Extended Summary of the Climate Dialogue on Long Term Persistence

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Content

Introduction

This summary is based on the contributions of the three invited scientists who participated in the dialogue entitled "Long-term persistence and trend significance". We want to thank Rasmus Benestad, Armin Bunde and Demetris Koutsoyiannis for their participation.

The summary is not meant to be a consensus statement. It's just a summary of the discussion and should give a good overview of how these three scientists view the topic at this moment. This summary was written by Marcel Crok and then reviewed and adjusted by the other editors of Climate Dialogue and the advisory board members. In some cases the editors disagreed about the text. In the summary we make clear when this is the case.

The summary was then reviewed by the three invited participants. They do not necessarily endorse the full text or our selection of the dialogue. We did ask them to check the claims in all the tables though in order to make these consistent with their views.

Long term persistence and trend significance

In science one often asks whether a change in some parameter, variable or process is statistically significant. So we could ask: is the increase in global average temperature statistically significant? Whether an observed trend is significant or not is related to the chance of occurrence and thus on the underlying variability, noise and errors, as well as the temporal stochastic structure thereof.

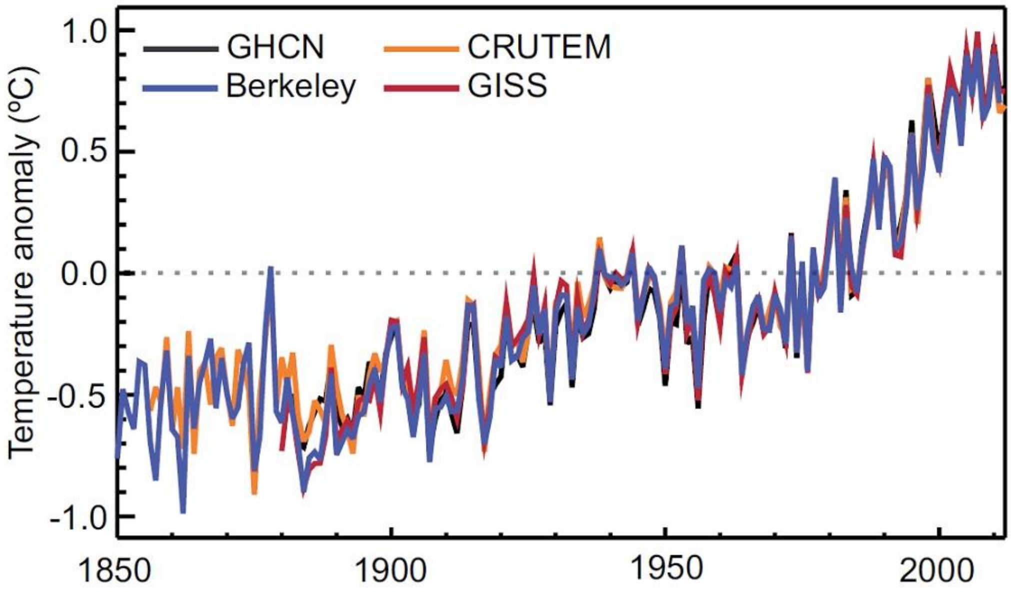


Figure 2.14 from the IPCC AR5 WGI report. Global annual average land-surface air temperature (LSAT) anomalies relative to a 1961–1990 climatology from the latest versions of four different data sets (Berkeley, CRUTEM, GHCN and GISS).

The temperature time series in the figure above shows variation on annual and multi-decadal scales. However, how do we know if this trend is part of the natural variability of the climate system or whether it is due to some forced changes and whether is significant or not? Is the increase very unlikely or quite normal in terms of natural variability?

This is a statistical problem and thus the way to look at it is making a statistical analysis of the time series to determine the amplitude of natural variability. For instance to answer the question for the year-to-year variability we would need to know for every single time step (year) what the chance is to go up or down and how strong these excursions can be. The difficulty is that we don't have a data set for the "undisturbed" climate, i.e. the climate without anthropogenic influences, which could be used as a reference period and to assess the significance of the recent warming trend. It is noted, though, that there are a lot of proxy data sets, which can be used to infer the stochastic structure of natural climatic variability. These data sets do not describe the climate precisely, but certainly can give information on its stochastic structure and also are free of anthropogenic influences.

With such issues we enter the arena of the Climate Dialogue about long-term persistence (LTP).

Definition of long-term persistence

Both Bunde and Koutsoyiannis showed figures in their guest blogs to explain the difference between independent or uncorrelated data and long-term correlated data. Below is the graph that Bunde showed:

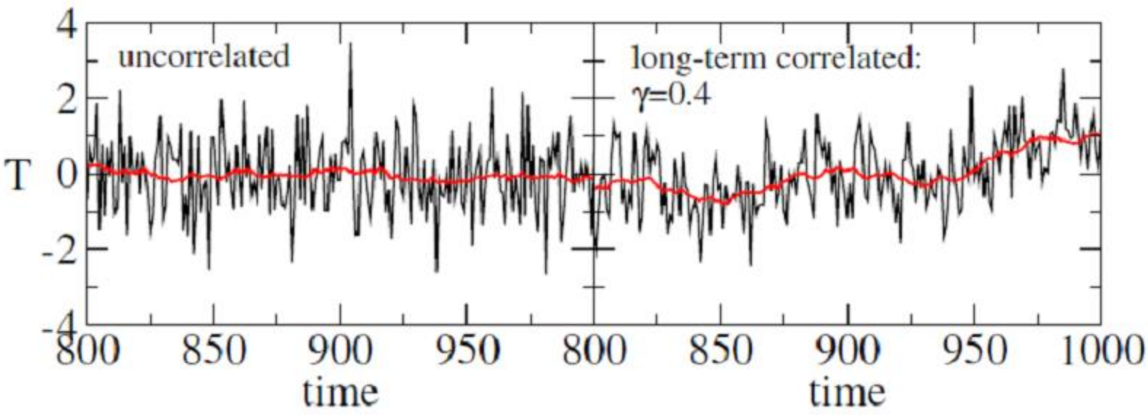


Figure 1 of Bunde's guest blog showing the difference between uncorrelated data (left) and data with long-term persistence (right). The coefficient γ (gamma) is a measure of persistence.

As he explained: "For the uncorrelated data, the moving average is close to zero, while for the LTP data, the moving average can have large deviations from the mean, forming some kind of mountain-valley structure that looks as if it contained some external deterministic trend. The figure shows that it is not a straightforward task to separate the natural fluctuations from an external trend, and this makes the detection of external trends in LTP records a difficult task."

Koutsoyiannis said it as follows: "No one would believe that the weather this hour does not depend on that an hour ago. It is natural to assume that there is time dependence in weather. (…) Now, if we average the process to another scale, daily, monthly, annual, decadal, centennial, etc. we get other stochastic processes, not qualitatively different from the hourly one. Of course, as the scale of averaging increases the variability decreases—but not as much as implied by classical statistics."

Benestad gave the following description of LTP: "Long-term persistence (LTP) describes how slow physical processes change over time, where the gradual nature is due to some kind of 'memory'. This memory may involve some kind of inertia, or the time it takes for physical processes to run their course. Changes over large space take longer time than local changes."

So they all accept that LTP 'exists' in the climate or is part of climate. There were disagreements though, even about the concept of LTP. Bunde and Koutsoyiannis are both in favour of a formal (mathematical) definition of LTP, which describes what Koutsoyiannis said above, that on longer time scales variability decreases—but not as much as implied by more "classical statistics" like AR(1)[1].

[1] In statistics and signal processing, an autoregressive (AR) model is a representation of a type of random process; as such, it describes certain time-varying processes in nature, economics, etc. The autoregressive model specifies that the output variable depends linearly on its own previous values. It is a special case of the more general ARMA model of time series. More details, see Wikipedia.

Benestad found this proposition “somewhat artificial” when dealing with temperature time series. He said a great deal of variance is usually removed before the data is analysed, like seasonal variations and the diurnal cycle. “Most of the variance is tied up to these well-known cycles, forced by regional changes in incoming sunlight. Furthermore, ENSO has a time scale that is ~3-8 years, and is associated with most of the variance after the seasonal and diurnal scales are neglected.” Elsewhere Benestad said: “There are some known examples of LTP processes, such as the ice ages, changes in the ocean circulation, and the El Niño Southern Oscillation.” Bunde disagreed that ENSO is an LTP process: “Rasmus [Benestad] will recognize that ENSO is not an example of LTP, in the same way as other quasi-oscillatory phenomena cannot be described as LTP.”

So there is confusion/disagreement about what LTP really “is”. The reason could be that for Bunde and Koutsoyiannis LTP is a statistical property of climatic time series and according to Bunde, as such, it is not an “abstract issue”.

A key issue seemed to be whether it is possible to talk about LTP in terms of physical processes. Koutsoyiannis thinks the system is just too complex to talk about simple physical causes for observed changes and he does not accept the dichotomy physics vs. statistics as in complex physical systems a statistical description is the most pertinent and the most powerful.

According to Koutsoyiannis it is unfortunate that LTP has been commonly described in the literature in association with autocorrelation and as a result of memory mechanisms. For him it is “the change, mostly irregular and unpredictable in deterministic terms, that produces the LTP”. For Benestad LTP is a manifestation of memory in the climate system.

Summary

To answer the question “is the increase in global average temperature statistically significant?” one needs to make assumptions about the statistical nature of the time series and one needs to choose what statistical model is the most appropriate.

If the temperature of this year is not related to that of last year or next year we can use classical statistics to determine whether the increase in global temperature is significant or not. In such an “uncorrelated climate” the average value becomes zero (or a fixed value) quickly and deviations from the mean last only shortly. If there is (strong) temporal dependence though the moving average can have large deviations from the mean. Bunde and Koutsoyiannis claim the climate displays such long-term dependence or long-term persistence (LTP).

The three participants agree that LTP exists in the climate (Table 1). They disagree about the exact definition though and about the physical processes that lie behind it. Benestad and Bunde describe LTP in terms of “long memory”. Koutsoyiannis says that in his opinion LTP is mainly the result of the irregular and unpredictable changes that take place in the climate (Table 2). Bunde and Koutsoyiannis are both in favour of a formal (mathematical) definition of LTP, which states that on longer time scales climate variability decreases—but not as much as implied by “classical statistics” such as AR(1).

Benestad said that ice ages and the El Niño Southern Oscillation are examples of LTP processes. Bunde and Koutsoyiannis disagreed and said that quasi-oscillatory phenomena cannot be described as LTP (Table 3).

Table 1

	Benestad	Bunde	Koutsoyiannis
Does LTP exist in the climate?	Yes	Yes	Yes

Table 2

	What is long-term persistence (LTP)?
Benestad	LTP describes how slow physical processes change over time, where the gradual nature is due to some kind of 'memory'.
Bunde	LTP is a process with long memory; the value of a parameter (e.g. temperature) today depends on all previous points.
Koutsoyiannis	It is unfortunate that LTP has been interpreted as memory; it is the change, mostly irregular and unpredictable in deterministic terms, that produces the LTP, while the autocorrelation results from change.

Table 3

	Benestad	Bunde	Koutsoyian nis
Quasi-oscillatory phenomena like ENSO can be described as LTP.	Yes	No	No

Is LTP relevant for the detection of climate change?

The full IPCC definitions of detection and attribution in AR5 are (our emphasis)[2]:

"Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in *some defined statistical sense* without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance *due to internal variability alone* is determined to be small."

Attribution is defined as "the process of evaluating the relative contributions of multiple causal factors to a change or event with an assignment of statistical confidence". As this wording implies, attribution is more complex than detection, combining statistical analysis with physical understanding.

The definition of detection has been differently interpreted by the members of the Editorial Staff:

Interpretation 1 (Rob van Dorland, Bart Verheggen): the second part clarifies the first part that you need (some defined) statistical model to distinguish between forced and unforced (internal variability) change. In the first part it is stated that this is done without knowing the *cause* of the forced change, i.e. whether it is anthropogenic or natural (sun, volcanoes etc).

Interpretation 2 (Marcel Crok): The first part of the definition suggests that you only need statistics to do detection. The second part suggests you need more than statistics (physical models), unless a statistical method would be able to distinguish between forced changes and internal variability. So the definition is self-contradictory.

Bunde and Koutsoyiannis both think detection is mainly a matter of statistics while Benestad thinks it also involves a physical interpretation of distinguishing unforced internal variability from forced changes.

Bunde wrote: "For detection and estimation of external trends ("detection problem") one needs a statistical model." Koutsoyiannis preferred the word "primarily" instead of "purely": "I would say it is primarily a statistical problem, but I would not use the advert "purely". Besides, as we wrote in Koutsoyiannis/Montanari (2007)[3], even the very presence of LTP should not be discussed using merely statistical arguments."

Benestad wrote: "Hence, the diagnosis ("detection") of a climate change is not purely a matter of statistics. The laws of physics set fundamental constraints which let us narrow down to a small number of 'suspects'. For complete probability assessment, we need to take into account both the statistics and the physics-based information, such as the fact that GHGs absorb infrared light and thus affect the vertical energy flow through the atmosphere."

Bart Verheggen wrote the following analysis of this part of the discussion: "This discussion showed that the participants used a slightly different operational definition of detection. Benestad followed the first interpretation of the IPCC definition, i.e. testing the significance of observed changes relative

[2] Section 10.2.1 in AR5.

[3] Koutsoyiannis, D., and A. Montanari (2007), Statistical analysis of hydroclimatic time series: Uncertainty and insights, Water Resources Research, 43 (5), W05429, doi: 10.1029/2006WR005592.

to what is expected from only unforced internal variability. Bunde and Koutsoyannis take detection to mean testing the significance of observed change w.r.t. some reference period without anthropogenic forcings (but with natural forcings). The latter definition in effect sets a higher bar for detection than the former (as the observed trend has to exceed not just unforced internal variability, but also the effect of natural forcings). These differences are probably rooted in different perceptions of what internal variability is (and whether or not it is different in principle from natural forcings)."

Summary

There was confusion about the exact meaning of the IPCC definition about detection. The definition reads: "Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small."

Bunde and Koutsoyiannis both think detection is mainly a matter of statistics and that it is very relevant for the detection of climate change. Benestad on the other hand thinks detection is not mainly a statistical issue and that it also involves a physical interpretation of distinguishing unforced internal variability from forced changes.

Table 4

	Benestad	Bunde	Koutsoyiannis
Is detection purely a matter of statistics?	No, laws of physics sets fundamental constraints	Yes	Not purely but primarily yes

LTP versus AR(1)

Bunde's main conclusion in his guest blog was: "My conclusion is that the AR1 process falsely used by climate scientists to describe temperature variability leads to a strong overestimation of the significance of external trends. When using the proper LTP model the significance is considerably lower." The AR(1) process refers to the simplest model for short-term persistence (STP). So Bunde is saying several things here: 1) LTP is the proper model to describe temperature variability; 2) climate scientists in general use a STP model like AR(1) and 3) this leads to a strong overestimation of the significance of trends.

In a comment Bunde added that "This crucial mistake appeared also in the IPCC report [AR4] since the authors were (…) not aware of the LTP of the climate. They assumed STP [in table 3.2] and thus got the trend estimations wrong by overestimating the significance."

Koutsoyiannis agrees with Bunde's conclusions. In figure 1 of his guest blog he showed that the clustering of warm years, for example, is orders of magnitude more likely to happen if you use an LTP model. "We may see, for example, that what, according to the classical statistical perception, would require the entire age of the Earth to occur once (i.e. clustering of 8-9 events) is a regular event for an HK [Hurst-Kolmogorov] climate[4], with probability on the order of 1-10%." He added that "this dramatic difference can help us understand why the choice of a proper stochastic model is relevant for the detection of changes in climate." In a comment he also said that "a Markov [AR(1)] process […] finally produces a static climate […]. The truth is, however, that climate on Earth has never been static."

Benestad agrees that "the AR1 model may not necessarily be the best model", but adds that "it is difficult to know exactly what the noise looks like in the presence of a forced signal." Elsewhere he wrote: "The important assumptions are therefore that the statistical trend models, against which the data are benchmarked, really provide a reliable description of the noise."

In the discussion of this summary Benestad disagreed with Bunde's claim that the AR(1)-process is falsely used by climate scientists and the IPCC. According to Benestad, Table 3.2 in AR4 as mentioned by Bunde is not seriously arguing that internal variability is AR(1), but merely uses this method as a crude estimate of the trend significance for that particular plot. Benestad: "The relevant question is whether the trend is anthropogenic or due to LTP (or signal versus noise) and to answer this question, you must look at chapter 9 in AR4 on detection and attribution and in particular figure 9.5 on the comparison between global mean surface temperature anomalies from observations and model simulations, and not at Table 3.2. In chapter 9 there are zero hits on 'AR(1)'."

He warns for the danger of circular reasoning when using statistical models. "It is the way models are used that really matters, rather than the specific model itself. All models are based upon a set of assumptions, and if these are violated, then the models tend to give misleading answers. Statistical

[4] Hurst-Kolmogorov is a term that Koutsoyiannis has introduced and which is synonymous to LTP. In his guest blog he explains where it comes from: "A decade before Hurst detected LTP in natural processes, Andrey Kolmogorov, devised a mathematical model which describes this behaviour using one parameter only, i.e. no more than in the Markov [AR(1)] model. We call this model the Hurst-Kolmogorov (HK) model."

LTP-noise models used for the detection of trends involve circular reasoning if adapted to measured data. Because this data embed both signal and noise."

This is a key argument of Benestad. He claims statistical models are useless when applied to what is called the instrumental period, because in this period the data embed both "signal" and "noise" and LTP or STP or whatever statistical model are meant to describe "the noise" only in his opinion. Benestad therefore favours other methods: "State-of-the-art detection and attribution work do not necessarily rely on the AR1 concept, but use results from climate models and error-covariance matrices based on the model results to evaluate trends, rather than simple AR(1) methods."

Koutsoyiannis in response gave a few examples why in his opinion the danger of circular reasoning is not justified in this case. In his first example he divided the global average time series in two parts: "The HadCrut4 data set is 163 year long. So, let us exclude the last 63 years and try to estimate H [the Hurst coefficient][5] based on the 100-year long period 1850-1949. The Hurst coefficient estimate becomes 0.93 instead of 0.94 for the entire period." So he disagrees that the global average temperature time series cannot be used because the record is 'contaminated' by anthropogenic forcing. He also referred to analyses of proxies made by Koutsoyiannis and Montanari (2007), who estimated high values of the Hurst coefficient (H between 0.86-0.93) for the period 1400-1855 and by Markonis and Koutsoyiannis (2013)[6], who showed that a combination of proxies supports the presence of LTP with H > 0.92 for time scales up to 50 million years.

However, Benestad is in favour of separating forced and unforced climate change (as the definition of detection implies), and part of the 1850-1949 temperature changes are due to (natural) forcing. This implies that it is difficult to draw conclusions like Koutsoyiannis did. There was no further discussion on this issue.

Summary

Bunde and Koutsoyiannis argue that LTP is the proper model to describe temperature variability, that climate scientists (and the IPCC) in general use an STP model like AR(1) and that this leads to a strong overestimation of the significance of trends (Table 5 and 7). Koutsoyiannis showed that the clustering of warm years, for example, is orders of magnitude more likely to happen if you use an LTP model. Benestad agrees that the AR(1) model may not necessarily be the best model, but in general statistical models are useless in his opinion when applied to what is called the instrumental period, because in this period the data embed both "signal" and "noise" and LTP or STP or whatever statistical model are meant to describe "the noise" only in his opinion: "Statistical LTP-noise models used for the detection of trends involve circular reasoning if adapted to measured data because this data embed both signal and noise." (Table 6). Koutsoyiannis in response gave a few examples why in his opinion the danger of circular reasoning is not justified in this case.

[5] The Hurst coefficient H is a measure for long-term persistence. H is a number between 0.5 and 1. The closer to 1, the more persistent a system is.

[6] Markonis, Y., and D. Koutsoyiannis, Climatic variability over time scales spanning nine orders of magnitude: Connecting Milankovitch cycles with Hurst–Kolmogorov dynamics, Surveys in Geophysics, 34 (2), 181–207, 2013.

Table 5

	Benestad	Bunde	Koutsoyiannis
Is LTP relevant/important for the statistical significance of a trend?	Yes (though physics still needed)	Yes, very much	Yes, very much

Table 6

	What is the relevance of LTP for the detection of climate change?
Benestad	Statistical LTP-noise models used for the detection of trends involve circular reasoning if adapted to measured data. State of the art detection and attribution is needed.
Bunde	For detection and estimation of external trends ("detection problem") one needs a statistical model and LTP is the best model to do this.
Koutsoyiannis	LTP is the only relevant statistical model for the detection of changes in climate.

Table 7

	Benestad	Bunde	Koutsoyiannis
Is the AR(1) model a valid model to describe the variability in time series of global average temperature?	No, if physics based information is neglected	No	No
Does the AR(1) model leads to overestimation of the significance of trends?	Yes, if you don't also take into account the physics-based information	Yes	Yes

LTP and chaos

There was disagreement about the relation between LTP and chaos. Obviously, the participants agree that the climate system possesses a chaotic component, but they differ in the extent and time scales of this component. For Benestad though the implication is that LTP cannot be a valid concept for the climate on longer terms. For example in his first reaction to Bunde's guest blog Benestad wrote: "I presently think one major weakness in your reasoning is [when you say that] 'in LTP records, in contrast, x_i depends on all previous points.' This cannot be true if the weather evolution is chaotic, where the weather system loses the memory of the initial state after some bifurcation point."

In another comment Benestad wrote: "The so-called 'butterfly effect', an aspect of 'chaos' theory, is well-established with meteorology, which means there is a fundamental limit to the predictability of future weather due to the fact that the system loses the memory of the initial state after a certain time period. (…) For geophysical processes, chaos plays a role and may give an impression of LTP, and still the memory of the initial conditions is lost after a finite time interval.”

Koutsoyiannis referred to some of his papers and said that yes, “these publications show that LTP does involve chaos.” In another comment that dealt with untangling the different causes of climate change he said: “in chaotic systems described by nonlinear equations, the notion of a cause may lose its meaning as even the slightest perturbation may lead, after some time, to a totally different system trajectory (cf. the butterfly effect).” So Koutsoyiannis and Benestad largely agree about how chaotic systems behave. The main difference though is that Benestad interprets “the system loses memory” as “LTP is not a useful concept” and here Koutsoyiannis and Bunde disagree with him. In particular, Koutsoyiannis considers memory as a bad interpretation of LTP: it is the change which produces the LTP and thus LTP is fully consistent with the chaotic behaviour of climate.

Summary
There was disagreement about the relation between LTP and chaos (Table 8). According to Benestad chaos theory implicates the memory of the initial conditions is lost after a finite time interval. Benestad interprets “the system loses memory” as “LTP is not a useful concept”. Koutsoyiannis considers memory as a bad interpretation of LTP: it is the change which produces the LTP and thus LTP is fully consistent with the chaotic behaviour of climate.

Table 8

	Benestad	Bunde	Koutsoyiannis
Is the climate chaotic?	Yes	Yes	Yes
Does chaos mean memory is lost and does this apply for climatic timescales as well?	Yes	chaos is not a useful concept for describing the variability of climate records on longer time scales	No; LTP is not memory
Does chaos exclude the existence of LTP?	Yes, at both weather and climatic time scales	No	No; on the contrary, chaos can produce LTP
Does chaos contribute to the existence of LTP?	No, but chaos may give an impression of LTP.	Yes	Yes, LTP does involve chaos

Signal and noise

There was disagreement about concepts like signal and noise. In his guest blog Benestad wrote: “The term ‘signal’ can have different meanings depending on the question, but here it refers to manmade climate change. ‘Noise’ usually means everything else, and LTP is ‘noise in slow motion’.”

Koutsoyiannis disagreed with this distinction: “I would never agree with your term “noise” to describe the natural change. Nature’s song cannot be called “noise”. Most importantly, your “signal” vs. “noise” dichotomy is something subjective, relying on incapable deterministic (climate) models and on, often misused or abused, statistics.”

In another comment Koutsoyiannis elaborated on this point: “The climate evolution is consistent with physical laws and is influenced by numerous factors, whether these are internal to what we call climate system or external forcings. To isolate one of them and call its effect “signal” may be misleading in view of the nonlinear chaotic behaviour of the system.”

Bunde seems to take a position in between Benestad and Koutsoyiannis. He does assume – as a working hypothesis - that there is an external deterministic trend from the greenhouse gases but he calls the remaining part of the total climate signal natural “fluctuations” and not noise. Bunde: “we have to note that we distinguish between natural fluctuations and trends. When looking at a LTP curve, we cannot say a priori what is trend and what is LTP. (...) The LTP is natural, the trend is external and deterministic.”

The distinction in signal and noise is another way of stating what detection aims to do: distinguishing whether the (forced) changes are significantly outside of the bounds of the unforced or internal variability. All three appear to agree that purely based on LTP, this distinction can’t be made.

Summary
There was disagreement about concepts like signal and noise. According to Benestad the term ‘signal’ refers to manmade climate change. ‘Noise’ usually means everything else, and LTP is ‘noise in slow motion’ (Table 9). Koutsoyiannis argued that the “signal” vs. “noise” dichotomy is subjective and that everything we see in the climate is signal. To isolate one factor and call its effect “signal” may be misleading in view of the nonlinear chaotic behaviour of the system. Bunde does assume there is an external deterministic trend from the greenhouse gases but he calls the remaining part of the total climate signal natural “fluctuations” and not noise (Table 9). All three seem to agree that one cannot use LTP to make a distinction between forced and unforced changes in the climate (Table 10).

Table 9

	Signal versus noise
Benestad	The signal is manmade climate change; the rest is noise and LTP is noise in slow motion.
Bunde	My working hypothesis: there is a deterministic external trend; the rest are natural fluctuations which are best described by LTP.
Koutsoyiannis	Excepting observation errors, everything we see in climate is signal.

Table 10

	Benestad	Bunde	Koutsoyiannis
Is the signal versus noise dichotomy meaningful?	Yes	Yes	No*
Can LTP distinguish between forced and unforced components of the observed change?	No	No	*
Can LTP distinguish between natural fluctuations (including natural forcings) and trends?	No	Yes	*

* Koutsoyiannis thinks that even the formulation of these questions, which imply that that the description of a complex process can be made by partitioning it into additive components and trying to know the signatures of each one component indicates a linear view for a system that is intrinsically nonlinear.

Forced versus unforced

In our introduction we introduced the three climate influences that climate scientists distinguish:

"Most experts agree that three types of processes (internal variability, natural and anthropogenic forcings) play a role in changing the Earth's climate over the past 150 years. It is the relative magnitude of each that is in dispute. The IPCC AR4 report stated that "it is extremely unlikely (<5%) that recent global warming is due to internal variability alone, and very unlikely (< 10 %) that it is due to known natural causes alone." This conclusion is based on detection and attribution studies of different climate variables and different 'fingerprints' which include not only observations but also physical insights in the climate processes."

There was a lot of discussion about the physical mechanisms behind LTP. Bart Verheggen of the Climate Dialogue team asked a series of questions about this: Can we agree that forcing introduces LTP? Can we agree that forcing is omnipresent for the real world climate? Is LTP mainly internal variability or the result of a combination of internal variability and natural forcings?

Bunde replied that "Natural Forcing plays an important role for the LTP and is omnipresent in climate (so yes and yes to first two questions)." Koutsoyiannis also agreed that "(changing) forcing can introduce LTP and that it [forcing] is omnipresent. But LTP can also emerge from the internal dynamics alone as the above examples show. Actually, I believe it is the internal dynamics that determine whether or not LTP would emerge."

Verheggen concluded: "All three invited participants agree that radiative forcing can introduce LTP and that it is omnipresent. It follows that the presence of LTP cannot be used to distinguish forced from unforced changes in global average temperature. The omnipresence of both unforced and forced changes means that it's very difficult (if not impossible) to know the LTP signature of each. Therefore, LTP by itself doesn't seem to provide insight into the causal relationships of change. It is however relevant for trend significance, but fraught with challenges since the unforced LTP signature is not known."

Summary
According to Bunde natural forcing plays an important role for LTP and is omnipresent in climate. Koutsoyiannis agreed that (changing) forcing can introduce LTP and that forcing is omnipresent, but LTP can also emerge from the internal dynamics alone.

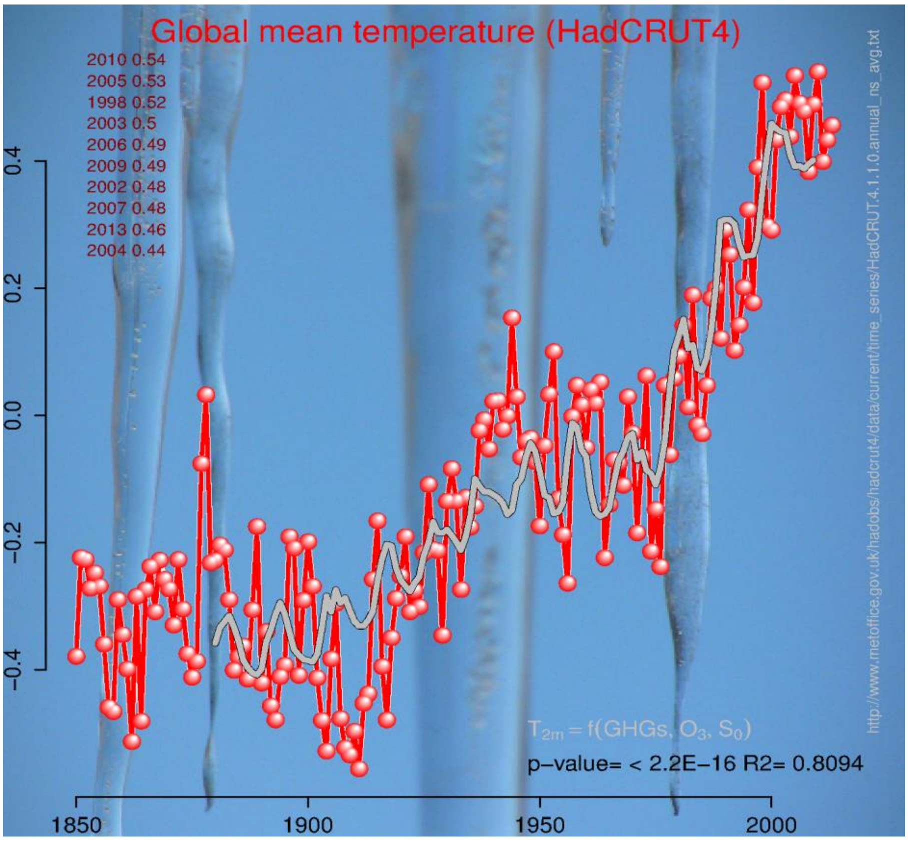
Table 11

	Benestad	Bunde	Koutsoyiannis
Does forcing introduce LTP?	Yes	Yes	Yes
Is forcing omnipresent in the real world climate?	Yes	Yes	Yes
What according to you is the main mechanism behind LTP?	Forcings	Natural Forcing plays an important role for the LTP and is omnipresent in climate.	I believe it is the internal dynamics that determines whether or not LTP would emerge.

Is the warming significant?

This brings us to one of the key questions in this climate dialogue: do you conclude there is a significant warming trend? The participants used different models and methods to answer this question and understanding their different views requests a detailed understanding of these methods which is outside the scope of this dialogue. So here we just mention the differences and focus on the results.

Benestad preferred to use a regression analysis of the global average temperature against known climate forcings as these may be considered as additional information with respect to any statistical model. The results are shown in his figure 1:



Benestad's Figure 1. The recorded changes in the global mean surface temperature over time (red). The grey curve shows a model calculation of this temperature based on greenhouse gases (GHGs), ozone (O_3), and changes in the sun (S_0).

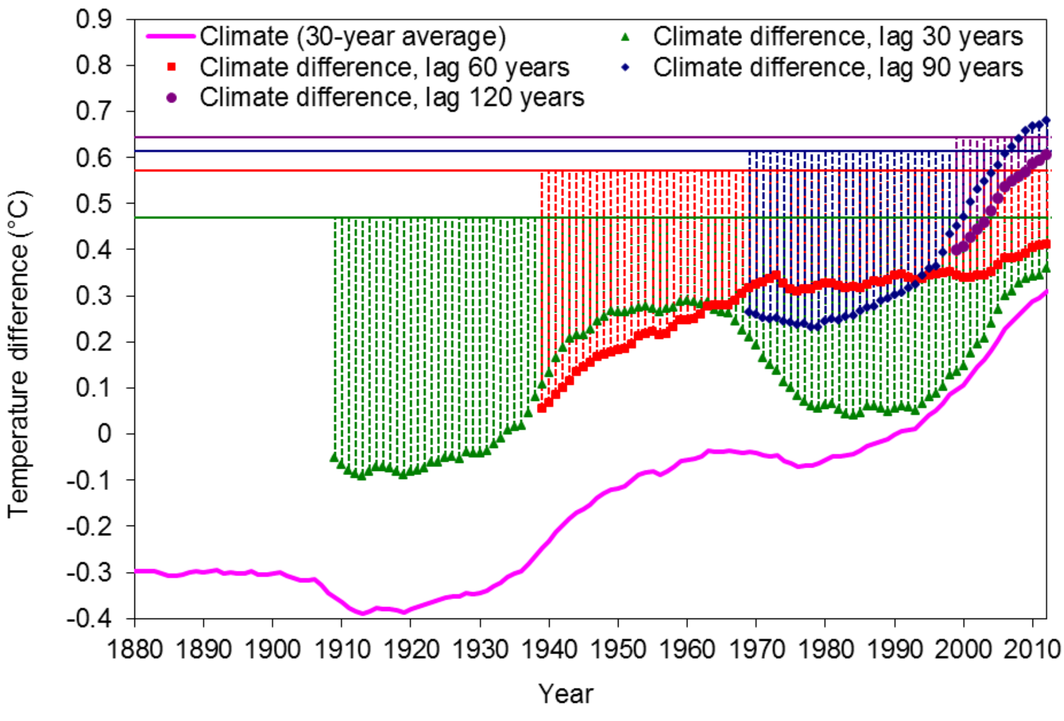
Benestad: "The probability that this fit [in the regression analysis] is accidental is practically zero if we assume that that the temperature variations from year-to-year are independent of each other. LTP and the oceans inertia will imply that the degrees of freedom is lower than the number of data points, making it somewhat more likely to happen even by chance." Benestad says it is very likely that the main physical causes of the change are clear and that greenhouse gases are the main contributors to the warming since the midst of the 20th century (as also illustrated by figure 9.15 in AR4 or figure 10.7 in AR5).

Koutsoyiannis asked Benestad whether his model shown in his Figure 1 is free of circular reasoning, which means that at least he has split the data into two periods for modelling and validation. Benestad left the question unanswered and there was no further discussion on this issue.

Bunde and Koutsoyiannis use different statistical methods. Bunde explained that “nowadays, there is a large number of methods available that is able to detect the natural fluctuations in the presence of simple monotonous trends. Two of them are the detrended fluctuation analysis (DFA) and the wavelet technique (WT).”

Based on these methods Bunde reached the following conclusions:
“(i) The global sea surface temperature increased, in the past 100y, by about 0.6 degree, which is not significant. The reason for this is the large persistence of the oceans, reflected by a large Hurst exponent.
(ii) The global land air temperature, in the past 100 years, increased by about 0.8 degrees. We find this increase even highly significant. The reason for this is the comparatively low persistence of the land air temperature, which makes large natural increases unlikely.”

Koutsoyiannis used a different method to identify and quantify the LTP which he calls a climacogram. Koutsoyiannis is the most ‘skeptical’ of the three participants when it comes to the significance of trends: “Assuming that the data set we used is representative and does not contain substantial errors, the only result that we can present as fact is that in the last 134 years the climate has warmed by 0.6°C (this is a difference of climatic—30-year average—values while other, often higher, values that appear in the literature refer to trends based on annual values). Whether this change is statistically significant or not depends on assumptions. If we assume a 90-year lag and 1% significance, it perhaps is.”



Koutsoyiannis’ Figure 5: testing lagged climatic differences based on the HadCrut4 data set (1850-2012). Differences are not statistically significant according to Koutsoyiannis, except maybe for the 90 year lag.

When asked specifically if his results mean that “detection” has not yet taken place, Koutsoyiannis replied: “Yes, I believe it has not taken place. Whether it comes close: It is likely.”

Koutsoyiannis argues that the current temperature signal is not outside of the bounds of what could be expected from natural forced and unforced changes, thereby using a stricter rating (1%) than the standard definition of “detection” (5%). He bases his statement on a higher Hurst coefficient than Bunde does which partly explains why Koutsoyiannis and Bunde don’t reach exactly the same conclusions.

Summary

The three participants gave different answers on the key question of this Climate Dialogue, namely of the warming in the past 150 years is significant or not. They used different methods to answer the question. Benestad is most confident that both the changes in land and sea temperatures are significant. Bunde concludes that due to a high Hurst parameter the sea temperatures are not significant but the land and global temperatures are. Koutsoyiannis concludes that for most time lags the warming is not significant. In some cases it maybe is.

Table 12

	Benestad[I]	Bunde[II]	Koutsoyiannis[III]
Is the rise in global average temperature during the past 150 years statistically significant?	Yes	Yes[IV]	No[V]
Is the rise in global average sea surface temperature during the past 150 years statistically significant?	Yes	No	No
Is the rise in global average land surface temperature during the past 150 years statistically significant?	Yes	Yes	No

[I] Benestad’s conclusions are based on the difference between GCM simulations with and without anthropogenic forcing (Box 10.1 or Figs 10.1 & 10.7 in AR5)

[II] Based on the detrended fluctuation analysis (DFA) and/or the wavelet technique (WT).

[III] Based on the climacogram and different time lags (30, 60, 90 and 120 years).

[IV] This change is 99% significant according to Bunde.

[V] For a 90 year time lag and a 1% significance level it maybe is significant (see Koutsoyiannis’ guest blog).

Is there a large contribution of greenhouse gases to the warming?

While Bunde and Koutsoyiannis share similar views about the importance of LTP for detection, there are some differences as well which are reflected in the table above. Koutsoyiannis for example does not agree with Bunde's conclusion that the increase in the global land air temperature in the past 100 years is significant.

Bunde and Koutsoyiannis seem to disagree about the level of LTP (i.e. the value of the Hurst coefficient) in land surface temperature records. Koutsoyiannis believes that on climatic time scales, sea surface temperatures (SSTs) and land surface temperatures (LSTs) should be highly correlated: "I believe if you accept that the sea surface temperature has strong LTP, then logically the land temperature will have too, so I cannot agree that the latter has "comparatively low persistence". (…) I believe climates on sea and land are not independent to each other—particularly on the long term." Bunde though thinks that the persistence in the SSTs is higher than that in LSTs.

Bunde is more convinced of a substantial role for greenhouse gases on the climate than Koutsoyiannis although he admits he cannot rule out that the warming is (partly) due to urban heating. "First of all, from our trend significance calculations we can see, without any doubt, that there is an external temperature trend which cannot be explained by the natural fluctuations of the temperature anomalies. We cannot distinguish between Urban Warming and GHG here, but there are places on the globe where we do not expect urban warming but we still see evidence for an external trend, so we may conclude that it is GHG."

In another comment Bunde wrote: "as a consequence of the LTP in the temperature data, the error bars are very large, considerably larger than for short-term persistent records. But nevertheless, except for the global sea surface temperature, we have obtained strong evidence from this analysis that the present warming has an anthropogenic origin." And in another comment: "Regarding GHG [greenhouse gases] I may not fully agree with Demetris [Koutsoyiannis]: We cannot show in our analysis of instrumental temperature data that GHG are responsible for the anomalously strong temperature increase that we see and that we find is significant, but it is my working hypothesis."

When we asked Koutsoyiannis whether he believes the influence of greenhouse gases is small he answered: "Yes, I believe it is relatively weak, so weak that we cannot conclude with certainty about quantification of causative relationships between GHG and temperature changes. In a perpetually varying climate system, GHG and temperature are not connected by a linear, one-way and one-to-one, relationship. I believe climate models and the thinking behind them have resulted in oversimplifying views and misleading results. As far as climate models are not able to reproduce a climate that (a) is chaotic and (b) exhibits LTP, we should avoid basing conclusions on them."

Benestad on the other hand wrote: "The combination of statistical information and physics knowledge lead to only one plausible explanation for the observed global warming, global mean sea level rise, melting of ice, and accumulation of ocean heat. The explanation is the increased concentrations of GHGs."

Summary

Bunde is more convinced of a substantial role for greenhouse gases on the climate than Koutsoyiannis although he admits he cannot rule out that the warming on land is (partly) due to urban heating. Bunde said he may not fully agree with Koutsoyiannis: “We cannot show in our analysis of instrumental temperature data that GHG are responsible for the anomalously strong temperature increase that we see and that we find is significant, but it is my working hypothesis.” Koutsoyiannis believes the influence of greenhouse gases is relatively weak, “so weak that we cannot conclude with certainty about quantification of causative relationships between GHG and temperature changes”. Benestad on the other hand said the increased concentrations of GHGs is the only plausible explanation for the observed global warming, global mean sea level rise, melting of ice, and accumulation of ocean heat.

Table 13

	Benestad	Bunde	Koutsoyiannis
Is the warming mainly of anthropogenic origin?	The combination of statistical information and physics knowledge lead to only one plausible explanation: GHGs	Yes, it is my working hypothesis	No, I think the effect of CO2 is small