. It is surrounded by suburbs that all have more than 10 million, combining for a metro area of about 75 million. There is wealth and fantastic public transportation, stores and restaurants and it is a thriving 21st century metropolis. There are 7 billion people on the planet but only 1 billion of those use substantial amounts of energy. Population growth used to be the concern decades ago, when the prediction was that there would be exponential growth in population. Actually, that has started to taper off. Population growth in this century is only expected to be about 30 percent, but the energy use is expected to increase 300 percent. The rate of increase in wealth is 10x the increase in population. Billions will climb out of poverty, but not if they do it by burning coal, oil and gas. To meet the objectives of the climate agreements, emissions need to be cut in half by the next decade, and then cut them in half again the decade after that, and then again the decade after that.

There is a common myth that when fossil fuels are eliminated, CO_2 will disappear. CO_2 is already the end result of chemical processes. Ten gigatons of carbon are burnt a year. Even if emissions are cut to 0, the CO_2 will go somewhere. It will go into the oceans. Except at the poles the oceans are not well mixed, and there is a warm buoyant layer on top of them. That is the only part of the ocean that is in physical contact with the atmosphere. All of the chemistry occurs in that warm water. CO_2 will last for thousands of years.

Is there a solution? Billions of people wish to improve their lives, but this needs to be accomplished without using gobs of energy that leaves a permanent residue of CO_2 in the atmosphere. There is energy efficiency and non-carbon sources of energy to be considered. Carbon footprint usually brings to mind modes of transportation. The carbon footprint of our buildings is about twice that of cars.
The US uses about twice the energy in built infrastructure as for transportation. About 46 percent of total energy in the US is in buildings. The world has become better at building much more energy-efficient buildings. Architecture 2030 has signed up every major architecture firm in the world, which produces about 90 percent of commercial construction in the whole world. This group has pledged that by 2030 they will not design any building that is not net 0 energy and puts as much energy out on the grid as it took to build the building. Just in the US that saves $4.5 trillion, and is all energy that otherwise would have been wasted. The cost for these technologies has collapsed. In 1977 photovoltaic panels were $77 a watt. They now cost less than $.5 a watt, which is almost 200x cheaper, 5x cheaper just since 2011. These technologies are now cost-competitive with coal and gas. A $1 billion-gigawatt solar plant will probably cost less and produce more revenue than a coal-fired plant.

Germany is an example of a country that is maximizing its renewable portfolio. Germany went from 4 percent wind and solar in the year 2000 to 32 percent last year. Germany gets less sun than Alaska. However, the resource potential must be coupled with infrastructure to bring electricity to market, easier in Germany where the load is concentrated, rather than hundreds of miles from a solar plant in Alamosa.

Battery storage has improved. In 2010 the batteries cost $1000/kw hr; last year the cost was about $400, with projections for 2030 at $100/kw hr. The Chevy Volt being released this year is already priced cheaper than the optimistic projection for 2025, which is 7x cheaper than in 2010. Next year a factory in Nevada will start production of these batteries on a grand scale, which will drive the cost down through economy of scale. From an engineering point of view the technology is constantly improving. It is estimated to cost about 1 percent of global GDP to retrofit and introduce the technology into India and Africa. Global GDP is $75 trillion. 1 percent is $750 billion/yr to solve the problem. For context, it is about what it cost to retrofit the world's cities with indoor plumbing 100 years ago, to dig up every street in NY, Paris, London and install pipes in every building. Work for plumbers and plumbing supply stores skyrocketed. This was a tribute to capitalism, where money was spent and dispersed. Rural electrification is another example, as was the construction of the interstate highway systems. The next generation invented PCs, the internet, and cell phones. The choice does not have to be between progress and prosperity. Progress is prosperity.

Questions.

Nuclear winter. Instead of nuclear winter, we can engineer the kind of climatic change that occurs after volcanic eruptions. Sulfur dioxide oxidizes into sulfate in the stratosphere, where it gloms onto other particles that then reflect. But you'd have to renew this every 2-4 yrs because the lifetime of a stratosphere aerosol is only about 3 yrs. It would only cost about $10 billion /yr and all you need is artillery. An island nation that is disappearing can geoengineer stratospheric sulfur to offset global warming without our permission. But the downside is that all those particles in the stratosphere are surfaces for chemical reactions and we're right back in the thick of the ozone hole problem. Worse than we ever were with CFCs. Also, it doesn't get rid of the CO2. You're just turning down the sun. CO2 dissolves in the oceans to make carbonic acid. More and more CO2 in the oceans depletes the carbonate ion. A bad geochemical consequence for any life in the ocean than produces shells.