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Interconnectivities of processes in the Earth System: A case study on the influences of Mt. Pinatubo eruption in June 1991 as a possible stochastic catalytic trigger on increased terrestrial vegetation resilience to the ENSO

M. Manobavan

Centre for Earth and Environmental Science Research, Kingston University, Penryhn Road, Kingston upon Thames, Surrey, UK. KT1 2EE
Now at: Department of Biology, Faculty of Applied Science, Vavuniya Campus, University of Jaffna, Vavuniya, Sri Lanka (e-mail: b4v4n@yahoo.co.uk)

Abstract

Interconnectivities in the Earth System, between physical and vegetative elements are explored using the Mt. Pinatubo eruption as a focal point in this paper. Simulations performed using the Hybrid v4.1, a mechanistic simulation model that is capable of mimicking vegetation processes suggest the possibilities of teleconnective loops between volcanic eruptions and vegetation response via climatic changes. This leads to the speculation/conclusion that the Earth System's behaviour could be explained using arguments developed based on the Gaia concept.

Key words: Earth System, Gaia, simulation modelling, teleconnections

1. Introduction

Anthropogenic forcing of the Earth's climate system through the release of green house gases such as carbon dioxide (CO_2) into the atmosphere has resulted in the need for understanding the likely impacts of any future climate change on the Earth System [3]. The land surface is an important boundary condition for the climate system, and vegetation the primary terrestrial interactive surface for the atmosphere [9]. Therefore, the need for analysis of land surface-vegetation interactions and climate is paramount. Of particular concern in this regard, is the shift of the El Niño Southern Oscillation (ENSO), which is the largest known interannual climatic variability mechanism (bimodal, with quasi-alternating warm and cold phases) at global scales, to frequent warm (El Niño) episodes [3]. This shift is attributed to enhanced global warming and is expected to influence terrestrial processes on a wider scale.

Previous studies based on terrestrial ecosystem simulation modelling have reported a reduction in terrestrial photosynthetic biomass corresponding to El Niño events [1]. However, a major criticism of this work is the lack of integration of real-world data. The counter argument to these criticisms is that it is simply impossible to consider or collect data at the spatio-temporal scales these processes demand. Arguably the best way forward is via the integration of remotely sensed data in Earth System investigations [11]. Previous work in terrestrial remote sensing has reported of connections between ENSO and vegetation activity e.g. [12]. However, both (modelling and remote sensing) approaches are yet to establish the systematic responsive behaviours in terms of resistance and/or resilience in terrestrial vegetation that could have arisen as a result of ENSO perturbations.

Furthermore, contemporary remote sensing research and Earth System modelling have (and are) been/being conducted without complementing (or cross-referencing) each other. Meanwhile, another problem encountered by the terrestrial vegetation modellers is how to couple vegetation processes to climate within the framework of the Earth System. This is an issue that is of many debates in the Global Circulation Modelling community. However, there has been some theoretical work that have attempted to illustrate the merits of direct coupling of climate with vegetation using tutorial models e.g. [13]. This work, which lacks the integration of real world data or references to real world scenarios, is based on the 'Gaian school of thought' that prescribes a geophysiological approach to terrestrial vegetation modelling. 'Geophysiology' is a term proposed by [7] and [8] who stressed the need for interdisciplinary research, which probes into the Earth System processes from a physiological perspective.

2 Previous research

An attempt was made in the work of [11] to establish the possible responsive mechanisms between ENSO phenomena and the terrestrial vegetation using geophysiological concepts. The holistic synergistic approach here was the analysis of terrestrial remotely sensed data from a systemic perspective (as opposed to the contemporary image processing or geographical information system based spatial pattern establishing studies), using a combination of time-series modelling and simulation modelling techniques. Time-series modelling analysis of Advanced Very High Resolution Radiometer derived Normalized Difference Vegetation Index (NDVI) data reveal a cause~effect connective (or teleconnective) link between terrestrial South American vegetation and ENSO, where the latter forced the former to respond after a lag period. Furthermore, it also showed that the terrestrial vegetation might have become resilient to ENSO over time.

These results are (or may seem) quite contradictory to the ideas of the contemporary Earth System modellers, who prescribe a decrease in photosynthetically active biomass during the warm phase of the ENSO. This is based on assumption that the warm phase causes droughts in a location, but it is entirely dependant on where actually (geographically) the area of concern is, as floods have been observed in South Asia during the warm phases. From a remote sensor's perspective the [11] study is not very attractive, as it did not involve (at all) in producing spatial models of analysed imagery. However, it can also be argued that this study overlaps both the Earth System modelling and remote sensing disciplines but, it should be stressed that this approach is completely different in some aspects for the following reasons:

- Use of a time-series model to analyse remotely sensed data
- Coupling of ENSO variability via Southern Oscillation Index to the remotely sensed vegetation time-series data in the time-series models
- Looking at vegetation responses from a physiological perspective and estimating lag (which is a function of resistance) and resilience

In an essence what [11] have done is building upon the work of [13]'s tutorial approach, where the climate dynamics was coupled to terrestrial vegetation processes. However, this study did not provide a mechanistic explanation to how vegetation might have developed resilience over the period of investigation.

So, the need for a proper vegetation simulation modelling approach was apparent. This led to the second phase of the research where, simulations were performed using the Hybrid v4.1 [1], a mechanistic model of vegetation dynamics for a 'hypothetical location' similar to that of terrestrial South America in vegetation composition and has a similar mean annual climate [9]. Methodology for climatic scenario development was adopted from [10]. The results of these simulations further confirm the hypothesis assumed. Moreover, Hybrid allows simulations to be performed under different atmospheric CO_2 concentration scenarios. Model simulations under different atmospheric CO_2 increase trends established that atmospheric CO_2, whilst initially inducing a fertilisation effect, can also act as a limiting factor that leads the system to collapse [9].

1 The Hybrid Version 4.1 is a combination or hybrid of a gap model (whose dynamics are determined by the physiological processes at the individual tree level) and an ecological process model (whose dynamics are defined mostly by interspecies competition at the forest gap level) which is capable of simulating the transient behaviour of the terrestrial vegetation when subjected to natural or anthropogenic perturbations.

This led to the development of the final argument that: 'terrestrial (South American) vegetation could have become resilient to the ENSO, within the present context of the atmospheric CO_2 concentration trends, and that quasi-random perturbations such as the ENSO, enhance the homeostatic property of the terrestrial vegetation system (within its geophysiological limits), rather than hinder it'. This phase of research differs from previous research for the following reasons:

- Using an ENSO treated climate to drive the model (as opposed to the contemporary approaches of using Global Circulation Model (GCM) generated climates to drive ecosystem models)
- Simulations performed assuming the null-hypothesis
- A geophysiological approach to the analysis

However, no matter how controversial these findings may sound they are not unworldly at all! Artificial Intelligence researchers have established that random perturbations are necessary for system stability. Resistance and resilience are such well-established facts in biology that nobody bothers citing any references when discussing these processes. Field based studies, laboratory research and simulation-modelling exercises (no matter how non-holistic they are) agree upon the fact of carbon fertilisation. It is obvious that change (in any system, species or organism) is inevitable and occurs through the passage of time which is the basis of Darwinism. Animal physiologists wholeheartedly agree with the homeostatic properties in biological entities (e.g. internal body temperature regulation at 37° C in mammals), which was the basis of the Gaian school of thought and the Daisy World Model which is its mathematical description [8].

In these investigations (i.e. [9, 10, 11]) it has been attempted to combine all these approaches thus giving a holistic geophysiological context to an Earth System problem. Moreover, it has also been shown that public domain data can be cost-effectively used in Earth Systems research to produce results that are comparable (some times contradictory) with model outputs that have taken years in the making and a lot of super-computer time. However, on the other hand even though prominence to the holistic approach is given, most of these work involves simplistic methods which may have sometimes led to over optimistic results. The question is whether, is it possible that these studies (i.e. [9, 10, 11]) might have produced any over optimistic results? As these studies were initially meant to have a remote-sensing origin, focus is given to a grey area relating to the remotely sensed data analysed in these studies.

3. Anomalous decrease/increases in NDVI?

The anomalous decrease in 1991/92 and the anomalous increases in 1994 of the NDVI were not properly addressed in the work of [11]. They tried to explain this condition by referencing [2], who have shown the anomalous decrease in 1991/92 is due to the aerosols ejected by the Mt. Pinatubo (in the Philippines) that corrupted the satellite generated NDVI data to an extent. In addition, [14] have reported of the similar effect by the El Chichon (in Mexico) eruption in 1982. Figure 1 is a comparison of the NDVI timeline with the time-series model. The model shows how the signal should have been if there was no influence from aerosols, which corrupted the NDVI signal, hence leading to anomalously low values. But, what about the anomalous increases during 1994/95? Furthermore, why there is not any significant discrepancy between the model and the data for 1982 apparent, if considering the fact that El Chichon had effected the NDVI signal? A possible explanation could be the fact that the time-series model uses the seasonalities from 1981 to 1983 to generate the forecasts, which leads to the NDVI values for that period being considered as the baseline. Hence, no effects of the El Chichchon is apparent. However, as Figure 2 illustrates, a significant decrease in values is shown for the 1982/83 period when the interannual components of the model and the NDVI data are compared.

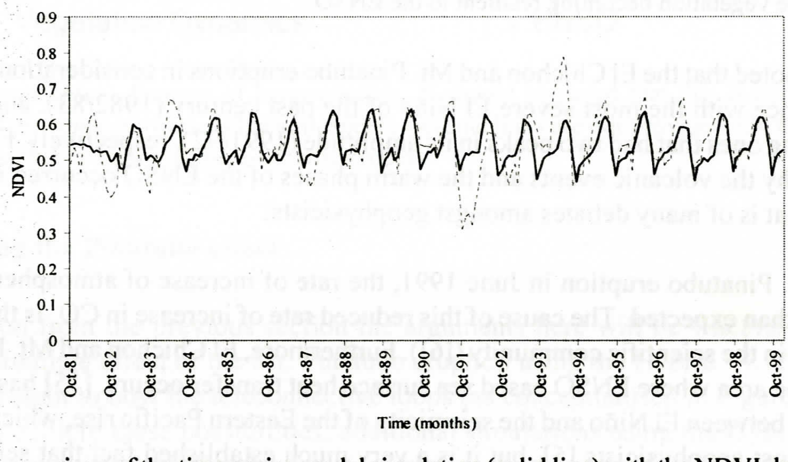

Figure 1: A comparison of the time-series model simulation (solid line) with the NDVI data time-series (dashed line). The model shows how the vegetation trends would have been if there were no influences from the Mt. Pinatubo eruption.

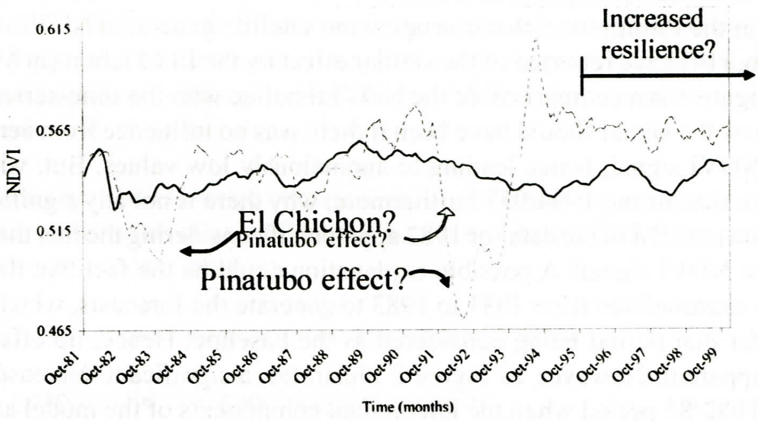

Figure 2: A comparison of the interannual components of the model output (solid line) and the NDVI data (dashed line). Please note the increased NDVI values of the post 1994 periods, which are speculated due to the vegetation becoming resilient to the ENSO.

It should be noted that the El Chichon and Mt. Pinatubo eruptions in consideration occurred in correspondence with the most severe El Niño of the past century (1982/83), and one of the long persisting ones that had two peaks in its amplitude (1991/92), respectively. Furthermore, the reason why the volcanic events and the warm phases of the ENSO occurred in parallel is something that is of many debates amongst geophysicists.

After the Mt. Pinatubo eruption in June 1991, the rate of increase of atmospheric CO_2 was much lower than expected. The cause of this reduced rate of increase in CO_2 is the subject of much debate in the scientific community ([6]). Furthermore, El Chichon and Mt. Pinatubo are situated in the area where ENSO based sea surface heat transfer occurs. [15] has reported of a correlation between El Niño and the seismicity of the Eastern Pacific rise, which is of much debate amongst geophysicists [5], but it is a very much established fact that seismicity and volcanism are linked. Consequently, from an oceanographic point of view, it is an accepted fact that volcanic eruptions causes trade wind collapses in the atmosphere and El Niño events lead to an enhanced atmospheric circulation [12]. As [12] states, **there is no evidence that volcanic eruptions produce El Niño events, but the volcanic eruptions must be separated to understand the terrestrial vegetation responses to each**. On the other hand, it is obvious that volcanism affects the climate and the terrestrial vegetation dynamics [4].

What is important from the perspective of this paper is whilst there is a possibility that vegetation has responded to the ENSO signal and eventually become resilient, two major volcanic events have also occurred in parallel. Whilst it is an accepted fact that these events and the

ENSO, on their own influence/impact terrestrial vegetation dynamics, the question is whether these events compliment or contradict each other's effect on the terrestrial vegetation system? From a geophysiological point of view, it can be argued that whilst there is no established link/correlation between volcanism and ENSO, there could be a teleconnective relationship via terrestrial vegetation dynamics. If so, then the counter argument will be (refer to Figure 3) that is there any feedback from the terrestrial vegetation dynamics that influence volcanism and/or ENSO?

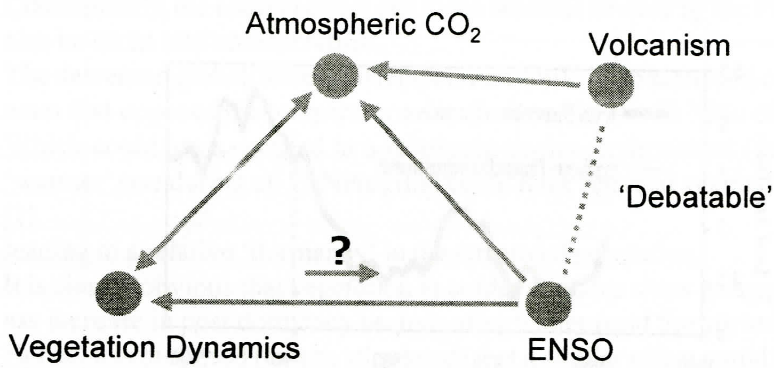

Figure 3: A conceptual diagram of connectivities. It should be noted that this is not a 'complete' description of the connectivities, as the atmosphere-oceanic links are not provided. On the other hand, the ENSO however is an atmosphere-oceanic process.

4. Simulating the Pinatubo effect

Continuing on from the previous section the arguments here will be whether would it be possible to simulate effect of the Mt. Pinatubo eruption using the Hybrid v4.1? If so, will it provide an insight to how the teleconnective loops (as conceptualised in Figure 3) could be possible? To explore these possibilities, additional simulations using the Hybrid v4.1 were performed considering the following facts/assumptions in the scenario development:

- Mt. Pinatubo eruption of 1991 occurred in parallel with the 1991/92 El Niño (a known fact)
- The 1991/92 El Niño was the longest persisting warm phase of the ENSO in the past century [3].
- Which was followed by a La Niña in 1994
- The Mt. Pinatubo volcanic eruption emitted aerosols and CO_2 part of which were transferred over terrestrial South America, via altered wind mechanisms in the atmosphere, another part of the emissions were ejected to the stratosphere contributing to the aerosol cooling effect. This has a life time of 1-3 years [12]

- As a result of this transfer mechanism CO_2 concentrations (could have) increased significantly over terrestrial South America for the latter part of the 1991/92 period

Results of the simulations are presented in Figure 4. Please note that 'without Pinatubo adjustment' refers to simulations under ENSO climatic variability, and 'with Pinatubo adjustment' refers to simulations under ENSO climatic variability+Pinatubo related CO_2 increase. ENSO variability was introduced via incorporating Southern Oscillation Index trends into the climatic data inputs (developed from: [10]).

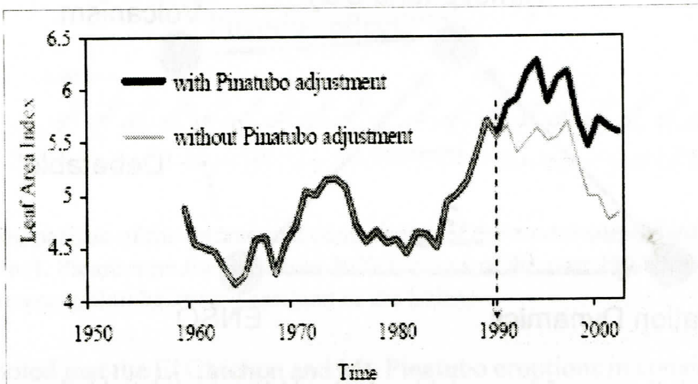

Figure 4: The comparison of the Hybrid simulations to test the Mt. Pinatubo adjustment in terrestrial vegetation response. Leaf Area Index (LAI) is a surrogate to photosynthetically active biomass that is frequently used by the modelling community. The dashed arrow indicates the time spec where the Pinatubo adjustment was made in the model. A 10 point moving average smoother has been applied on the data to enable prominence to decadal trends[2]. Time is given in a decadal scale.

5. Discussion

The simulations incorporating the Pinatubo effect support the trends evident in the NDVI data. Moreover, whilst a decrease in LAI is observed in and around 1991/92, an increasing trend is apparent post 1991/92 periods. Which further strengthens our hypothesis (or rather, does it provide yet another conceptual visual display?). A mechanistical explanation to these observations can be argued as:

- The 1991/92 El Niño due to its long persistence induced drought conditions for the area of concern.
- That led to an increased atmospheric temperature and resulted in water related physiological stress in the vegetation.
- Which increased the transpiration rate(s) and a decreased stomatal rigidity leading to a lowered photosynthetic rate (based on [1] and [2]).
- As a result, less biomass was produced, hence lowered NDVI/LAI values during 1991/92 till 1994.

- All this occurred within the context of an increasing trend in atmospheric CO_2 concentrations.
- Which eventually led to the fertilisation effect in and around the post 1991/92 periods.
- That corresponded with the La Niña (wet) conditions that prevailed
- The anomalous increases in the NDVI/LAI values (post 1994) can be attributed to the 'enhanced' fertilisation effect due to the excess CO_2 transferred to the terrestrial system via the Mt. Pinatubo eruption.
- Consequently, the cooling effect due to the aerosols emitted by the Pinatubo should also be taken into consideration.
- The decreased global/ terrestrial temperature could have acted as a counter mechanism that opposed the temperature rises induced by the El Niño of the 1991/92.
- Which could have resulted in a relatively cooler environment (as opposed to a 'warmer' one during an El Niño) that could have reduced vegetation respiration [1],
- leading to a relative 'dormancy' in the terrestrial vegetation.
- It is simply obvious that vegetation in colder climates show an aggravated biomass increase in post dormancy periods after winter (mid Spring to late Summer).
- Hence, it is proposed (can be stipulated) that a similar effect could have occurred as a result of the aerosol related cooling.

Based on this arguments, it can be stipulated that that the Mt. Pinatubo eruption in June 1991 could have acted as a stochastic catalytic trigger that enhanced the resilience in the terrestrial vegetation to the ENSO phenomenon (within the context of the global warming and related increasing trends in atmospheric CO_2 concentrations, which led to the fertilisation effect).

If so, the counter argument here is, why did not the eruption of El Chichon act as a catalyst? The obvious answer will be that the terrestrial vegetation was not in a geophysiological state where an increased resilience to the ENSO was possible at that particular point of time. However, if we refer back to Figures 1 and 2 a 'minor' anomalous increase in NDVI values can be observed (in relation to the modelled values) post 1982/83 after the El Chichon eruption, which also corresponded with a La Niña!

To close the argument, it is appropriate to refer back to [12], who says **there is no evidence that volcanic eruptions produce El Niño events, but the volcanic eruptions must be separated to understand the climatic responses to each, by the terrestrial vegetation system**. Furthermore, this argument stresses (in a sense) the possible teleconnective (feedback) loops between vegetation~ENSO~vlocanism and emphasises (once again) on the need of a holistic, interdisciplinary approach in Earth System Science. Figure 5 is a conceptual diagram of the further developed arguments. The possibility that the terrestrial vegetation could function as a biotic regulator within the system of consideration is also illustrated.

[1] F test was used to establish equal variances between 'without ' and 'with' Pinatubo adjustment outputs. Then T test was performed to establish that they are different at 95% confidence limits (p value <0.001).

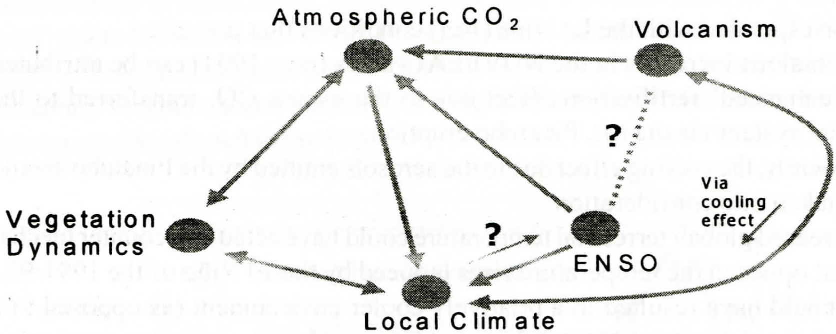

Figure 5: A conceptual diagram of the further developed arguments. This illustrates the possibility of a circular (tele-) connective loop (feedback) between vegetation, ENSO, volcanism and atmospheric CO_2. Please note that a new component, 'local climate', which refers to the location-based climate for the terrestrial system of concern has also been introduced.

As [8] observes, hypotheses that are full of predictions (and/or results), that can easily be tested are considered of value in the scientific world. It matters little whether the **view** of the researcher is **right** or **wrong** as long as further investigation and thought are simulated, new facts discovered and new theories/hypotheses composed. All in all, the results produced in this research (post and pre thesis submission dates) are a testament to the Gaia theory (or the geophysiological approach) as a possible hypothesis generator. Furthermore, going back to the physiological approach in Earth System analysis, a new term is proposed, which is:

'geophysical immunisation'.

Which suggests that random perturbations from geophysical processes (such as the Mt. Pinatubo eruption) could have acted as an immunising agent that further enhanced the resilience of the terrestrial vegetation to ENSO. However, these arguments need further development and more 'careful' thought.

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