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THE EXPONENTIAL INCREASE IN ANTHROPOGENIC ATMOSPHERIC CARBON DIOXIDE AND ITS RELATION TO HUMAN POPULATION GROWTH

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1. INTRODUCTION

Carbon dioxide is increasing in the atmosphere and is of considerable concern in global climate change because of its greenhouse gas warming potential. The rate of increase has accelerated since measurements began at Mauna Loa Observatory in 1958 where carbon dioxide increased from less than 1 part per million per year (ppm/yr) prior to 1970 to more than 2 ppm/yr in recent years (Keeling et al., 1995). This accelerating growth rate, which the London Guardian (2007) headlined a "Surge in carbon levels raises fear of runaway warming", suggested that the terrestrial biosphere and oceans ability to take up carbon dioxide may be lessening as predicted from models and data (Fung et al., 2005; Le Quéré et al., 2007). Here we show that the anthropogenic component (atmospheric value reduced by the pre-industrial value of 280 ppm) of atmospheric carbon dioxide has been increasing exponentially with a doubling time of about 35 years since the beginning of the industrial revolution (~1800). Even during the 1970's, when fossil fuel emissions dropped sharply in response to the "oil crisis" of 1973, the anthropogenic atmospheric carbon dioxide level continued increasing exponentially at Mauna Loa Observatory. Since the growth rate (time derivative) of an exponential has the same characteristic lifetime as the function itself, the carbon dioxide growth rate is also doubling at the same rate. This explains the observation that the linear growth rate of carbon dioxide has more than doubled in the past 40 years. The accelerating linear growth rate is simply the outcome of exponential growth in carbon dioxide with a nearly constant doubling time of about 30 years (about 2 %/yr) and appears to have tracked population since the pre-industrial era.

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2. ATMOSPHERIC OBSERVATIONS

Society owes a debt of gratitude to Charles "Dave" Keeling who, in 1958, began one of the most important environmental records, a continuous measurement of atmospheric carbon dioxide (CO_2) at Mauna Loa Observatory on the island of Hawaii in the mid-Pacific ocean (Keeling, 1998). Were it not for his understanding of the problem of accurately measuring CO_2 levels at the sub-part per million level, his continuing effort in the face of difficulty in sustaining a "monitoring' program (Keeling, 1998), and the 50 years of support provided by various U.S. organizations, we would not have the remarkable record shown in Fig. 1a (Keeling and Whorf, 2005; Conway et al., 2008).

As indicated in Fig. 1a, when expressed as a linear growth rate, parts per million per year (ppm/yr), the CO_2 growth rate increased from less than 1 ppm/yr in the 1960's to about 2 ppm/yr after about 2000. While clearly not a "surge in carbon levels" the non-linearity of the de- seasonalized trend curve in Fig. 1a is obvious. It is related to a non-linear addition of CO_2 to the atmosphere and to study it properly, one should look at that addition by itself, i.e., remove the pre-industrial CO_2 level of about 280 ppm (IPCC, 2007). This has been done in Fig. 1b after first removing the seasonal variation (Thoning et al., 1989; Hofmann et al., 2006) related to summer uptake of CO_2 in the northern hemisphere. Except for a shift up from about 1978 to 1980 and a shift down from about 1992 to 1994, the data follow an exponential behavior with a doubling time of 31 years, for this time period, very closely. The latter downward shift is believed to be related to the eruption of the volcano Pinatubo in 1991 which cooled the troposphere, reducing respiration, and is believed to have caused enhanced photosynthesis through scattered sunlight (Gu et al., 2003). Data from the NOAA global flask sampling network (Conway et al., 2008) are also shown in Fig. 1b beginning in 1979 when an adequate number of monitoring sites was established. The agreement between Mauna Loa Observatory and the global average is remarkable. For "business as usual" global CO_2 would be expected to double (2 x pre-industrial levels or 560 ppm) in about the year 2050.

A characteristic of an exponential function is that the growth rate of C, dC/dt is proportional to C itself, i.e., the derivative of an exponential function is also an exponential function with the same characteristic exponent; thus the CO_2 growth rate is also doubling about every 31 years. Therefore, the smoothed CO_2 growth rate can be obtained from the same curve with the scale on the right-hand side in Fig 1b. This average functional growth rate agrees well with the average linear growth rates estimated in Fig. 1a and shown in Fig. 1b for the average 5-yr slope of the de-seasonalized CO_2 curve in Fig. 1a. The two unusually low CO_2 growth rate points (1965 ± 2.5 and 1990 ± 2.5) cover the periods of the eruptions of Mt. Agung in 1963 and Pinatubo in 1991.

3. ICE CORE RECORDS

Having established that anthropogenic CO_2 has increased exponentially since at least the past 50 years we can extend the CO_2 record using ice core and firn data (Etheridge et al., 1996) as in Fig. 2. These data suggest that CO_2 did not increase as rapidly before 1950 as after, with a flattening of the curve for about 10 years after 1940, possibly related to World War II. Also shown in Figure 2 are data for world population, gross domestic product (GDP) and fossil fuel emissions. A steep rise in fossil fuel emissions between 1950 and 1970 was curtailed by the "oil crises" of 1973 and 1979 (Kerr, 1998). It is notable that the CO_2 increase does not reflect fossil fuel increases very well, in particular the oil crises inflections. Neither is it affected, on average, by El Niño – Southern Oscillation (ENSO) events, for example, the major events of 1982-83 and 1997-98. ENSO conditions are determined by the surface pressure difference between the equatorial eastern and western Pacific ocean (characterized by the Southern Oscillation Index –SOI). El Niño events coincide with minimums in SOI and generally show up as interannual increases in the CO_2 growth rates (Bacastow, 1976; Bacastow et al., 1980) although the physical connection is not clear. The equatorial oceans are generally sources of CO_2 owing to upwelling of water rich in CO_2. Upwelling is curtailed during the El Niño which would have the opposite effect. Major droughts following El Niño give rise to extensive wild fires which can increase the CO_2 growth rate as apparently occurred in 1997 (Page et al., 2002).

4. RELATION TO WORLD POPULATION

As indicated in Fig. 2, atmospheric CO_2 is best reflected by world population. Anthropogenic CO_2 and population have tracked each other extremely well over the past century. The world population has been increasing exponentially for some time because the growth rate is proportional to the existing population. Recently efforts to curb population growth, for example a goal of one child per family in China, is beginning to have an effect as can be seen in the population data for the last ten years in Fig. 2.

The relation between population and CO_2 is highlighted in Figure 3 where they are plotted against each other. For the past 50 years, anthropogenic atmospheric carbon dioxide has tracked world population with a power law relation having an exponent of about 1.35. It has been estimated (World Population Prospects, 2007) that world population will reach a maximum of about 9 billion in 2050. If the observed relation between carbon dioxide and population, for business as usual, continued for another ~40 years, anthropogenic carbon dioxide would reach a value of about 150 ppm, or a total atmospheric level of about 430 ppm. However, as atmospheric CO_2 stabilization models show, for emissions scenarios that peak in about 2050, e.g., IPCC (2007) scenario A1B (emissions peak of about 16 GtC/yr with slow decline in emissions after 2050) and B1 (emissions peak of about 12 GtC/yr with fast decline in emissions after 2050), atmospheric CO_2 would reach values of about 525 and 475 ppm in 2050, respectively for the two scenarios, but would continue to rise and would stabilize at values of 750 and 550 ppm for the two scenarios, respectively. The value of 430 ppm is close to the 2050 equilibrium atmospheric carbon dioxide level predicted if emissions from coal were phased out by 2030 (Hansen et al., 2008).

5. SUMMARY AND CONCLUSIONS

Besides showing the insight gained by removing pre-industrial CO_2 and explaining the curvature in the Mauna Loa CO_2 record, and organizing the confusion on growth rates, does this new analysis of the CO_2 record have any further use for the future? One possibility is to use it to watch for the expected and necessary break of the exponential nature of CO_2 and its growth rate. Fig. 4 shows an exponential fit to the past 14 years of Mauna Loa anthropogenic CO_2 data and the residual between the data and the exponential function. The residual has varied from zero less than ± 1% over this time period. A sustained downward trend of the residual by more than 1% (in the absence of any known major volcanic event) would be a clear sign of a change in the nature of anthropogenic atmospheric carbon dioxide, and a possible gauge of progress in the inevitable need to limit atmospheric CO_2. Similarly, a break in the close relation between anthropogenic CO_2 and population would signal that a change in "business as usual" had occurred.

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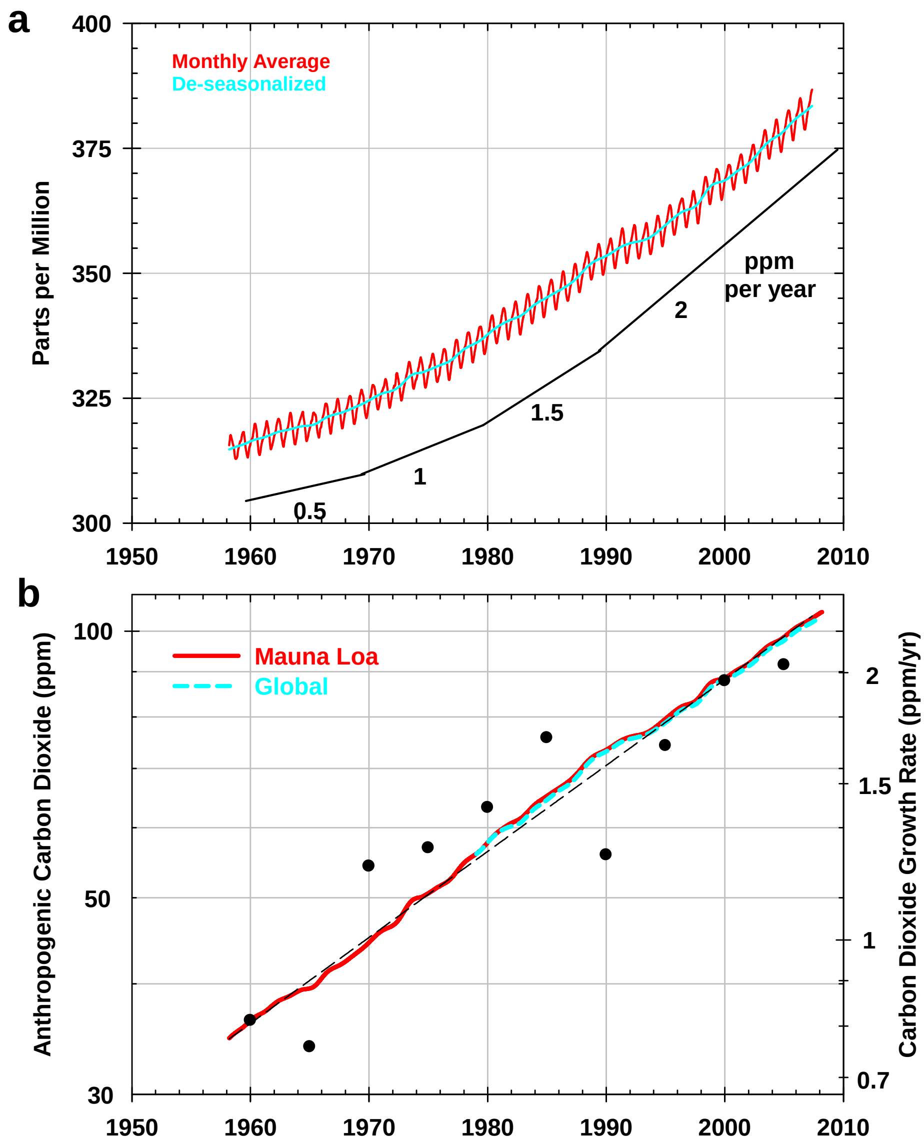

Figure 1. Atmospheric carbon dioxide measurements. **a**. Monthly averages at Mauna Loa Observatory (red curve) and smoothed data with seasonal variations removed (blue curve) (Keeling and Whorf, 2005; Conway et al., 2008; Thoning et al., 1989). The average carbon dioxide growth rates (ppm per year) are given by straight lines along the curve. **b**. The de-seasonalized data for both Mauna Loa Observatory (red curve) and the global average (blue curve – Conway et al., 2008), the latter available since 1979, have been reduced by 280 ppm, the pre-industrial value (IPCC, 2007), and plotted in semi-logarithmic format to show the exponential behavior of the excess (termed anthropogenic) carbon dioxide (Hofmann et al., 2006). The dashed straight line is an exponential function with a doubling time of 31 years. Since the time derivative of an exponential is also an exponential function with the same characteristic time, the smoothed carbon dioxide growth rate can be obtained from the same curve with the scale on the right-hand side. The black filled circles are 5-yr average CO_2 growth rates determined from the slope of the de-seasonalized CO_2 curve in Fig. 1a.

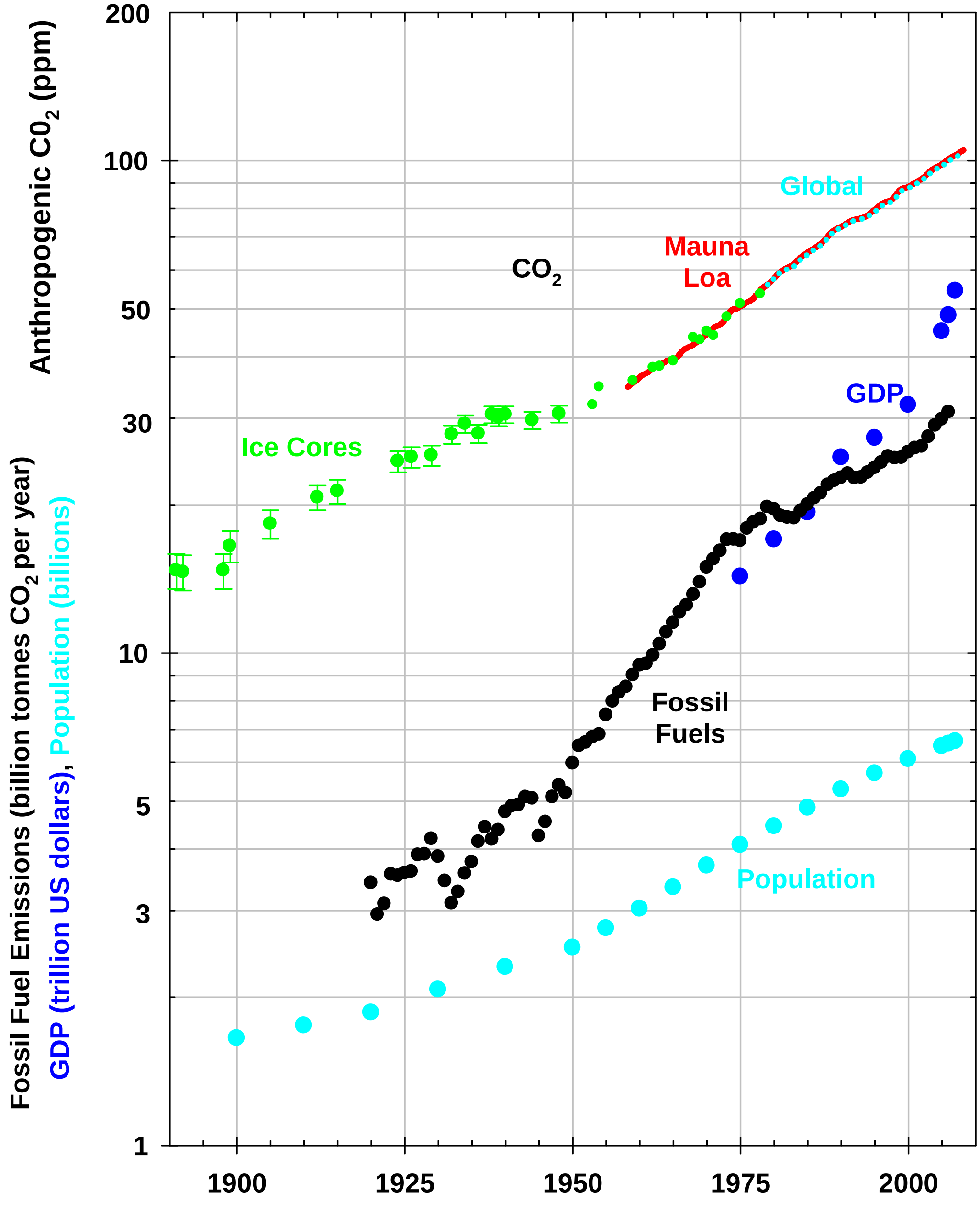

Figure 2. Anthropogenic atmospheric carbon dioxide, fossil fuel emissions, world gross domestic product (GDP), and world population for the past century. Carbon dioxide data are from Antarctic ice cores (green points – Etheridge et al., 1996), Mauna Loa Observatory (red curve) and the global network (blue dots). Population, GDP and fossil fuel information sources: United Nations, World Bank, Energy Information Administration, and Carbon Dioxide Information Analysis Center.

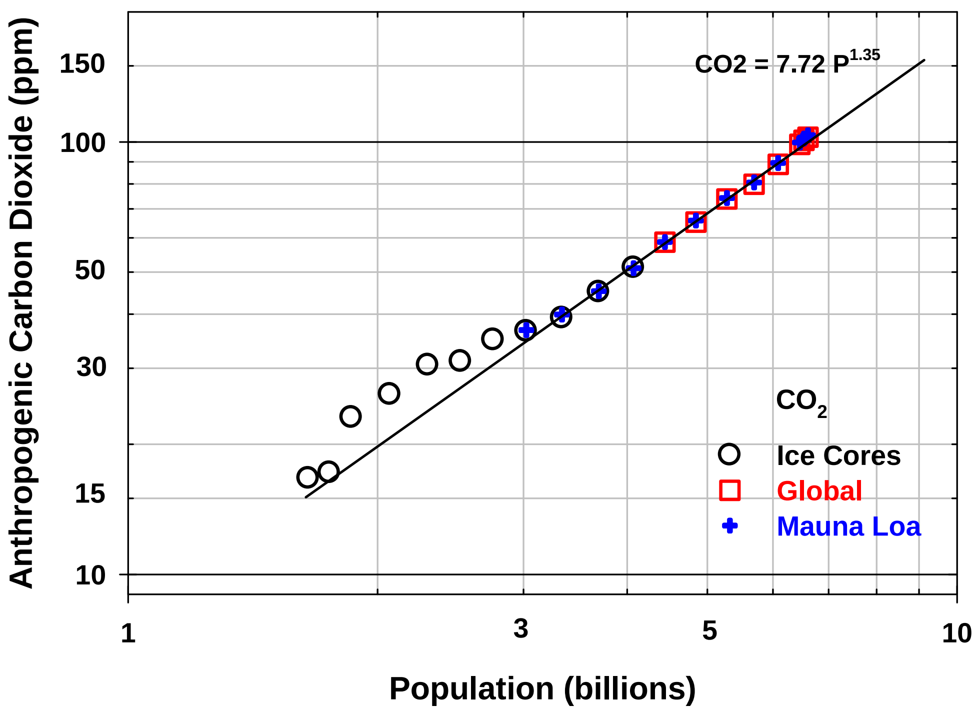

Figure 3. Anthropogenic atmospheric carbon dioxide vs population. As indicated in the figure, for the past 50 years, anthropogenic atmospheric carbon dioxide and world population have followed a power law relation with an exponent of about 1.35.

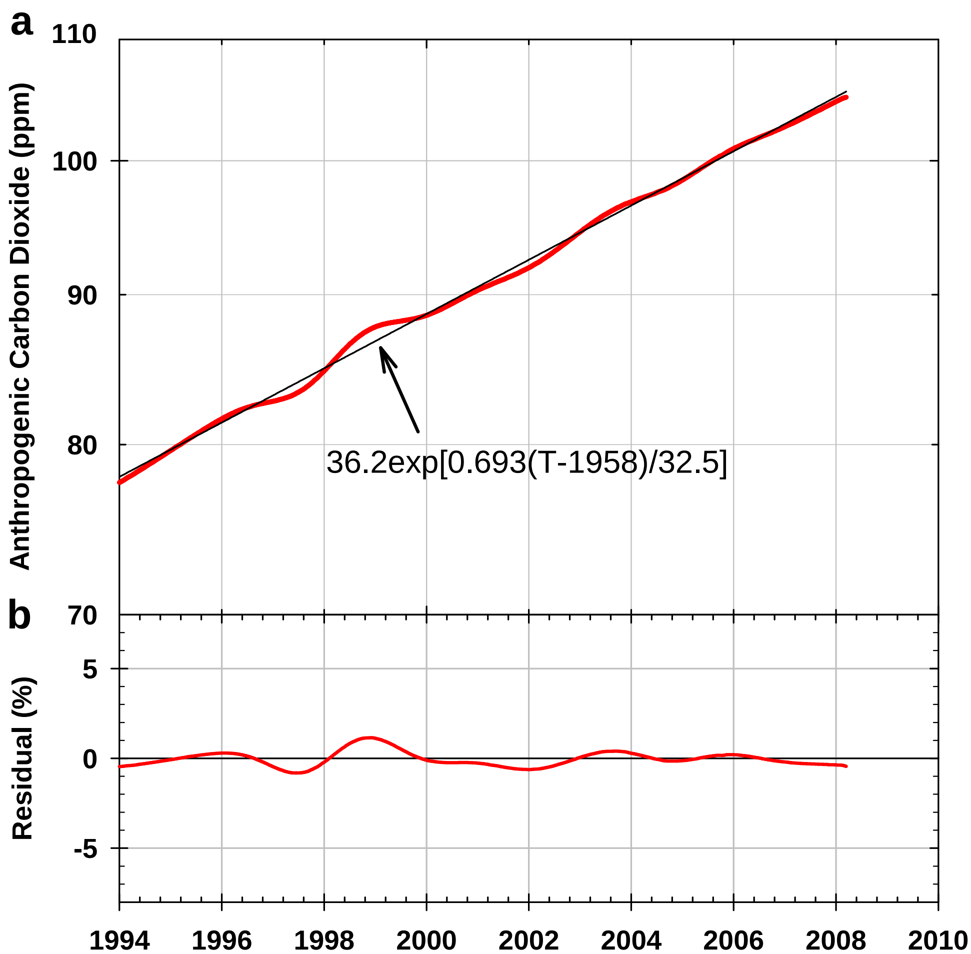

Figure 4. Utilizing the exponential nature of atmospheric carbon dioxide growth to keep track of future increases. **a.** Exponential fit to the Mauna Loa Observatory anthropogenic atmospheric carbon dioxide data. **b.** Percent difference between the observations and the exponential function (residual).