Research Article

Isoprene and Evapotranspiration Time Series Provide Further Empirical Evidence for a Natural Global Atmospheric Temperature Control System

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There is evidence that an increase in plant-emitted isoprene causes an increase in cloud condensation nuclei, and is one way in which an increase in cloud cover occurs. Similarly, an increase in plant-emitted water vapour from transpiration can cause an increase in wind speed, which can transfer more heat out of the atmosphere into the ocean. Each of these pathways can reduce global atmospheric surface temperature. With this background, we investigated whether there was empirical evidence that isoprene and transpiration were components of the natural atmospheric temperature control system for which we have previously provided empirical evidence[1][2].

Using the statistical hypothesis test of Granger causality as well as autoregressive distributed lag (ARDL) modelling we found generally very highly statistically significant evidence that isoprene and transpiration are components of the control system, and that they are placed in the early part of the control system chain immediately after the lead element, the global biota. Prior evidence[1][2] indicates that the information used by the control system to detect a disturbance to the setpoint of its outcome – global surface temperature – is a combination of the level of atmospheric CO_2, its integral, and its first and second derivatives. Evidence is presented that this information pattern is created in each plant that participates in the control system and is impressed on isoprene and water vapour before they are emitted from the stomata of leaves to enter the atmosphere.

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1. Introduction

Leggett and Ball[1] analysed patterns of correlations between time series of global surface temperature and atmospheric CO_2 and mathematical transformations of the atmospheric CO_2 series. The paper provided statistically significant evidence that the observed patterns were consistent with the existence of a natural feedback control system operating coherently at global scale to moderate surface temperature. Further, evidence was provided that this control system is of a sophisticated type, involving the corrective feedback not only of a linear error term but also its derivative and its integral. This is the same type as the most widely used control system developed by humans, the proportional-integral-derivative (PID) control system.

Leggett and Ball[1] provided evidence of the *functioning* of the control system. A further paper[2] then investigated the physical components that might make up the control system. Leggett and Ball[2] provided statistically significant evidence of one-way causal chains of physical components making up a physical control system consistent with that described in process terms in Leggett and Ball[1]. The later paper also provided evidence that the control system was better described as of four-term Proportional-Integral-Derivative Plus Second Order Derivative (PID+DD) type (using the terminology of Raju et al.[3]).

The present paper addresses five issues arising from the results of the above papers.

1.1. Issues addressed in this study

The present study firstly seeks to identify where the four control system signals making up the four-term (PID+DD) transformations of the linear atmospheric CO_2 time series (as identified in Leggett and Ball[2]) might physically be created. We term these transformations 'the PID+DD CO_2 information pattern'.

Secondly, we look for physical entities that might be candidates for carrying the PID+DD CO_2 information pattern to the observed actuators of the control system. In seeking to answer this question, the paper investigates whether there may be evidence for two further physical components of the control system.

Thirdly, the present paper uses the ARDL time series analysis method to seek the sign of the change associated with the causal evidence found in Leggett and Ball[2]. That paper used the Vector Autoregression (VAR) method to step through the hypothesised control system chain, one link at a time,

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reporting the presence or absence of evidence of causal links, but without identifying the sign of the change.

Fourthly, the extent of two-way causality across the control system chain, and its concentration in particular parts of the chain, is analysed.

Finally, in this study we carry out more extensive Granger causality testing to seek a further activity expected of a control system: that is, of closing the feedback loop from the outcome – global surface temperature reduction – back to the leading element – global vegetation activity.

We provide evidence that, in this study, Granger causality is likely to reflect true causality. The case for this is set out in the Supplementary Information.

Subsequent sections of this Introduction develop detailed hypotheses for each of the five issues outlined in Section 1.1.

1.2. Methodological issues relating to the study

In this section we address some broad considerations relating to the method used for the present study.

To set the scene for this, we first refer to certain definitions of the standard control system terminology utilised in Leggett and Ball[1] and Leggett and Ball[2]. In the former of these two papers we wrote:

> In a control system a controller is used to automatically adjust a controller output so as to hold the trend over time of the variable of interest (termed the process variable) at its setpoint[4]. The setpoint is the value of the preferred level for the process variable time series. A factor driving the process variable away from its setpoint is termed a disturbance. The error is defined as the difference between the level of the setpoint and the level of the disturbance.
>
> The most widely used industrial general-purpose controller uses a control-loop feedback mechanism. In this, it has been found that feeding back the derivative and the integral of the error term as well as the level of the error term gives more accurate control than simply feeding back the error term. These two extra terms reduce the problems of overshoot and undershoot of the variable being controlled. Based on the nature of the three feedback terms used, this control system is called a proportional-integral-derivative (PID) controller[5][4].

In Leggett and Ball[2] we provided statistically significant evidence that a further improvement in the statistical significance of system characterisation was gained by using a further control term reflecting the second difference of the error, making it what is termed a four-term control type – consisting of proportional, integral, derivative, and second order derivative terms (PID+DD). In man-made engineering, such systems can perform better than PID systems[6][3].

With respect to control system nomenclature for the control system chain, we wrote[2]:

> The terms used for the sequence of control system element types (for which evidence was found) are, in sequence: leading element, controller, actuator … and outcome.

The connection between two adjacent elements of the chain is termed a link.

As mentioned, the aim of Leggett and Ball[2] was to seek the physical components that might comprise the above steps. This was carried out by firstly selecting global-scale atmospheric or oceanic series that, if they showed an increase over time, would decrease global surface temperature. From these, series were selected that showed an increase. These were then tested for Granger-causal connectivity between them.

At this juncture, noting that a finding of Granger causality from A to B is in fact evidence that A predicts B not automatically evidence that A causes B (for example, Stern and Kander[7]), it is also noted that with extra information, a case can be made that Granger causal results can likely represent true causality. In the Supplementary Information we provide evidence that the Granger causality results in Leggett and Ball[2] likely represent true causality

In Leggett and Ball[2] such Granger-causal connectivity was found between many of the series consistent with their being elements of a global scale temperature control system. The specific physical components for which we found evidence as part of the control system are as follows[2]:

> The leading element of the control system, represented by the Normalized Difference Vegetation Index, is the global biosphere. The main actuators of the control system found are shown to be ocean surface wind speed and cloud cover. Cloud cover is shown to influence the final outcome, global surface temperature, directly. It and wind speed also influence what were termed penultimate outcomes, those of enhanced ocean heat uptake and enhanced outgoing longwave radiation. The actuators and penultimate outcomes together led to control system output to the final outcome, global atmospheric surface temperature.

Statistically significant empirical evidence was provided in Leggett and Ball[2] that the physical atmospheric temperature control system consisted of two parallel control system channels.

We pointed out in Leggett and Ball[2] that the paper neither attempted to nor claimed to identify all of the physical control system components or their linkages.

Two linkages in the control system chain demonstrated for mathematical processes but not shown for physical planetary components in Leggett and Ball[2] occurred in the early stages of the control system. The present paper investigates the question of whether there is evidence for physical components matching the process evidence for these two linkages.

For the first linkage, while the leading element of the control system was demonstrated to be physically present in the biota, the next step outlined in the control system process was the PID+DD CO_2 information pattern: this was demonstrated but not physically located.

The second linkage of interest occurs between the second and third steps. This links the PID+DD CO_2 information pattern to the atmospheric variables for which we provided statistically significant evidence consistent with their being actuators of the control system – land and ocean cloud cover, and wind speed at the ocean surface[2].

The control system elements referred to in the present study, then, are of two types: newly hypothesised, and therefore putative control system elements; and those for which we already have statistically significant evidence that they are control system elements[2].

The convention that we will use in this paper when referring to elements of the control system for which we have statistically significant evidence is as follows: the first time we mention such an element we will state the statistically significant evidence we have for it being a control system element; thereafter we refer to the element without reference to the statistically significant evidence for it. For example, ‘the control system actuator, land cloud cover’, would replace ‘land cloud cover, for which there is statistically significant evidence that it has a role as a control system actuator’.

This paper aims to achieve a quite simple result – a single end-to-end depiction of the control system in terms of its components. However to attain this end requires the assessment of each of more than two dozen hypothesised links between control system components. This is achieved by applying to each of these links an extensive battery of tests and checks. We therefore note that the section of the paper where this occurs involves some length and intricacy.

1.3. The physical location for the PID+DD CO_2 information pattern demonstrated for the control system

It is possible that the PID+DD CO_2 information pattern demonstrated for the control system could be a process within each participating individual organism of the biosphere. For this to be possible, there would need to be capacity for the organism to compute the CO_2 elements shown to be a part of the control system process[2]. With respect to such computational capacity, we wrote[1]:

> … the processing of information required for a control system displaying marked proportional, integral and derivative dynamics at monthly level is quite within the capability of plants. Spitzer and Sejnowski[8] argue that rather than occurring rarely, differentiation and other computational processes are present and potentially ubiquitous in living systems, including even at the single-celled level where a variety of biological processes – concatenations of chemical amplifiers and switches – can perform computations such as exponentiation, differentiation, and integration.

This is considered to provide a strong basis for hypothesising that the first two control system elements each reside in the tissue of each participating organism of the biosphere.

Using control system terminology, we hypothesise that both the leading element of the control system and the step at which the CO_2 computations take place reside in each of the organisms of the biosphere participating in the control system.

Isoprene is synthesised in the chloroplasts of plants[9]. Water evaporates into water vapour within plant leaves[10]. Both of these are subsequently emitted from plant surfaces into the atmosphere. Therefore both isoprene and water vapour are potential vectors that might carry some or all of the PID+DD CO_2 information pattern that is generated in the plant tissue into the atmosphere, and thence to control system actuators residing in the atmosphere.

1.4. Physical entities carrying the information about the observed transformations of atmospheric CO_2 to the observed actuators of the control system

As noted in Section 1.2, a second linkage for which physical planetary components had yet to be identified occurs between the PID+DD CO_2 information pattern and the observed actuators of the control system – land and ocean cloud cover, and wind speed at the surface of the ocean. The two candidate

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physical components hypothesised to link the PID+DD CO_2 information pattern to the observed actuators are the isoprene and water vapour emissions outlined in the preceding section.

1.4.1. Isoprene

There is evidence that isoprene emissions by terrestrial plants are the most significant contributor to the formation of secondary organic aerosols, which act as cloud condensation nuclei[11][12]. Cloud condensation nuclei increase both the extent of cloud cover[13] and the degree of reflectivity of those clouds[14]. Increases in each of these aspects of clouds can lead to atmospheric cooling[15].

In Leggett and Ball[2], evidence was provided for a Granger-causal link from increased cloud cover to reduced global atmospheric temperature.

Hence we have a further potential causality pathway from the observed range of mathematical transformations of atmospheric CO_2, by way of production of isoprene, to the cloud cover actuators.

This study therefore investigates whether there is Granger causality between global isoprene emissions and global extent of cloud cover. As isoprene is emitted mostly by land plants[16], a control effect could be expected to be seen mainly to the land component of the cloud cover actuator.

As mentioned in Section 1.2, there is evidence that wind speed at the ocean surface is an actuator in the causal chain for global temperature reduction[2]. Hence we also look for Granger causality between global isoprene emissions and ocean surface wind speed.

With this role requiring the transmission of information at a global scale, the question arises as to whether the distribution of isoprene in the atmosphere is sufficient to enable this.

According to Sindelarova et al.[16], the most abundant type of biogenic volatile organic compound emitted into the atmosphere is isoprene (making up 64 per cent of the total). A large proportion of isoprene emissions comes from forests, both broadleaf and conifer. The tropical and southern subtropical band is the most important source of global isoprene, with additional sources in northern temperate latitudes. Sellar et al.[17] found a similar global distribution.

With regard to distribution in the vertical air mass, there is substantial atmospheric isoprene in the mid- to upper- free troposphere (up to 11 km above the surface of the earth) in addition to that in the air directly above the earth's surface (the lower troposphere)[18].

Isoprene is produced in vastly lesser quantities over ocean than land – oceanic isoprene production is only 0.2 per cent that of land[19] and therefore is expected to occur less there[20] (although in-situ measurements are sparse).

In this paper we seek Granger-causal evidence for connections at global scale between isoprene and the atmospheric components for which there is evidence of being control system actuators – land cloud cover, ocean cloud cover, and ocean surface wind speed[2].

1.4.2. Transpiration

Evaporation of water occurs when liquid water turns into water vapour, its gaseous phase[21]. Evapotranspiration is the entirety of evaporation that occurs from the liquid water of the earth's surface into water vapour[21], with transpiration being the component of evapotranspiration that comes from water emitted to the atmosphere by plants from their aerial surfaces, such as from leaves, stems and flowers[10].

From the control system perspective, we are interested only in transpiration because by definition that is uniquely from plants[10], and therefore potentially directly under the control of the biota, where our evidence suggests the leading element of the control system resides.

The measurement of transpiration is not straightforward at global scale[22]. However, we make a case that evapotranspiration can provide an adequate empirically-based indicator of transpiration.

Most estimates conclude that transpiration makes up the largest part of evapotranspiration. Isotope observational methods have been used to estimate the percentage of total terrestrial evapotranspiration that is comprised of transpiration: from run-off-based stable isotope techniques, 80% to 90%[23]; and from hybrid stable isotope techniques, 64% ± 13%[24]. It can be seen that from both estimates, the transpiration proportion is large and hence evapotranspiration would seem to be a useful proxy indicator of transpiration.

A further issue arises, in that global evapotranspiration itself is challenging to measure[25]. Both ground measurements and those from satellites, while having strengths, also have uncertainties[26][27][22].

An alternative approach is to use proven laws to derive an estimate of evapotranspiration from other atmospheric time series that are more readily measurable than evapotranspiration.

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One such readily available derived measure of global evapotranspiration is termed ‘potential evapotranspiration’. This measure is objective and empirical: potential evapotranspiration is a concept for predicting evapotranspiration in the specific case of sufficient water being available for the health of existing plants globally[26]. How then is sufficient water available to plants worldwide?

Firstly, only a minority of global land area grossly lacks water. The proportion of area in drought at any one time is around 10 per cent[28][29]. The extent of severe plus extreme drought conditions in 2022 was found to be 15 per cent[30].

In contrast to other vegetation such as grassland, forests (which are expected from biomass estimates to be a prime part of modern Gaia[31]) have greater root depth, which allows them to better withstand the immediate impacts of drought[32]. Consistent with this, forests are estimated to comprise 64 per cent of the total of forest and grassland evapotranspiration[33].

The adequacy of potential evapotranspiration time series data in predicting evapotranspiration can be tested as follows. If the results of Granger causality analyses behave in line with the performance expected from the above literature in the present context, this would suggest the adequacy of using the series in the analyses.

Hence for the purposes of this study, we can consider the potential evapotranspiration time series to be usable as an indicator of global evapotranspiration.

1.4.2.1. Evapotranspiration and increase in global cloud cover

Global vegetation can have large negative (net cooling) effects in the global heat budget, particularly through evaporation from the tissues of plants[10], as a result of transpiration[34][35][36][37][38][39].

In looking into the mechanism, Ban-Weiss et al.[15] observed that evapotranspiration removes sensible heat by turning it into latent heat. Increased latent heat flux to the atmosphere has a local cooling influence known as ‘evaporative cooling’. However, as Ban-Weiss et al. point out, this energy will be released back to the atmosphere wherever the water condenses. That said, the above studies provide evidence that a longer lasting global cooling effect does occur by some mechanism. Using idealised climate model simulations, Ban-Weiss et al. suggest that a decrease in global mean surface air temperature of about 0.54 K can occur via this effect, largely as a consequence of planetary albedo increases associated with an increase in low elevation cloudiness caused by the increased evapotranspiration.

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This result leads to the situation where a mechanism involving a large but transitory cooling influence may lead to a large long-term effect on the heat budget not as a direct cooling influence but via reflection of fresh incoming energy away from the Earth's surface

So for the purposes of this paper, Granger causality is sought between global potential evapotranspiration and extent of global cloud cover.

A further proposed effect of evapotranspiration is that it fosters extra wind in the atmosphere. The case for this effect is outlined in the following section[40].

1.4.2.2. Evapotranspiration and ocean surface wind speed

There is evidence that condensation in the atmosphere can accelerate air movement in it –that is, increase windiness[41][42]. In what has been termed the condensation-driven theory of winds[40], regions that generate high evapotranspiration rates relative to surrounding regions develop lower-pressure zones that draw in air. This air converges, rises and cools, and moisture condenses, generating rainfall that can surpass local evapotranspiration in volume. All else being equal, the difference in mean evapotranspiration between adjacent regions predicts the wind between them. Regions with higher leaf area are thus expected to attract winds from areas with lower leaf area[41]. This relationship implies that sufficiently large areas of tree cover actively draw in air and moisture from elsewhere. This process has been termed the 'biotic pump'[40]. For the purposes of this study, we seek Granger causality between global potential evapotranspiration and global wind speed.

1.5. Hypothesis for a natural global atmospheric temperature control system investigated in this paper

Resulting from the above literature review, the hypothesis investigated in this paper has five aspects.

1.5.1. Hypothesis for the roles of isoprene and transpiration in a natural global atmospheric temperature control system

Drawing from the literature described in Section 1.4 for isoprene and transpiration, we present a hypothesis for the roles of isoprene and transpiration in a natural global atmospheric temperature control system.

The previously referenced literature showing synthesis within leaves of isoprene, and formation and marshaling within them of water vapour, may be the stages at which the PID+DD CO_2 signature is impressed on the water vapour and isoprene emissions within each leaf as they are emitted into the atmosphere.

Noting that isoprene and water vapour are prepared within a plant and emitted from the plant surface, it can be seen that what were called 'controllers' in Leggett and Ball[2] are very likely to be a process *within* each participating individual plant of the biosphere, rather than *outside* as implied in the control system flowchart in that paper.

In Section 1.4 we proposed that isoprene and transpiration could be seen as candidate controllers in the control system. These are hypothesised to potentially connect causally to the control system actuators. The further connection of actuators and outcomes is proposed to be as previously depicted in Leggett and Ball[2].

The flowchart shown in Figure 1 depicts the hypothesis for the roles of isoprene and transpiration in the global atmospheric temperature control system.

In the hypotheses for this paper, the leading element of the control system is postulated to reside somewhere in the totality of the actions of the individual plants of the vegetation of the biosphere. (We note that for the signals from such a leading element made up of the actions of individual plants to cause the action observed in Leggett and Ball[1][2] at global scale must involve global synchronisation of these actions, a topic beyond the scope of this paper.)

The computations component of the control system would also putatively occur within those individual plants. We then hypothesise that the controllers are the emissions into the atmosphere from the surfaces of the plants constituting global vegetation activity. These putatively drive the actuators, which are atmospheric processes. Penultimate outcomes (which also appear as atmospheric processes) and the final outcome (seen in temperature – an atmospheric property) are hypothesised to be the same as depicted previously in the control system flowchart derived from Leggett and Ball[2] and depicted in Figure 1.

In summary with respect to the roles of isoprene and transpiration in a natural global atmospheric temperature control system, then, the aim of this study is to investigate causal links into and from (i) global atmospheric isoprene and (ii) global atmospheric water vapour from transpiration (represented by potential evapotranspiration). If these links are found, their connection to the wider control system structure is also assessed.

We consider the possibility that the two parallel channels, for which statistically significant evidence was provided in Leggett and Ball[2], are started off by isoprene for one channel and transpiration for the other channel.

1.5.2. Direction of effect via sign of coefficient

As noted in Section 1, we use the Vector Autoregression (VAR) method to step through the hypothesised control system chain, one link at a time, reporting the presence or absence of evidence of causal links.

As well as the causal connection, it is also hypothesised that for each link of the causal chain a positive increase in the leading element of the control system is except in one case specified below followed by a positive increase in each link of the chain to the final outcome – a reduction in global surface temperature. In other words, each component of the control system is except in one case specified below positively correlated with the succeeding component.

The Autoregressive-Distributed Lag (ARDL) analysis method[43] is used to address this question. The pair of variables in each successive link in the chain must be shown by the ARDL method (except in one case specified below) to be positively correlated at an adequate level of statistical significance.

The exception to this expectation of positive correlation is for correlations involving certain expressions of the CO_2 series used in the study. For a PID-type control system, the integral and derivative terms have the role of correcting overshoot and undershoot in the response of the control system to the factor disturbing the outcome. This enables the system to carry out correction of the outcome more quickly and stably. Hence here, depending on the situation, negative or positive correlations may be seen[4].

1.5.3. Methodological rationale for steps followed in the ARDL analyses

If Granger causality between a pair of putative control system variables is achieved, we then turn to the ARDL method to seek the sign of the regression coefficient for the regression model of the relationship between the two variables to see if the sign is consistent with that hypothesised.

According to the ARDL rationale, the required regression model for this assessment must be of long-run form.

Before a long-run model for the relationship is specified, as it is a time-series model, we must first see if we can achieve a significant model with autocorrelation adequately taken into account. This is determined from the short-run form of the model.

If this is achieved, we can proceed to see if there is a statistically significant long-run model for the relationship.

This is carried out by running an ARDL Bounds Test. If the Bounds Test result is statistically significant, there is a long-run relationship between the variables.

If this is achieved, the regression output for the long-run model can be inspected for the sign of the coefficient of the regression equation.

This can then be interpreted to see if it is consistent with that hypothesised.

1.5.4. Findings adequate to provide comprehensive support for the hypothesis that there is a control system

With regard to both causal connection and direction of causal effect, we need to provide evidence that there are sufficient links to make up at least one end-to-end chain of links for each of the two control system channels proposed.

Many elements of the control system chain are components of the atmosphere. Of course, many forces act on the components of the atmosphere[21]. Nonetheless, our study design enables us to see if any particular proposed control system driver has an effect on the particular selected component of the atmosphere, no matter what other forces may also be having an effect on it.

If the direct hypothesised link in a chain is not found, plausible bypass links that could achieve control are conceived and assessed.

In conclusion, the aim of this part of the study is to seek control system-type links in the control system chain that are evidenced by (i) a Granger-causal connection between any two elements in question and (ii) in which an increase in variable A leads unless otherwise specified to an increase in variable B.

1.5.5. Closure of feedback loop expected of a control system

In Leggett and Ball[2] the focus was on (i) seeking to lay out components of the control system and their linkages end-to-end, and (ii) the evidence arising from that layout that the biosphere is the leading element of the components.

In this study we carry out more extensive Granger causality testing to seek the activity expected of a control system in closing feedback loops, in this case of causality from the outcome (temperature reduction) back to the leading element (global vegetation activity).

1.5.6. Overview of foregoing hypotheses

The whole control system, end to end, is hypothesised to involve six stages with five links (Figure 1). Each link comprises a pair of time series variables, involving a putative causal component (driver) and a putative component being driven. That causal effect, unless otherwise stated, is also postulated to involve an increased level of the driver, leading to an increased level of the driven component.

For the first link of the control system, it is hypothesised that the control system leading element, global vegetation, has a causal effect on the PID+DD CO_2 information pattern.

The next stages of the control system are hypothesised to consist of two parallel channels.

These two channels of the control system, their links, and the causal directions for the pairs of stages for each link are hypothesised to be:

Channel 1:

- Link 2: the PID+DD CO_2 information pattern causal to isoprene
- Link 3: isoprene to cloud cover
- Link 4: cloud cover to outgoing longwave radiation
- Link 5: outgoing longwave radiation to global surface temperature reduction

Channel 2:

- Link 2: the PID+DD CO_2 information causal to transpiration (indicated by potential evapotranspiration).
- Link 3: transpiration to ocean surface wind speed
- Link 4: ocean surface wind speed to ocean heat uptake
- Link 5: ocean heat uptake to global surface temperature reduction

The final link involves global surface temperature reduction completing the feedback loop by having a causal effect on global vegetation activity.

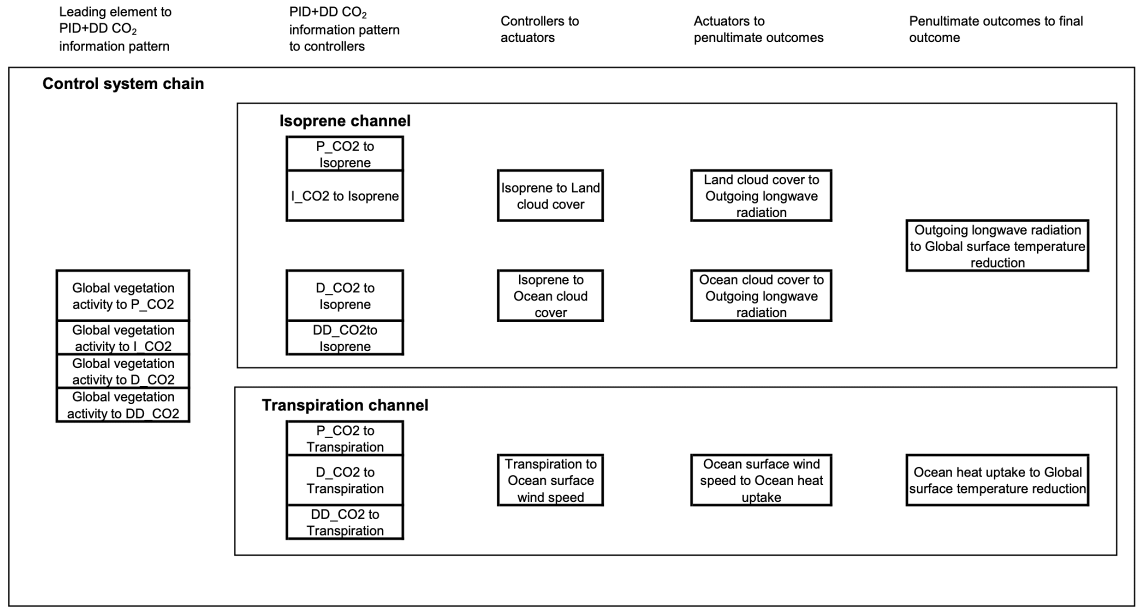

Figure 1. Diagrammatic representation of hypotheses to be tested – flow chart of links in the control system chain hypothesised to display both causality and positive correlation between pairs of variables (links) in the control chain

1.5.7. One- and two-way causality

We now discuss instances where causality may be two-way, rather than one-way as previously conceived for the control system in Leggett and Ball[2]. Here the control system was reported to involve statistically significant one-way Granger causality across each link of the hypothesised control system sequence.

The present paper investigates the possibility that (at least some) causality could be two-way. Regarding the implications for two-way causality in a control system, Cakmakci and Ulsoy[44] write:

> Components of a feedback control system, usually one per feedback loop, are controllers (i.e., the "brains"), actuators (i.e., the "brawn"), sensors (i.e., the "senses"), and the controlled system, or plant. Traditionally, the actuator and sensor are considered "brainless" devices...

From the perspective of our terminology, the separate 'leading element' and 'controller' components are part of the single controller component as outlined by Cakmakci and Ulsoy.

Cakmakci and Ulsoy[44] describe subsidiary control systems termed ‘smart’ components being nested within an overall control system outside the controller. One feature of this type of smart component is that it can communicate bidirectionally.

Cakmakci and Ulsoy[44] wrote that a networked controller system design with bidirectional communication showed significant improvements in performance compared with the traditional unidirectional feedback-loop design. It was considered that the improved control system performance was due to the decentralised, yet more connected, nature of these systems.

As a result, and from the point of view of our conception of the global atmospheric temperature control system, we consider that if some of the causal linkages are two-way, rather than one-way, it is not necessarily evidence against the hypothesis.

Therefore the hypothesis from Leggett and Ball[2] that ‘A to B control-only must be present’ is amended to be that ‘A to B control must be present, but the presence of B to A control is not of itself contrary to the hypothesis’.

In concluding this Introduction, we wish to stress that our evidence that an atmospheric temperature control system is likely to exist does not rely on the findings of the present paper. From the point of view of the present predominant view of mechanism[45], control in system behaviour can be detected even if we do not have insight into the entities and activities by which that control is achieved. In terms of this view, adequate evidence based on system performance alone that an atmospheric temperature control system exists was provided by Leggett and Ball[1].

Multiple further lines of empirical evidence consistent with the above were brought together in Leggett and Ball[46].

Evidence about some of the entities and activities by which control is achieved were provided in Leggett and Ball[2],

2. Methods

Statistical methods used are standard[47] and generally as described and previously used in Leggett and Ball[48][49][1][2]. Categories of methods used are: normalisation; differentiation (approximated by differencing); integration (approximated by the cumulative sum); and time-series analysis. Within time-series analysis, methods used are: Z-scoring; smoothing; testing for the order of integration of each series (a prerequisite for using data series in time-series analysis); Vector Autoregression (VAR) modelling to enable Granger causality testing between each hypothesised pair of control system elements; and Auto Regressive Distributed Lag (ARDL) time series modelling to enable determination of the sign of the regression relationship between the hypothesised pair of control system elements.

As mentioned in Section 1.2, noting that a finding of Granger causality from A to B is in fact evidence that A *predicts* B not automatically evidence that A causes B it is also noted that with extra information, a case can be made that Granger causal results can likely represent true causality. In the Supplementary Information we provide such evidence that the Granger causality results in Leggett and Ball[2] likely represent true causality.

Full methods are given in Leggett and Ball[48][49][1][2], and in the on-line Supplementary Information Section 1.

2.1. Interpretation of the set of Granger causality and ARDL results for any given proposed linkage

The control system as hypothesised in the present paper is comprised of about 20 linkages (Figure 1). To assess each proposed linkage for a result fully in line with the hypothesis requires as described above the use of two separate statistical methods – the VAR method for Granger causality assessment, and the ARDL method for the required determination of the sign of the regression coefficient of the relationship in question. For the VAR result to support the hypothesis, three separate tests must each meet a threshold; and for the ARDL result, four separate tests. This makes a total of seven tests being required for each linkage to address the hypothesis.

Given this number of tests, we believe that it is reasonable to assert that, if most but not all of the seven tests for a particular linkage fell the hypothesised way, our knowledge would have still advanced. More substantively, even if a large majority but not quite all of the 140 or so tests for the full hypothesised control system are passed, we believe that the overall hypothesis can still be considered to be supported.

With respect to statistical significance, we use the standard cut-off point of a probability of occurrence being due to chance occurring once in 20 times or less (p = 0.05).

In our study, if six of the tests of a linkage were statistically significant at the 0.05 level or better, and the remaining seventh result was near significance but outside the 0.05 level, that seventh result is reported as further support for the hypothesis for that link.

All series are expressed such that a positive control action by the control system leading element leads to further positive changes in control series step-by-step down the chain leading to the final outcome, global surface temperature reduction. The exception is for the I_, D_ and DD_CO_2 terms. These may be positive or negative as they are corrective to the P term effect, providing a more rapid settle time after a control action, reducing over- and under-shoot[4].

2.2. Data

For global surface temperature, we use the Hadley Centre–Climate Research Unit combined Landsat and SST monthly surface temperature series (HadCRUT) version 4.6.0.0[50]. In the paper, this series is termed 'global surface temperature'.

For atmospheric CO_2 data from 1958 to the present, we use monthly data from the CO_2 series produced by the US Department of Commerce National Oceanic and Atmospheric Administration Earth System Research Laboratory Global Monitoring Division Mauna Loa, Hawaii[51]. In the paper, this series is termed 'CO_2'.

For atmospheric CO_2 data from 1600 to the present we use a composite series prepared by KNMI Climate Explorer from data from the Law Dome Antarctica ice cores[52] and the Mauna Loa Observatory, Hawaii[51].

For global vegetation activity, we use the Normalized Difference Vegetation Index (NDVI)[53]. Monthly NDVI data is from the spatiotemporally consistent global dataset of the GIMMS Normalized Difference Vegetation Index (PKU GIMMS NDVI) from 1982 to 2022[54]. (Data series kindly provided by Dr Li, personal communication, 2024). In the paper, this series is termed 'global vegetation activity'.

Global monthly data for atmospheric isoprene is from the MEGAN-MACC inventory[55][16]. The data included are for the period of 1980-2022. (Data series kindly provided by Dr Sindelarova, personal communication, 2024). In the paper, this series is termed 'isoprene'.

Global monthly data for evapotranspiration is from the ERA5 global climate data reanalysis project. (The series produced are fully empirical. Reanalysis here means primarily that any missing data is estimated using standardised agreed processes[21]). The specific data series used is entitled ERA5 potential evaporation[56]. In the paper, this series is termed 'evapotranspiration'.

Two cloud cover data sets are used – ocean cloud and land cloud. The monthly cloud cover data set used for ocean cloud is the Cloudiness Monthly Mean at Surface ICOADS v2.5 cloud cover[57]. The monthly land cover data set used is the CRUTS 4.03 (land) series[58]. In the paper, these series are termed 'ocean cloud cover' and 'land cloud cover'.

Ocean surface wind speed data comes from the monthly global ICOADS v2.5 wind speed (Variable wind speed – Scalar Wind Monthly Mean at Surface – in m/s)[57]. In the paper, this series is termed 'ocean surface wind speed'.

Net ecosystem productivity data published in Sellar et al.,[17] was kindly provided by Dr Sellar (personal communication, 2024). In the paper, this series is termed 'net ecosystem productivity'.

Outgoing longwave radiation monthly data was accessed from Climate Explorer[59]. In the paper, this series is termed 'outgoing longwave radiation'.

As in Leggett and Ball[2], in the present study the data series entitled 'Ocean heat from surface to 700 metres'[60] is used to indicate ocean heat uptake. Quarterly data is used as it is the highest frequency data available. In the paper, this series is termed 'ocean heat uptake'.

3. Results

The first results presented are of (i) trends in the earth system components for which there is evidence of their being components of a global temperature control system, or (ii) new putative control system components investigated in this study, and (iii) the measure used for the outcome of the control system[2]. This is done in the context of trend types expected for a control system undergoing a disturbance.

Following that, for each proposed control system link we present the results of an assessment of causality across the link together with the direction of the control system effect across the link.

3.1. Nature of trends in data series used in the study in the context of that expected for a control system undergoing a disturbance

A control system that is experiencing disturbance should increase the activity of its components to resist the disturbance. There is strong evidence that a major indicator of a disturbance to a steady global surface temperature is a changed level of atmospheric CO_2 because that is a major source of the greenhouse effect[21].

Leggett and Ball[1][2] provided evidence that, given that atmospheric CO_2 produces the greenhouse effect, it would be unsurprising if a global temperature control system used the level of atmospheric CO_2 as an indicator of the disturbance being experienced.

Adopting this argument, the level of disturbance of the system over time is displayed in Figure 2, which shows the trend in Law Dome Ice Core CO_2 from 1 CE to 2001 CE[61].

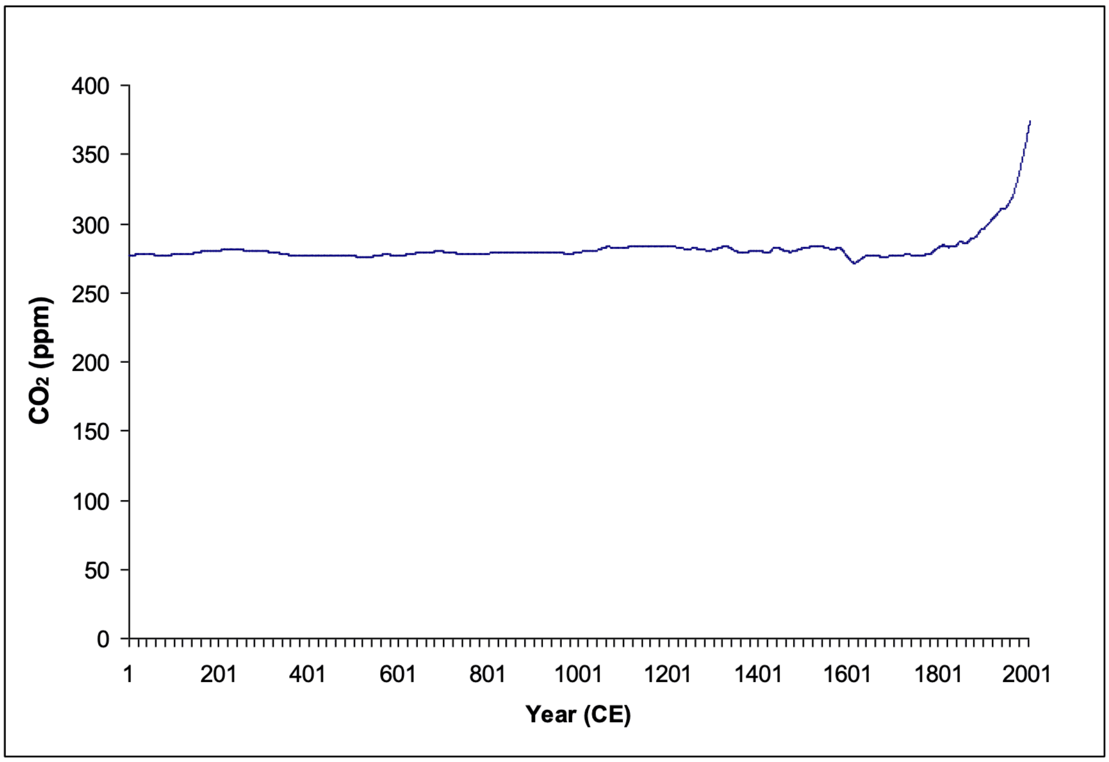

Figure 2. Trend in CO_2 in parts per million from 1 CE to 2001 CE: Law Dome Ice Core (Annual data; 20-year spline-smoothed)

The figure shows that from a 2000-year perspective, the control system can be seen as presently experiencing a sudden – almost square wave – shock. Under this level of disturbance, there is a strong possibility that some components of the control system may well have been overwhelmed and not work as intended.

Focusing on the more recent period, Figure 3 shows the level of atmospheric CO_2 since 1600[52].

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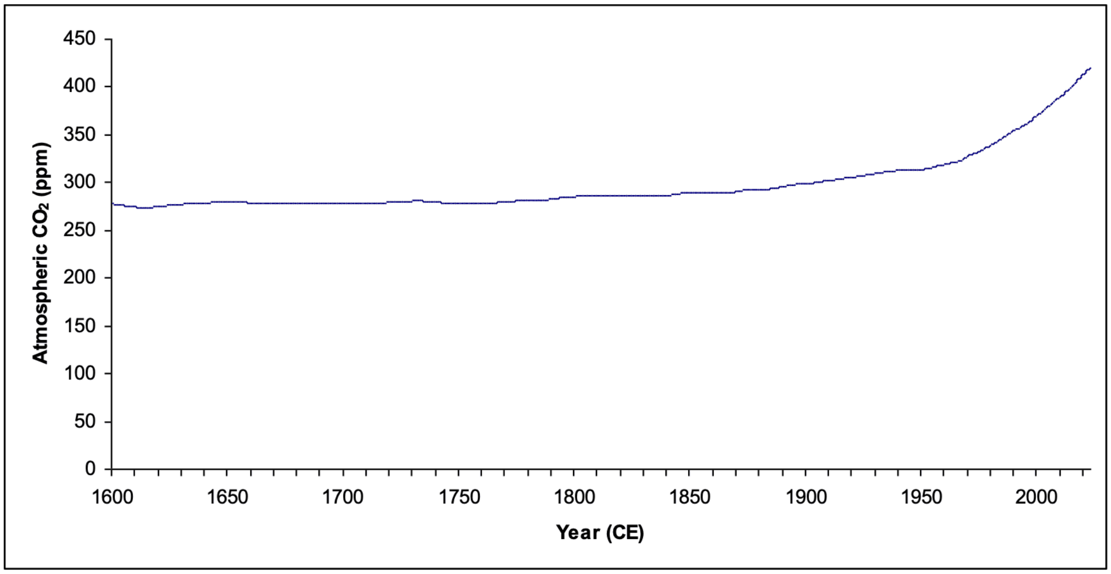

Figure 3. Level of atmospheric CO_2 in parts per million from 1600 to 2023: annual data

Figure 3 shows that little or no change in trend in CO_2 (and therefore disturbance) occurred from 1600 to 1750. A slightly rising trend is seen from 1800 to 1955, with a notably more marked increasing trend in CO_2 occurring after 1955. Hence the components of a global temperature control system might be expected to increase in activity after 1955, thus reducing global surface temperature compared with what might be expected in the absence of a control system.

The next two series depicted are those for two specific candidates for control system components – global vegetation activity (represented by the Normalized Difference Vegetation Index (NDVI)) and isoprene. These are selected because data for these series have been recorded only since 1979, when satellites became available to take measurements, and hence these are the shortest series used. The two series, in annual form, are shown in Figure 4.

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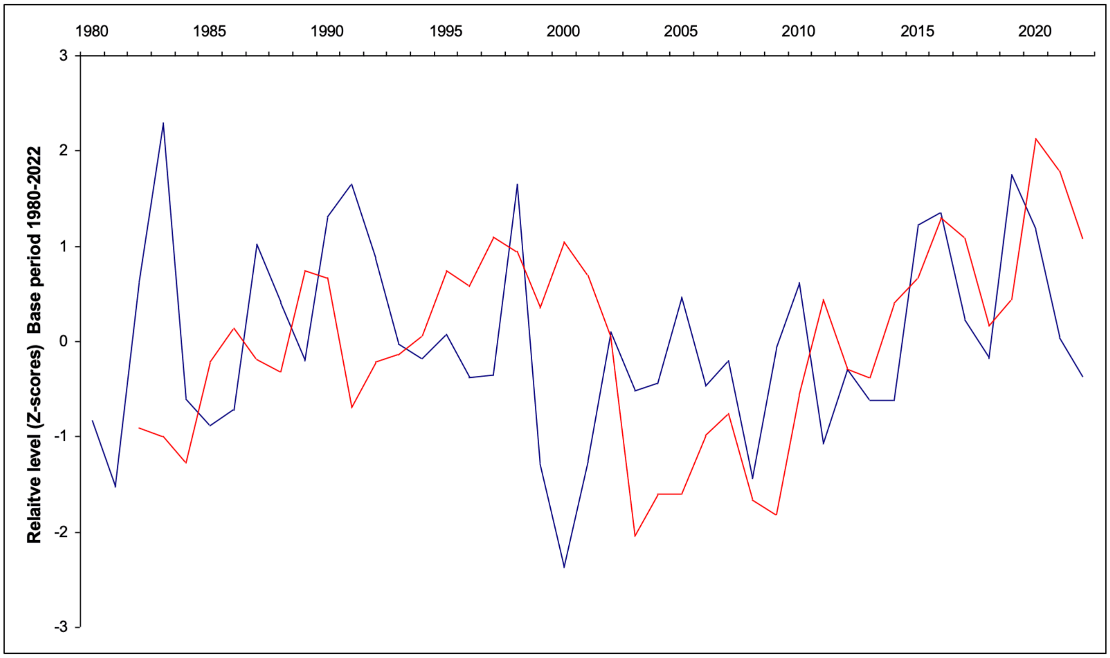

Figure 4. Global atmospheric isoprene (blue curve) and global Normalized Difference Vegetation Index (NDVI) (red curve) (Annual data; Z-scored, using the base period shown in the figure)

It can be seen from Figure 4 that neither series displays a marked net trend over the period depicted.

Vegetation indices such as NDVI are closely correlated with measures such as terrestrial ecosystem gross primary production[62], and gross primary production-related data is available prior to the satellite measurement era.

Figure 5 depicts the isoprene and NDVI series as displayed in Figure 4 together with a gross primary production-related series. All primary productivity measures (gross primary productivity (GPP), net primary productivity (NPP), and net ecosystem productivity (NEP)) show similar trends[17]. NEP is depicted in the graph.

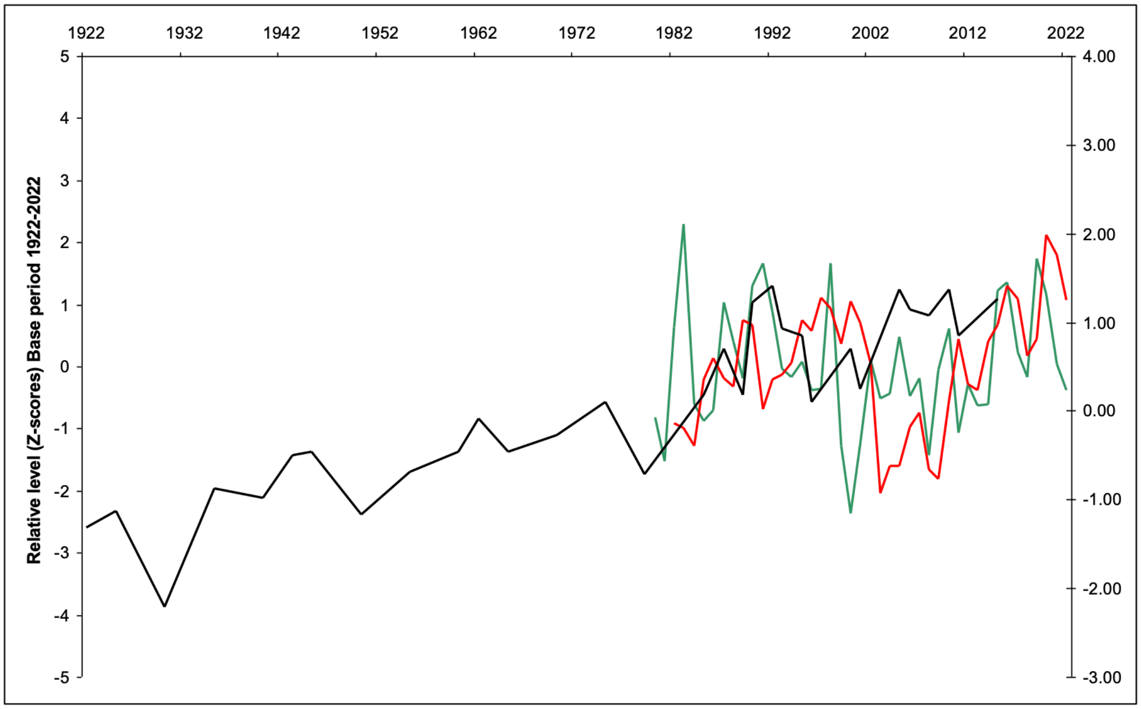

Figure 5. Global atmospheric isoprene (green curve); global Normalized Difference Vegetation Index (NDVI) (red curve) and NEP (black curve) (Annual data; Z-scored, using the base period shown in the figure)

It can be seen from Figure 5 that the NEP shows a similar leveling off to that of NDVI and atmospheric isoprene since around 1990. But as with the CO_2 series in Figure 3, the NEP is markedly higher since 1970 than in the period prior, starting in 1922.

From the above, we can conclude that vegetation activity and isoprene levels experienced on the planet have shown somewhat related signatures over the longer period, and may well be at higher levels now than prior to1970.

3.1.1. Trend in global surface temperature reduction

The outcome measure used for the control system, global surface temperature reduction, is the difference between the temperature expected from the observed trend in atmospheric CO_2[21] and the observed temperature[49].

These expected and observed temperatures are shown in Figure 6 (using normalised data), and the difference between them, the trend in global surface temperature reduction, is shown in Figure 7.

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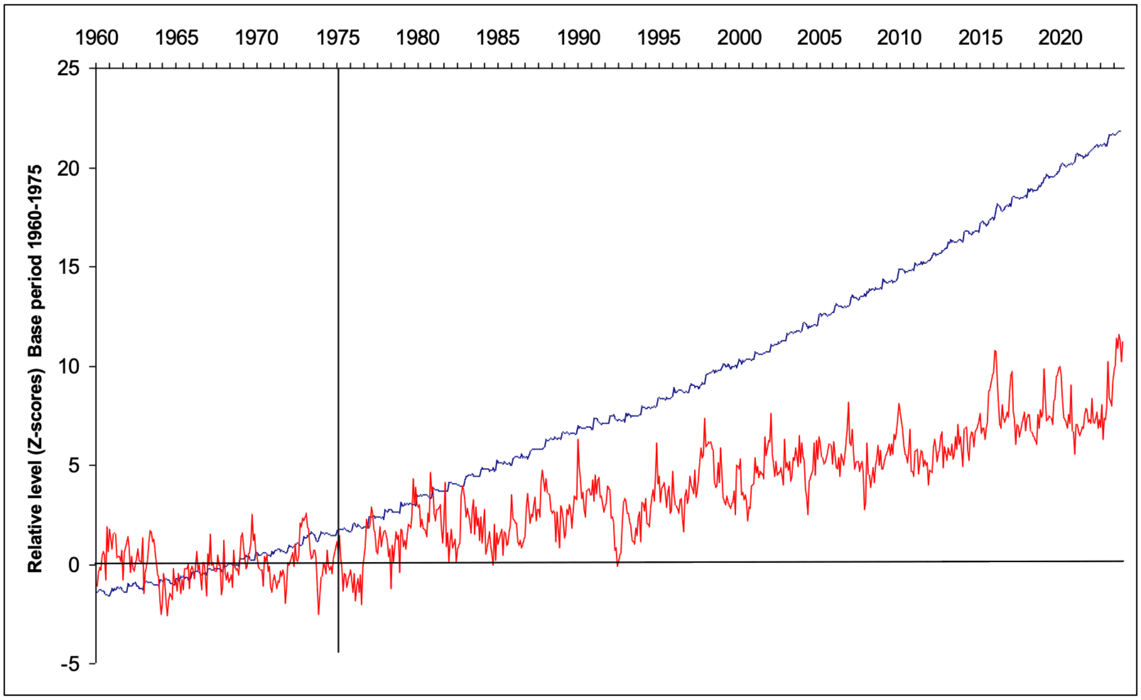

Figure 6. Trend in atmospheric CO_2 from Mauna Loa Observatory (blue curve) and global atmospheric surface temperature (red curve). (Monthly data; Z-scored, using the base period shown in the figure)

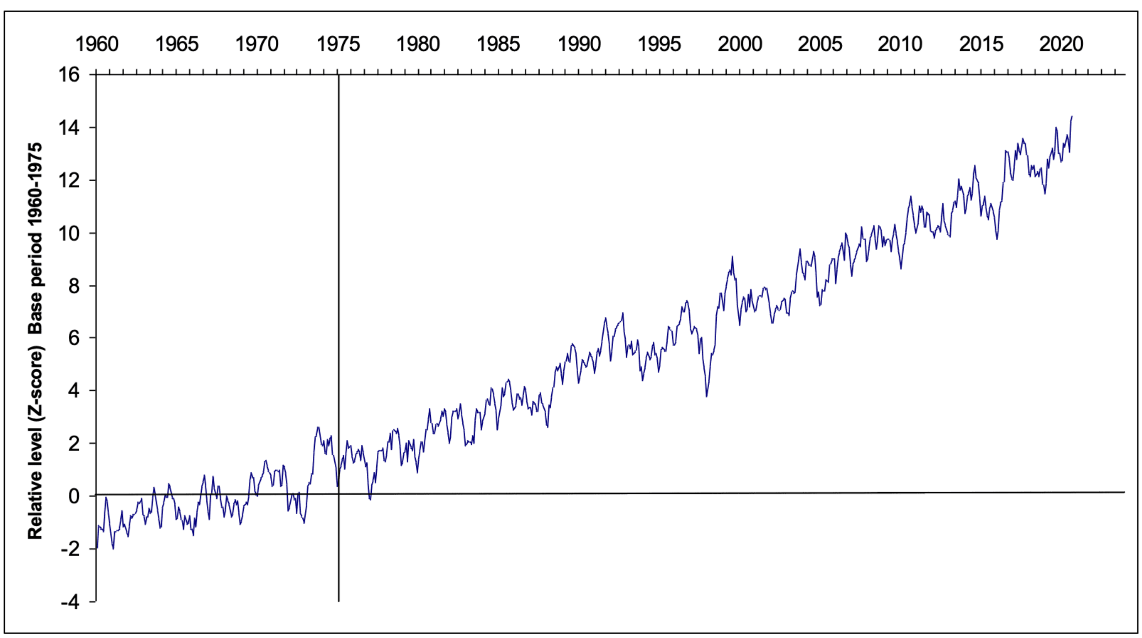

Figure 7. Trend in global surface temperature reduction (Monthly data; Z-scored, using the base period shown in the figure)

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These two figures taken together reveal a steadily increasing trend in global surface temperature reduction over the period under consideration.

3.1.2. Trends in control system components

The trends in the control system components for which there is evidence[2], the putative new control system components, and the final outcome are compared side-by-side. Because of the number of series in this comparison, for clarity they are presented in two figures (Figure 8 and Figure 9).

All series should rise over time as postulated by the control system hypothesis.

To enable this assessment, all series are Z-scored over the period from 1960 to 1975 to create a baseline level. Hence any increase in the subsequent period is seen as a rise above the baseline.

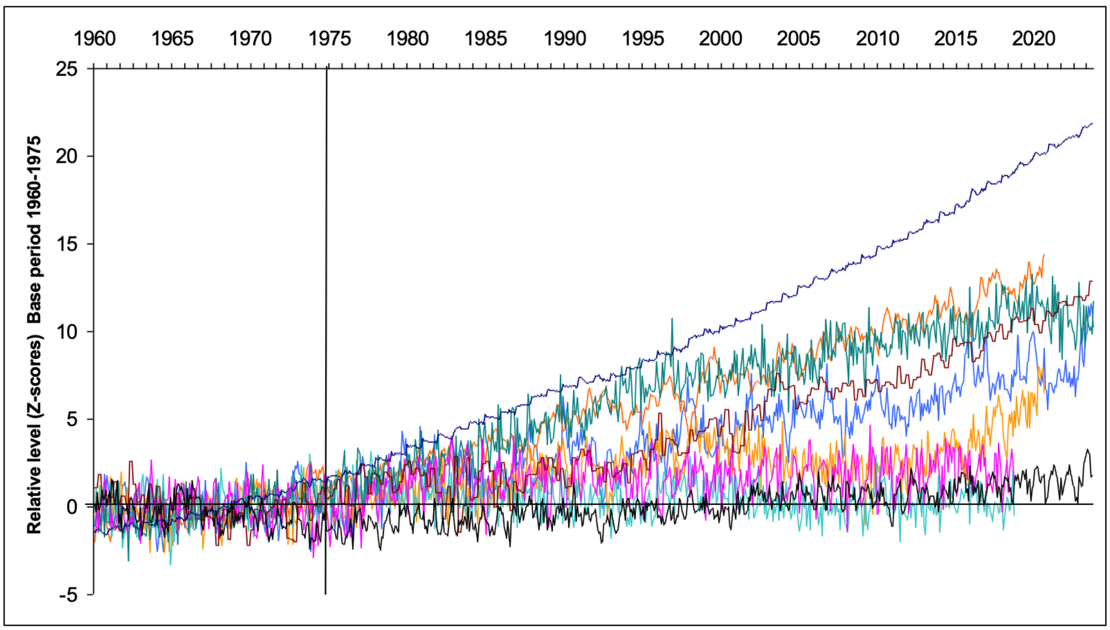

Figure 8. Relative trends in atmospheric CO_2 (dark blue curve); ocean surface wind speed (teal curve); global surface temperature (light blue curve); ocean cloud cover (light orange curve); land cloud cover (aqua curve); potential evapotranspiration (black curve); ocean heat uptake (brown curve); outgoing longwave radiation (purple curve); temperature reduction from control system (orange curve) (Monthly data; Z-scored, using the base period shown in the figure)

Figure 8 shows that, to varying degrees, the relative level of each series is greater after 1975 than before, with no series being lower.

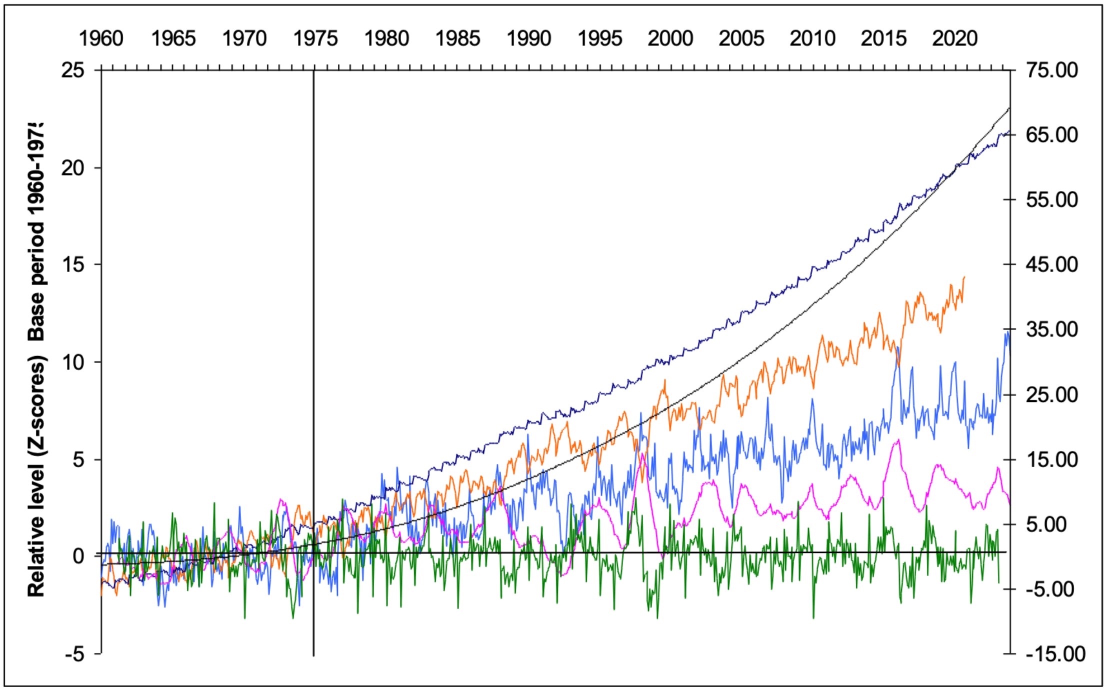

Figure 9. Relative trends in level of atmospheric CO_2 (dark blue curve); integral of CO_2 (black curve); first difference CO_2 (purple curve); second difference CO_2 (green curve); global surface temperature (light blue curve); temperature reduction from control system (orange curve) (Monthly data; Z-scored, using the base period shown in the figure)

Figure 9 shows that all series with the exception of second difference CO_2 show rising trends over the period. Second-difference CO_2 shows no trend.

Figures 8 and 9 together show that the candidate control system components all show trends over the period as hypothesised.

We note that the rising trends shown in Figures 8 and 9 may have been induced solely by the rising temperature occurring over the period. This does not create a problem for the control system hypothesis. Granger causality methods will clearly show whether there is causality between pairs of proposed control system components, but the hypothesis does not require that there be no other sources of causality affecting individual series.

In conclusion, all of the control system component series plotted in Figures 8 and 9 show increased activity after 1975, consistent with what is expected from elements of a temperature control system under increased disturbance.

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A case can be made that this increased control system activity has been successful: Leggett and Ball[1] (Figures 1 and 4) showed that since 1975 a lower global surface temperature has been measured than would be expected from the rise in levels of atmospheric CO_2 over the same period.

Granger causality analysis is used to seek information contained in a putative driver series that is reflected in the recipient series. In this connection we note that causality can be found between series other than those that display a trend.

In the study, NDVI and isoprene series are used undeseasonalised to maximise the high definition information available for use in analysis (see Figures 10 and 11).

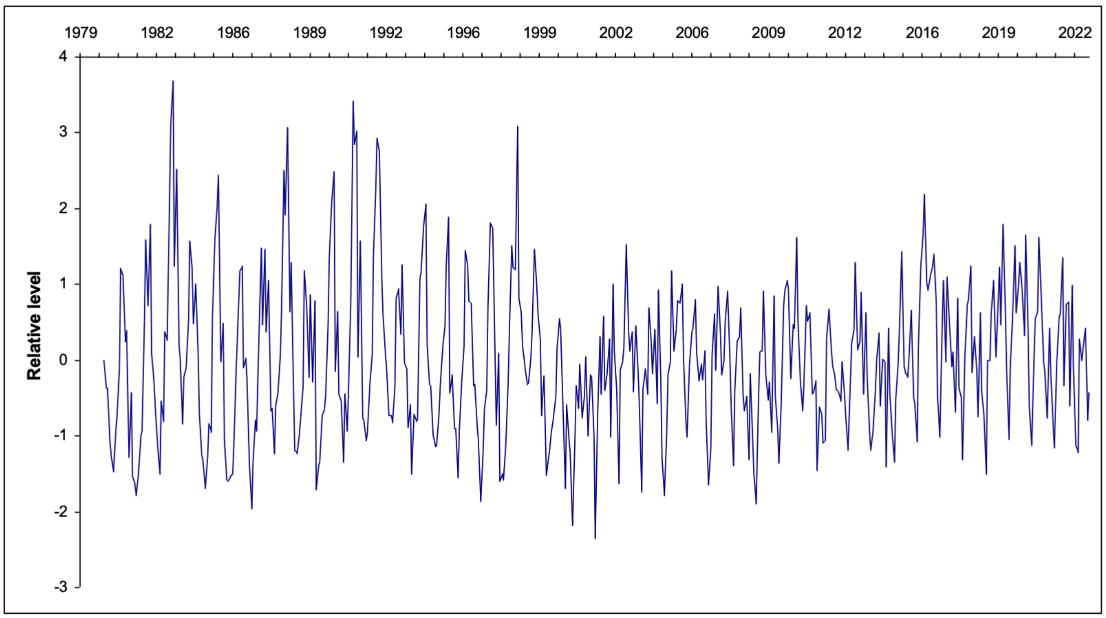

Figure 10. Trend in global atmospheric isoprene: monthly data

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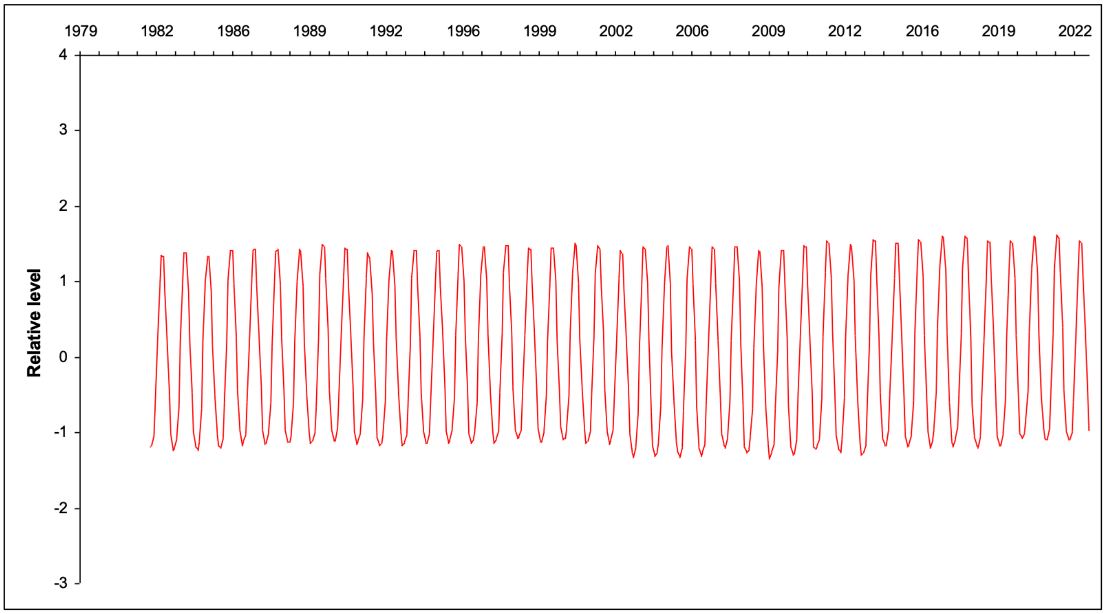

Figure 11. Trend in global Normalized Difference Vegetation Index (NDVI): monthly data

Despite the strong seasonal signals present for each series, and particularly for the NDVI series, non-seasonal modulations can also be seen.

The following sections use the control system component series to conduct two types of analysis. The first is to seek causal connectivity by means of Granger causality analysis.

The series for control system components either for which there is evidence[2] or putative control system components proposed in this paper are used in the assessments, which seek possible causal linkages between such control system components and also to the control system final outcome of global surface temperature reduction.

The hypothesis for the control system also proposes that except for the I_, D_ and DD_CO_2 terms, a positive control action by the control system leading element leads to further positive changes along the chain in the control system to the final outcome. This question is assessed by a second type of analysis, ARDL analysis.

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3.2. Control system linkages: link-by-link assessment of causality and direction of effect of control system elements

3.2.1. Aim of section

This section aims to see if there is statistically significant evidence for the end-to-end pathways hypothesised to be present in the global atmospheric temperature control system.

3.2.2. Presentation of results on control system linkages

From the hypothesis laid out in Section 1.5.6 it can be seen that for each linkage assessed between a given pair of control system elements, we seek only two pieces of simple information: the existence or otherwise of Granger causality between the pair of elements – at least from the element of the pair temporally earlier the chain to that next in the chain; and the sign of the regression coefficient of the relation between them – generally sought to be positive by the control system hypotheses being proposed.

In reporting from the extensive output of our Granger causality and ARDL analyses available, there is, as Clarke and Mirza[63] note "...a challenge to present the results from our extensive set of experiments in a way that is both compact and useful. The usual tabular approach, aside from taking up (many) pages, does not allow much information to be conveyed or assimilated. Accordingly, we use ... methods that communicate the relevant information compactly (and in a form) to be easily noted."

We adopt a similar practice: Tables 1 to 4 present for each pair of variables assessed the core results of the Granger causality and ARDL analyses. These are for Granger causality the statistical significance and direction of causality (if found) and for the ARDL analysis the significance and sign of the regression coefficient for the RD long-run relationship.

Extended results for each pair of variables, and relevant commentary, are set out in the Supplementary Information to the paper.

Tables 1 to 4 present results by row in the order outlined in the hypothesised structure of the control system (Section 1.5).

As described in Section 1.2, the elements from left to right in the control system chain are grouped in pairs into links. Analyses are reported one link at a time. Each analysis of a link involves both a Granger causality analysis and then an ARDL analysis. The Granger causality analysis seeks causality between the variables of the link, and the ARDL analysis seeks the directionality of the effect of any correlation found between the variables making up the link.

The following tables show results of assessments using groups (generally pairs) of time series variables. These variables fall into two classes: the first is series for which statistically significant evidence was provided in Leggett and Ball[2] of a causal linkage in a way supportive of a global atmospheric temperature control system; the second is new candidate series that are being investigated.

Results presented in this paper are of new analyses, even if the variables were present and analysed in Leggett and Ball[2], because longer time series are now available, potentially leading to clearer results for the relationships.

3.2.3. Granger causality and ARDL results for hypothesised links in the control system chain

The results in Tables 1 to 4 step sequentially through the hypothesised links as depicted above in Section 1.5.5.

Recalling that the purpose of this section is to determine those linkages that fit the hypothesis, the convention used in the analysis of Tables 1 to 4 is: links fitting the hypothesis are indicated by unhighlighted cells and further aspects of these results are presented in the Discussion: results which do not fit the hypothesis are highlighted in grey and are discussed on a case by case basis in this section of the paper, and further in the Discussion.

Table 1 provides the results of an assessment of Granger causality together with the sign of the coefficient of the associated regression equation for the hypothesised first link of the control system: global vegetation activity to the PID+DD CO_2 information pattern.

Row	Variable A	Variable B	Probability that relationship not Granger causal		ARDL short-run relationship	ARDL long-run relationship	
			Causality A to B	Causality B to A	Statistical significance of relationship (from F-statistic)	Statistical significance of relationship (from F-statistic for the Bounds Test)	Sign of coefficient of equation for relationship
1	Global vegetation activity	P_CO2	**3.42E-09**	**2.53E-09**	p<0.0001	p<.01	Positive
2	Global vegetation activity	I_CO2	**0.044**	**8.44E-29**	p<0.0001	p<.01	Negative
3	Global vegetation activity	D_CO2	**6.24E-10**	**3.20E-09**	p<0.0001	p<.01	Positive
4	Global vegetation activity	DD_CO2	**8.66E-12**	**0.0329**	p<0.0001	p<.01	Negative

Table 1. Granger causality and sign of coefficient of equation for relationship for hypothesised first link of the control system: global vegetation activity to the PID+DD CO_2 information pattern

The set of results in Table 1 shows the minimum requirements to meet the hypothesis for this stage of the control system: at least A to B causality, and statistically significant ARDL regression equations, with the Global vegetation activity to P_CO2 coefficient being positive.

The ARDL regression coefficient value for Global vegetation activity and P_CO2 is positive, supporting the hypothesis that this link is operating as expected for this part of the control system, with increased

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Global vegetation activity leading to an increased P_CO2 signal.

As well as A to B causality, all rows in Table 1 also show B to A causality. As discussed in Section 1.5.2, from the point of view of our conception of the global atmospheric temperature control system, some causal linkages in an advanced control system may be two-way, and this may be the case in this instance.

The remaining rows of Table 1, involving I_CO2, D_CO2 and DD_CO2, show varying signs for their regression coefficients. As mentioned above in Section 1.5.2, this is not unexpected for a PID-type control system.

As described in Section 1.5.1, the two parallel channels of the control system for which evidence was provided in Leggett and Ball[2] are hypothesised in this paper to commence for one channel with isoprene, and the other with water vapour from transpiration.

All series are expressed such that a positive control action by the leading element of the control system leads to further positive changes in control series step-by-step down the chain leading to the final outcome, global surface temperature reduction.

The exception is for the I_CO_2, D_CO_2 and DD_CO_2 terms in the first step of each of the parallel channels. These terms may be either positive or negative at any given time as they are corrective to the P term effect, providing a more rapid settle time after a control action, by reducing over- and under-shoot[4].

In the following sections, assessment of the isoprene channel will be taken in the sequence hypothesised from isoprene to cloud cover to outgoing longwave radiation through to the final outcome of the control system, global surface temperature reduction.

Rows 1 to 4 of Table 2 provide the results of the assessment of Granger causality and the sign of the coefficient of the associated regression equation for the candidate control system link of the isoprene channel involving the PID+DD CO_2 information pattern and isoprene.

Row	Variable A	Variable B	Probability that relationship not Granger causal		ARDL short-run relationship	ARDL long-run relationship	
			Causality A to B	Causality B to A	Statistical significance of relationship (from F-statistic)	Statistical significance of relationship (from F-statistic for the Bounds Test)	Sign of coefficient of equation for relationship
1	P_CO2	Isoprene	**0.0066**	**2.88E-13**	p<0.0001	p<.01	Positive
2	I_CO2	Isoprene	**0.0208**	**7.69E-07**	p<0.0001	p<.01	Positive
3	D_CO2	Isoprene	**0.000013**	**0.0001**	p<0.0001	p>.1	n.a.
4	DD_CO2	Isoprene	**0.0237**	**6.85E-07**	p<0.0001	.01< p<.025	Positive
5	Isoprene	Land cloud cover	**0.0195**	**0.0021**	p<0.0001	p<.01	Positive
6	Isoprene	Ocean cloud cover	**0.0338**	*0.5153*	p<0.0001	p >.1	n.a.
7	Land cloud cover	Ocean cloud cover	**0.0006**	*0.9566*	p<0.0001	.01<p<.025	Positive
8	Land cloud cover	Outgoing longwave radiation	**0.0047**	*0.1703*	p<0.0001	p<.01	Positive
9	Ocean cloud cover	Outgoing longwave radiation	**0.0265**	*0.239*	p<0.0001	p<.01	Positive
10	Outgoing longwave radiation	Global surface temperature reduction	**6.80E-12**	**7.20E-08**	p<0.0001	p<.01	Positive

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Table 2. Granger causality and sign of coefficient of equation for relationship for each hypothesised component of the Isoprene channel of the global atmospheric temperature control system

With two exceptions at first glance, a substantial majority of results in Table 2 – 8 of the 10 rows – show the minimum requirements to meet the hypothesis for this stage of the control system: at least A to B causality, and statistically significant ARDL regression equations, with the Global vegetation activity to P_CO2 coefficient being positive.

Rows 1 to 4 of Table 2 assess the hypothesised link of the control system of global vegetation activity from the PID+DD CO_2 information pattern to Isoprene. All of rows 1 to 4 fit the hypothesis except for row 3, D_CO2 to isoprene. The bounds test result for D_CO2 to isoprene is not statistically significant, showing no evidence for a long-run relationship between the variables. Hence the other statistics reported in row 3 of the table should be disregarded in this instance.

The other exception involves the relationship between isoprene and ocean cloud cover.

As isoprene is predominantly emitted over land (with only 0.2 per cent arising from ocean sources[19]), it would not be expected that isoprene would drive ocean cloud cover.

It is therefore perhaps surprising that row 6 of Table 2 shows that one-way causality is seen from Isoprene to Ocean cloud cover.

The bounds test result in row 6 is statistically significant, showing that there is a long-run relationship between the variables. The coefficient value is positive, in line with the hypothesis. The *p*-value result, however, shows that the long-run relationship is not statistically significant at the 0.05 level (note that the results in row 6 of Table 2 are the best fit found after an extensive search of the lag space, as recommended by Thornton and Batten[64]). That said, the *p*-value result is only slightly larger than the 0.1 level of statistical significance. Given that all the other results for Isoprene to Ocean cloud cover are in line with the hypothesis, it is plausible that row 6 could be seen as being in line with the hypothesis overall.

There is also another possible way for isoprene information to pass to ocean cloud cover – via land cloud cover.

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For the candidate control system elements of land cloud cover and ocean cloud cover, row 7 of Table 2 shows that Granger causality of one-way form is shown between land cloud cover and ocean cloud cover and that the correlation between the two is positive.

Hence we can consider that, by one and possibly two pathways, isoprene control system activity is seen in both land and sea cloud cover. This is of relevance both of itself and also when it comes to considering the effects of the putative land and sea cloud cover control system actuators on outgoing longwave radiation.

Table 3 deals with the hypothesised second parallel channel of the control system, involving global transpiration.

For reasons given in the Introduction, we use global evapotranspiration as the indicator for transpiration, and potential evapotranspiration as the indicator for evapotranspiration.

In the following sections, assessment of the transpiration channel will be taken step by step from the PID+DD CO_2 information pattern to potential evapotranspiration to land cloud cover, ocean cloud cover, and ocean surface wind speed, then to ocean heat uptake and to global surface temperature reduction.

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Row	Variable A	Variable B	Probability that relationship not Granger causal		ARDL short-run relationship	ARDL long-run relationship	
			Causality A to B	Causality B to A	Statistical significance of relationship (from F-statistic)	Statistical significance of relationship (from F-statistic for the Bounds Test)	Sign of coefficient of equation for relationship
1	P_CO2	Potential evapo-transpiration	**0.0207**	*0.2302*	p<0.0001	p<.01	Positive
2	I_CO2	Potential evapo-transpiration	*0.6305*	**0.002**	p<0.0001	p<.01	Negative
3	D_CO2	Potential evapo-transpiration	**0.0267**	*0.8543*	p<0.0001	p<.01	Positive
4	DD_CO2	Potential evapo-transpiration	**0.0095**	*0.7735*	p<0.0001	p<.01	Positive
5	Potential evapo-transpiration	Land cloud cover	**0.0213**	**0.0011**	p<0.0001	p<.01	Negative
6	Potential evapo-transpiration	Ocean cloud cover	*0.4548*	*0.4983*	*n.a.*	*n.a.*	n.a.
7	Potential evapo-transpiration	Ocean surface wind speed	**0.0082**	*0.3375*	p<0.0001	05<p<.1	Positive

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8	Ocean cloud cover	Ocean surface wind speed	**0.0275**	*0.2022*	p<0.0001	.01<p<.025	n.a.
9	Land cloud cover	Ocean surface wind speed	**0.0256**	*0.7533*	p<0.0001	p>.25	Positive
10	Ocean surface wind speed	Ocean heat uptake	**0.0029**	*0.1377*	p<0.0001	p<.01	Positive
11	Ocean heat uptake	Global surface temperature reduction	**0.0039**	*0.3429*	p<0.0001	p<.01	Positive

Table 3. Granger causality and sign of coefficient of equation for relationship for each hypothesised component of the Evapotranspiration channel of the global atmospheric temperature control system

Of the results in Table 3, the majority – 8 of the 11 rows – show the minimum requirements to meet the hypothesis for this stage of the control system: at least A to B causality, and statistically significant ARDL regression equations, with the Global vegetation activity to P_CO2 coefficient being positive.

The first candidate control system link of the transpiration channel involves the relationship between the PID+DD CO_2 information pattern and potential evapotranspiration. Rows 1 to 4 of Table 3 assess the hypothesised link of the control system of global vegetation activity from the PID+DD CO_2 information pattern to Isoprene. All of rows 1 to 4 fit the hypothesis except for row 2. Here one of the three exceptions to the hypothesised results occurs – there is one-way causality, but it is the opposite to that hypothesised, being from potential evapotranspiration to I_CO_2. This is inconsistent with the simple control system model, and will be addressed later in this section.

The next exception occurs at row 5, Potential evapotranspiration and Land cloud cover.

The negative coefficient sign is at variance with that expected for this part of the control system hypothesis, for which a positive correlation would be expected.

These results for both Land and Ocean cloud cover leave open the possibility that the control system does not use the potential channel between transpiration and cloud cover at all. It may be that cloud cover control is adequately dealt with by the isoprene channel.

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The final exception in Table 3 is for the relationship between Land cloud cover and Ocean surface wind speed, shown in row 9. Despite the evidence for causality shown, the bounds test result is far from statistically significant (p >.25), providing no evidence for a long-run relationship between the variables. The *p*-value result shows that any relationship would not be statistically significant.

Hence there is no evidence for a materially causal relationship from land cloud cover to ocean surface wind speed.

However there are clear positive causal correlations with ocean surface wind speed from both evapotranspiration (row 7) and ocean cloud (row 8), so there is a range of ways to for achieving this link in the control system chain.

Table 4 addresses the question that in a control system causal feedback should be found from the effect produced to the leading element of the control system[4].

Row	Variable A	Variable B	Probability that relationship not Granger causal		ARDL short-run relationship	ARDL long-run relationship	
			Causality A to B	**Causality B to A**	**Statistical significance of relationship (from F-statistic)**	**Statistical significance of relationship (from F-statistic for the Bounds Test)**	**Sign of coefficient of equation for relationship**
1	Global surface temperature reduction	Global vegetation activity	**0.0197**	**2.91E-11**	p<0.0001	.025<p<.05	Positive

Table 4. Granger causality and sign of coefficient of equation for hypothesised relationship between Global surface temperature reduction and Global vegetation activity for the global atmospheric temperature control system

Table 4 shows statistically significant causality from global surface temperature reduction to global vegetation activity. Causality from global vegetation activity to global surface temperature reduction is also shown.

The *p*-value result shows that the ARDL long-run relationship between Global surface temperature reduction and Global vegetation activity is very highly statistically significant. The coefficient value is positive.

Considering these results, Table 4 shows the control system feedback loop is being completed by causality back from increased global surface temperature reduction to global vegetation activity.

3.2.4. Integrated survey against hypothesis of Granger causality and ARDL results in Tables 1 to 4

Having discussed the exceptions to the hypothesis in Tables 1 to 4, the combined results are assembled into two overviews of the hypotheses to see the extent to which the hypotheses are supported.

The extent of support or otherwise can be demonstrated by way of a flowchart showing which of the hypothesised links meets the requirement of the hypothesis.

This depiction of the results is built up in two stages. First, Figure 12 deals with the point that a link can only be considered to be a link if it displays both (i) causality in the hypothesised direction; and (ii) a positive correlation between the two variables making up the link. All links meeting both of these requirements are displayed in Figure 12 using the layout hypothesised in Figure 1. For simplicity Figure 12 does not show the directionality of causal connections between elements.

Having described the observed causality, in Figure 13 we deal with the causal direction between elements.

Figure 12 depicts all links that have been identified that show both (i) A to B causality and (ii) a positive correlation between the two variables making up the link.

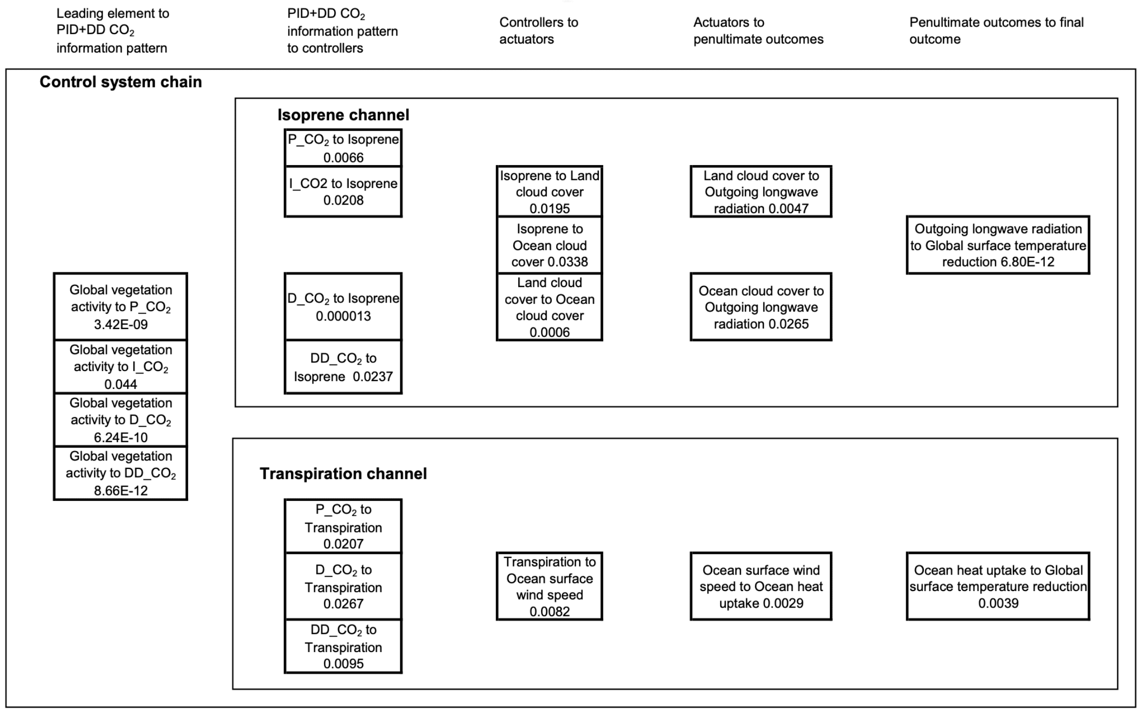

Figure 12. Depiction of each hypothesised control system link found to display (i) at least one-way Granger causality in the hypothesised direction (P-value shown) and (ii) positive correlation between the pair of variables making up the link.

Figure 12 shows that full end-to-end paths for the control system chain, including for both channels, are demonstrated. This finding meets the requirements for adequately supporting the hypothesis in this regard.

Figure 12 contains one extra link over and above those hypothesised in Figure 1 – that shown in the Results in Table 2 from land cloud cover to ocean cloud cover. We noted there that the result meant that we can consider that isoprene control system activity to be seen to affect both land and sea cloud cover – directly from isoprene to land cloud, and at one remove, via land cloud cover, to sea cloud cover.

In contrast to Figure 12, where the control system was depicted broken down by control system link, in Figure 13 the directionality of Granger causality is assessed by means of a breakdown by control system element.

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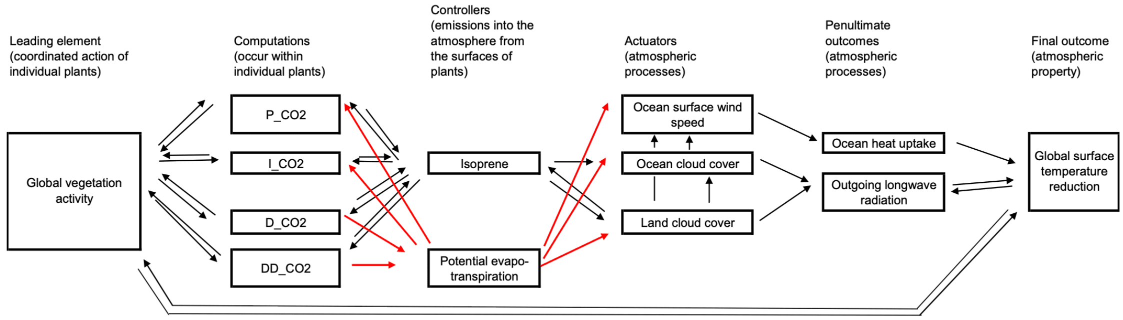

Figure 13. Global surface temperature control system showing causal direction between elements (for clarity, causality from Potential evapotranspiration is depicted in red)

In considering Figure 13, we note that in Leggett and Ball[2], most causal linkages were found to be one-way. This made it easy to infer and depict causal chains. Two-way causality has been demonstrated in this paper, and shows dominance in some aspects.

The question is how best to deal with two-way causality being introduced to the model. The following outlines the arguments that we use in support of the structure of the control system depicted in Figure 13.

It is suggested that where two-way causality is involved, the *proportion* of one-way to two-way causality impinging on an element be used as an indicator of whether the element is likely to be temporally ahead of or behind another in the control system sequence.

This proportion by causal-chain link is shown in Tables 5 and 6.

Instances by type of of causal connectivity	Control system link from leading element to CO2 computations	CO2 computations to isoprene link	Total
One-way	0	0	0
Two-way	4	4	8
Per cent two-way	100	100	100

Table 5. Occurrences by type of causality from leading element to CO_2 computations

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Instances by type of of causal connectivity	CO2 information pattern to transpiration link	Isoprene to actuators link	Transpir-ation to actuators link	Actuators to penultimate outcomes link	Penultimate outcomes to outcome link	Total
One-way	4	1	4	3	1	13
Two-way	0	1	0	1	1	3
Per cent two-way	**0**	**50**	**0**	**25**	50	18.75

Table 6. Occurrences by type of causality by link from CO_2 computations to outcomes

Tables 5 and 6 show that links involving CO_2 or isoprene (8 cases) are all two-way, while links not involving CO_2 or isoprene are almost all one-way (13 out of 16 cases).

This information can be used to justify the structure of the control system depicted in Figure 13.

First, in the figure global vegetation activity displays two-way causality with all four CO_2 series making up the PID+DD CO_2 information pattern. A case is made in Section 1.3 that the creation of the four series can be considered to only plausibly occur within the biota, so the placement of the CO_2 elements where they are adjacent to the global vegetation activity element can be considered reasonable.

Next, the CO_2-isoprene relationships also display entirely two-way causality. As with the PID+DD CO_2 information pattern, isoprene is also a product of the biota. As the creation of the PID+DD CO_2 information pattern is likely to occur faster than the more massive synthesis of isoprene, it is more likely that the PID+DD CO_2 information pattern elements appear ahead of the isoprene element in the control system chain. The same logic of scale of synthesis can be used for transpiration relative to the PID+DD CO_2 information pattern, even though no two-way causality was found for potential evapotranspiration.

All of the subsequent four links in the control system chain display predominantly the same one-way causal links found in Leggett and Ball[2], so there is no basis from these results for positioning the CO_2, isoprene and transpiration elements further down the chain, and no basis for changing the positioning of the subsequent four links from that reported in Leggett and Ball[2].

4. Discussion

The first question asked in this paper was where the four-term (PID+DD) transformations of the linear atmospheric CO_2 time series might physically be created (this was termed the ‘PID+DD CO_2 information pattern’).

We concluded that it was most likely to exist physically within the biosphere.

We then sought to determine the physical entities that might be candidates for carrying the PID+DD CO_2 information pattern to the observed actuators of the control system. In seeking to answer this question, the paper investigated whether there is evidence for two further physical components of the control system.

We concluded that isoprene emissions and evapotranspiration were highly likely candidates.

Literature review revealed that increased isoprene is connected to increased cloud cover, and increased evapotranspiration is connected to increased wind speed. With this background, this paper investigated isoprene and evapotranspiration as putative elements of the global temperature control system.

This was carried out by seeking the presence of both hypothesised Granger causal relationships and hypothesised signs of the coefficient of the associated regression equation.

Such hypothesised results were found, leading to the placement of isoprene and evapotranspiration in parallel channels between the leading element of the control system and its actuators, cloud cover and wind speed (Figures 12 and 13).

We also sought the presence of both hypothesised Granger-causal relationships and hypothesised signs of the coefficient of the associated regression equation to step through the entire hypothesised control system chain, one link at a time, at each stage reporting the presence or absence of evidence of causal links.

Adequate control system links were found that met this dual requirement, and that enabled the depiction of the control system. The control system was comprised of links of chains or channels joining unbroken from the leading element to the final outcome.

The characteristics of the control system found in Leggett and Ball[2] were of a control system displaying statistically significant one-way Granger causality across each step of the hypothesised control system sequence. Based on further findings of two-way causality in this study, the extent of this type of causality across the control system chain, and any concentration in particular parts of the chain, was analysed.

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We found that of all the control system elements found, links not involving CO_2 or isoprene elements are almost all one-way, while links involving CO_2 or isoprene elements are all two-way.

What might such two-way causality in a control system context mean?

As previously described, Cakmakci and Ulsoy[44] wrote that a networked controller system design with bidirectional communication showed significant improvements in performance when compared with the traditional unidirectional feedback-loop design. It was considered that the improved control system performance was due to the decentralised, yet more connected, nature of these systems.

From the above, we conclude that the evidence that the CO_2 and isoprene elements display such a bidirectional nature is evidence that they might be part of subsidiary control systems within the overall temperature control system, and that that may contribute improved performance to the whole control system.

In Leggett and Ball[2] the focus was on seeking to characterise components of the control system and their linkages in terms of an end-to-end chain, and then presenting evidence that the biosphere is the leading element of the chain. In the present study, we carried out more extensive Granger causality testing to seek the activity expected of a control system in closing feedback loops: that is, of causality from the outcome –temperature reduction – back to the leading element – global vegetation activity.

The results, presented in Table 4, showed that increased temperature reduction leads to increased control system activity. It is stressed that this positive correlation is in operation at the present time. What of the control system in the future? Leggett and Ball[1] provide evidence that the current global surface temperature is presently higher than the control system setpoint. Should the setpoint be returned to at some point in the future, we note that matters may fundamentally change for the control system: one would expect *temperature-reducing* control system activity to cease and *temperature-maintenance* activity to commence.

It is also of note that, at that stage, and under the control system outlined in this paper, vegetation activity overall may not decrease. Vegetation activity could continue to increase while the temperature control activity component of vegetation activity would adjust to foster a maintained temperature.

This study then addressed the question of what findings would be adequate to provide comprehensive support for the hypothesis that there is a planetary temperature control system. The hypothesis outlined in Section 1.5.3 considered that, with regard to both causal connection and direction of causal effect, we needed to find these for sufficient links to provide one set of end-to-end linkages for each of the two control system channels proposed.

Some negative directions of causal effect can remain in line with the hypothesis and some of these were found involving the PID+DD CO_2 information pattern (for example, the first step involving vegetation activity as described in Section 3.2.5).

In one case, a link (potential evapotranspiration to land cloud cover) was found involving a negative direction of causal effect which was not as hypothesised.

Given this, we sought an alternative control system path within the control system. One was found from isoprene to land cloud cover Table 2, row 5). Here the direction of causal effect was positive, as hypothesised.

Isoprene is produced vastly less over ocean than land and is therefore expected to occur less there. Hence it is somewhat surprising that causality was found between (land-based) isoprene and cloud cover over the ocean. However it is not surprising that there was no statistically significant ARDL relationship found. These two results together can be interpreted as there being a causal signal from isoprene seen in ocean cloud cover, but not producing a physical effect on the amount of ocean cloud cover.

But the control system cooling effect from cloud cover would be much greater if ocean cloud cover were affected by the control system as well. It is of particular note then, that land cloud cover is Granger causal of and positively correlated with ocean cloud cover. In other words, there is a causal connection from the control system in which increased land cloud cover leads to increasing ocean cloud cover.

Isoprene has many roles in plants, particularly including plant-to-plant communication. The occurrence of this role in plants that have been studied is so widespread that it has led to the suggestion of a general signalling function for isoprene in all plants[65]. This situation – added to the fact of the lightness and low inertia of the isoprene molecule and therefore its capacity to be highly dynamic – might make it an ideal carrier for more types of message in the functioning of the control system beyond that shown in this paper to affect cloud cover.

Finally, we turn to the fact that very large amounts of isoprene are emitted from vegetation, especially from trees[66]. The amounts emitted cost the plant significant amounts of carbon. Under experimental conditions, plants have even been shown to use more carbon to produce isoprene than their photosynthesis is simultaneously producing – that is, they dip into their vital stored carbon reserves to produce isoprene[66].

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Sharkey and Yeh[66] observed that, given this level of cost, plants that do not emit isoprene would outcompete those that do emit isoprene, unless isoprene emission provides a benefit of a scale that exceeds the cost of emission.

The evidence presented in this paper indicates just how large-scale is one of the benefits provided by isoprene.

4.1. Opportunities for further research

Several opportunities for next steps in research are suggested:

4.1.1. Isoprene emissions and evapotranspiration

The more detailed processes by which isoprene emissions and evapotranspiration contribute to the regulation of global climate are clearly a rich topic for further research.

4.1.2. Replication studies

The findings in this manuscript build on the authors' previous work, and while some independent studies have cited these earlier papers, explicit arms-length replication by independent research groups has not been carried out and would be of benefit.

4.1.3. The biotic atmospheric temperature control system process and Global Climate Models (GCMs)

Climate simulations, termed Global Climate Models (GCMs)[67], including those referenced by the Intergovernmental Panel on Climate Change (IPCC), primarily attribute global temperature regulation to greenhouse gas forcing and physical climate feedbacks. The observation-based biotic atmospheric temperature control system process has not been included in such climate simulations. There would be benefit in assessing the effect of such inclusion on the match of the GCMs' output with the observed global surface temperature trend.

Statements and Declarations

Data Availability

All data underlying the study are available from the references cited.

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