Climate Change Policy Based on Accurate Trend Forecasting.

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Despite any global policy efforts to curb CO_2 emissions, we are currently in the midst of accelerating CO_2 deposition into the atmosphere. On average, we have doubled (see the Mauna Loa CO_2 data summarized in the table) our CO_2 emissions over the last 20-25 years. Indeed in 2016 a new record was set at 3.38 ppm leading to a cumulative value of 404.2 ppm. Clearly any previous policy emission scenarios designed to prevent us from reaching 400 ppm have failed. When you are on an accelerating rate of change, the future becomes harder to predict – which adds uncertainty to the overall process. Instead of paralyzing the policy process, this increased uncertainty should focus efforts for policy to be based on more accurate trend forecasting. As we show below via it is quite erroneous to assume that the linear changes of the past will hold for the future. Policy should be based on reasonable worst-case scenarios and avoiding that outcome, instead of assuming that the future of the planet will be driven by simple linear change. If the policy world ignores these increasing rates, then the subsequent real changes in the world will be far greater than those predicted by the benign, linear approach to trend prediction,

2011-2016	2.39 +/- 0.32 ppm increase
1989-1994	1.21 +/- 0.41 ppm increase

To best illustrate this point we use data on both the rate of Arctic Sea Ice loss and the recently compiled (by NASA) global land+sea temperature measurements (since 1880) to demonstrate that we are now clearly in the non-linear regime where change is escalating each year. Sensible climate policy should now incorporate and strongly weight the information provided by the last few years of data to better recognize the increased necessity of acting **sooner and not later on effective climate policy.**

Beyond the data presented here, there are also compelling physical reasons to believe that the climate system response will be non-linear. The fundamental physical driver behind climate change is the systematic heating of the oceans since the industrial revolution. The most recent calibrated ocean heating data is shown in Figure 1. This heating is driven primarily by the waste heat generated from an industrial society; -94% of this waste heat is eventually absorbed by the oceans. The oceans therefore act as an enormous planetary buffer. However, that buffer directly couples to the atmosphere and escalated ocean heating in turn will produce escalating climate change over some timescale.

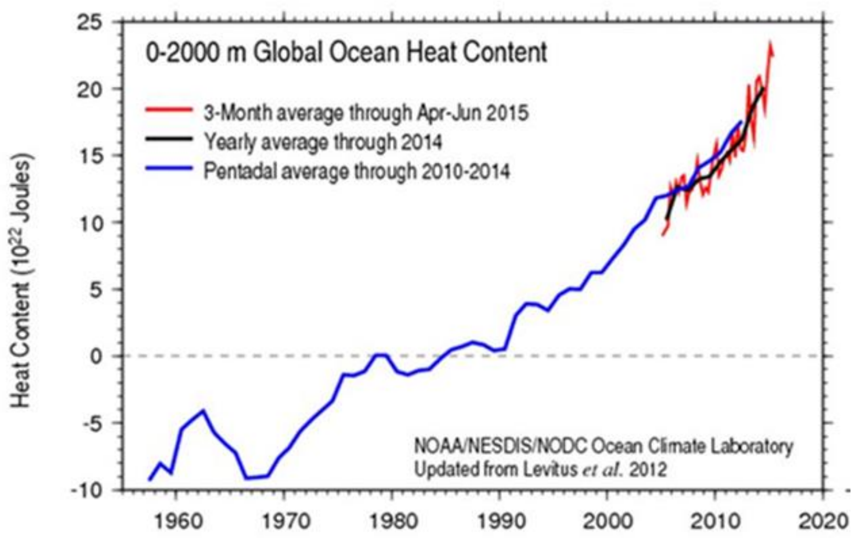

Figure 1 Ocean Heating

Figure 1 informs us of a few things:

a) The rise in ocean heating since the mid-1990s is fairly linear although the most recent data falls a bit above the linear extrapolation.

b) Since 1990, the oceans have experienced reduced efficiency in terms of handling waste heat input and are clearly retaining more heat. In turn, this inevitably changes the horizontal (ocean currents) and vertical temperature distributions within the oceans and this directly drives jet stream patterns which determine regional weather.

c) Because of b) we would expect the signature of climate change as increasing weather volatility to start to emerge around 1990 and continue to escalate simply because more energy is being added to the system.

Our oceans now have reduced capacity to re-distribute this extra heat through its normal channels (e.g. deep ocean transport). Our rate of waste heat generation is accelerating as human industry rapidly converts planetary resources into more and more consumer goods. At some point we expect continued increases in ocean heat content to lead to a non-linear response in the atmosphere and we believe the data show that his response is now occurring.

The rate of Arctic Sea Ice loss provides a good example of the difference between linear and non-linear fits to the data that extrapolate to the issue of "when will the Arctic Ocean be free of ice in September". The data, complied from the National Snow and Ice Data Center (NSIDC) is shown below where we plot average September sea ice vs time – where time starts in 1979 the first year of satellite measurements. In figure 2 we show three fits to this data that are each extrapolated to zero ice extent.

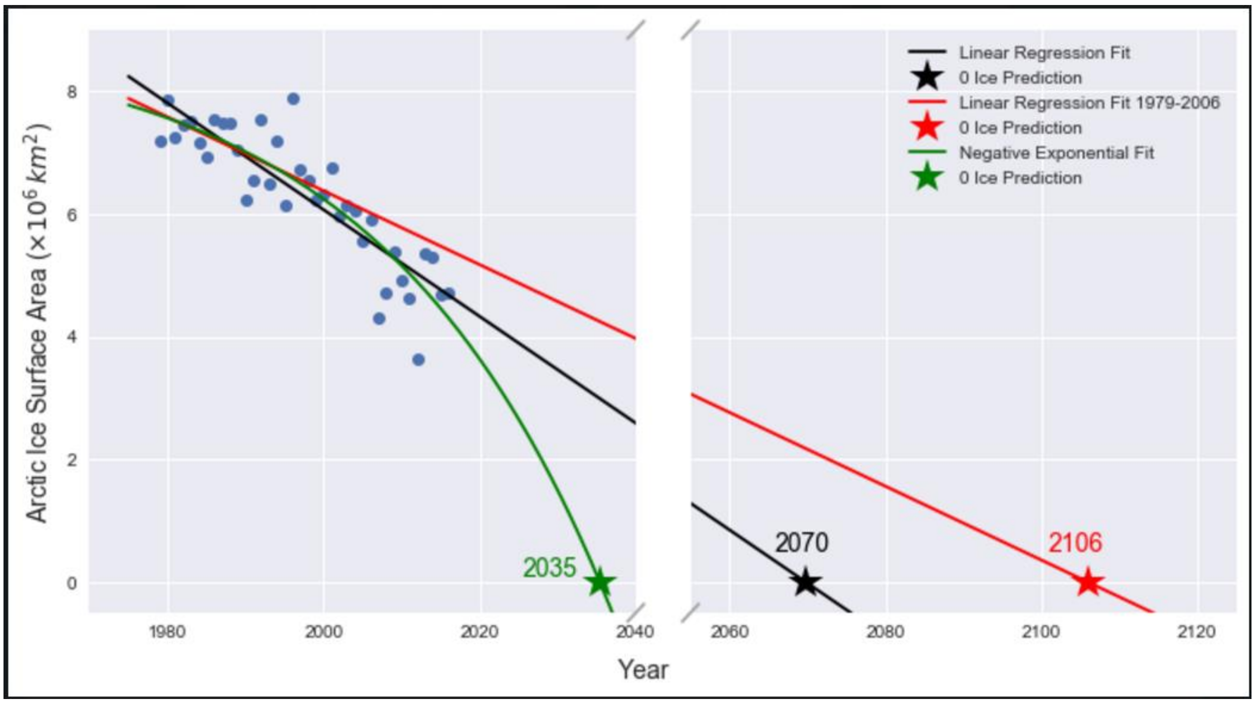

Figure 2: Various Fits to the observed annual minimum Arctic sea ice extent

- Fit 1: Linear regression over the period of 1979 – 2006 which leads to a zero ice date of 2106 and hence no hint of a problem and hence no need for policy.
- Fit 2: Linear regression now over the entire period of record. Here we note that 2007 was the first year that suggests non-linear behavior or at least a change in the slope of the line. In 2012 the record minimum September sea ice extent was achieved. Using all of the data we now get a zero ice date of 2070, considerably shorter than the previous estimate but still relatively long in policy-decision years.
- Fit 3: A non-linear damped exponential fit to the data which has us reaching zero ice in the year 2035, which is now less than 20 years away! Note also that while this non-linear fit to the data is the best one (in the statistical sense) there are a number of recent points that are disturbingly still below this line (the 2012 point remains outstanding) suggesting that the accelerating sea ice decline maybe even more rapid that this shows.

The difference between the linear and non-linear fit predictions is 30-40 years, which is significant in terms of human decision making timescales. In the year 2017, in the linear policy world, we would just punt on the issue since the crises point is way into the future. However, if the non-linear approach yields the correct trend, but we remain stuck with our linear mindset then it's quite likely that policy will be set after the time when children can visit Santa's home on a cruise ship (for which now Greenpeace has launched the Santa Relocation Project).

This state of affairs is highly analogous to the Dec 12 2015 Paris accord to "*keep a global temperature rise this century well below 2 degrees C …*" at a time when data indicate we are already at 1 to 1.5 C and clearly on the way to smash through 2 C (see also the data presented below). Overall, the Paris Accord is a good example of linear based policy which seems quite of out touch with what is actually happening.

We now illustrate the issue of linear vs. non-linear trend extrapolation to global temperature measurements. It is important to make the caveat that the Authors don't believe that global temperature, especially over the land surface, is a very physically meaningful quantity (i.e. how is it measured, how many thermometers do you need, where do you put the thermometers, does the thermometer environment change over time?). The use of both land and ocean is a far more sensible approach than just using land based data. For instance, urbanization effects over the period of record are not likely to influence ocean based temperatures. Nonetheless, these data are commonly used in public discussion about climate change.

For our study we make use of the composite Land-Ocean temperature anomalies, with respect to the baseline of 1951-1980, as provided by NASA Goddard (https://data.giss.nasa.gov/gistemp/graphs_v3/Fig.A2.txt).

We start by simply plotting (Figure 3) the raw data with a standard, unweighted, linear regression fit projected out to the year 2050 and compare that to the standard 5 year running average plot. Both predict a temperature anomaly of +0.75 C.

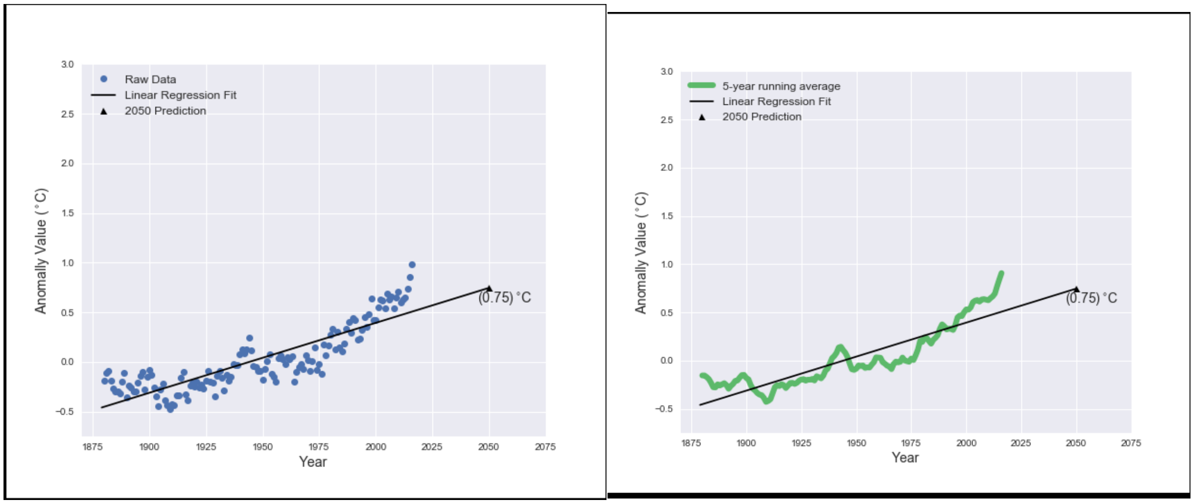

Figure 3: Raw data on the left; 5 yr running average on the right

This temperature anomaly refers to the 1951-1980 period. To compare to the Paris Accord we need to renormalize and refer the anomaly to the typical 1881-1910 period that is used for the "pre industrialized" level. In this case, the predicted 2050 temperature anomaly is +1.01 C – well beneath the stated goal of the Paris Accord, under the policy statement that "the linear trend is the most appropriate". That statement, however, is not very scientific as just your eye, let alone statistical tests, suggests that recent years are systematically departing from the linear trend and perhaps another kind of fit is in order. Indeed, should this data be equally weighted as if all temperature points are independent and equally valid? Or should this systematic departure of the recent data carry with it more weight as being indicative of an actual manifestation of climate change?

For this kind of data, it is often better to average the data over some timescales. We will bin the data in units of 9 years. This gives us 15 bins from 1880 to 2014 and we will initially leave the 2015 and 2016 data points out. Note that there are no special rules for how to bin and smooth data – one just wants enough binning to see the waveform, but not too much binning to see the noise. Figure 4 shows the resultant plot. This predicts ΔT = **0.71**, not appreciably different from what was obtained before.

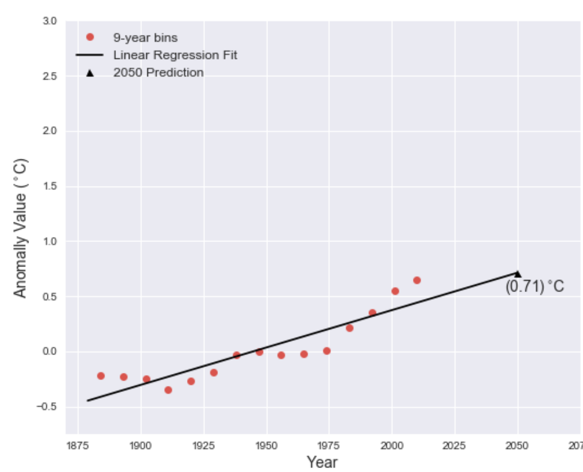

Figure 4: Data binned in 9 year increments

This data depiction clearly shows the well-known "mid-century" cooling that followed the period of warming earlier in the record. This cooling has been used to suggest that a similar event will happen in the near future. While the origin of this cooling is unknown, a very likely hypothesis is that industrial pollution from aerosols dominated over GHG pollution leading to this period of global cooling. This is plausible because a) there was little law or regulation concerning industrial pollution and b) during this period total greenhouse gas emissions was ~ 4--5 times less than today (1958 Mauna Loa data show 0.6—0.7 ppm per year; 2016 was ~3.4 ppm).

Next we address the issue of weighting by simply adding the 2015 and 2016 as two additional points to the diagram. Figure 5 shows the weighted fit leading to a higher predicted ΔT than the previous unweighted treatment. Hence, weighting the linear fit can manipulate the trend prediction to some degree and one therefore needs some reasonable scientific validity for the weights. The scientific reasoning behind this form of weighting is simple: a) the years 2015 and 2016, are two successive record breaking years and b) this is likely an indication that we indeed are now in the non-linear regime of climate response to ocean heating. However, whether the data is weighted or not, the linear fit to the data is poor and does not pass any scientific validity statistical test.

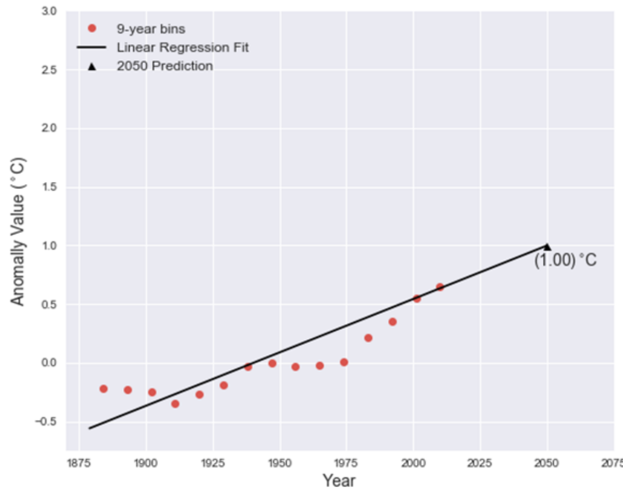

Figure 5: Weighted linear fit to the binned data

To improve the validity of the fit we finally turn to a non-linear approach. Figure 6 shows such a fit for both the unweighted and weighted data.

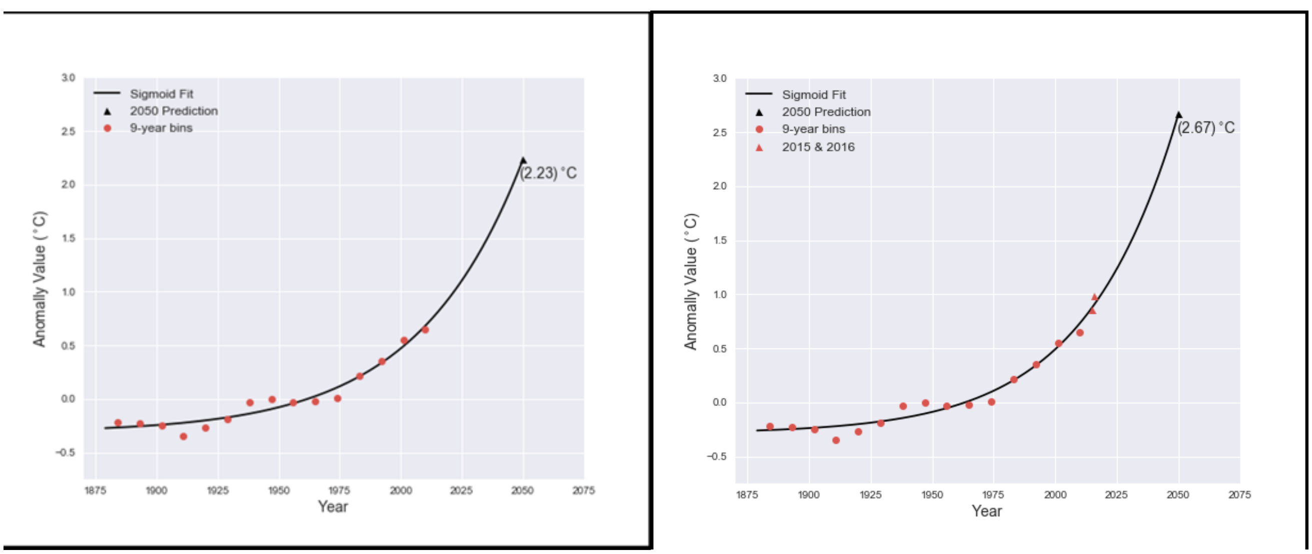

Figure 6: Sigmoidal Fits to the Unweighted and Weighted Data

The function used here is a symmetrical sigmoidal function: The resultant fit from that function significantly reduces the scatter of the data points and predicts a temperature anomaly of 2.23 C which is 1.5 C **higher** than the previous

$$y = D + \frac{A - D}{1 + \left(\frac{x}{C}\right)^B}$$

prediction. In lay terms, this means that the “scientific” choice of fitting the proper curve should have strong policy implications. If for instance we “believe” that linear fits are the best, then our future is far less dire, than that predicted by this improved functional form. Furthermore, this approach predicts a value of **2.49** C by 2050 as the pre-industrialized temperature rise which now **violates the Paris accord.** The weighted fit predicts ΔT = **2.67 which puts us quite close to a 3 C rise in global temperature above the pre-industrialized level, by the year 2050.**

So what do we do? Do we pay attention to these non-linear trend estimates or do we just ignore them since the future is always a simple straight line? Do we keep our heads in the sand and just wait for a few more years’ worth of data that might show the above non-linear expectations are not continued by the future data? Or, do we use better scientific principles to guide our policy making and recognize that we are now in the non-linear regime which no longer offers the luxury of time, either for global average temperature changes or melting Arctic sea ice. This is the lesson here; if non-linear trend extrapolation is the best way to represent the future, then climate change policy needs to become **more aggressive and enacted more immediately.**

This eventual non-linear response of the Earth system to our consumption is likely a signature of our enormous consumption rate. At the moment, we are adding a few x 10^{22} joules of heat annually to the ocean; that of course is an incomprehensible number. However, this heat content is equivalent to every human using **50-100 gallons of gas per day!** Continuing at this rate is insane. Eventually, this enormous consumption will affect the physical systems of the planet. In the policy world, the word “eventually” has always been code for “yeah it might be a future problem but it’s not a problem now, so we will ignore it …” Ignoring data trends generally allows the next generation to inherit a problem with a reduced timescale to “fix it”. The data presented here strongly suggests that **eventually = now**. The policy world needs to wake up to the reality of accelerating rates, as borne out by the data, and refrain from continued wishful thinking that the physical world follows linear trends. It does not and that stark reality cries out for more intensive and thoughtful policy and planning processes so as to change our trajectory towards a more livable future.