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Earth System Dynamics
Discussions

Interactive comment on "The Pacific Ocean heat engine: global climate's regulator" *by* Roger N. Jones and James H. Ricketts

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Overall comment

The manuscript describes an approach to the study of the role the tropical Pacific ocean has for the thermodynamics of the climate system, relying on the thermal engine concept. Starting from a previous work by the authors, a rigorous statistical testing is used in order to investigate step-like changes in the observed evolution of sea-surface temperatures (SST) in the Tropical Western Pacific (TWP) and Tropical Eastern Pacific (TEP), relating them with the evolution of global mean surface temperatures (GMST) and some indices describing inter-annual and decadal natural variability (in particular the Pacific Decadal Oscillation, PDO, the Atlantic Multi-decadal Oscillation, AMO, and

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ENSO). It is argued that the tropical Pacific can be seen as a thermal engine transporting heat up-gradient (i.e. from a cold to a warm region), and that this mechanism is characterized by two modes: until the second half of the 20th Century a free mode is associated with the natural variability at the decadal timescales, while in more recent years a forced mode is established, in which the natural variability is enhanced by the anthropogenic greenhouse gas (GHG) forcing. The authors argue that these findings provide evidence that the classical view of the response of the system to the GHG forcing as a trend-like behavior with superimposed noise-like natural variability is faulty in describing the transient climate change on a decadal timescale.

Overall, I appreciated that the authors started from a climatological point of view (i.e. from observations) in addressing the challenging issue of how climate change projects on the natural modes of variability at inter-annual to decadal timescales. However, conclusions do not seem supported by sufficient evidence from results, at least the way these have been illustrated.

In the first part, authors argue that step-like changes in TEP and TWP, in part related to changes in the phase of the AMO and PDO, as well as ENSO events, shape the decadal evolution of GMST. The emergence of step-like changes is detected through the usage of established statistical methodologies. On the contrary, the propagation of the signal (cfr. Sect. 3.1) is discussed in terms of timing across different time series, and this qualitative argument severely undermine the robustness of the results. The authors seem to claim that conclusions similar to those based on observational-based datasets can be drawn from investigation of CMIP model outputs. A visual inspection of the model results shown in the supplementary material, though, does not seem to support this conclusion.

In the second part (Sect. 6), arguments are provided to describe the Pacific ocean thermal engine, how its changes propagate to the global climate, and how its internal variability is affected by the forcing through nonlinear mechanisms. This section is deliberately qualitative, and in some parts speculative, and this is of course absolutely fine. The problem is, that the section has the form of a review of existing literature, particularly in sections 6.2, 6.4 and 6.5, with insufficient or completely absent relation to results described in the first part. These sections alone sum up to almost 40% of the manuscript, making it dispersive and difficult to read. This is not appropriate, in my opinion, for an original research article, and shall be reconsidered.

Overall, even though the results from the first part are potentially interesting and supporting the conclusions given at the end of the manuscript, I think that a more rigorous scientific approach is needed in order to make the manuscript worth publishing. My suggestion is that the authors consider splitting it into two parts. In a first paper (approximately sect. 2-5), the statistical methodology is explicitly accounted (instead of referring to a previous paper), the shifts in TEP-TWP temperatures and their relations with GMST, AMO, PDO, ENSO are explicitly addressed through rigorous methods for causal inference detection. The network approach outlined in sect. 6.5 might also be helpful in this respect. In a second paper (sect. 6), more emphasis is given on the description of the conceptual model of Pacific thermal engine. In doing so, the heat sources and sinks, the working temperatures, the Carnot efficiency and actual efficiency have to be quantitatively addressed, possibly considering the compliance to the 1st and 2nd laws of thermodynamics via energy and entropy budget.

Authors' response.

We thank the reviewer for their careful consideration of the paper and detailed responses. Many we agree with and some we do not – and will carefully try to explain why. We realise it is a lengthy and difficult paper, particularly the second part. We felt, and still do that the behaviour of the heat engine illustrated in part one needs a conceptual explanation, especially as it departs from the standard explanation of gradual atmospheric warming.

A major goal of the paper was to strengthen the case for warming being a non-gradual process, established by severe testing in Jones and Ricketts (2017, JR2017). The dis-

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cussion paper had two aims: (1) to present a process and mechanisms that identify where the shifts in temperature originate and how they propagate through the climate system, and (2) to describe a conceptual model or framework for how this works. Referee 1 was not persuaded that climate change cannot be gradual, but an episodic response to forcing is fundamental to the whole hypothesis. We aim to provide a more convincing interpretation of the evidence in the following.

We are grateful that Referee 1 appreciates the focus on observations. The overall approach has been informed by a natural science approach – analysing observations to better understand how the climate behaves as a complex dynamic system while articulating how and why the current understanding cannot explain the results of those analyses. We fell short in doing so. Prompted by the comments and queries of the referees, we aim here to provide a more complete explanation of the conceptual model in addition to tightening up the description of the heat engine and associated network.

Referee 1 suggests that more attention be paid to the quantification of the thermal aspects of the heat engine, considering the 1st and 2nd law of thermodynamics, quantifying Carnot efficiency and actual efficiency. We believe we are dealing with a complex thermodynamic system that is self-organising where dissipation occurs in a fluid-dominated system far from (internal) equilibrium. As this is an inductive process, we need to first understand how it is organised before getting a better idea of the rules that govern the patterns and processes being observed and what the organising principle(s) may be.

At best, we can only provide a general interpretation. With respect to the first law, the overall energy balance of the climate system is influenced by changes in radiative forcing, which acts as a changing boundary condition rather than directly forcing the atmospheric climate. This is because physical constraints prevent the atmosphere warming independently of the ocean. To address the second law with respect to entropy, we would have to solve the issue of what compliance to that law means in terms of entropy in nonequilibrium complex systems, which is currently a work in progress and unresolved (Endres, 2017; Zia & Schmittmann, 2006). The 2nd law governs the dissipative process that transfers heat vertically and meridionally, the main role of the heat engine. Under forcing, a heat storage and release system in the shallow ocean results in complex system responses producing rapid shifts in climate on decadal timescales.

Without generalisable rules of how the 2nd law governs this process, we first need to work out what the system is doing before being able to figure out how it works. Our aim is to understand the ‘what’ before the ‘how’. Later in the comments we suggest that energy rate density may be the measure that serves as a unifying principle for self-organised behaviour. However, this is very tentative and would need to be tested.

Conventional theory maintains that radiative forcing by greenhouse gases in the atmosphere results in gradual warming mediated by variability. The development of radiative transfer functions linking forcing to temperature change (Hansen et al., 1997; Hansen et al., 2005) produces a monotonic curve. Our position is that the additional heat energy from greenhouse gas forcing is absorbed by the shallow ocean due to its greater thermal conductivity and capacity resulting in strong negative feedbacks. Heat is released in response to thermodynamic forcing as the build-up of heat exceeds the capacity of climate to dissipate that heat. The resulting regime change produce step-like warming that over sufficient timescales form a complex trend (Jones & Ricketts, 2017).

Fig. 1 is a simplified schematic of the major processes involved in the modelling and downscaling of climate information. Most assessments move straight from the first to the third chevron by either considering the second as broadly synonymous with the first and/or as a generator of stochastic variations superimposed on the first. Not shown in Fig. 1 are the feedback processes involved in self-regulation, which feed information back up this process at every level (and are essential parts of any complex system).

Figure 1: Schematic diagram showing the major climate the major processes involved in modelling and downscaling. Not shown are feedback mechanisms moving back up

this sequence.

Thermodynamic forcing is the missing link in the existing analytical structure. Moving from radiative forcing to dynamic distribution generally involves linearisation. Even if stochastic elements are introduced into a time series, the underlying forced response is assumed to be gradual. Linking effective radiative forcing to the climatic response formalises this relationship. The storage of heat in the shallow ocean means that the radiative forcing component becomes indirect and the thermodynamic forcing aspect becomes direct. This treats the climate system as two separate but interacting components as per Ozawa et al. (2003), where the radiative component is linear and additive, and the thermodynamic component involved in the dissipation of heat, is nonlinear.

The role of thermodynamics in contributing to complex behaviour in climate is often acknowledged in principle, but in practice is largely overlooked in favour of dynamics; i.e., the act of subtracting interannual and decadal-scale behaviour from climate time series is to separate the dynamic and forced components of climate. We are proposing that thermodynamic forcing plays a largely unrecognised role in climate change. The mechanisms involved are the subject of the paper: climate acting as a self-regulating complex dynamic system, with the Pacific Ocean heat engine playing a governing role.

Regarding the suggestion to take a more scientific approach by quantifying energy and entropy budgets according to the 1st and 2nd law of thermodynamics. We do not believe that in a complex, dynamic system that working from first principles will bear fruit. Arguably, it has not succeeded to date. An empirical understanding of complex system behaviour is important when diagnosing governing equations and gaining an accurate description of how the system works is our primary goal. We also consider this to be a rigorous scientific approach if accompanied by sufficient testing and review.

This problem is described by Champion et al. (2019): The traditional derivation of governing equations is based on underlying first principles, such as conservation laws and symmetries, or from universal laws, such as gravitation. However, in many modern systems [read complex], governing equations are unknown or only partially known, and recourse to first-principles derivations is untenable. Instead, many of these systems have rich time-series data due to emerging sensor and measurement technologies (e.g., in biology and climate science). This has given rise to the new paradigm of data-driven model discovery.

Champion et al. (2019) describe a methodology that uses sparse identification of nonlinear dynamics to diagnose parsimonious governing equations from data measured in complex dynamic systems. It can also incorporate partially known physics and constraints. Models diagnosed in this way include those containing Lorenz attractors, a reaction diffusion system and nonlinear pendulum (Champion et al., 2019). We believe that to utilise this type of methodology, the basic structure of how the system works needs to be understood first. That is our goal.

Complex system dynamics informed the thinking behind part 2 of the original discussion paper, but this was not openly declared. Instead discussion points were taken from different parts of the literature and the result was scattered and confusing. A revision would introduce the key features of complex dynamic systems such as networks, emergence, state changes, symmetry, attractors and boundary conditions and discuss them in the light of our results. This would be largely descriptive, supported by quantitative methods and tools where available.

For example, introducing the network approach currently in Section 6.5 earlier will provide the context for analyses describing the behaviour of ENSO, PDO and AMO, and free and forced modes. Emergence is also an important issue. Most of the phenomena we deal with are emergent, affecting how causality can be analysed and interpreted. Appendix II discusses some of the arguments as to why emergence is important.

Taking up the suggestion of Referee 1, we used Granger causality methods to analyse temperature changes on monthly and annual timescales for 29 regions covering the hot and cold heat engine nodes, zonal and hemispheric regions to global means for land-ocean, land and ocean. However, Granger causality cannot in itself identify externally-forced nonlinear change because the test requires a stationary time series. A stationary time series can only describe internally generated influences. However, by comparing stationary with nonstationary results and being able to independently verify the nature of change, we can infer what processes and regions heat is moving through by assessing changes in temperature. The method and some results are described in Appendix 1.

Another important aspect of complex systems are boundary conditions and the manifold, or operating space. In the discussion paper we were unsure of what driving the shifts – an oversupply of heat at the surface, an imbalance in the heat engine itself, or Earth's energy imbalance as measured through the top of the atmosphere energy deficit. We now believe the main role of the heat engine is in governing meridional transport from the equator to the poles, with the geostrophic limits to meridional heat transport imposing very strong boundary conditions for total transport. The heat engine sits within a network that combines various oscillating and circulating systems around the globe acting as nodes via teleconnections. More detailed descriptions are provided in the responses to both referees.

Change to manuscript Both referees suggested dividing the paper into two. The additional work carried out has made this the most appropriate step, which would address their concerns about the focus on the analyses of heat engine behaviour. The first paper would concentrate on the mechanics of the heat engine based on the analysis of observations. The second paper would describe climate as a complex system governed by responses to thermodynamic forcing using the findings from the first paper, incorporating analyses from climate models and more widely from the literature, along with considerations of complex system behaviour.

The following structure is proposed.

Paper 1

1. Introduction 2. Context and general approach 2.1 Previous research and measuring nonlinear change 2.2 Limitations of the standard approach 2.4 Data, methods and tools 2.5 Physical setting 3. Results 3.1 Relationship between TEP, TWP and broader climate 3.2 Tracking changes 1: the heat engine 3.3 Tracking changes 2: teleconnections 3.4 Tracking causality: Granger analysis 4. Discussion and conclusions

Paper 2

1. Introduction 2. Context and general approach 2.1 Climate as a complex dynamic system 2.2 Data, methods and tools 3. The hidden climate 3.1 Emergence 3.2 Representation of the Pacific Ocean heat engine in climate models 3.3 Regime changes in energy transport 4. Complex system behaviour in the coupled atmosphere-ocean 4.1 Boundary conditions (e.g., meridional heat transport) 4.2 Attractors and regime changes 4.3 The heat engine and self-regulation 5 Discussion and conclusions

Note that responses to comments 1 to 31, technical notes and two Appendices are in the attached supplement. We apologise on the length but we have presented some challenges for orthodox approach to understanding how the climate changes and many of the points we make are barely covered in the existing literature.

Please also note the supplement to this comment:
https://esd.copernicus.org/preprints/esd-2019-72/esd-2019-72-AC2-supplement.pdf

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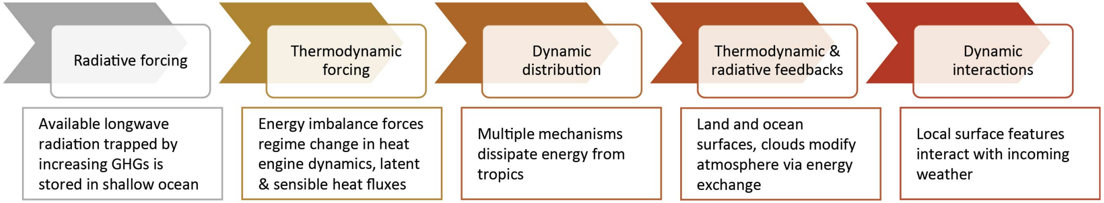

Figure 1: Schematic diagram showing the major climate the major processes involved in modelling and downscaling. Not shown are feedback mechanisms moving back up this sequence.

Fig. 1.

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