Developing financial market instruments to protect against what could be dramatically escalating costs, should certain possible future climate change scenarios be realised.

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ABSTRACT

The cost of protecting against global climate change may be established by applying financial market mathematics to data associated with drivers of that change. This approach is used to derive a risk management model that evaluates the cost of protection. Data employed to develop the model include long-term time series of measures associated with such drivers. The data are statistically analysed to establish their relative importance. It is found that Atmospheric Carbon Dioxide is of profound importance, but that other drivers do have an influence. The findings are then applied to derive the statistical distribution of possible future trends out to 2030 of the Global Mean Temperature, based upon a set of Monte-Carlo-generated scenarios. These scenarios show that it is much more likely for the Global Mean Temperature in 2030 to be higher than that in 2015. The statistical distribution is then interrogated to provide estimates of what are the 'fair value' prices of put and call options on Global Mean Temperature futures contracts set to expire on Dec-31 in each year out to 2030. The options considered include European style options (exercise only on expiry date) and Bermudan style options (exercise on any Dec-31 prior to expiry date) with the 'fair value' prices of the call options with particular expiry dates shown to be higher than those of the corresponding put options. To summarise, the paper demonstrates how to evaluate the cost of hedging and speculative instruments related to climate change. Whilst their development allows those who wish to place 'bets' on their views as to the likely future climate, the real value of the foregoing to those involved in disaster and emergency management lies in the instruments providing the opportunity to protect against what could be dramatically escalating costs, should certain possible future climate change scenarios be realised.

BACKGROUND

McGregor (2006) places the material that follows in a broad context, when he writes:

"The science of meteorology is deeply intertwined with the process of emergency management. Weather phenomena are the cause of many disaster events such as tornadoes and hurricanes and a factor in many others. Weather can also affect the way assistance is provided during or after an emergency. Since time to prepare is vital, much of meteorology is concerned with forecasting … (but) the future poses its own special brand of weather hazards due to the uncertainties and scale of global warming and consequent changes in global climate patterns".

I now quote, somewhat extensively, from a 17-Feb-2017 speech by the *Australian Prudential Regulation Authority* (APRA)'s Executive Member (Insurance), Geoff Summerhayes, to the *Insurance Council of Australia* Annual Forum in Sydney, which provides a very nice background. He said, in part (Summerhayes, 2017):

"To begin with a generalisation, while climate risks have been broadly recognised, they have often been seen as a future problem or a non-financial problem. The key point I want to make today, and

that APRA wants to be explicit about, is that this is no longer the case. Some climate risks are distinctly 'financial' in nature. Many of these risks are foreseeable, material and actionable now. Climate risks also have potential system-wide implications that APRA and other regulators here and abroad are paying much closer attention to … I think the days of viewing climate change within a purely ethical, environmental or long-term frame have passed. More and more, the conversations we are having are about the practical realities and consequences of a changing climate. One reason for this is that we now have a much more sophisticated, granular, quantifiable understanding of the impacts, risks and probability distributions around climate change … We also have a much keener idea of impacts at a local level, and the implications for countries, regions, cities and, yes, companies … today, climate change is not just the realm of scientists – but of planners, policymakers, businesspeople and economists … In November, the Centre for Policy Development and the Future Business Council released an influential legal opinion on company directors' legal obligations to consider the impacts of climate change. The opinion was authored by barrister Noel Hutley SC (2016). The opinion found that company directors who fail to properly consider and disclose foreseeable climate-related risks to their business could be held personally liable for breaching their statutory duty of due care and diligence under the Corporations Act … The terminology I would like to adopt now, consistent with the FSB (Financial Stability Board) Taskforce, is physical and transition risks ... for the sake of clarity: (1) physical risks stem from the direct impact of climate change on our physical environment – through, for example, resource availability, supply chain disruptions or damage to assets from severe weather. (2) transition risks stem from the much wider set of changes in policy, law, markets, technology and prices that are part of the now agreed transition to a low-carbon economy … A critical implication of what I have just recounted is the importance of considering, and modelling, the potential impact of climate-related risks under different scenarios and over different time horizons … So climate risks will become an important and explicit part of our thinking. This is absolutely consistent with the approach that is being taken by regulators overseas. I hope the remarks I've made today show that we are very much alive to this issue too."

Before closing this very current background piece, I refer readers to a review of some of the early work in the area of climate and weather financial risk management, which was covered in a *Risk Books* publication edited by Dischel (2002), and to the *Stern Review on the Economics of Climate Change*, which was commissioned by the Government of the United Kingdom, and authored by the now Lord Nicholas Stern (2006)[1].

INTRODUCTION

The current author, in a paper more than two decades past (Stern, 1992), and also in a series of follow-up papers (Stern, 2001a, b, c & d, 2002a&b, 2005, 2006, 2007, 2008, 2009, 2010; Stern & Dawkins, 2003, 2004; Dawkins & Stern, 2004; and Stern *et al*., 2010), has explored how one might best apply financial market instruments to protect against risks related to climate variability and change. In so doing, the intersection between the atmospheric sciences and economics, which is where this work resides, is acknowledged in Stern's earlier (1992) paper with a quote from an article by Sutton (1951). This quote is also repeated (in part) here:

"The analogy between astronomy and meteorology is often made…There is a closer resemblance, to my mind, between meteorology and economics. Both deal fundamentally with the problem of energy transformations and distribution…"

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[1] Although not related to each other, both our fathers were Jewish refugees from Nazi Germany who were forcibly transported in World War 2 to Australia from Great Britain on the *HMT Dunera*.

Given that the financial market instruments applied in this work are options, the following quote from an article which appeared in The Economist (1991) - author unknown, and which was also referenced in Stern's earlier (1992) paper, is also repeated here:

"Economists are sometimes challenged to cite a discovery from economics that is both true and surprising. For many years, the principle of comparative advantage was the best example. An equally good reply, thanks to Messrs Black and Scholes (Black and Scholes, 1973), is the theory of options pricing".

DISCUSSION

The primary purpose of the paper is, in demonstrating how one may evaluate a "fair value" price for hedging and speculative instruments related to climate change, to propose that such products may be applied as an "insurance policy" to ameliorate, from a long-term perspective, the potentially escalating costs of managing the consequences of disasters and emergencies that may arise from climate change.

Labadie (2011) puts the issue of addressing difficulties from such a perspective thus:

"Emergency managers will have to deal with the impending, uncertain, and possibly extreme effects of climate change. Yet, many emergency managers … are unsure of their place in the effort to plan for, adapt to, and cope with those effects. This … mostly is due to (a not unexpected) … focus on … a shorter event horizon (5 years vs. 75–100 years); and a shorter planning and operational cycle".

The National Climate Change Adaptation Research Facility (NCCARF, 2013) Policy Guidance Brief 10, *Emergency Management and Climate Change Adaptation*, which *"deals with the management of climate related disasters under climate change"*, includes the following presentation of future projections of extreme climate events:

Box 1 Future projections of extreme climate events and the associated confidence (from Handmer et al. 2012 citing Garnaut 2011).

- *Heat waves:* high level of certainty of increased frequency and intensity.
- *Fire danger:* strong evidence that south-eastern Australia will experience an increased frequency of high fire risk days, with uncertainty about magnitude of change.
- *Rising sea levels and storm surge events*: high level of certainty of some sea-level rise resulting from thermal expansion, but rate and extent of rise caused by ice melt uncertain.
- *Storm surge affected by intensity of storms:* less certainty over extent and frequency.
- *Rainfall events:* high level of agreement that some areas will become drier, and some areas will be likely to experience intensified rainfall events and therefore suffer an increased risk of flooding, but uncertainty over which areas will be affected and how.
- *Tropical cyclones:* considerable uncertainty remains over climate change impacts on the location, frequency and severity of tropical cyclones.
- *Strong winds from east coast lows:* East Coast Lows are intense low-pressure systems that occur off the eastern coast of Australia. While some types of east coast lows have increased in number since 1970, it is still uncertain how climate change is likely to alter their frequency and magnitude.
- *Hail:* significant uncertainty over the potential for hail events to increase in some regions.

NCCARF (2013) notes that:

"Recent unprecedented climate-related extreme events have … brought the (Australian) nation's vulnerability to such disasters into sharp focus and placed a significant financial … emotional and social burden on governments and affected communities".

It is the aforementioned financial burden that, through application of the market instruments whose development are discussed in this paper, one hopes to ameliorate.

CLIMATE CHANGE DRIVERS

The Intergovernmental Panel on Climate Change (IPCC, 2013) define *climate change drivers* as being "natural and anthropogenic substances and processes that alter the Earth's energy budget".

Over the millennia

By way of further background, the very long term impacts of key drivers upon the Earth's energy budget are now briefly flagged. Milutin Milankovitch (1879–1958) was a Serbian mathematician and physicist from the University of Belgrade, who made important studies of solar radiation (Allaby, 2008) and his name is written into the climate science literature as the *Milankovitch cycles*. The NCSU (North Carolina State University) (2017) describe the cycles as being caused by changes in the earth's orbit around the sun, like its shape or eccentricity[2] (Figure 1), the tilt of its axis or obliquity[3] (Figure 2) and its precession or wobble[4] (Figure 3). These changes evolve over the millennia, rather than being short-term phenomena. The NCSU further notes that:

- *Each of these have a different effect on how much of the sun's energy reaches the earth and when the strongest sunlight occurs;*
- *The orbit has an effect on climate by determining the amount of incoming sunlight;*
- *The cycle of ice ages is linked to changes in the earth's orbit, so it is important to the long-term climate variability of the earth.*

In modern times

However, the main purpose of this work is to statistically analyse the short term impacts of a selection of climate change drivers about which we possess sound data bases, and utilising the results of such analyses to demonstrate how to design financial market instruments that may be applied to protecting against what could be dramatically escalating costs, should certain possible future climate change scenarios be realised. Short term climate change drivers considered herein are:

- Global Mean Temperature
- Atmospheric Carbon Dioxide
- The Sunspot Cycle
- The El Niño Southern Oscillation Cycle

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[2] Eccentricity is the shape of the earth's orbit. Over a time period of 100,000 years, the orbit ranges from being a nearly perfect circle to being an oval and back to a near-circle again. Right now, the orbit is almost a perfect circle. This causes the earth to be a little closer to the sun in January than it is in July, which leads to more solar energy reaching the earth in January than in July. But this effect is small compared to the variation in incoming sunlight caused by the tilt of the earth, and so at this point in time the eccentricity has very little effect on the climate over the year. If the orbit became a pronounced oval, it would be warmer when the earth was closer to the sun regardless of tilt, and the length of the seasons would be different (NCSU, 2017).

[3] Obliquity is the earth's tilt relative to the earth's orbit around the sun. The earth's tilt causes the seasons (see Tilt and Latitude under Background and Basics). The tilt away from the axis changes from 22.1° to 24.5° over a period of 41,000 years. The current tilt is 23.5° and is slowly decreasing. When the tilt becomes larger, the seasons are more extreme, with more severe winter and summer weather. When the tilt is smaller, the seasons are milder and less different from each other (NCSU, 2017).

[4] The precession is how much the earth wobbles on its axis. The earth wobbles like a top that is slowing down. The result is that the North Pole on earth changes where it points to the sky. At present it is pointing at what we call Polaris, the Northern Star. However, 13,000 years ago it was pointing somewhat away from Polaris. The position of the North Pole on the sky forms a circle that is traced out every 26,000 years. The combination of the precession with whether the earth is nearer or farther from the sun can affect the severity of the seasons in one hemisphere compared to the other (NCSU, 2017)..

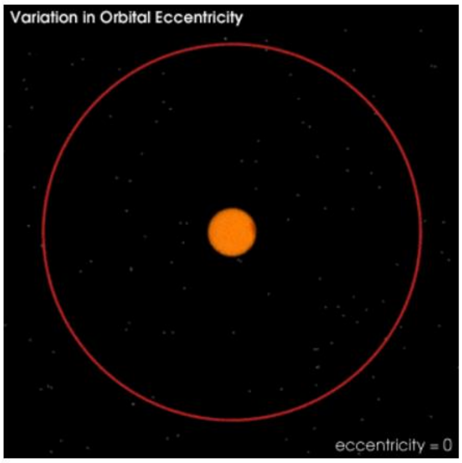

Figure A

Image from NASA

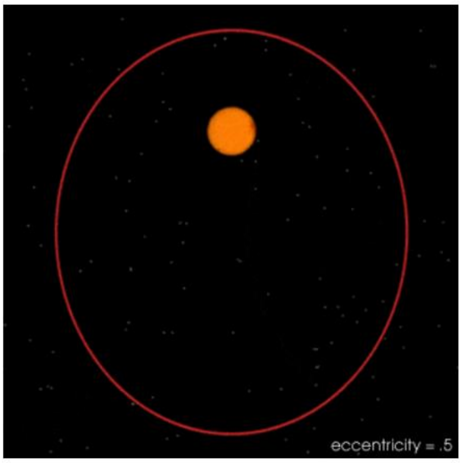

Figure B

Image from NASA

Figure 1 An illustration of *orbital eccentricity* (as presented by NCSU, 2017).

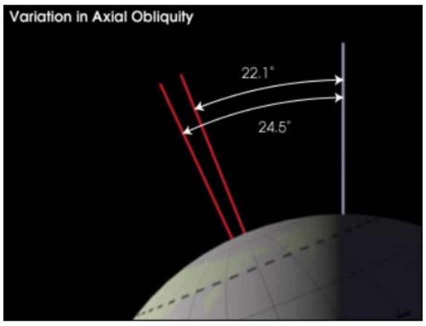

Figure C

Image from NASA

Figure 2 An illustration of *axial obliquity* (as presented by NCSU, 2017).

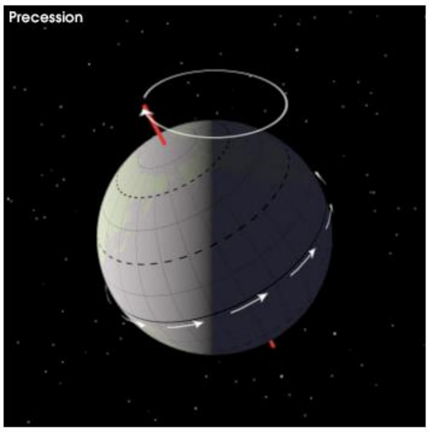

Figure D

Image from NASA

Figure 3 An illustration of *precession* (as presented by NCSU, 2017).

Global Mean Temperature

Utilising the (Australian) Bureau of Meteorology's Global Mean Temperature (GMT) data base (Bureau of Meteorology, 2017a), from 1850 to 2015 inclusive, the following regression relationship is established between each year's GMT, $GMT_{previous\ year}$, and $GMT_{two\ years\ previous}$:

$$\mathbf{GMT_{current\ year} - GMT_{previous\ year} =}$$

$$\mathbf{0.028 - 0.22*[GMT_{previous\ year} - GMT_{two\ years\ previous}] + 0.00040(Year-2015) + 0.0000013[(Year-2015)^2]} \qquad \textbf{Equation 1}$$

Whilst the coefficients +0.028, +0.00040 and +0.0000013 are not statistically significant, the coefficient -0.22 is highly significant, the probability of a value lower than -0.22 occurring by chance being only 0.12%. This indicates that following a sharp rise in GMT from one year to the next, the probability of a cooler year to follow is more likely than otherwise. This is a feature that needs to be taken into account when modelling climate change scenarios.

Atmospheric Carbon Dioxide

Utilising Carbon Dioxide Mixing Ratio (CDMR) data - Ice-Core, Mauna Loa and South Pole Data, all adjusted for the global mean (Earth System Research Laboratory (ESRL), 2017; National Aeronautics and Space Administration (NASA), 2017), from 1876 to 2015 inclusive, a regression relationship is established between each year's CDMR and each of the CDMRs of the preceding 15 years. This relationship is depicted in Figure 4, both for the period based upon observed data (15 years to 2015) and for forecast data out to 2030 derived via the aforementioned relationship. The relationship, depicted in Figure 4, suggests that CDMR is likely to reach 440 parts per million by the year 2030, should past trends continue.

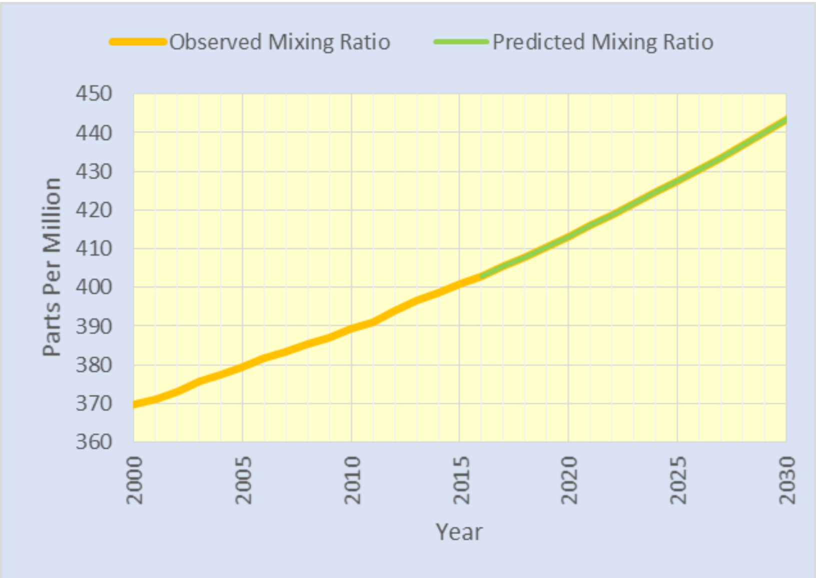

Figure 4 Trend in the Carbon Dioxide Mixing Ratio (CDMR) that is suggested by the regression relationship established between each year's CDMR and each of the CDMRs of the preceding 15 years.

The Sunspot Cycle

Utilising sunspot number data from the World Data Center SILSO, Royal Observatory of Belgium, Brussels (2017**),** 1876 to 2015 inclusive, a regression relationship is established between each year's sunspot number and each of the sunspot numbers of the preceding 15 years. This relationship is depicted in Figure 5, both for the period based upon observed data (15 years to 2015) and for forecast data out to 2030 derived via the aforementioned relationship. The relationship, depicted in Figure 5, nicely reflects the sunspot cycle.

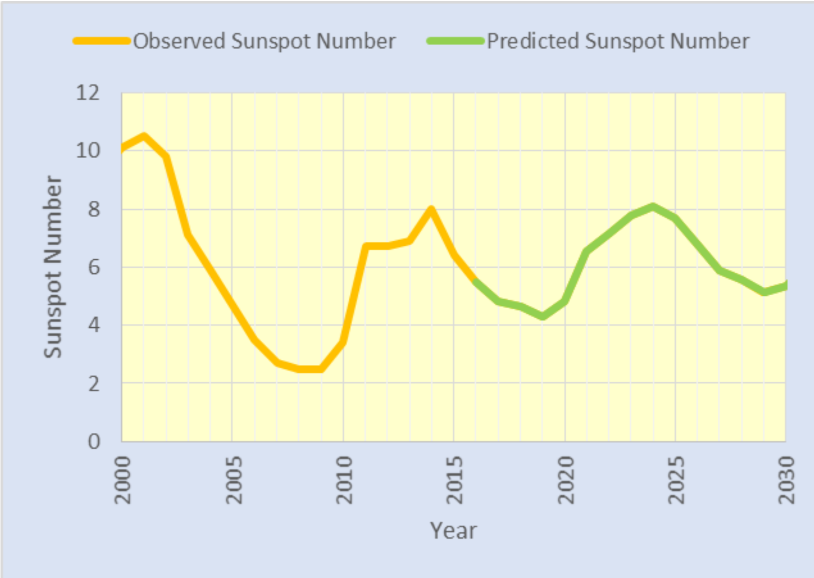

Figure 5 Trend in the Sunspot Number that is suggested by the regression relationship established between each year's Sunspot Number and each of the Sunspot Numbers of the preceding 15 years.

<u>The El Niño Southern Oscillation Cycle</u>

Utilising mean annual Southern Oscillation Index (SOI) data from the Bureau of Meteorology (2017b**),** 1876 to 2015 inclusive, a regression relationship is established between each year's SOI and each of the SOIs of the preceding 15 years. This relationship is depicted in Figure 6, both for the period based upon observed data (15 years to 2015) and for forecast data out to 2030 derived via the aforementioned relationship. The relationship, depicted in Figure 6, when compared with that depicted in Figure 5, indicates that the El Niño Southern Oscillation Cycle is much more poorly defined than that of the sunspot number.

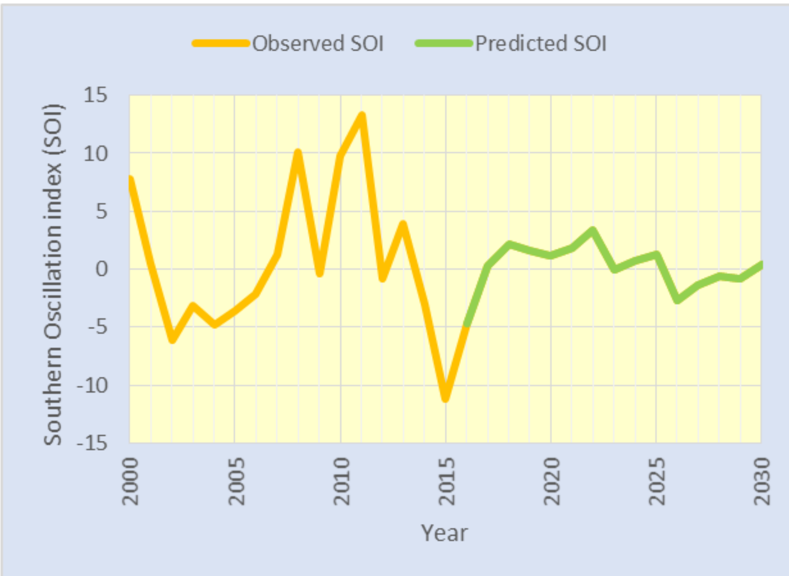

Figure 6 Trend in the Southern Oscillation Index (SOI) that is suggested by the regression relationship established between each year's SOI and each of the SOIs of the preceding 15 years.

A combined relationship

A relationship is now established between the change in each year's global mean temperature from the preceding year and the aforementioned parameters. This is carried out in order to establish their relative importance and also to provide a background prediction upon which the probability distribution of the range of possible future global mean temperature evolutions may reside. The relationship, depicted in Figure 7, indicates (among other things) that whilst the previous year's mean carbon dioxide mixing ratio is the most important parameter (P-value 0.00004%), the sunspot number has little influence. Interestingly, the development of an El Niño during the preceding year, accompanied by a falling SOI, prompts a lift in global mean temperature (P-value 0.003%).

Predictor	*Value of Regression Constant*	*t Stat*	*P-value*
Regression Constant C_0	3.32738	4.23	***0.002%***
Previous Year's Mean Carbon Dioxide Mixing Ratio	0.00478	5.20	***0.00004%***
Previous Year's Mean Southern Oscillation Index	0.00250	1.49	*6.9%*
Previous Year's Mean Sunspot Number	0.00108	0.37	*35.6%*
Change in Mean Sunspot Number from Year-2 to Previous Year	0.00114	0.25	*40.3%*
Change in Global Mean Temperature from Year-2 to Previous Year	-0.11859	-1.36	*8.7%*
Change in Mean Carbon Dioxide Mixing Ratio from Year-2 to Previous Year	-0.06241	-2.58	***0.5%***
Change in Mean Southern Oscillation Index from Year-2 to Previous Year	-0.00541	-4.17	***0.003%***
Previous Year's Mean Global Temperature	-0.34661	-4.83	***0.0002%***

Figure 7 The relationship between the change in each year's global mean temperature from the preceding year and various parameters.

MONTE CARLO GENERATED SCENARIOS

Description of the Monte Carlo model (refer to Appendix 1)

Between 1850 and 2015, we have 165 year-to-year Global Mean Temperature (GMT) changes.

For each year, in each 'run' or 'scenario', starting with the year 2015 and finishing with the year 2030, the model randomly selects one of these GMT changes and then applies Equation 1 in order to take into account the preceding change in GMT.

The model is 'run' 100 times, and a distribution of possible outcomes is thereby obtained. The mean of these outcomes is calculated for each year from 2016 to 2030.

All of the outcomes for each year are then adjusted by an amount equal to the difference between that mean GMT and the GMT that is suggested by the relationship depicted in Figure 7, using inputs for Atmospheric Carbon Dioxide, the Sunspot Number and the Southern Oscillation Index, that are indicated by the relationships depicted in Figures 4, 5 and 6, respectively.

Deriving the statistical distribution of the possible future global mean temperature trend

Having applied the Monte Carlo model, as described above, the standard deviation about the mean of all the scenario outcomes is calculated and used to derive the 1%, 5%, 10% and 20% upper and lower bounds for the expected global mean temperature in each year from 2016 to 2030.

These are illustrated in Figure 8, which shows that there is only a 20% chance that the Global Mean Temperature in 2030 will be below that recorded in 2015.

By contrast, Figure 8 also shows that there is a 20% chance that the Global Mean Temperature will be more than half a degree warmer than it was 2015.

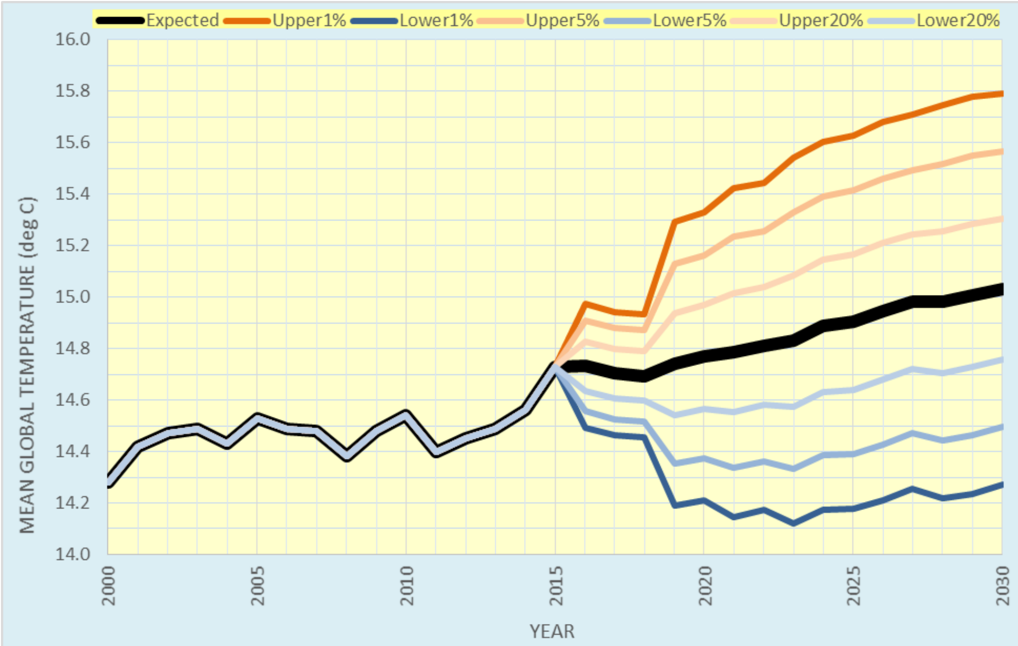

Figure 8 The fluctuations in global mean temperature from 2000 to 2015 and the 1%, 5%, 10% and 20% upper and lower bounds for the expected global mean temperature in each year from 2016 to 2030.

Application to 'fair value' pricing of related financial market instruments

Using the interest rates suggested by Bloomberg (2017), the statistical distribution derived above is then interrogated to provide estimates of what are the 'fair value' premiums (costs) of sets of put[5] and call[6] options. Both sets of options are based upon on Global Mean Temperature futures contracts with a value of $100 per °C at expiry. Two types of options are considered: European style options - exercise only on expiry date, and Bermudan style options - exercise on any Dec-31 prior to expiry date. The array of the 'fair value' premiums of the put and call options so derived, are depicted in Figure 9 and Figure 10, respectively. Figures 9 and 10 show that, at least for the 14.73°C options considered here (which is the 2015 Global Mean Temperature) that, with the exception of several of the short-dated options, the 2030 European style call options are more valuable than the corresponding put options.

CONCLUDING REMARKS

The paper demonstrates how to evaluate the cost of hedging and speculative instruments related to climate change. Whilst their development allows those who wish to place 'bets' on their views as to the likely future climate, the real value of the foregoing to those involved in disaster and emergency management lies in the instruments providing the opportunity to protect against what could be dramatically escalating costs, should certain possible future climate change scenarios be realised. From the paper's analysis of the economics data, there emerges a strategy to ameliorate the financial burden arising from managing disasters that arise from climate-change-related extreme events.

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[5] The Options Guide (2017a) defines a put option thus: "A put option is an option contract in which the holder (buyer) has the right *(but not the obligation)* to buy a specified quantity of a security at a specified price (strike price) within a fixed period of time (until its expiration)."

[6] The Options Guide (2017b) defines a call option thus: "A call option is an option contract in which the holder (buyer) has the right *(but not the obligation)* to sell a specified quantity of a security at a specified price (strike price) within a fixed period of time (until its expiration)."

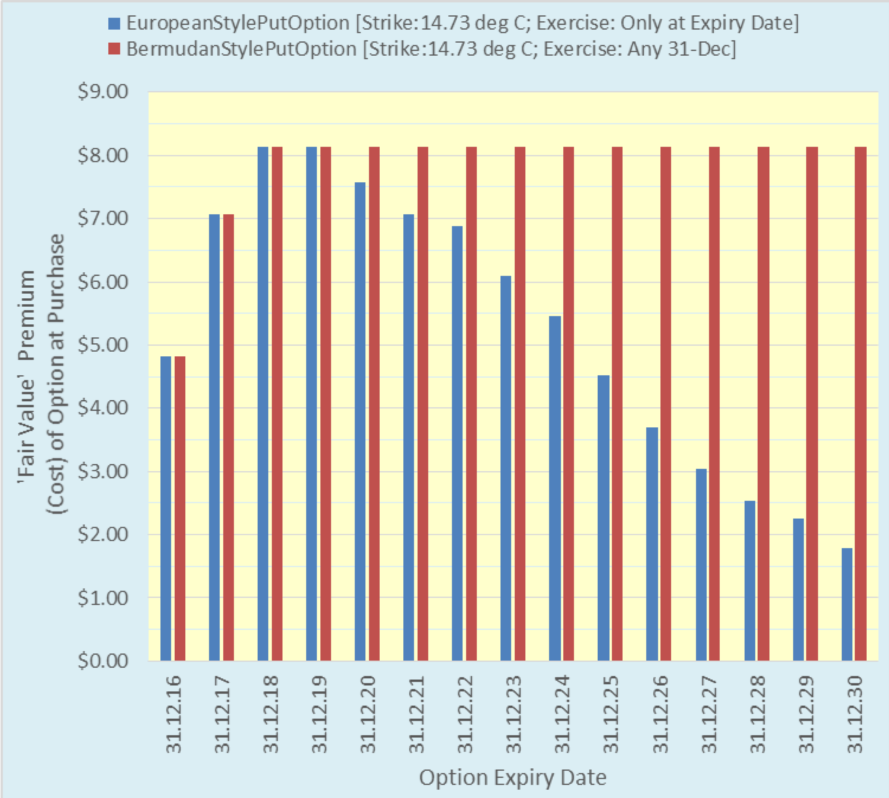

Figure 9. 'Fair value' *premiums (costs)* of a set of put options purchased on 31-Dec-2015 all with a *strike* of 14.73°C (the 2015 Global Mean Temperature) and a *premium (value)* of $100 per °C at expiry.

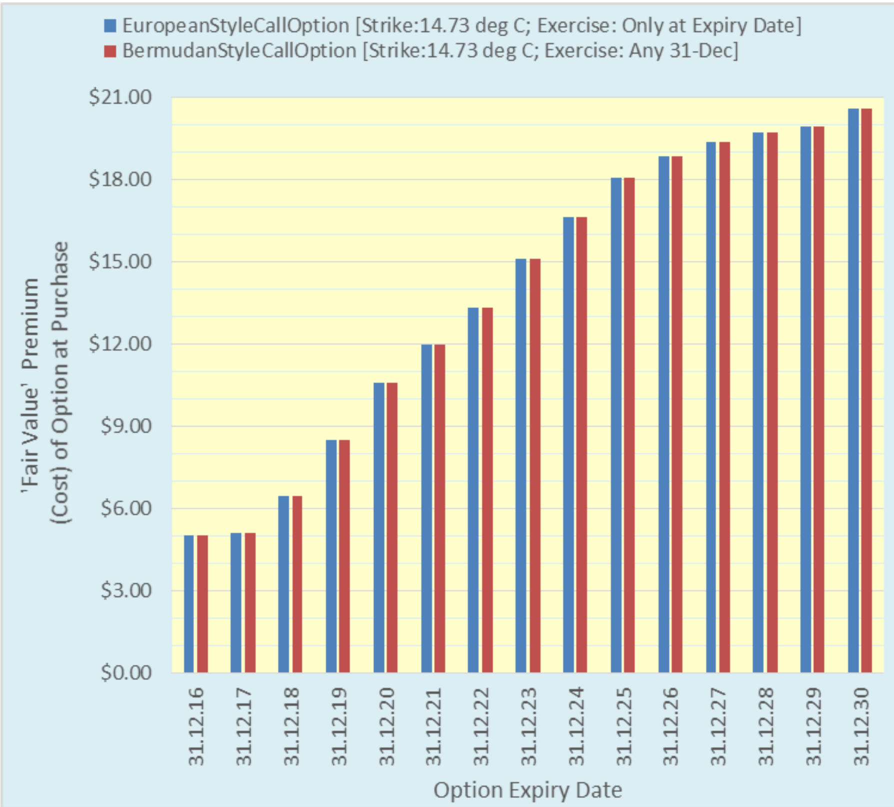

Figure 10. 'Fair value' *premiums (costs)* of a set of call options purchased on 31-Dec-2015 all with a *strike* of 14.73°C (the 2015 Global Mean Temperature) and a *premium (value)* of $100 per °C at expiry.

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APPENDIX

The Program used to produce the Global Mean Temperature sequence

```
<!DOCTYPE HTML PUBLIC "-//W3C//DTD HTML 3.2 Final//EN">
 <html>
  <head>
   <title>
    Global Mean Temperature Generator (Harvey Stern)
   </title>
  </head>
 <body>
<script language="JavaScript">
//COMMENT 1 Function generates a random number between 0 and 1
//COMMENT 2 Function multiplies random number by 100, subtracts 0.5,
//COMMENT 3 Function rounds it to the nearest whole number
//COMMENT 4 Declare counter
counter=1;
//COMMENT 5 Declare temperature anomaly set
var tempanomaly1,tempanomaly2,tempanomaly3, … ,tempanomaly164; tempanomaly165,tempanomaly166;
//COMMENT 6 List temperature anomaly set
tempanomaly1=-0.37;
```

```
tempanomaly2=-0.21;
tempanomaly3=-0.22;
…
tempanomaly164=0.52;
tempanomaly165=0.59;
tempanomaly166=0.76;
//COMMENT 7 Declare temperature change set
var tempchange1,tempchange2,tempchange3, … ,tempchange164,tempchange165;
//COMMENT 8 List temperature anomaly set
tempchange1=0.16;
tempchange2=-0.01;
tempchange3=-0.05;
…
tempchange163=0.04;
tempchange164=0.07;
tempchange165=0.17;
//COMMENT 8 Declare first temperature
var oldtemp;
//COMMENT 9 Define first temperature
//COMMENT 10 Oldtemp is that of the year 2015
oldtemp=14.73;
//COMMENT 11 Declare first temperature change
var oldchange;
//COMMENT 12 Define first temperature change
//COMMENT 13 Oldchange is the change from 2014 to 2015
oldchange=+0.17;
//COMMENT 14 Prepare to generate sequence out to 2100
while(counter<=85)
{
var result=Math.random();
//COMMENT 15 Noting that there are 165 possible values for change
var result=Math.round(165*result+0.5);
var tempchange;
//COMMENT 16 Now selecting the change from the random set of 165 possible values
if(result=="1"){tempchange=tempchange1;}
else if (result=="2"){tempchange=tempchange2;}
else if (result=="3"){tempchange=tempchange3;}
…
else if        (result=="163"){tempchange=tempchange163;}
else if        (result=="164"){tempchange=tempchange164;}
else if        (result=="165"){tempchange=tempchange165;}
//COMMENT 17 now correcting for the change based on historical analysis
//COMMENT 18 We calculate what is the usual change for every 1 deg C rise; we find the next change is a fall of -0.22, and so on.
//COMMENT 19 The relationship is y=0.00719-0.218 (t statistic= -2.83) y=next change; x=previous change.
//COMMENT 20 At counter 1, and so on, we calculate new temp with background change year 2016 minus year 2015, and so on.
if(counter=="1"){oldchange=0.17;}
if(counter=="1"){oldtemp=14.73;}
if(counter=="1"){document.write(oldtemp,"<br>");}
//COMMENT 21 The relationship is y=0.028-0.22*previous change+0.00040(Year-2015)+0.0000013[(Year-2015)^2]
if(counter=="1"){newtemp=oldtemp-0.22*oldchange+tempchange+(counter)*(counter)*(0.0000013)+(counter)*(0.00040)+0.0028;}
if(counter>1){newtemp=oldtemp-0.22*oldchange+tempchange+(counter)*(counter)*(0.0000013)+(counter)*(0.00040)+0.0028;}
//COMMENT 22 Generating the new temperature
newtemp=(Math.round(newtemp*100))/100;
document.write(newtemp, "<br>");
if(counter=="1"){oldchange=newtemp-oldtemp;}
if(counter>1){oldchange=newtemp-oldtemp;}
oldchange=(Math.round(oldchange*100))/100;
oldtemp=newtemp;
counter++;
}
</script>
</body>
</html>
```