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Betting strategies on fluctuations in the transient response of greenhouse warming

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We examine a series of betting strategies on the transient response of greenhouse warming, expressed by changes in 15-year mean global surface temperature from one 15-year period to the next. Over the last century, these bets are increasingly dominated by positive changes (warming), reflecting increasing greenhouse forcing and its rising contribution to temperature changes on this time scale. The greenhouse contribution to 15-year trends is now of a similar magnitude to typical naturally occurring 15-year trends. Negative 15-year changes (decreases) have not occurred since about 1970, and are still possible, but now rely on large, and therefore infrequent, natural variations. Model projections for even intermediate warming scenarios show very low likelihoods of obtaining negative 15-year changes over the coming century. Betting against greenhouse warming, even on these short time scales, is no longer a rational proposition.

1. Introduction

One of the fundamental measures of the Earth's climate is the global mean surface temperature (GMST). This is important as an attribute of the state of the climate and because many feedbacks in the climate system depend on temperature [1]. It has also been relatively well observed and estimated for more than a century [2,3]. The surface temperature is also one of the variables of most relevance to surface dwelling species.

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GMST fluctuates from decade to decade (in response to internal and external processes) while undergoing a long-term CO_2-driven warming trend [4–6]. Though decadal fluctuations are important in understanding sources of variability, they are generally regarded as 'noise' from the perspective of CO_2 climate change [5].

Nonetheless, some have argued that the most recent fluctuation in GMST implies that climate change has 'stalled' [7]. Indeed, one climatologist is reported to have forecast (*ca* 2005) that the next two decades are as likely to cool as to warm [8], and another projects that GMST 'will remain mostly flat for at least another decade' [9]. Some government planners assert that the most recent fluctuation in GMST presages a period of prolonged cooling [10], but have apparently refused to bet on that [11].

Very few bets have actually been placed on whether the coming decade or so will be warmer or cooler than the previous decade, and where those who foreshadowed cooling have been challenged to bet on the outcome, they have generally declined [8]. While *The Australian* newspaper wrote that there are 'No sure bets in the climate debate' [11], we seek here to test that proposition. That is, what are the historical odds of winning a bet that GMST is not going to warm over the coming decade and a half, and how are those odds likely to change in the future? The remainder of this paper provides a discussion of climate variability in relation to bets of this type, an assessment of bet outcomes from observed GMST data, and an assessment of bet likelihoods from multimodel ensemble simulations of GMST.

In this paper, we focus on 15-year periods to assess temperature changes. We choose this length because it is representative of decadal variability, because it is the length often chosen in studies assessing the most recent fluctuation in GMST [12,13], and because bets on climate change have typically been for periods of about this length (10–20 years). The 15-year period is also relevant for strategic planning in sectors such as water, energy and agriculture [14], though sectoral impacts relate more to regional than global changes. The focus on 15-year periods means that we are examining fluctuations in the transient response of the climate [4] about the longer term greenhouse warming trend.

Some bets have been set over much longer periods, as is appropriate for CO_2 climate change, but they are less interesting to examine because the outcome is near certain warming and because such bets are barely verifiable within the lifetime of those postulating them. A recent bet based on a climate 'normal' of 30-year means [15] has been posed by the Center for Inquiry [16]. They are willing to bet that each year the past 30-year mean will exceed the previous one. They note that those who believe there is no basis for the ongoing warming ought to take up the bet, and that those who reject greenhouse climate change presumably must believe that global temperatures must soon stabilize or fall. The fact that so few bets have actually been taken against greenhouse warming implies that the level of actual resistance to greenhouse theory by climate contrarians is not as strong as claimed. The analysis of betting strategies here shows that contrarians are rational insofar as they are not betting against greenhouse warming.

2. Climate variability across temporal scales

Any bet on temperature changes over the next decade and a half will depend on natural variations on this time scale as well as any greenhouse forced response on this time scale. These are mixed in together in the climate record, but this discussion is intended to show how their relative roles are changing.

Climate varies on all time scales. What changes with scale are the magnitudes and rates of temperature changes and the processes driving variation. For this discussion, we only need to be concerned with century and shorter time scales. The GMST record in figure 1*a* provides a good illustration of variability on sub-century scales. Three different types of line are drawn here relating to the following scales:

— *Interannual*. The solid black lines in figure 1*a* are annual values of GMST (from [18]) and vary from year to year, with changes on this time scale far exceeding the yearly change

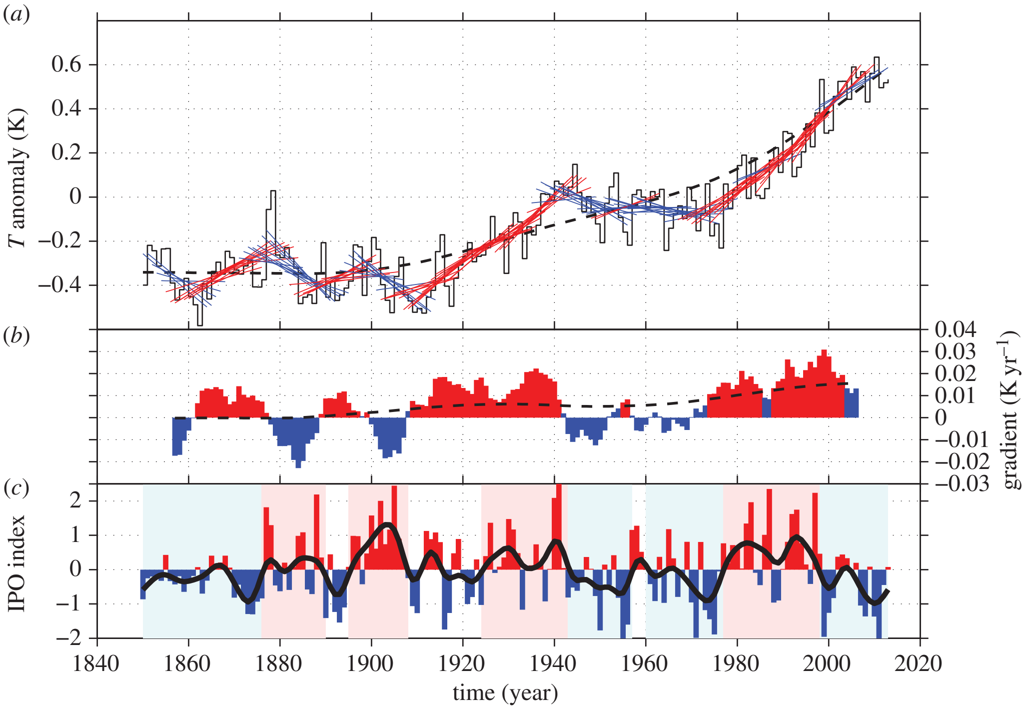

Figure 1. (*a*) Time series of GMST (solid black line), a set of running 15-year trends of GMST (red and blue lines), and a 50-year lowpass fit to the GMST series (dashed black line). The 15-year trend lines are red/blue when the 15-year trend is greater than/less than the 15-year trend in the lowpass line over the same 15-year period. (*b*) The magnitude (slope) of the 15-year trend lines plotted at the central year of each 15-year period with the same colour code as in (*a*). The dashed black line represents the magnitude (slope) of the lowpass 15-year trends. (*c*) The annual IPO index plotted red/blue when positive/negative. The solid black line is a 5-year lowpass fit to the annual IPO values. The shaded red/blue regions indicate where the lowpass IPO line is predominantly positive/negative. The IPO is calculated from COBE2 sea surface temperature (sst) [17] in the domain 40°S–60°N, 105°E–290°E. A 50-year lowpass fit is removed from the sst data at every grid point, then a principal component analysis is performed on the residuals. The IPO index is given by the first principal component (PC1) normalized by its own standard deviation. (Online version in colour.)

that could be expected from slow processes like greenhouse forcing. These fast variations are driven by the El Ninõ Southern Oscillation (ENSO) and other processes [19].

— *Decadal to multi-decadal*. We represent this time scale by a series of 15-year trend lines plotted (red and blue) on a moving 15-year window in figure 1*a*. Variations on this time scale are driven by internal processes such as the decadal cycles in ENSO [19] known as the Interdecadal Pacific Oscillation (IPO) or Pacific Decadal Oscillation (PDO) [20], and by variations in external forcing related to aerosols and solar variations [7].

— *Multi-decadal to century*. The long-term warming in figure 1*a* is represented by the dashed black line, which is a 50-year lowpass fit [21] to the GMST series. While non-greenhouse forcing processes (solar and aerosol variations) change global temperature on this time scale, their rate of change on this scale is typically much slower than the greenhouse forced rate [5,22,23]. The best estimate of the greenhouse contribution to the warming is similar to the observed warming [7]. Thus, we can regard the lowpass dashed line as a rough representation of the greenhouse forced part of GMST change. This is an approximation as the actual transient greenhouse response [4] depends on the forcing and feedbacks to the forcing, as well as on any response of the natural modes of variability (like ENSO/PDO) to the forcing. As the greenhouse forcing is relatively smoothly increasing and as the temperature response to that forcing is lagged [24], the greenhouse temperature response behaves in a similar manner to the lowpass fit of the temperature series. To be sure, any response of the natural modes of variability to greenhouse forcing could induce higher frequency variability into the greenhouse response, which would not be represented in our lowpass approximation.

The role of decadal to multi-decadal variations can be drawn out by comparing the red and blue 15-year trend lines in figure 1*a*. The 15-year trend lines are red/blue when the 15-year GMST trend is warming faster/slower than the 15-year trend in the lowpass series over the same time period. The magnitudes (slopes) of the 15-year trends coded this way in red and blue are shown in figure 1*b*. It is clear from the contiguous clustering of colours that there are periods of several decades or more at a time when the 15-year trends are consistently faster or slower than the lowpass warming rate. Part of the source of these multi-decadal variations is apparent in figure 1*c*, which shows the IPO index over the same period. Over the last century, periods of faster/slower warming correspond roughly to positive/negative IPO regimes. However, this relationship is not apparent in the first part of the record (prior to about 1920), possibly because the IPO depends on spatial measurements of sea surface temperature, which were not systematically observed then.

One of the features of figure 1*b* is that the blue 15-year trends (when warming is slower than the lowpass rate) are progressively less negative with time. For example, there has not been an actual 'negative' 15-year trend since about 1970, even though the IPO returned to a negative state around about 2000. To see why this is happening, we show the lowpass (greenhouse) 15-year trend magnitudes as the dashed black line in figure 1*b*. In the first-half century of the record, we see that the greenhouse contribution to 15-year trends is near zero and the naturally occurring 15-year trends have a magnitude in the vicinity of about $\pm 0.01\,\mathrm{K\,yr^{-1}}$. By contrast, in the last-half century of the record the greenhouse contribution to 15-year trends is now about $+0.01\,\mathrm{K\,yr^{-1}}$ and growing. If we assume that the naturally occurring 15-year trends continue to have similar magnitudes as in the earlier part of the record (approx. $\pm 0.01\,\mathrm{K\,yr^{-1}}$), then the net 15-year trend (as the sum of greenhouse and natural contributions) is increasingly less likely to be negative. This does not mean that it cannot be negative, as there are clearly some occasional large amplitude 15-year trend excursions in figure 1*b*. However, such excursions would need to be large now in order to yield a negative trend, which means that they occur less frequently. This has implications for bets about future warming and cooling likelihoods on the 15-year time scale.

The conclusion that the greenhouse contribution to 15-year trends now rivals the natural contributions on this time scale is unlikely to be very sensitive to our choice to represent the greenhouse contribution by a 50-year lowpass fit to the GMST series. The point here is that the greenhouse contribution is small in the earlier part of the record when the increase in greenhouse forcing is small in each period, and that it has grown to the point that it now rivals the natural variations on the 15-year time scale. Any more complex functional representation of the greenhouse temperature response would still include these characteristics, and this is what underlies the conclusion. The conclusion does, however, depend on the assumption that the magnitude of natural 15-year fluctuations has not changed appreciably and consistently from the earlier to the latter part of the record. This is not trivial to test because of the possibility of the natural modes of variability [25], varying in time and/or responding to greenhouse and other forcing [26]. The conclusion is consistent with studies of the emergence of a greenhouse signal in GMST data [27], though those studies do not relate specifically to 15-year trends.

3. Observations

This section of the paper addresses the likelihood of winning bets on 15-year GMST trends in the observational data covering the past century. The observational data used here is Cowtan & Way [18], but results are not sensitive to the choice of GMST series. We examine two types of bets: a simple binary bet and one based on multiple predictive bettors as described below.

The bets described here refer to changes from a baseline prior period (the past 15 years) to the oncoming period (the next 15 years). The bets thus assess relative changes about the current point. When the oncoming period is warmer/cooler than the prior period, we mean to imply only

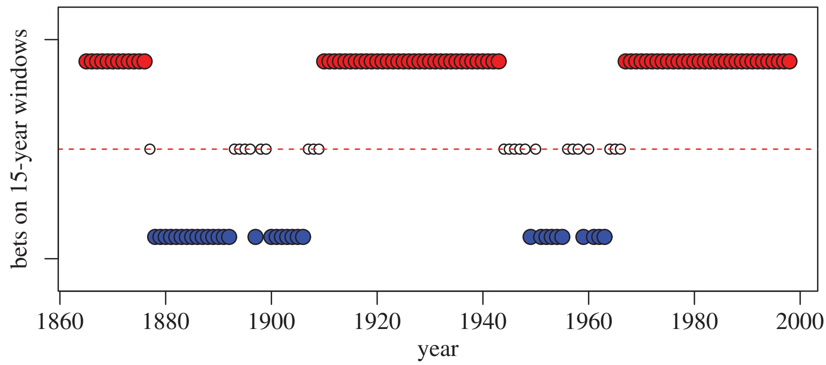

Figure 2. Binary bets from observations. The results of bets that the 15-year mean GMST will increase (red dots), decrease (blue dots) or stay within a threshold change (white dots) from the previous 15-year mean. (Online version in colour.)

that there is short-term warming/cooling relative to the current short-term baseline, not that the climate is warming/cooling *per se*. We are thus referring to short-term fluctuations about a longer term warming trend and not to meaningful changes in the longer term trend [6].

(a) Binary bets

The binary bet is formulated as a change in temperature from the 15 years prior to the point at which the bet is made to the 15 years following the bet point. We show results here where the mean is used to assess the temperature change, $\Delta T = \bar{T}_{[+15]} - \bar{T}_{[-15]}$, across the 15-year periods such that: if $\Delta T > \epsilon$ the climate has warmed, if $\Delta T < -\epsilon$ the climate has cooled and if $-\epsilon \leq \Delta T \leq \epsilon$ then no appreciable warming or cooling is deemed to have occurred and the bet is declared a draw. Here we set $\epsilon = 0.02$ K and $\bar{T}_{[\pm 15]}$ refers to the mean temperature over the 15 years following (+) or preceding (−) the bet point. The results are not sensitive to whether we use means or trends to assess ΔT.

The results of the binary bets on 15-year means as a function of the year in which the bet is made are shown in figure 2. The results broadly mirror the multi-decadal variability evident in figure 1. Periods of warming and cooling alternate until about 1910. Thereafter, there are three decades (1910–1940) where warming dominates in the 15-year differences, then about three decades (1940–1970) where cooling or no trend dominates, and then warming dominates through the end of the record.

A telling feature of figure 2 is that the warming bet continues to win in the most recent period for every bet since 1970. This occurs despite the IPO moving to a negative state in the period since 2000 and despite some evidence for enhanced negative forcing from volcanic aerosol and solar cycles since 2000 [7]. This behaviour can be understood from figure 1, which shows that the rate of warming drops below the lowpass warming rate after 2000, but is still positive because the rate of warming from greenhouse gases now rivals the rate from natural fluctuations over 15-year periods.

The binary bet was repeated with a 30-year outlook period ($\bar{T}_{[+30]}$) instead of 15-years ($\bar{T}_{[+15]}$). The 30-year outlook smooths out some of the variability inherent in the 15-year outlook. The results (not shown) are qualitatively similar to those shown in figure 2, but there are fewer winning cool bets or draws. The increase in the number of warm bet wins reflects the dominance of the warming trend on longer time scales.

(b) Multiple bettors

As a refinement on the simple binary bet above, one might try to predict the temperature over the coming 15 years. There are many ways to do this, and we test here a few simple methods for illustration. The goal is to predict the mean GMST over the next 15 years. We test five simple methods (or predictive bettors) that form part of a betting pool as follows:

— *Persistence bettor*. This bettor assumes that the best predictor of the next 15 years is the past 15 years: $\bar{T}_{[+15]} = \bar{T}_{[-15]}$. The persistence bettor is saying that current conditions will persist. Since warming of the climate has already taken place, the persistence bettor is not neutral about the longer term warming trend and believes that any enhanced warming will be maintained.

— *Trend bettor*. This bettor assumes that the trend in GMST over the past 15 years, $T'_{[-15]}$, will continue for the next 15 years, $T'_{[+15]} = T'_{[-15]}$, and calculates $\bar{T}_{[+15]}$ from that trend extrapolation.

— *Warm cherry bettor*. This bettor uses a trend too, but is looking for the warmest possible (maximum +ve) recent trend measured back from the present year. The bettor tests all trends from 6 years prior to the present year (so the trend length is not too short) to 15 years prior to the present year, and cherry picks the warmest trend from that set: $\max(T'_{[-6]} \cdots T'_{[-15]})$. That is, only the present year is fixed and the bettor cherry picks how far back they go in the 15-year window to find the warmest recent trend. The bettor extrapolates this trend over the next 15 years to predict the forward mean. If the warmest trend found is not positive, this bettor declines to bet that year. The warm cherry bettor is defined to mimic the opposite behaviour of those who tend to cherry pick cooler trends to support their argument of a slowdown in warming rate [28].

— *Cool cherry bettor*. This bettor is the opposite of the warm cherry bettor and picks the coolest (maximum −ve) trend by cherry picking how far back they go from the present year: $\min(T'_{[-6]} \cdots T'_{[-15]})$. The bettor extrapolates this coolest trend over the next 15 years to predict the forward mean. If the coolest trend found is not negative, this bettor declines to bet that year.

— *Long-term bettor*. This bettor calculates a lowpass fit to the temperature series using all available years at the bet point. The lowpass fit ramps up with available years and is capped at a 50-year lowpass. For a given bet year with n prior years available, the lowpass fit is $\min(n/2, 50)$-year lowpass. The bettor uses the last 15 years of the lowpass fit to fit a linear trend and then extrapolates that forward to estimate temperatures over the next 15 years. This bettor attempts to smooth out some decadal variability.

Every year the five bettors predict the mean temperature of the next 15 years, $\bar{T}^{\text{pred}}_{[+15]}$, using their respective algorithms. We determine the actual mean over the period, $\bar{T}^{\text{actl}}_{[+15]}$, from the observed series (figure 1*a*), and the bettor whose prediction is closest to the actual wins the bet that year. In the rare event of a tie, we introduce random variation in each $\bar{T}^{\text{pred}}_{[+15]}$ to break the tie.

The warm and cool cherry bettors are intended to mimic the behaviour of those who cherry pick short-term trends in the data to claim that climate change is accelerating on the one hand, or not happening on the other. In practice, most of this has been cherry picking ‘cooler’ trends to claim that climate change has ‘stalled’ [28], but we include the warm cherry bettor to test the symmetrically opposite claim. As the warm/cool cherry bettors are backing a warming/cooling temperature swing, they only bet when their prediction, $\bar{T}^{\text{pred}}_{[+15]}$, is in accordance with that expectation.

The results for the series of bets over the observational period are shown in figure 3. The number of winning bets for each bettor over the period are shown in the right margin of the figure. The persistence bettor wins most (43 times), but those wins are accumulated during the periods when GMST is flattest, and the persistence bettor has not won a bet since 1970. The trend bettor wins the next most number of times (30), followed closely by the warm cherry bettor (28). The warm cherry trend bettor tends to beat the straight trend bettor during those periods when the rate of warming is much faster than the average rate (figure 1*a*, lowpass fit). The straight trend bet can fall positive or negative, depending on the 15-year period, but the vast majority of

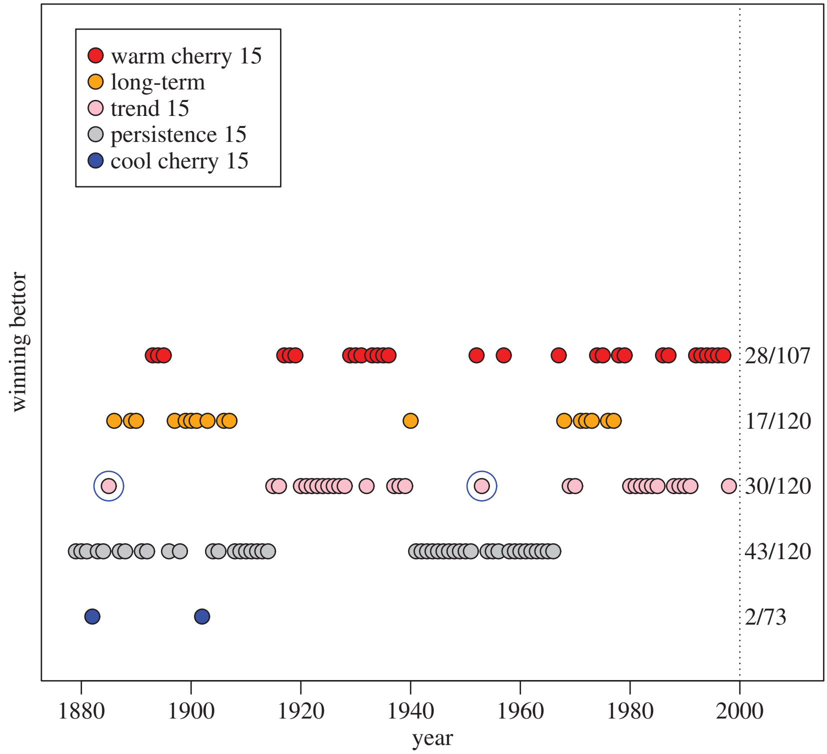

Figure 3. Multiple bettors from observations. The bettors in the legend are defined in the text. Each year the bettor with the closest prediction of the mean temperature of the next 15 years wins the bet and this is denoted by a dot of their colour along the time axis. Wins for the trend bettor correspond to positive trends, except where a blue circle surrounds the point, in which case the trend is negative. The total number of wins and the total number of bets made are listed at the end of each row. The warm/cool cherry bettors only bet when $\bar{T}^{\text{pred}}_{[+15]}$ is positive/negative. (Online version in colour.)

bet wins for the trend bet are positive trends. The least successful bettor is the cool cherry bettor (two wins), who rarely wins in the entire instrumental record. This bettor is picking trends that are cooler than the straight 15-year trend, which is unsuccessful in a warming climate where most 15-year changes are either near zero or positive.

The multiple bettor plot (figure 3) shows only the winning bet each year. The locations of all the bettor bets expressed as the difference between the predicted 15-year mean and the past 15-year mean, $\Delta T_{\text{pred}} = \bar{T}^{\text{pred}}_{[+15]} - \bar{T}_{[-15]}$, are shown in figure 4*a*. The observed bet outcome, ΔT_{obs}, is the black line in this figure. The persistence bettor (grey) is close to observed when ΔT_{obs} is near zero. The trend bettor (pink) follows the actual excursions of ΔT_{obs} from decade to decade better than the other bettors. The warm cherry (red) and cool cherry (blue) bettors often have large values of ΔT_{pred}. This sometimes succeeds for the warm cherry bettor as ΔT_{obs} is sometimes large and positive, but it rarely succeeds for the cool cherry bettor as there are no large negative excursions of ΔT_{obs}. Furthermore, the cool cherry ΔT_{pred} often yielded a positive trend (meaning no bet is made, so no value is plotted), reflecting the difficulty of even cherry picking to find a negative change in a warming climate. The long-term bettor (yellow) is quite persistent (because of the lowpass fit) and changes bet too slowly to keep up with the decade to decade changes in ΔT_{obs}. The long-term bettor ΔT_{pred} jumps around at the start of the series when fewer years are used for the lowpass fit, and is not always smoothly continuous from year to year because low pass fits are sensitive to end points, creating some sharper changes in inflection at the end of the fit as new years are added.

We calculated the mean bet error over the observational period for each of the bettors. The bet error is calculated as the mean of the absolute value of the yearly differences between the

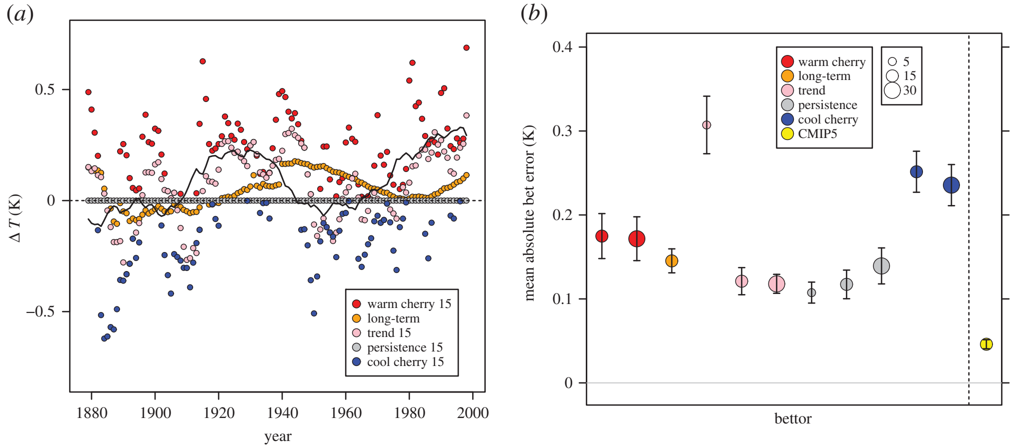

Figure 4. Multiple bettor ΔT and bet errors. (*a*) $\Delta T_{\text{actual}} = \bar{T}_{[+15]} - \bar{T}_{[-15]}$ for GMST observations (black line) and $\Delta T_{\text{pred}} = \bar{T}^{\text{pred}}_{[+15]} - \bar{T}_{[-15]}$ for the five bettor predictions shown in the legend. (*b*) The mean bet error, which is the mean of the absolute value of the difference between predicted and actual 15-year means for each bettor as labelled in the colour legend. The variation in circle size (5, 15, 30) refers to bettors with the same algorithm, but using the 5, 15 or 30 past years to make the prediction for the next 15 years. The whiskers are 95% confidence intervals. (Online version in colour.)

predicted and actual 15-year mean: $|\bar{T}^{\text{pred}}_{[+15]} - \bar{T}^{\text{actl}}_{[+15]}|$. The results are shown in figure 4*b*. In this case, we have added some variations for bettors to allow them to use 5 and 30 past years in addition to the standard 15 past years. This is possible for the trend and persistence bettors. For the cherry bettors, we can test 30 years, but not 5 as those bets require at least 6 prior years. The lowpass bettor always uses all past years and so there is no variation for this bettor.

The trend and persistence bettors have the lowest overall errors in figure 4*b*. However, trend bets based on only the past 5 years have large errors because 5-year trends in GMST have wildly divergent magnitudes [29]. For the persistence bettor, the opposite is the case, where the past 5-year mean is a good extrapolation, but the longer persistence period of 30 years is worse. Errors in the persistence bet grow with the past number of years used for the persistence mean because the climate is warming and the long period persistence bets increasingly under-predict the future 15-year mean. The largest mean bet errors are for the warm cherry and cool cherry bettors as expected, because they select more extreme trends.

The bettor labelled 'CMIP5' in figure 4*b* is the ensemble mean prediction from a large ensemble of model runs ($n = 109$) from the CMIP5 [30] historical runs over the past century [12]. The mean bet error for CMIP5 is much lower than for any of our predictive bettors. CMIP5 does, however, have an advantage over those bettors, as the CMIP5 runs have information about the radiative forcing in the future (the period of time after the bet is made) [31], whereas the bettor algorithms are all based on past information (prior to the bet point). The CMIP5 bettor is the only bettor with knowledge of the physics of the system being bet on. When we include CMIP5 in the bet competition in figure 3, it wins most of the bets against the other bettors. The low bet error for CMIP5 does indicate that the CMIP5 ensemble mean with knowledge of radiative forcing is well calibrated to 15-year GMST fluctuations.

4. Models

Since the interest in bets around climate change relates to the future, we now turn to bets over future periods as well as the past by examining bet outcomes in the CMIP5 ensemble of model runs. The CMIP5 ensemble has been run with historical forcing for the period 1850–2005 and with a range of different forcing futures for 2006–2100 (so-called representative concentration

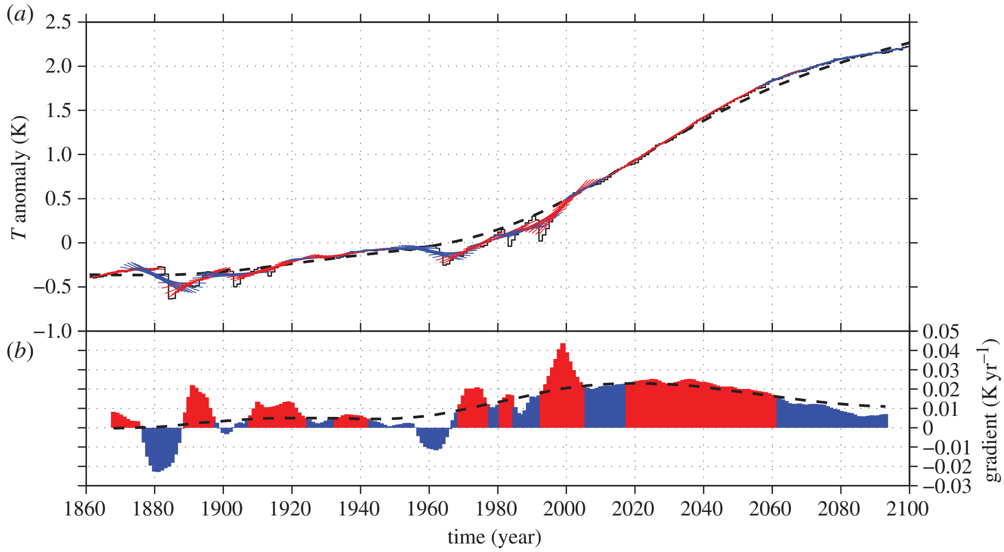

Figure 5. CMIP5 RCP4.5 multi-model ensemble mean 15-year trends. (*a*) Time series of GMST (solid black line), a set of running 15-year trends of GMST (red and blue lines), and a 50-year lowpass fit to the GMST series (dashed black line). The 15-year trend lines are red/blue when the 15-year trend is greater than/less than the 15-year trend in the lowpass line over the same 15-year period. (*b*) The magnitude of the 15-year trend lines plotted at the central year of each 15-year period with the same colour code as in (*a*). The dashed black line represents the magnitude of the lowpass 15-year trends. (Online version in colour.)

pathways (RCP)) [31]. We show results based on RCP4.5 future forcing here, which is regarded as an intermediate scenario in the RCP set.

The results of 15-year bets in the future will eventually depend on the particular greenhouse forcing scenario (RCP) followed. The greenhouse contribution to 15-year trends depends on the rate of change of greenhouse forcing and on whether the climate has come into equilibrium with the forcing. At present, the greenhouse contribution to 15-year trends is growing as greenhouse forcing grows. When the forcing is stabilized in the future, the climate will eventually come into equilibrium with the forcing [24]. At that point the greenhouse contribution to 15-year trends will again be small, but the whole system will sit at a higher global mean temperature.

To get a general idea of the CMIP5 GMST response, we show the multi-model ensemble mean annual GMST and its 15-year trends in figure 5. The CMIP5 ensemble mean response is different from observations (figure 1) in several respects. The ensemble mean averages out internal variability in the models [12], so interannual and decadal variations are greatly reduced. The model runs each have the same historical forcing, including volcanic eruptions, which contribute to 15-year variations in the period to 2005 in the ensemble mean. After 2005, there are no volcanic eruptions in the RCP forcing, and internal variability continues to average out, so the ensemble mean GMST response is smoothly increasing (such that the annual mean GMST is nearly indistinguishable from the 15-year trend lines after 2005 in the figure).

For RCP4.5 forcing results shown here, emissions decline from around mid-twenty-first century, which roughly stabilizes the level of greenhouse forcing from then through the rest of the century. Accordingly, the rate of GMST increase eventually also slows down in figure 5 as the Earth's surface temperature approaches an equilibrium level for the near stabilized forcing. Thus, the contribution of greenhouse warming to 15-year trends (represented by the dashed line in figure 5*b*) peaks around $+0.02\,\mathrm{K\,yr^{-1}}$ by 2030 and slowly declines back to about $+0.01\,\mathrm{K\,yr^{-1}}$ by 2100 for RCP4.5. For the RCP2.6 scenario, the forcing stabilizes earlier in the century, whereas for the RCP8.5 scenario, the forcing increases throughout the century. Were we to consider the RCP8.5 scenario, the greenhouse contribution to 15-year trends would continue to grow through

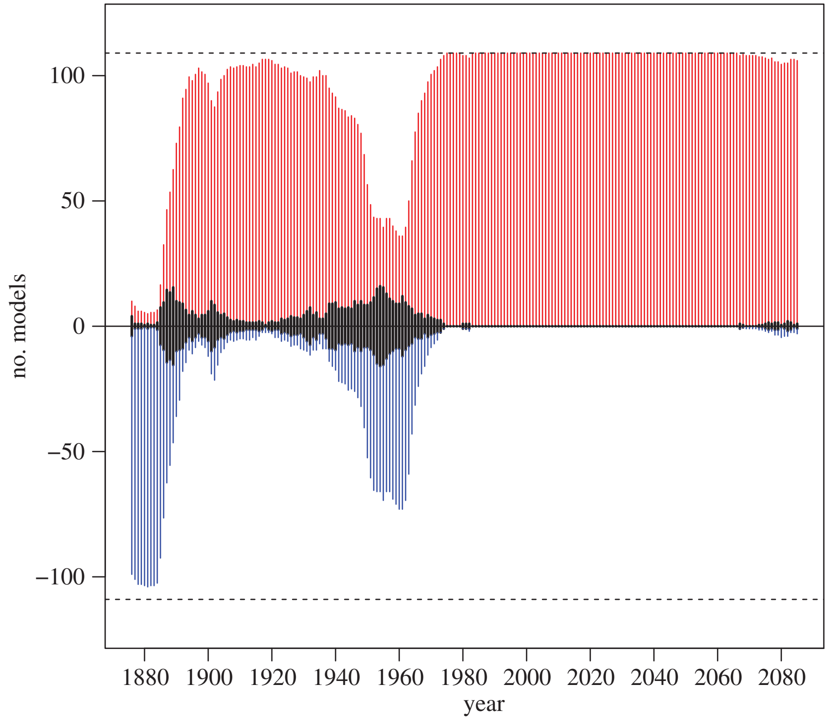

Figure 6. Binary bets from CMIP5 models. For each bet year, the number of models where the following 15-year mean GMST increases (red bars) relative to the previous 15-year mean, decreases (blue bars), or stays within a threshold change (±0.02 K) (black bars). For years after 2005 the RCP4.5 scenario is used. (Online version in colour.)

the twenty-first century, even further dominating natural variability on the 15-year scale. Because of the lag in system response to the forcing, 15-year trend results would be broadly similar for each of RCP2.6, 4.5 and 8.5 for the first-half of the twenty-first century and start to diverge thereafter.

While all 15-year trends are positive for the ensemble mean in the twenty-first century in figure 5, this need not be the case for every model run in the ensemble. Individual model runs will contain some negative 15-year trends, but likely few given that the greenhouse contribution to 15-year trends is above $+0.01\,\mathrm{K\,yr^{-1}}$ for the entire twenty-first century. We consider individual model runs in the following sections.

(a) Binary bets

We tested the binary bets (as in figure 2) for each model run over the entire period spanning the historical and future forcing. As for observations, at each bet year we assessed the difference in each model's GMST over the next 15 years relative to the previous 15 years. At each bet year, we counted up the number of models that displayed relative warming, cooling or no change. The results are shown in figure 6.

First, considering the overlap period with observations, the model predictions (judged by the number of models favouring relative warming or cooling at each bet point) are in general accord with the observed results. That is, they show predominance of cooling runs just prior to 1900, warming predominated runs until about 1940, and then a brief period of cooling dominated runs through about 1970, then warming dominated runs through to the end of the observations period (2000). Like observations, by 1970 there are few wins by either cooling bets or ties. The number of models showing a relative cooling win drops to zero for the first time in the record of bets by about 1975 and remains there.

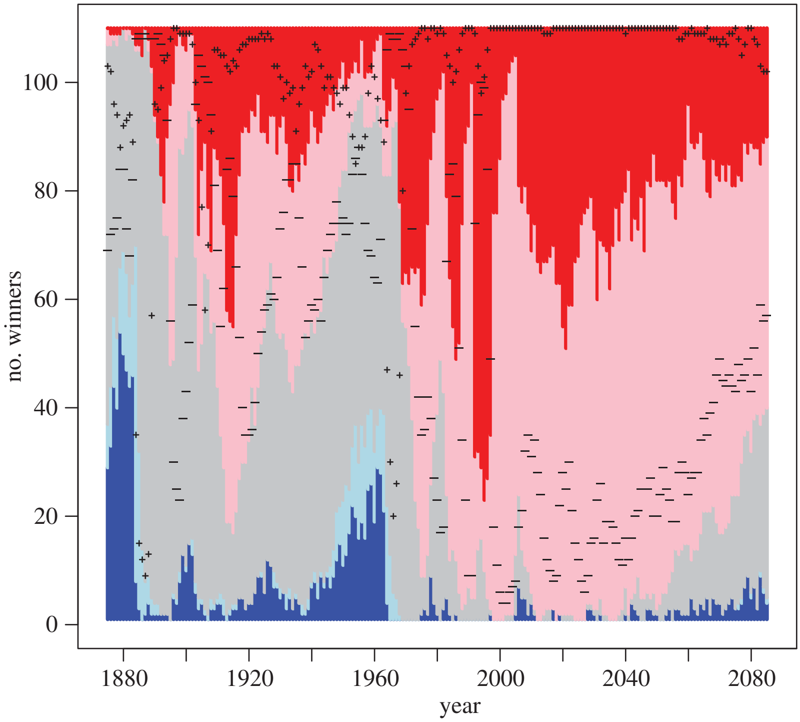

Figure 7. Multiple bettors from CMIP5 models. At each bet year, the number of bet winners of each of the bet types is calculated across the 109 CMIP5 model runs. The results are stacked such that the length of each colour relates to the number of bet wins by that colour bettor. The bettors are as defined in §3b, except that we subclassify the trend bettor wins into those predicting positive/negative trends as trend +/−. The colour code is warm cherry (red), trend+ (pink), persistence (grey), trend− (light blue) and cool cherry (dark blue). The + and − symbols indicate the number of models where the warm cherry and cool cherry bettors found positive and negative trends, respectively, on which to place a bet. For RCP4.5 after 2005. (Online version in colour.)

For 15-year bets after the 2000 bet year there are no observations. Thus, we cannot validate the model bets after 2000. In the period to 2100, the model bets in figure 6 are almost entirely dominated by warming bet wins. The first model runs showing any cooling bet wins reappear late in the record for the RCP4.5 scenario after greenhouse forcing stabilizes and GMST has risen by about 2 K. The RCP8.5 scenario results are similar (not shown), but warming wins continue to dominate all the model runs as there is no stabilization of forcing.

The dominance of warming wins is likely to be a little overestimated here. That is because the RCP scenarios do not include large volcanic eruptions that can and do induce large negative contributions to decadal trends [13,23,32]. When the contribution of large volcanic eruptions is added to CMIP5 model runs, negative 10-year trends are displayed for RCP4.5 runs, but rarely in RCP8.5 runs [32]. For the 15-year periods considered here, negative trends are less common than for 10-year periods and volcanic forcing would have a slightly reduced role. Nonetheless, we might expect *some* cooling 15-year changes when large eruptions occur for a forcing scenario like RCP4.5. While volcanoes are important, their influence on GMST is generally limited to the decadal scale. Volcanoes can induce longer variations in the ocean, but their surface signature is mostly small beyond decadal scales [33].

While figure 6 may produce a slight overestimate of the tendency for warming wins in the twenty-first century, the results are emphatic in showing a near complete disappearance of cooling wins over this period. Volcanic eruptions would produce only short, and limited, variations on that theme.

(b) Multiple bettors

As we did for observations in figure 3, we ran a version of the betting exercise with multiple predictive bettors for models. In this case, we treat each entire model run from 1850 to 2100 as a record of the system and determine the winning bettor each bet year from the preceding 15 years (to determine the bettor predictions) and the following 15 years (to determine which bettor came closest to the model 15-year evolution). The bettors are as for observations except that we drop the lowpass bettor to keep the betting simple and symmetric. The persistence bettor bets on the warming being maintained at the same level, the trend bettor can be positive or negative (depending on the slope of the prior 15-year GMST), and the warm/cool cherry bettors have identical, but opposite, algorithms to select more extreme positive/negative trends.

The number of winning bets are tallied up each bet year across the 109 CMIP5 runs and are shown in figure 7. In the first-half of the period until about 1970, persistence (grey) is the dominant winner, but then virtually disappears for the next century as the positive trend bettor (pink) takes up the most wins. Persistence bet wins only start increasing in number again at the end of the twenty-first century as the forcing stabilizes and the approach to equilibrium in RCP4.5 starts to take effect. The negative trend bettor (light blue) wins in some model runs in the twentieth century, and then hardly ever again after 1970. The warm-cherry bettor (red) is successful over the entire period, and particularly in the first-half of the twenty-first century as the rate of warming from the RCP4.5 scenario ramps up. The cool cherry bettor (blue) virtually drops out of contention after 1970 and remains very low thereafter.

5. Conclusion

We have assessed bets on near term climate change here by considering GMST over the 15 years following the time at which a bet is made. In the observed record over the past 150 years, there is substantial multi-decadal variability and persistent periods over which GMST is consistently increasing or decreasing from one 15-year period to the next. In the earlier part of the record, the odds of getting a cooler 15-year period than the previous 15 years are relatively evenly split, but in the latter half of the observed record the odds are largely in favour of warming. The shift in odds to favour warming changes reflects the growing greenhouse contribution to 15-year trends. The greenhouse contribution is now about the same magnitude as typical naturally occurring 15-year trends. There has not been a negative 15-year change since about 1970. While it is still possible to get negative 15-year changes that will rely on large amplitude and less frequent natural triggers of 15-year changes such as large volcanoes or large amplitude negative PDO events.

In simple schemes to predict 15-year changes in GMST, the standard climatological measure of 'persistence' is the most successful predictor in the observed record. However, the persistence wins all occur before the greenhouse forcing contribution to 15-year trends is large, and there are no persistence wins since 1970. For bets since 1970, all bets are won by positive 15-year changes, and almost all bets by bettors predicting straight warm trends (trend bettor) or accelerated warm trends (warm cherry bettor). There are hardly any wins by bettors cherry picking the coolest possible trend to extrapolate (cool cherry bettor) because there are very few times in the instrumental record when the 15-year temperature changes are appreciably negative. Cherry picking recent 'cooler' short-term trends is a very unsuccessful strategy for predicting future trends in the instrumental record and in CMIP5 projections for the twenty-first century. On the other hand, cherry picking recent warmer than average trends to predict future trends often works well because of the acceleration of the warming trend from about 1970.

For the CMIP5 ensemble of model runs, the outcome of bets over the observed period is consistent with the multi-decadal variation in bet outcomes in the observations. The CMIP5 ensemble mean is a very accurate bettor on 15-year changes over this period, reflecting its foundation on the physics of the system, but has the advantage of knowing the forcing history ahead of time. The CMIP5 ensemble of runs is consistent with observations in showing no 15-year cooling bet wins since about 1970. Projecting forward to 2100 in the RCP4.5 scenario, this pattern continues with virtually all model runs yielding warming bet wins. This result may slightly overstate the likelihood of warming wins because there are no large volcanic eruptions in the RCP scenario, but such events would be relatively short-lived and not change the basic character of the results.

The CMIP5 15-year bet results are likely to be similar for different RCP scenarios in the first-half of the twenty-first century, and then diverge somewhat according to whether greenhouse forcing is nearly stabilized (RCP2.6,4.5) or continues to increase (RCP8.5). For the scenarios where emissions are reducing and forcing nearly stabilizes, the greenhouse contribution to 15-year trends starts to decline slowly as the climate comes into equilibrium with the forcing at a higher global mean temperature. Natural fluctuations will then again eventually rival and surpass greenhouse contributions on the 15-year time scale, but on a higher temperature base and many decades hence.

What this means for the foreseeable future is that it is now very unlikely to win a bet that the next 15-year period is cooler than the previous one. While a few contrarian climatologists and others may say that they expect GMST to show no warming or cool over the next decade or so, they generally would not bet on it. That is, their stated position is not supported by their position as revealed by requiring a financial bet. As some have pointed out [8], this implies that the apparent gulf between climate contrarians (who say they expect little future warming) and the Intergovernmental Panel on Climate Change (IPCC) (who project ongoing long-term warming) may be largely posturing on the part of the contrarians. Bets against greenhouse warming are largely hopeless now and that is widely understood.

Data accessibility. Observational GMST data was obtained from http://www-users.york.ac.uk/~kdc3/papers/coverage2013/series.html. CMIP5 GMST data was obtained from http://cmip-pcmdi.llnl.gov/cmip5.

Authors' contributions. J.S.R., S.L. and J.R.H. conceived of and designed the study. S.L., J.S.R. and D.P.M. performed the data analysis. J.S.R. drafted the manuscript.

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References

1. Hansen J, Takahashi T. 1984 *Climate processes and climate sensitivity*. Geophysical Monograph Series. Washington, DC: AGU. (doi:10.1029/GM029)
2. Jones PD, New M, Parker D, Martin S, Rigor I. 1999 Surface air temperature and its changes over the past 150 years. *Rev. Geophys.* **37**, 173–199. (doi:10.1029/1999RG900002)
3. Hansen J, Ruedy R, Sato M, Lo K. 2010 Global surface temperature change. *Rev. Geophys.* **48**, 1–29. (doi:10.1029/2010RG000345)
4. Schneider SH, Thompson S. 1981 Atmospheric CO_2 and climate: importance of the transient response. *J. Geophys. Res.* **86**, 3135–3147. (doi:10.1029/JC086iC04p03135)
5. Houghton JT, Meira Filho LG, Callander BA, Harris N, Katenberg A, Maskell K. 1996 *Climate Change 1995: The Science of Climate Change*, 572pp. Cambridge, UK: Cambridge University Press.
6. Risbey J. 2015 Free and forced climate variations. *Nature* **517**, 562–563. (doi:10.1038/517562a)
7. Stocker T *et al.* 2013 Technical summary. In *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the fifth assessment report of the Intergovernmental Panel on Climate Change, pp. 33–115. Cambridge, UK: Cambridge Univ. Press.
8. Annan J. 2005 Betting on climate change. See http://www.realclimate.org/index.php/archives/2005/06/betting-on-climate-change/.
9. Curry J. 2015 'Warmest year', 'pause', and all that. See http://judithcurry.com/2015/01/16/warmest-year-pause-and-all-that/.
10. Newman M. 2014 We're ill-prepared for the iceman cometh. *The Australian*, 14 August 2014, p. 21.
11. Jones C. 2014 No sure bets in the climate debate. *The Australian*, 23 April 2014, p. 18.

12. Risbey J, Lewandowsky S, Langlais C, Monselesan D, O'Kane T, Oreskes N. 2014 Well-estimated global surface warming in climate projections selected for ENSO phase. *Nat. Clim. Change* **4**, 835–840. (doi:10.1038/nclimate2310)
13. Marotzke J, Forster P. 2015 Forcing, feedback, and internal variability in global temperature trends. *Nature* **517**, 565–570. (doi:10.1038/nature14117)
14. Risbey JS, Kandlikar M, Graetz D. 1999 Scale, context, and decision making in agricultural adaptation to climate variability and change. *Mitig. Adapt. Strateg. Glob. Change* **4**, 137–165. (doi:10.1023/A:1009636607038)
15. Arguez A, Vose R. 2011 The definition of the standard WMO climate normal: the key to deriving alternative climate normals. *Bull. Am. Meteorol. Soc.* **92**, 699–704. (doi:10.1175/2010BAMS2955.1)
16. Fidalgo P. 2015 Skeptics dare Heartland Institute to take up $25,000 climate challenge. See http://bit.ly/1dGtfmo.
17. Hirahara S, Ishii M, Fukuda Y. 2014 Centennial-scale sea surface temperature analysis and its uncertainty. *J. Clim.* **27**, 57–75. (doi:10.1175/JCLI-D-12-00837.1)
18. Cowtan K, Way R. 2014 Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. *Q. J. R. Meteorol. Soc.* **140**, 1935–1944. (doi:10.1002/qj.2297)
19. Monselesan D, O'Kane T, Risbey J, Church J. 2015 Internal climate memory in observations and models. *Geophys. Res. Lett.* **42**, 1–11. (doi:10.1002/2014GL062453)
20. Mantua N, Hare S. 2002 The pacific decadal oscillation. *J. Oceanogr.* **58**, 35–44. (doi:10.1023/A:1015820616384)
21. Elsner JB, Tsonis AA. 1996 *Singular spectrum analysis: a new tool in time series analysis*. New York, NY: Springer.
22. Mann ME *et al.* 2003 On past temperatures and anomalous late 20th century warmth. *Eos Trans. Am. Geophys. Union* **84**, 1–2. (doi:10.1029/2003EO270003)
23. Lean J, Rind D. 2008 How natural and anthropogenic influences alter global and regional surface temperatures: 1889 to 2006. *Geophys. Res. Lett.* **35**, 1–6. (doi:10.1029/2008GL034864)
24. Hansen J, Russell G, Lacis A, Fung I, Rind D, Stone P. 1985 Climate response times: dependence on climate sensitivity and ocean mixing. *Science* **229**, 857–859. (doi:10.1126/science.229.4716.857)
25. Risbey J, O'Kane T, Monselesan D, Franke C, Horenko I. 2015 Metastability of Northern Hemisphere teleconnection modes. *J. Atmos. Sci.* **72**, 35–54. (doi:10.1175/JAS-D-14-0020.1)
26. O'Kane T, Risbey J, Franzke C, Horenko I, Monselesan D. 2013 Changes in the metastability of the mid-latitude Southern Hemisphere circulation and the utility of non-stationary cluster analysis and split flow blocking indices as diagnostic tools. *J. Atmos. Sci.* **70**, 824–842. (doi:10.1175/JAS-D-12-028.1)
27. Muir L, Brown J, Risbey J, Wijffels S, Sen Gupta A. 2013 Determining the time of emergence of the climate change signal at regional scales. *CAWCR Res. Lett.* **10**, 8–19.
28. Lewandowsky S, Oreskes N, Risbey J, Newell B, Smithson M. 2015 Seepage: climate change denial and its effect on the scientific community. *Glob. Environ. Change* **33**, 1–13. (doi:10.1016/j.gloenvcha.2015.02.013)
29. Santer B *et al.* 2011 Separating signal and noise in atmospheric temperature changes: the importance of timescale. *J. Geophys. Res.* **116**, 1984–2012. (doi:10.1029/2011JD016263)
30. Taylor K, Stouffer R, Meehl G. 2012 An overview of CMIP5 and the experiment design. *Bull. Am. Meteorol. Soc.* **93**, 485–498. (doi:10.1175/BAMS-D-11-00094.1)
31. Moss R *et al.* 2010 The next generation of scenarios for climate change research and assessment. *Nature* **463**, 747–756. (doi:10.1038/nature08823)
32. Maher N, Sen Gupta A, England M. 2014 Drivers of decadal hiatus periods in the 20th and 21st centuries. *Geophys. Res. Lett.* **41**, 5978–5986. (doi:10.1002/2014GL060527)
33. Stenchikov G, Delworth T, Ramaswamy V, Stouffer R, Wittenbery A, Zeng F. 2009 Volcanic signals in oceans. *J. Geophys. Res.* **114**, 1984–2012. (doi:10.1029/2008JD011673)