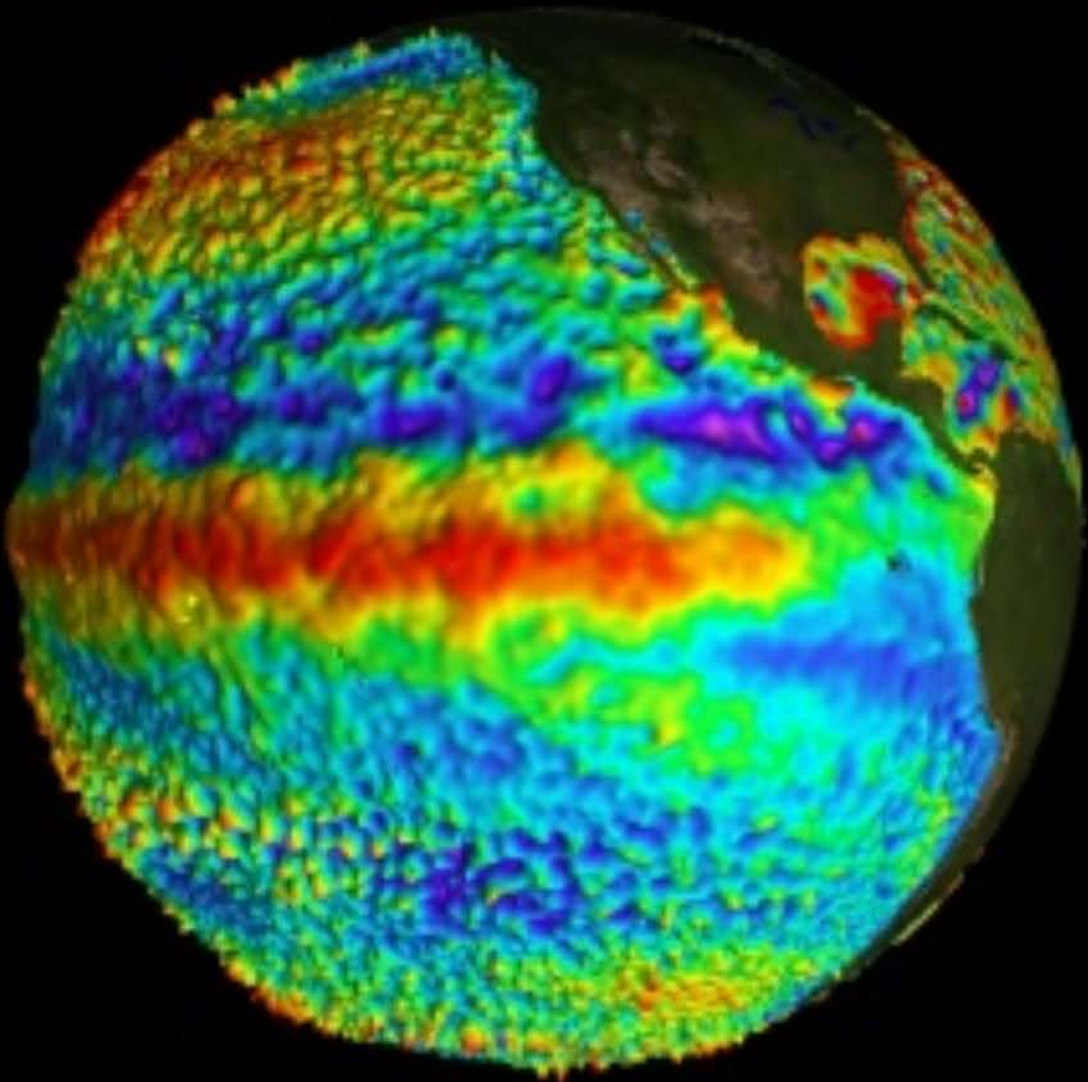

THE LITTLE BOY

El Niño and natural climate change

Anastasios Tsonis

The Global Warming Policy Foundation

GWPF Report 26

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Anastasios Tsonis

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Contents

Foreword

By Professor Christopher Essex

Anastasios Tsonis is a world expert on the global physical significance of ultra-low-frequency ocean oscillations such as the El Niño Southern Oscillation (ENSO). Its odd name originates from old knowledge of odd, temporary changes in ocean conditions off the coast of South America, occurring once or twice a decade around Christmas time. This report describes this phenomenon and brings it into a modern global context. But the story is more than simply one of some old South American geophysical phenomenology seen from a global perspective; it is tied to an extraordinary story about new scientific thinking, arising at the end of the 20th century, concerning the nature of change itself.

It was a revolution that affected all of science, particularly re-energising classical physics. It altered forever how we look at change, and how we comprehend our capability to predict the future. Ironically it was touched off in part by the work of an MIT meteorologist, Edward Lorenz, in the late 1960s. A milestone in this change of outlook was the 1986 apology to the Royal Society,† by Sir James Lighthill (a late-20th-century icon of mechanics):

> We are deeply conscious today that the enthusiasm of our forebears for the marvelous achievements of Newtonian mechanics led them to generalizations in this area of predictability which, indeed, we may have generally tended to believe before 1960, but which we now recognize as false. We collectively wish to apologize for having misled the general educated public by spreading ideas about the determinism of systems satisfying Newton's laws that, after 1960, were proved incorrect. In this lecture, I am trying to make belated amends by explaining both the very different picture that we now discern, and the reasons for it being uncovered so late.

How does this revolution of modern science connect to the oceans off of South America? Well, answering that is what Tsonis accomplished in his seminal works and what he explains in this report.

What jumps out about El Niño data to someone with a 'before-1960' perspective is that the signal data, accumulated over many decades, does not really appear as an oscillation, in the sense of being simply periodic like that of a child's swing in a park. It is markedly irregular for an 'oscillation'. The revolution in how we look at determinism in systems like the climate gave us mathematical machinery and language to help us comprehend this behaviour. It also gave us mathematical object lessons that suggested a deeper understanding could be had by considering El Niño and its cousins. These cousins are additional 'oscillations', subsequently found in other places, such as

† Lighthill, J (1986) *J. Proc. Roy. Soc. London. Series A, Mathematical and Physical Sciences,* Vol. 407, 35–50.

the Atlantic Ocean and elsewhere in the Pacific Ocean: the North Atlantic Oscillation, the Pacific Decadal Oscillation and others.

With this knowledge Tsonis reversed the approach of the classical work of Lorenz. Lorenz had tried to explain the well-known irregularity and unpredictability of common weather in terms of a few simple coupled modes. Instead of concluding with simple coupled modes as Lorenz did, Tsonis began with them (i.e. the ocean modes of El Niño and its cousins), to discover unexpectedly a wholly new sort of 'weather'. It is not like the weather Lorenz tried to explain, with which we are all familiar. It is something completely new. Instead of changing from day to day, it changes from decade to decade.

This immediately answers some old questions and raises new ones. If a reliable person of great age claims daily weather or seasons were different when he or she was young, this could well be true, but without any need to appeal to climate change. Of course this new kind of 'weather' could as well be described as a sort of short-term climate change instead, but that is a matter of semantics. What is not semantical is that these changes occur naturally, whether humans are present or not. Moreover, current attribution arguments are rendered invalid by it, because natural internally-caused 'weather' is shown here to be able to explain things – as well as the state of the art permits – without any need to appeal to external causes.

Christopher Essex
Professor Essex is Chairman of the Academic Advisory Council of the GWPF.

About the author

Anastasios Tsonis is distinguished professor of atmospheric sciences at the University of Wisconsin-Milwaukee. He is also an adjunct research scientist with the Hydrologic Research Center in San Diego.

1 Introduction

The El Niño Southern Oscillation cycle (ENSO) was discovered in the 1970s, when satellite images of the Earth were first routinely collected. Since then it has been recognised as a major driver of the dynamics of the climate system. Its connection to global warming is frequently discussed; for example, its role in global warming and whether there will be more El Niño events in a warmer climate. In this essay we will discuss the relationship between ENSO and climate change. We will start with a short description of ENSO, and then we will present a complete discussion of its relationship with other climate signals and global temperature.

2 The El Niño/La Niña cycle

El Niño, Spanish for 'the little boy', is a recurring phenomenon in the tropical Pacific Ocean and is considered one of the most influential phenomena of our climate system. Its name comes from the 'Christ child' because it usually starts some time in December. It was coined in the late 1880s by Peruvian fishermen, who noticed that the cold north-flowing current in which they fished would change, every few years, into a warm south-flowing one. They understood that this change meant trouble for their business. What they did not know is that many other areas of the world, one way or another, also suffer the consequences of El Niño.

To explain how El Niño occurs we have to start with the fact that in the subtropics the surface winds are on the average easterly. As they travel westward over the Pacific Ocean they act like a broom, sweeping up the warm surface water – warm because it is exposed to solar heating – and accumulating it in the western Pacific in the area of Indonesia. In the eastern Pacific Ocean, because of the removal of warm surface water, an upwelling of colder water takes place. This colder water brings up nutrients from the deep waters, and these maintain the healthy fish populations off the shores of Peru, Ecuador, and Chile.

The accumulation of warm surface water in the west and the upwelling of colder water in the east cause a large-scale convection pattern: the air rises over Indonesia and sinks off the west coast of South America. This pattern, which is shown by the black arrows in Figure 1, is called the *Walker circulation*, in honour of Sir Gilbert Walker, director-general of British observatories in India, who, early last century, identified a number of relationships between seasonal climate variations in Asia and the Pacific region. The Walker circulation brings rainfall to the west and clear skies to the east.

The conditions described above represent normal or La Niña conditions.[‡] The general Pacific Ocean topography has a 'groove' along the equator, deepening to the east (where surface water is removed) and highest toward the west (where surface

‡ La Niña being 'the little girl'.

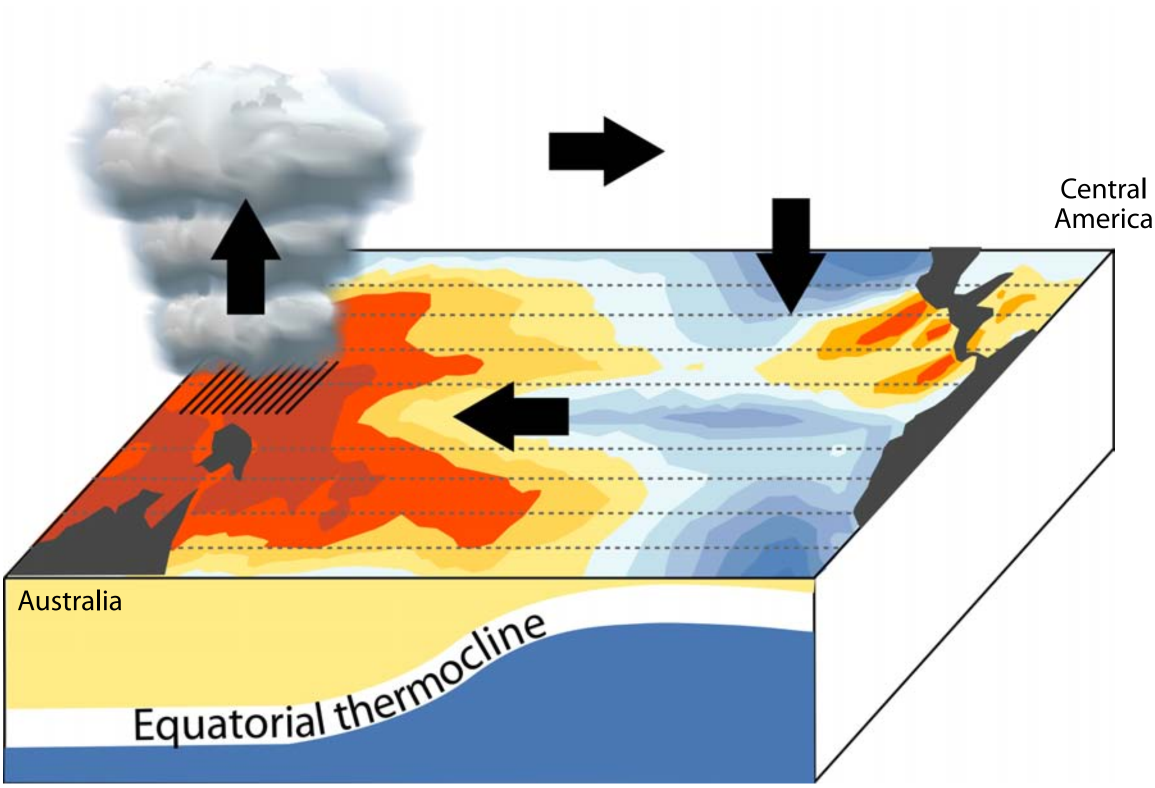

Figure 1: La Niña conditions.

The easterly surface winds near the equator sweep warm surface water westwards. Colder water from the depths replaces the warm swept water, thereby creating a warm and a cold pool of water in the western and eastern Pacific respectively.

water is accumulated). When a wind anomaly occurs – for example, weaker trade winds – the warm water to the west sloshes back and spreads over the whole tropical Pacific basin, covering the colder surface water to the east. Everywhere in the tropical Pacific we now have warm surface water. This causes the Walker circulation to break down, because air now rises everywhere in the central Pacific. The upwelling in the eastern Pacific stops and the supply of nutrients needed to sustain the fish population is cut off. As a result there are fewer fish and the fishing industry suffers great losses. We now have an El Niño (Figure 2). El Niño is also referred to as a warm event and La Niña as a cold event.

Once an El Niño has matured, the trade winds return to normal and the cycle is repeated. However, it does not repeat regularly. The El Niño/La Niña cycle is rather aperiodic, with an average period of about 4–5 years.

The processes described above are the latest theories and models of how ENSO evolves.[1–8] However, they cannot yet explain the finer details of the initiation of an

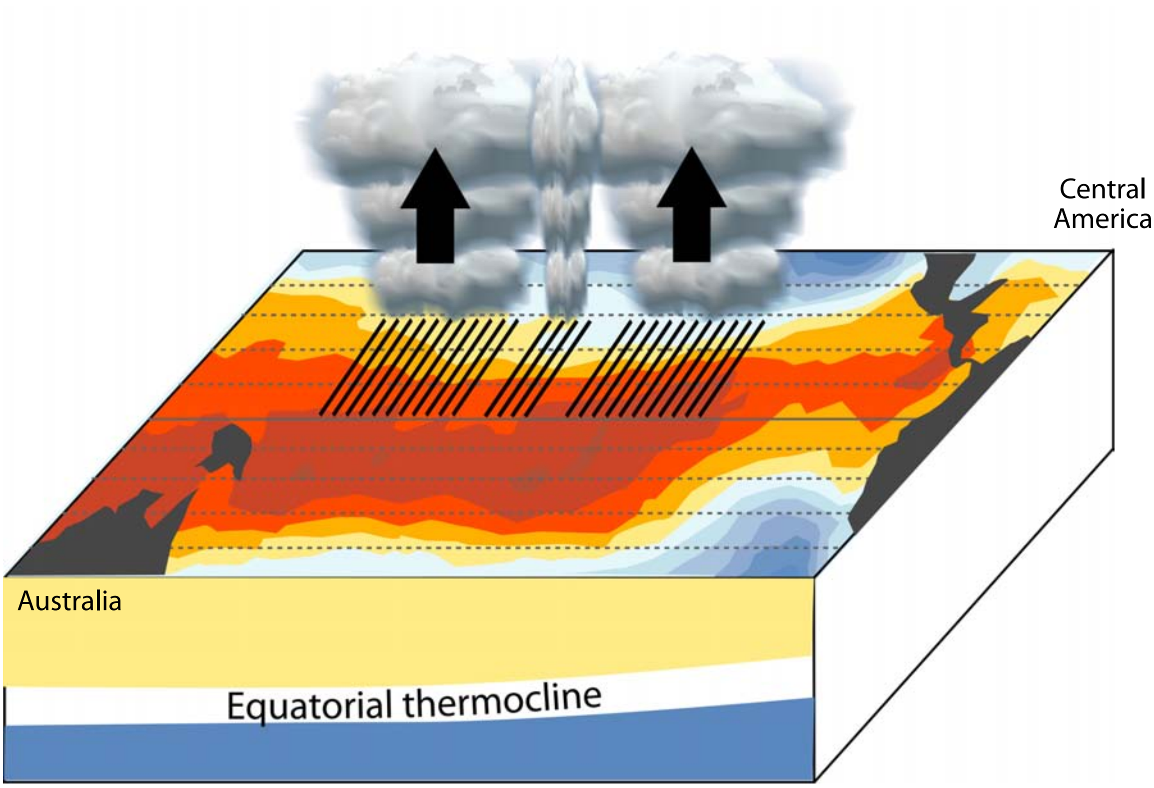

Figure 2: El Niño conditions.

The continuous accumulation of warm water in the western Pacific cannot be sustained forever and eventually the warm water in the west sloshes back and spreads over the whole tropical Pacific basin.

event and the role global change plays. For example, why in the period 1976–1998 were there several strong El Niño events and hardly any La Niña events? And why do the models differ in their responses when subjected to the same global temperature changes?[9–10]

3 Global temperature and ENSO

It appears that there are two complementary aspects of the relationship between ENSO and global temperature. The first (and well-known) aspect is that global temperature increases after an El Niño event and that a La Niña event follows an El Niño event, which causes the global temperature to drop again. In other words, El Niño 'forces' global temperature. While this is an important result, it is not a complete picture; if it were, ENSO would be independent of global temperature. The second aspect suggests that there is a deeper connection between global temperature and

ENSO. Computer simulations suggest that positive global temperature trends tend to trigger El Niño events, while negative trends will trigger La Niña events. Thus, in a warming climate, El Niño events should be more frequent than La Niña events. For example, an analysis of the output of a climate simulation in which temperatures are forced to increase through rising carbon dioxide concentrations[§] confirms that sustained positive global temperature trends lead to 20 El Niño events per century, but only 11 La Niña events. Meanwhile, in a steady-state run of the same model,[||] El Niño and La Niña events occured at roughly the same frequency: about 17 events/century.

Note that this result refers to a warming climate. It does not mean that in a warmer but steady climate there will be more El Niño events. In fact, models suggest that El Niño frequency is a very weak function of temperature, and that it takes a much higher global temperature to significantly change the frequency of El Niño events.[9–12] The question then arises as to whether or not the observations support the relationship suggested by the models; that the frequency of ENSO depends on the *change* in global temperature.

Figure 3 shows an annual global temperature anomaly record (negative anomalies in blue, positive anomalies in red). It is easy to see from the annual anomaly values (not the five-year mean smooth line) that the record exhibits 'regimes' of changing trends:

- From about 1880 to about 1910 the trend is negative.
- From about 1910 to about 1943 it is strongly positive.
- From about 1943 to about 1976 it is slightly negative.
- From about 1976 to about 1998 it is strongly positive.
- After 1998 it is more or less flat.

Note that due to a very strong El Niño, global temperature rose sharply in 2016. Whether this will signal the end of the recent flat regime (the so-called 'pause') remains an open question, as we now are in a strong La Niña regime.

Figures 4 and 5 show the Southern Oscillation Index (SOI) and the Multivariate ENSO Index (MEI) from 1950 to early 2017. The SOI is a standardised index based on the observed air pressure differences at sea level between Tahiti and Darwin, Australia. The MEI is calculated by extracting key patterns[¶] from records of six observed variables over the tropical Pacific:

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§ NCAR's Climate System Model 1 (CSM1) Case b006, a 119-year run in which the global temperature is forced to increase by carbon dioxide concentration rising at a rate of 1%/year above its pre-industrial level. Data accessible at www.ucar.edu.

|| Case b003, a 300-year run.

¶ MEI is calculated as the first unrotated principal component (PC) of all six observed fields combined. This is accomplished by normalising the total variance of each field first, and then performing the extraction of the first PC on the co-variance matrix of the combined fields.[13,14]

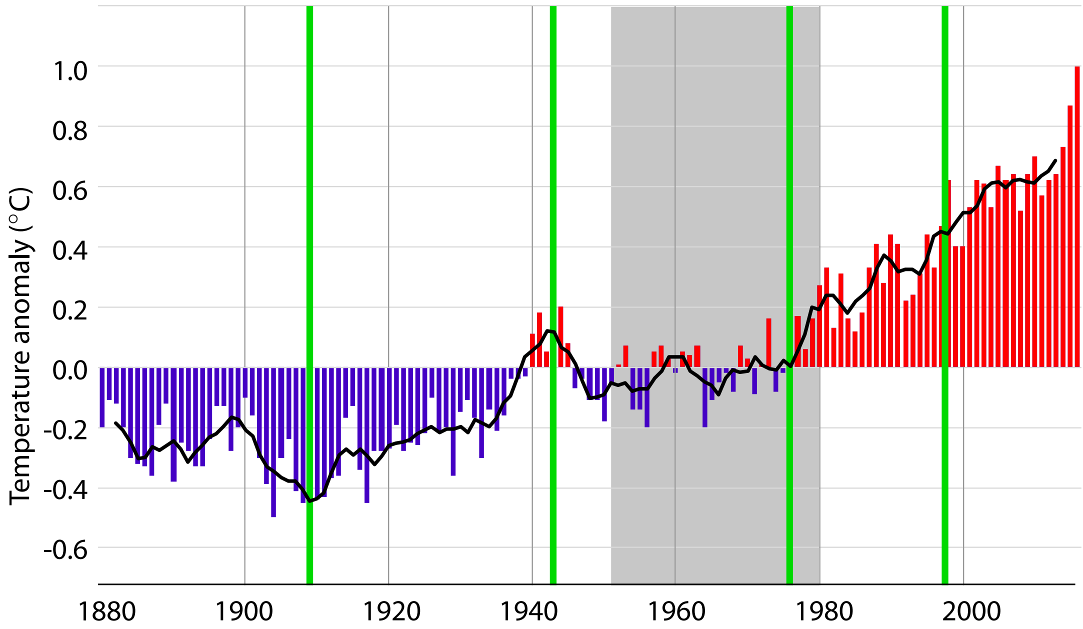

Figure 3: The global temperature anomaly record.

GISS land/ocean index 1880–2016 and five-year centred running mean (black). Green lines separate the different temperature regimes. Baseline period in grey.

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- sea-level air pressure
- zonal and meridional components of the surface wind
- sea-surface temperature
- surface air temperature
- total cloudiness fraction of the sky.

The vertical green lines separate intervals of different global temperature tendencies (as in Figure 3). Note that in the SOI, El Niño (red) is negative whereas in the MEI it is positive (red again). Regardless, the two indices are consistent with each other:

- During the slight cooling period of 1943–1976, there is a hint of more La Niña events than El Niño events.
- In the flat regime since 1998, the frequency is practically the same.
- In the period 1976–1998 with the strong positive trend in temperature, El Niño is clearly more frequent.

This supports what the models suggest, namely that in a global warming scenario the frequency of El Niño events will increase, and in cooling regimes La Niña events will be more frequent.

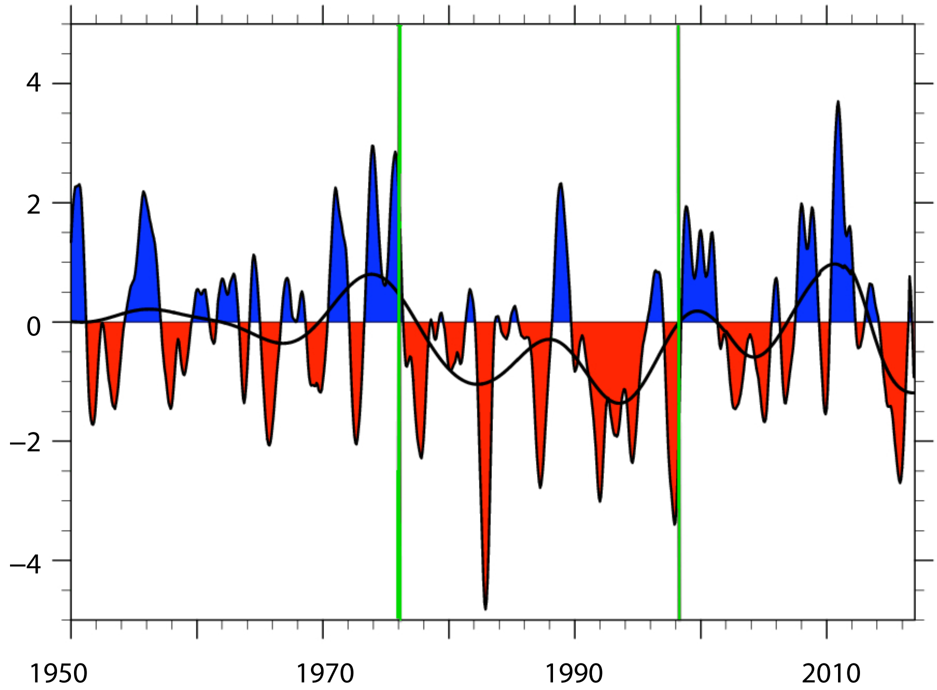

Figure 4: The SOI record in the period 1950–present.

Positive values (blue) represent La Niña and negative values (red) represent El Niño. Source: CGD's Climate analysis section NCAR. The black smooth line is discussed in the text.

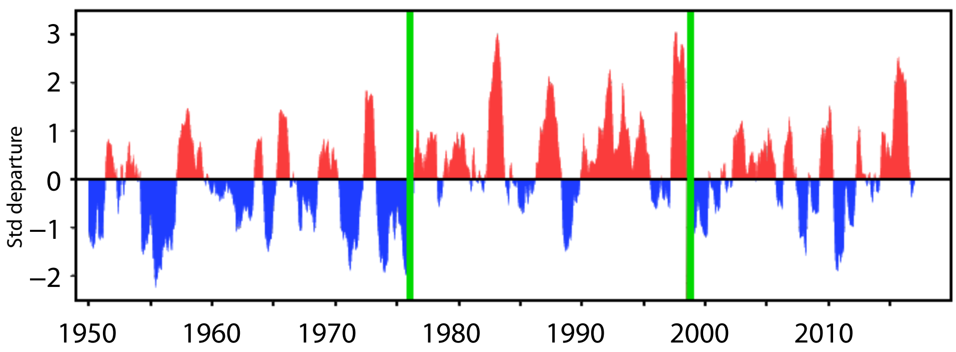

Figure 5: The Multivariate ENSO index in the period 1950–present.

Here negative values (blue) represent La Niña and positive values (red) represent El Niño. Source: CGD's Climate analysis section NCAR

However, Figure 6 shows the SOI from the late 1860s (MEI is not available before 1950); the vertical green lines again separate positive and negative trends in global temperature. It is important to note here that the two strong positive trends (1910–1943 and 1976–1998) have practically the same value and that the negative trends are of smaller absolute values. This is because this multi-decadal variability in global temperature trend is superimposed on a low-frequency positive trend – global warming – which accentuates warming trends and suppresses cooling trends.

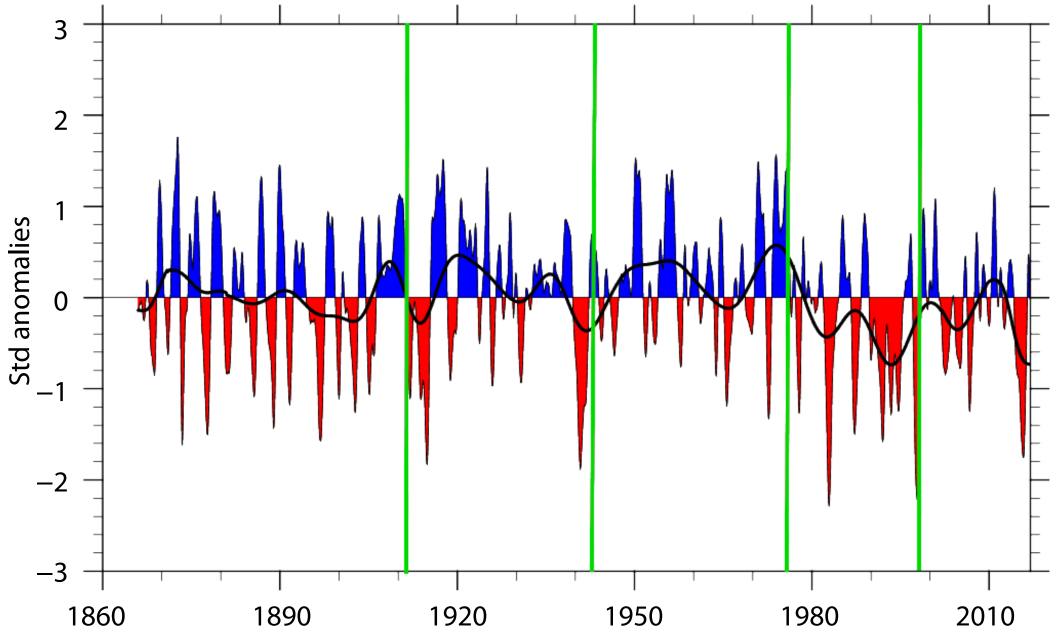

Figure 6: SOI as per Figure 2, but for the period 1868–present.

We can see that during the strongly positive trend of 1910–1943 the frequency of La Niña events was *greater* than the frequency of El Niño events, which is not what we observe in the period 1976–1998 and not what the models suggest. This is despite the fact that these two periods both saw strong – and equally strong – increases in global temperature.

In the cooling regime before 1910 there is again a hint of more frequent La Niña events. Overall, while there are some indications in the data that in warmer regimes there will be more frequent El Niño events and in cooling regimes there have been more La Niña events, this is not always true.

Finally, we should mention that some scientists have suggested that a very strong La Niña (El Niño) may lead to a reversal of a current trend from negative to positive (positive to negative). But as is clear from the data in Figures 3–6 this is not always the case. We conclude that there may be more to the ENSO-multidecadal variability/global temperature picture than models suggest.

4 Some background theory and history

The flow chart in Figure 7 is an outline of the following sections.

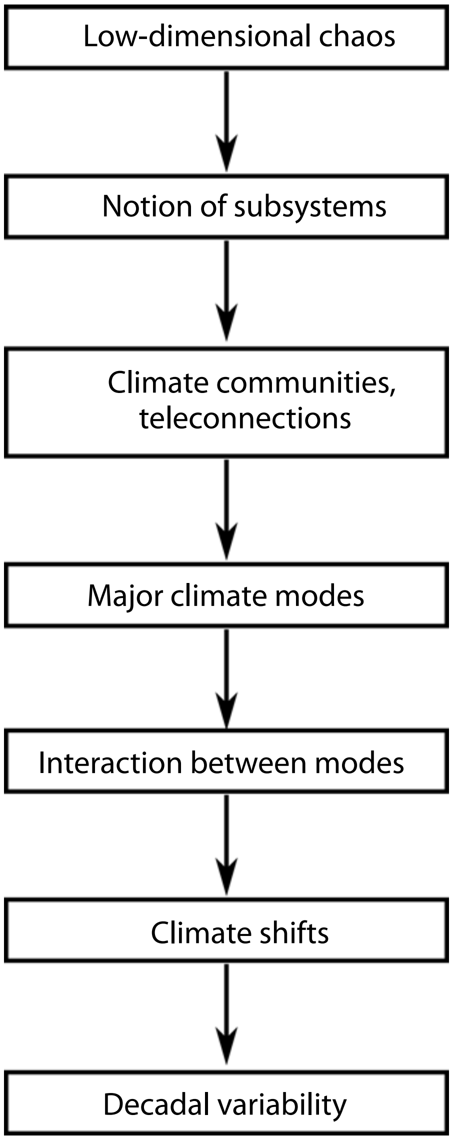

Figure 7: Outline of the discussion to follow.

First we must consider dynamical systems, chaos theory and fractals. Fractals are amorphous non-Euclidean structures (such as clouds), which nevertheless obey a certain type of geometry. A dynamical system is a system of N differential equations describing the interactions between N variables. The evolution of such a system takes place in its 'state space', which is a Cartesian coordinate system, whose axes are the N variables.

For example, consider a pendulum the resting position of which is indicated by the broken line (Figure 8). You can take the pendulum to some initial condition away from its resting position and let it swing. What will eventually happen? The pendulum will swing back and forth and, due to air friction, it will eventually come to rest at the original resting position. During the back and forth swinging of the pendulum, the state of the system at any time is defined by two variables: its velocity and its diplacement (angle) from the resting point. Thus, the state space in this example is two-dimensional, so we can visualise it on a plane, with axes for velocity and angle.

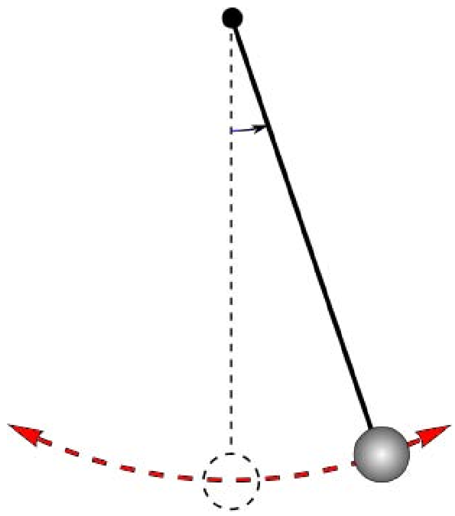

Figure 8: A pendulum.

The resting position is indicated by the broken vertical line.

Figure 9 shows what can happen to the pendulum when released from two different initial conditions (indicated by the arrows). The final result will be the same, independent of the initial condition (the point from which you let it swing). We can therefore say that the resting point is the *attractor* of the system, because all evolutions from different initial conditions are finally attracted to it. The origin in this state space represents the attractor, which is called a *fixed point*.

If we now consider a pendulum where a spring compensates for friction (as in a grandfather clock), then the attractor is not a fixed point but a *limit cycle*: the motion is periodic and any fluctuation away from that limit cycle is damped back to the cycle. Systems with a fixed point or a limit cycle are said to have Euclidean attractors and they are predictable: the final state of the system can be known, regardless of the initial condition. However, in most *nonlinear* dynamical systems (the majority of systems found in nature) the attractor is not Euclidean but a fractal. In such systems,

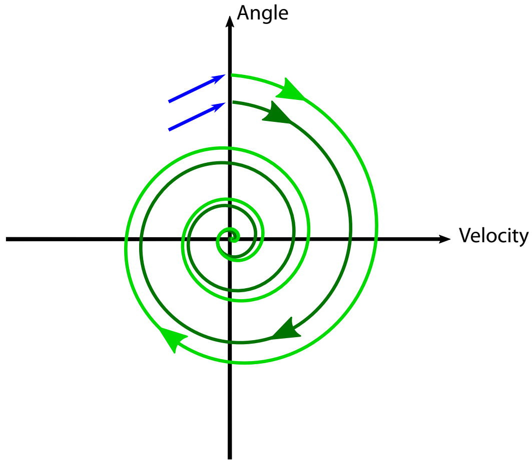

Figure 9: The state space of the swinging pendulum in Figure 8.

The two green trajectories depict two evolutions from two different initial conditions (indicated by the two arrows).

even slightly different initial conditions will cause the system to evolve along trajectories that diverge and ultimately become completely different. The system is said to be 'chaotic' and it will evolve in a way that often appears random. Predictability is therefore very limited. There is still an attractor because the system is deterministic and in fact in many cases it can be described by a small number of equations (the chaos is said to be 'low-dimensional'). We call the attractors in chaotic systems *strange attractors*.

The relevance to this paper starts in the mid-1980s. At that time, very few in the atmospheric sciences community had heard of fractals, chaos theory, or strange attractors. However, reports of 'fractality' in climate records and other geophysical data gradually began to surface. These climate records represented dynamics over different timescales ranging from thousands of years[15] to just hours.[16] Importantly, virtually every report suggested that the underlying attractors might be low-dimensional, which in turn suggested that climate variability might be described by a relatively small set of equations. This was important, because it gave researchers great hope that climate variability might be tamed and that climate would become more predictable.

However, there was also fierce opposition to this idea. The initial objection was that in all these studies the sample size was simply too small. While this issue has been debated extensively,[17–20] it still remains contentious, although the debate has led to a deeper understanding of the nonlinear character of nature and to new insights about the properties of the climate system. In a sense, it is naïve to imagine that our climate system is described by a grand attractor, let alone a low-dimensional attractor. If that were true, then all observables representing different processes should have the same dimension; this is unlikely to be true in practice because a myriad array of dimensions has been reported in different climate datasets.

If low-dimensional attractors exist in the climate system they should be associated with subsystems operating in different spaces and/or time scales.[21,22] Such subsystems may be nonlinear and exhibit a variety of complex behaviours. Being parts of the grand climate system, all subsystems would be connected to each other, as in a web, with various degrees of connectivity or coupling. Accordingly, any subsystem may transmit 'information' to another subsystem, thereby perturbing its behaviour. This 'information' plays the role of an ever-present external noise, perturbing the subsystem and, depending on its connectivity to other subsystems, having a dramatic or negligible effect. Those subsystems with weak connectivity would be approximately 'independent' and so might exhibit low-dimensional chaos. It is also possible that the connectivity between subsystems might vary in time, thus dictating the natural variability of the climate system.

Thus, evidence of low-dimensional chaos leads to the notion of climate subsystems. Given this, a question arises: If subsystems exist in the climate system what are they and what physics can we infer from them?

5 Searching for subsystems

Answers about the nature and geographical basis of these subsystems and the physical mechanisms underlying them have come from recent developments in graph theory and networks. A network is a system of interacting agents. In the literature, an agent is called a 'node'. The nodes in a network can be anything. For example, in the network of actors, the nodes might be actors who are connected to other actors if they have appeared together in a movie. In a network of species, the nodes are species that are connected to other species they interact with. In the network of scientists, the nodes are scientists that are connected to other scientists if they have collaborated. In the grand network of humans each node is an individual, connected to people he or she knows. Networks have found many applications in many fields of science. More details on networks and their applications to the climate system can be found in the literature.[23–26]

The topology of a network can reveal important and novel features of the system it represents.[27–29] One such feature is communities.[30] Communities represent groups of densely connected nodes with only a few connections to other groups. It has been conjectured that each community represents a subsystem, which operates relatively independent of the other communities.[31] Thus, identification of these communities can offer useful insights about the dynamics involved. In addition, communities can be associated with network functions. An example is found in metabolic networks, where certain groups of genes have been identified that perform specific functions.[32,33]

Recently, concepts from network theory have been applied to climate data organised as networks, with impressive results.[24,34–41] In these studies, several major communities/subsystems have been identified, most notably ENSO, the North Atlantic Oscillation (NAO), and the Pacific North America pattern (PNA), each representing a major climate signal and/or climate teleconnection.

6 Interaction between subsystems

An important aspect of the collective behaviour of coupled nonlinear oscillators is synchronisation and coupling strength. Here we need to explain the difference between synchronisation and coupling. Think of a cycling team taking part in a team time trial. The riders are all synchronised, with their motions carefully planned to maximise the team's overall speed. However, if those riders were coupled together, for example by attaching their bikes together with a rope, the slightest misstep by one of the riders would be communicated immediately through the team and would lead to a group crash. Moreover, the stronger the rope the higher the likelihood of this happening.

In physical terms, coupling is a property of an individual oscillator's phase relative to the phases of other oscillators. When two oscillators' phases lock – that is, they retain a fixed relationship for a sufficiently long time – then, regardless of the phase lag between them, those oscillators are considered coupled.

The theory of synchronised chaos predicts that in many cases when such systems synchronise, an increase in coupling between the oscillators may destroy the synchronous state and alter the system's behaviour.[42,43]**

To show this in a climate context, we constructed a network of four major climate indices:[34] the Pacific Decadal Oscillation (PDO),[44] the NAO,[45] ENSO,[46] and the North Pacific Index (NPI)[47].†† These indices are associated with major climate subsystems and represent regional but important modes of climate variability, with timescales ranging from months to decades. The NAO and NPI are the leading modes of surface pressure variability in the northern Atlantic and Pacific Oceans respectively, the PDO is the leading mode of SST variability in the northern Pacific, and ENSO is a major signal in the tropics. Together these four modes capture the essence of climate variability in the northern hemisphere. Each is assumed to represent a subsystem of the climate, each involving different mechanisms and different geographical regions. Some of

** For more details on the definitions of synchronisation and coupling the reader is referred to Tsonis et al., 2007.[34]

†† Monthly-mean values in the period 1900 to the present are available for all four indices.

the dynamics involved are now sufficiently well understood to enable them to be represented by simple models.[3,48–50]

Figure 10 shows yearly anomaly values of global temperature.[26] The black solid line is a smoothed version of this record. As discussed earlier, it is evident from the smoothed line that on decadal timescales there are times when the global temperature trend is shifting from negative to positive and vice-versa. These 'shifts' are superimposed on a low-frequency signal known as 'global warming'. Here we are not interested in the origins of the low-frequency signal. Rather we are interested in the departures from this signal on decadal timescales.

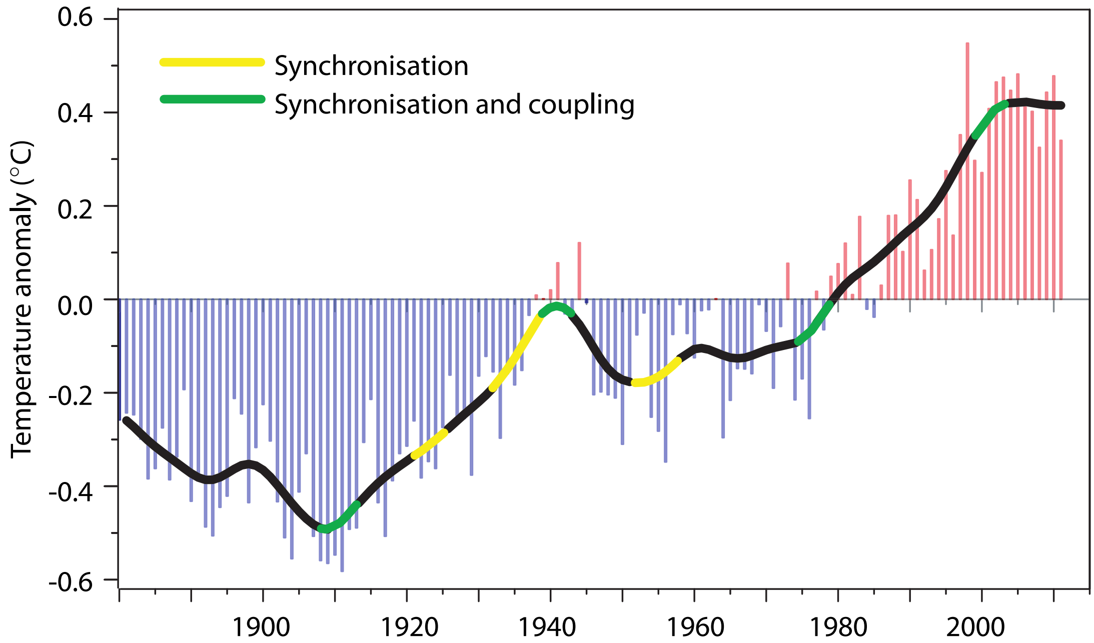

Figure 10: Summary of synchronisation events, coupling and climate shifts.

Refer to text for details.

On top of the black line are superimposed coloured lines, which are the result of an analysis of our network of climate indices. The yellow sections are where the four climate modes are synchronised during a period when the coupling between the modes is *not* increasing. The green sections are where the four climate modes are synchronised during a period when the coupling between the modes *is* increasing. Thus, we can see that the network synchronised seven times. On three of these occasions – coloured yellow – synchronisation was not associated with an increasing coupling strength and there was no change in the temperature trend. However, on four occasions – coloured green – synchronisation *was* associated with an increase in coupling strength. On these occasions, if the modes remain synchronised and the coupling strength keeps on increasing, at some coupling threshold the synchronised state is destroyed and the climate shifts into a new state (for example around 1910, 1943, 1976, and 1998). This shift is characterised by a reversal in the global temperature trend.

This mechanism appears to be intrinsic to the climate system: it is found in both control and forced climate simulations.[34,51] It also appears to be a very robust mechanism. In all 13 synchronisation events found in the observations and model simulations, when the modes are synchronised and the coupling begins to increase, then at some coupling strength threshold synchronisation is destroyed and the system shifts to a new state.

Due to noise or uncertainties in the data, synchronisation cannot be perfect and this threshold is not always the same or always a maximum at desynchronisation. Once the modes are desynchronised the coupling may continue to increase as the modes may fall into phase with each other. This is consistent with the general theory of synchronised chaos, in which coupling strength may keep on increasing after desynchronisation. No temperature shift occurred (in observations and model simulations) when, during the synchronous state, the coupling strength was decreasing.

Recently this analysis was extended to proxy data for climate modes going back several centuries.[52] While noise in the proxy data in some cases masks the mechanism, it was found that significant coherence between both synchronisation and coupling and global temperature exists. These results provide further support for the idea that the mechanism of climate shifts discussed here is a robust feature of the climate system.

These results tell us something about the *collective* behaviour of the four modes in the network. As such they do not bring any insights about the mechanism through which they interact. For example, does strong synchronisation result from all of the modes synchronising or from a subset of them? When the network is synchronised, does the coupling increase require that all modes must become coupled with each other? To answer these questions Wang et al. split the network of four modes into its six component pairs and investigated the contribution of each pair during each synchronisation event and in the overall coupling of the network.[51] They found that one mode is behind all climate shifts. Surprisingly, the mode concerned is not ENSO but the NAO: it is, without exception, the common ingredient in all shifts in the climate regime and when it is not coupled with any of the Pacific modes no shift ensues. In addition, in all cases where a shift occurs, the NAO is necessarily coupled to the north Pacific. In some cases, it may also be coupled to the tropical Pacific – that is, ENSO – but in none of the cases of a shift was NAO coupled only to ENSO. Thus, the results indicate not only that NAO is the instigator of climate shifts but that the likely evolution of a climate shift has a path in which the north Atlantic couples to the north Pacific, which in turn couples to the tropics.[‡‡]

This co-variability of climate modes and their influence on global temperature has recently been confirmed by a different approach. Wyatt et al. analyzed a network of climate indices[†] and discovered the so-called 'stadium wave'; a sequence of lagged atmospheric and oceanic 'teleconnections' leading to northern hemisphere temperature reversals every about 30 years.[53] Recently, Wang et al. investigated whether the collective behaviour of these modes affects shorter (seasonal) timescales.[54] They applied a nonlinear prediction approach in order to assess directional influences in the climate system and found evidence that input from four major climate modes from the Atlantic and Pacific can improve predictions of global temperature. Moreover, they found that this causality is not a result of a particular mode dominating but a result of nonlinear collective behaviour in the network of the four modes.

7 Conclusions

The findings presented here and in the references support the view that the climate system consists of distinct subsystems whose interplay dictates decadal variability. At the same time, these results provide clues as to what these subsystems might be. As such, while 'weather' may be complicated (consisting of many parts and difficult to understand), 'climate' may be complex but not complicated (with fewer parts and easier to understand). Moreover, it appears that the interaction between these sub-

‡‡ Solid dynamical arguments and past work offer a concrete picture of how the physics may play out (the following discussion may involve some unfamiliar terminology but we present it for the information of the reader). NAO with its huge mass re-arrangement in north Atlantic affects the strength of the westerly flow across mid-latitudes. At the same time through its 'twin', the Arctic Oscillation (AO), it impacts sea level pressure patterns in the northern Pacific. This process is part of the so-called intrinsic mid-latitude northern hemisphere variability; the intrinsic variability through the seasonal footprinting mechanism couples with equatorial wind stress anomalies, thereby acting as a stochastic forcing of ENSO.[55,56] This view is also consistent with recent studies showing that PDO modulates ENSO.[57,58] Another possibility of how NAO couples to north Pacific may be through the five-lobe circumglobal waveguide pattern.[59] It has been shown that this waveguide pattern projects onto NAO indices and its features contribute to variability at locations throughout northern hemisphere. Finally, north Atlantic variations have been linked to northern hemisphere mean surface temperature multidecadal variability through redistribution of heat within the northern Atlantic with the other oceans left free to adjust to these Atlantic variations.[60] Thus, NAO, being the major mode of variability in the northern Atlantic, impacts both ENSO variability and global temperature variability. Recently a study has shown how ENSO with its effects on PNA can, through vertical propagation, influence the lower stratosphere and how in turn the stratosphere through downward propagation can influence NAO.[61] These results coupled with our results suggest the following 3-D super-loop: NAO $\rightarrow$ PDO $\rightarrow$ ENSO $\rightarrow$ PNA $\rightarrow$ stratosphere $\rightarrow$ NAO, which captures the essence of decadal variability in the northern hemisphere and possibly the globe.

† The authors considered the lagged covariance structure.

systems may be largely responsible for observed decadal climate variability. In the past, this decadal variability was 'modeled' as a tug-of-war between aerosols and carbon dioxide effects. The argument was that in times when aerosols were 'winning', the Earth would cool, while in times when carbon dioxide effects were more dominant, the Earth would warm. The results presented here refute this arbitrary assumption as they demonstrate that a dynamical mechanism is responsible for climate shifts. Thus ENSO and its 'cousins' do not tell us anything about human contributions to climate change. They do, however, underscore the importance of natural variability in climate change. While humans may play a role in climate change, other natural forces such as the oceans and extraterrestrial influences such as the sun and cosmic rays[62] may play important roles too.

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