World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Review Article)

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CHAOS THEORY REMAINS VOID FOR THE REAL CLIMATE

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World Journal of Advanced Research and Reviews, 2026, 31(03), 576–579

Publication history: Received on 02 August 2026; revised on 09 September 2026; accepted on 11 September 2026

Article DOI: https://doi.org/10.30574/wjarr.2026.31.3.2342

ABSTRACT

Weather and climate model results, and studies related to Chaos Theory, are examined for evidence that Chaos Theory applies in the real world rather than only to models. No such evidence is found, and in some cases rapid growth in model divergence as expected from Chaos Theory has been found to be an artefact of the models. Results from models coded with mathematical formulae that exhibit rapid growth in divergence cannot be used to assess the applicability of Chaos Theory to the real world, because that would necessarily involve circular logic: the model results are only exhibiting an emergent property of the formulae as used in the models. Tests with atmospheric analogues have been unable to assess the applicability of Chaos Theory to the real world, because they could not emulate the infinitesimal perturbations at the core of Chaos Theory. Some AI models have shown that their rapid growth in divergence, as expected from Chaos Theory, is caused only or primarily by numerical noise, and is therefore an artefact of the computation rather than a real atmospheric process. General Circulation Models use processes with inaccuracies similar to numerical noise, which could have a similar effect. Other AI models do not exhibit rapid growth in divergence. The model findings apply only to the models, so they cannot be used to assess Chaos Theory's relevance to the real world. In the real world, Chaos Theory remains void (scientifically inapplicable).

Keywords: Chaos Theory, Climate Models, Divergence, Lyapunov exponents, Navier–Stokes, Weather Models

1 INTRODUCTION

This paper provides additional analysis as a follow-up to a previous paper by the same author which argues that Chaos Theory cannot be applied to the real world [1].

Chaos Theory as defined by Bishop (2023) refers only to models: "*Chaos is typically understood as a property of a dynamical system. A dynamical system is a deterministic mathematical model for how observable properties of a system evolve with time. [..] In addition to exhibiting sensitive dependence, chaotic systems are deterministic and nonlinear and exhibit aperiodic behavior.*" [2]. Here, "*sensitive dependence*" means sensitive dependence on initial conditions. More generally, though, Chaos Theory has been accepted as applying in the real world, on the basis that Chaos Theory applies to deterministic nonlinear systems and Earth's climate is a deterministic nonlinear system [9].

This paper looks for evidence that Chaos Theory applies in the real world and is not an artefact of the models, but the findings extend the argument that Chaos Theory can apply to models but not to Earth's climate.

2 ANALYSIS

Chaos in a model is typically quantified by Lyapunov exponents. The Lyapunov exponent gives the rate of exponential divergence from perturbed initial conditions [3]. The divergence increases exponentially over time if the Lyapunov exponent is positive, or decays exponentially over time if the Lyapunov exponent is negative. Zeng et al (1991) point out that "*The Lyapunov-exponent spectrum can be computed relatively easily for known model systems. However, it is difficult to estimate Lyapunov exponents from experimental data for a complex system (e.g., the atmosphere).*" [4]. The primary reason that it is difficult to estimate Lyapunov exponents for the real climate is that direct twin experiments as used with numerical models are not possible for the single real atmospheric trajectory.

There are two ways in which it has been attempted to demonstrate Chaos Theory in the real climate.

- With models

There have been many attempts to identify and demonstrate Chaos Theory in the real climate, using or citing models [5] [6] [7] [8] [9] [10] [11] [12]. Typically, they claim that the instability of the atmosphere places an upper bound on model predictions, but because their analyses use or cite model results the studies only actually demonstrate chaos in the models. In other words, they are based on circular logic: Chaos (rapid growth in divergence) is an emergent property of the mathematical formulae when they are truncated and integrated into models, so the model results are exhibiting only the characteristics of those formulae as coded in the models. At no point in these studies is Chaos Theory demonstrated to apply to the real climate.

In more detail: Much of the claimed chaos (as per Chaos Theory) in the real climate is based on the Navier–Stokes equations (NS), which are genuinely based on real atmospheric characteristics. The problem is that NS as applied in a model is only an approximation [13] [14]. With infinitesimal differences in initial conditions, models coded with NS diverge as expected. But, because NS is only an approximation, it cannot be claimed that the model results at this highly detailed level really do represent the real climate - a small NS inaccuracy (or model inaccuracy) could swamp the effect of the differences in initial conditions. This concept is explored further, below (see Model artefact?).

- With atmospheric analogues

In these studies, pairs of similar observed atmospheric states are found in past observations, and the way that they diverge from each other over subsequent days is then analysed [15] [16] [17]. The concept is that the difference between the observed atmospheric states is a proxy for a difference in initial conditions, ie, that deviation between atmospheric behaviours over subsequent days is representative of the deviation expected by Chaos Theory from a difference in initial conditions.

A serious drawback with these studies is that all of them start with initial states that are already a lot further apart than the tests of sensitivity to initial conditions usually used in models. They are therefore unable to test the feature of Chaos Theory in which infinitesimal differences grow exponentially at a positive Lyapunov rate. They are also unable to test the growth-to-saturation period that models produce from infinitesimal perturbations. They do show divergence, in that after a few days they are no longer distinguishable from randomly paired states, but that is consistent with ordinary weather variability. Consequently, the analogue tests neither support nor reject Chaos Theory's application to the real atmosphere.

NB. The fact that the observed deviation in the analogue tests is consistent with ordinary weather variability does not support Chaos Theory. Models are developed and tuned so that their weather variability roughly matches what is observed [18]. The range of model divergence at saturation is therefore constrained to be comparable to ordinary observed weather differences, and is not a product of the Chaos mechanism.

- Model artefact?

Selz and Craig (2026) show that in AI models which exhibit the rapid growth in divergence expected from Chaos Theory, the rapid growth could be eliminated or significantly reduced by running the model unchanged on a more accurate processor [19]. As they say, in those models the rapid growth "*is caused by numerical noise, which is an artifact of the computation rather than a real atmospheric process*". That does not show that Chaos Theory is only a feature of iterative models, but it does show that a butterfly effect in a model can be numerical rather than physical.

3 DISCUSSION

AI models have shown that numerical noise from processor inaccuracy can look like the rapid growth in divergence expected from Chaos Theory. In a General Circulation Model (GCM), calculations are iterated for cells that can be several thousand square km at Earth's surface and for time periods that are typically about 30 minutes. The model error from one iteration at one cell is likely to be similar to or exceed the "*numerical noise*" reported for the AI models. When rapid growth in divergence is found in GCM tests, it could therefore be an artefact of the GCM.

It is well known that weather and climate are variable and are hard to predict. However, the variations are not necessarily the exponential divergence described by Chaos Theory. At least some of the variability may ultimately be resolvable by better observations and better understanding, exactly as happens in other complex fields. For example, in the field of medicine there are routinely cases of people with only minor observable differences who experience very different outcomes from the same treatment, or from no treatment [20]. The normal scientific response is that all the relevant factors are not yet understood, rather than that it is deterministic chaos. Only in a few carefully studied physiological systems, notably some cardiac arrhythmias and some neural dynamics, is a chaotic explanation seriously advanced, and even there it remains contested [21]. It seems reasonable to take a similar approach in the field of weather and climate.

4 CONCLUSION

Models coded with mathematical formulae (such as NS) that exhibit Chaos Theory's expected rapid growth in divergence are unable to assess the applicability of Chaos Theory to the real world, because that would necessarily involve circular logic: the model results are only exhibiting an emergent property of the formulae as used in the models. Tests with atmospheric analogues are unable to assess the applicability of Chaos Theory to the real world, because they cannot emulate the infinitesimal perturbations at the core of Chaos Theory. Some AI models have shown that their rapid growth in divergence, as expected from Chaos Theory, is caused only or primarily by numerical noise. This is therefore an artefact of the computation rather than a real atmospheric process. GCMs use processes with inaccuracies similar to numerical noise, which could have a similar effect. Other AI models do not exhibit rapid growth in divergence. These findings apply only to the models, so they are not an assessment of the applicability of Chaos Theory to the real world. Chaos Theory remains void (scientifically inapplicable) with respect to the real world.

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