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Would be the Atmosphere Chaotic?
Seria a Atmosfera Caótica?

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Abstract

The atmosphere has often been considered "chaotic" when in fact the "chaos" is a manifestation of the models that simulate it, which do not include all the physical mechanisms that exist within it. A weather prediction cannot be perfectly verified after a few days of integration due to the inherent nonlinearity of the equations of the hydrodynamic models. The innovative ideas of Lorenz led to the use of the ensemble forecast, with clear improvements in the quality of the numerical weather prediction. The present study addresses the statement that *"even with perfect models and perfect observations, the 'chaotic' nature of the atmosphere would impose a finite limit of about two weeks to the predictability of the weather"* as the atmosphere is not necessarily "chaotic", but the models used in the simulation of atmospheric processes are. We conclude, therefore, that potential exists for developments to increase the horizon of numerical weather prediction, starting with better models and observations.
Keywords: atmospheric modeling; chaos; numerical weather prediction

Resumo

A atmosfera tem sido muitas vezes considerada "caótica" quando de fato o "caos" é uma manifestação dos modelos que a simulam, os quais não incluem todos os mecanismos físicos nela existentes. Uma previsão do tempo não se verifica perfeitamente depois de alguns dias de integração devido a não linearidade inerente às equações dos modelos da hidrodinâmica. As ideias inovadoras de Lorenz conduziram ao uso da previsão por conjunto, com melhorias flagrantes na qualidade das previsões. O presente estudo se contrapõe à afirmação de que *"mesmo com modelos e observações perfeitas, a natureza 'caótica' da atmosfera imporia um limite finito de cerca de duas semanas para a previsibilidade do tempo"*, uma vez que a atmosfera não é necessariamente "*caótica*", mas sim os modelos usados na simulação de seus processos. Conclui-se, portanto, que há espaço para o desenvolvimento no sentido de aumentar os horizontes da previsão numérica do tempo, a partir de melhores modelos e melhores observações.
Palavras-chave: modelagem atmosférica; caos; previsão numérica do tempo

1 Introduction

One question that transcends the philosophical aspect asks whether the atmosphere is “chaotic” in its physical nature or whether the state of chaos is inferred from the nonlinearity of the mathematical equations used in weather prediction models. The atmosphere has often been considered “chaotic” when the forecasts do not correspond to the reality, but in fact the “chaos” is a manifestation of the models that simulate the atmosphere because they do not include all the physical mechanisms that exist in nature. If “atmospheric chaos” really exists, it should not be explained by the nonlinearity of the model’s equations but rather by the physical behavior of the atmosphere itself (Santos & Buchmann, 2011).

The great contribution of Lorenz (1963) to weather forecasting is the use of ensembles, aiming not only to improve the quality of weather forecasts but also to increase the predictability term of the dynamic models used for this purpose. In this technique, weather forecasts employ initial conditions that are slightly perturbed and statistically evaluate the divergence of the solutions after a few days of the model integration (Krishnamurti & Zang, 1999). Currently, even when using the best models, the errors inherent in the observations used for the initial conditions lead to a prediction that is not verified observationally after a few days of integration. This failure is due to the nonlinearity inherent in the hydrodynamic equations of the models and is therefore a matter of mathematical order.

The objective of this work is not to demystify existing modeling techniques but to stimulate the scientific thinking of meteorological science researchers, especially younger generations, to seek new ways to approach physical processes in models to improve their responses. Certainly, the introduction of more physical processes in the models will raise the quality of weather forecasts.

2 “Chaotic Atmosphere” or Incomplete Models?

Lorenz’s system of nonlinear equations is a mathematical model that features the classical “chaotic” behavior known as “deterministic chaos”, which is unlike what happens in linearized equations whose response may be of a wave type. It is noteworthy that the two aforementioned systems are deterministic and differ from what is usually called “atmospheric chaos”, a problem that, if it indeed exists, should be explained through purely physical and not mathematical considerations. The system of nonlinear equations is a classical model that shows “chaotic” behavior. “Deterministic chaos” is a term that appears in Lorenz’s 1963 work related to the nonlinear equations of the hydrodynamic used to describe convection phenomena. In 1961, Lorenz, creator of the “chaos theory”, proposed this theory supported by mathematical models and not the physics of the atmosphere, and with consideration for the differences that the response of the model could suffer from due to tiny discrepancies in the input data. Thus, from slightly different initial states, the system of non-linear differential equations representing the atmosphere eventually results in different solutions.

Obviously, these different solutions originate from the intrinsic nature of the systems of the nonlinear differential equations used, which are extremely sensitive to small variations in the initial state. In linear systems, which have analytic or numeric solutions, very small variations in the initial condition also impose little variations on the final solution, and the responses differ very little, which does not occur in nonlinear systems. The linearized equations system is obtained by applying the perturbation method to the nonlinear equations of the hydrodynamics, which are linearized with respect to a basic state at rest. Then, using the separation of variables method, a set of linear equations is produced that consists of horizontal and vertical structures functions, the latter with convenient boundary conditions, constituting a Sturm-Liouville problem. In the horizontal structure, the homogeneous equations are identical to the linearized equations of the shallow-water model. The general solution is given by both, can be of a wave transient type, and does not amplify. (Matsuno, 1966; Kasahara & Puri, 1981; Kasahara, 1984; Santos & Buchmann, 2011).

A nonlinear system of differential equations can lead to unstable results even in deterministic systems, because they are highly sensitivity to disturbances, resulting in solutions that are unpredictable or “chaotic”. The nonlinearity, or at least a large number of interactions between components of the model, may lead to a random result. The nonlinear equations of hydrodynamics, or the primitive linearized equations, are deterministic from the point of view of classical mechanics. However, equations in their primitive form can lead to “deterministic chaos”, as discovered by Lorenz (1963). From these findings, Lorenz concluded that the prediction of climatic phenomena could only acquire a certain degree of accuracy using mathematical equations that take into account observational uncertainties. The central idea of this theory is that randomness or casual behavior is not governed by physical laws and can produce different results starting from slightly different input data.

Current models do not yet cover all relevant physical mechanisms found in nature, which could inhibit the growth of uncertainties, thereby improving the performance of those models. What happens physically in the real atmosphere cannot be fully explained by models. This is because models have both physical and mathematical limitations. Therefore, one should not form inadequate conclusions about the atmospheric environment based on the limitations of the models in use today. Thus, the problem of “deterministic chaos” is largely caused by the presence of nonlinear terms in the equations of the models, rather than by the physics existing therein. When we make use of the perturbation theory in nonlinear models, we eliminate the possibility of “deterministic chaos” emerging in the model. Therefore, “deterministic chaos” is a mathematical artifact, not a physical one. If “atmospheric chaos” exists, this could only result from the physical processes of the atmosphere. Put simply, the argument that the atmosphere is “chaotic” should only come from observation and experimentation in nature itself, not from the “chaotic” behavior of models. There are various physical processes inherent in the atmosphere acting to shape its behavior. Moreover, the shortcomings of models result from our very limited understanding of what is actually occurring in nature.

3 The Question of “Atmospheric Chaos”

Kalnay states: “even with perfect models and perfect observations, the ‘chaotic’ nature of the atmosphere would impose a finite limit of about two weeks to the predictability of the weather” (Kalnay, 2003). According to the author, this affirmative proposition would be based on studies mostly conducted by Lorenz, especially in his 1963 and 1965 articles. Observational experience, however, suggests that the atmosphere does not behave in a “chaotic” way. This fact allows for the use of climatology as a tool to predict future atmospheric behavior. In contrast to Kalnay’s consideration related to the problem of predictability being restricted to just two weeks, this limitation does not seem to come from the supposedly “chaotic” nature of the atmosphere but rather from the system of nonlinear equations of hydrodynamics. Therefore, this is a problem of mathematical order because those equations always lead to differing responses due to small differences in the initial conditions of the model variables (Lorenz, 1963).

In current models, failure to address several relevant physical mechanisms or limitations in our knowledge of the real state of the atmosphere should not result in the conclusion that nothing can be done to achieve better responses for longer prediction horizons.

In the real atmosphere, various inherent physical processes act to determine their behavior, which is diagnosed by the meteorological parameters observed. These physical processes are combined in an extremely complex way, making it appear that the atmosphere is “chaotic”, but this is not necessarily true. The shortcomings of our models are due to a very limited understanding of what is actually occurring in nature. Nonlinear atmospheric models show more ‘realistic’ results than linear models, and their “chaotic” answers therefore seem to be ‘realistic’, but this behavior is a mathematical, not a physical, problem.

A butterfly flapping its wings in one part of the world does not lead to a “chaotic” state in the atmosphere; for example, tornadoes and hurricanes that could supposedly be considered “atmospheric chaos” have known causes and only occur in specific seasons and in locations relatively well-defined climatologically. Thousands of bird wings agitate the air continuously. The propagation of those disturbances does not cause “chaos” in the atmospheric environment, as nobody ever has found this. The energy from wings flapping over time is not lost but is insufficient to cause atmospheric disorder elsewhere, near or far. Obviously, the energy of a butterfly or even thousands of them is not sufficient to cause a tornado and, at present, observations do not suggest that any existing physical process that could converge or canalize (manifold) the kinetic energy of the beating wings of birds or butterflies in certain preferred locations, times and paths. Could a butterfly beating its wings in Brazil cause a tornado in Texas, as proposed by Lorenz (1993)? Experience and observations indicate that energy does not cross easily from one hemisphere to another because of a critical latitude demonstrated theoretically by Dickinson (1971), synoptically by Namias (1972), and also by Buchmann (1981) and Buchmann *et al.* (1986) using numerical modeling.

Buchmann *et al.* (1995) indicated that the existence of low energy associated with low frequencies in the atmospheric environment comes from the interaction, dispersion and dissipation of high energy linked with high frequencies generated in the atmosphere by impacting meteorological phenomena and not by the exclusive presence of gravity waves. This, however, does not explain the presence of permanent chaos but only a temporary disturbance.

The concept of "slow manifold" was originally defined by Leith (1980) and Lorenz (1980). More detailed investigations have been made by Silva Dias *et al.* (1983) and Schubert & DeMaria (1985). After this, the physics controversy on this subject was described by Lorenz (1986), Lorenz & Krishnamurthy (1987) and Lorenz (1992).

The goal of meteorological science should be to search for alternatives to the nonlinear models whose predictability is limited today to a period of only two weeks (Kalnay, 2003). The introduction of more consistent physics in the models certainly will lead to more realistic responses and could eventually minimize the damaging effects caused by the nonlinearity of the system of mathematical equations used in atmospheric models today.

4 Conclusions and Suggestions

There is no physical explanation for what qualifies as "atmospheric chaos" or any reason to consider the atmosphere in a state of disarray. In fact, it is not possible to prove yet that the atmosphere is "chaotic" because of the absence of experiments for this purpose. Even the physical explanation of Lorenz (1963) that the flapping of a butterfly's wings could lead to "chaos" in the atmosphere would be difficult to prove scientifically starting from the observational point of view. A question that remains is: What is the basis for the argument that the atmosphere is "chaotic"? The physical behavior of the atmosphere? There is no observational evidence to indicate that the atmosphere is "chaotic". Is the argument based on the mathematics and/or the physics of the models used? In this case, the "chaos" would not be an attribute of the atmosphere but of the models. All arguments relating to "atmospheric chaos" refer to models that rely on one set of equations to represent the behavior of atmosphere. It is obvious that these models are "chaotic". If the atmospheric models cannot accurately represent the behavior of the atmosphere, then these models indicate deficiencies in the simulations. The "chaos theory" was developed precisely because Lorenz's model had failures, but the atmosphere is not necessarily "chaotic".

If atmospheric models have problems, they result from deficiencies in the models themselves, and those failures do not necessarily have anything to do with the atmospheric state. The air absolutely does not interfere with the model's response. It is possible that an association exists between them, but because there is no cause-effect relation, there is no interference. In other words, the limitations of the models are independent of the actual state of the atmosphere, whether chaos exists or not. Therefore, there is no interference of the atmosphere on the models response. It is possible to deduce from this discussion that the present limitation of the models' predictability to two weeks is inherent to the models itself, and cannot be attributed to an eventual "atmospheric chaos". Lorenz (1993) said about chaos: "It soon struck me that, if the real atmosphere behaved like the simple model, long-range forecasting would be impossible." Here is the actual problem: the real atmosphere has no obligation to behave like any model. Contrarily, models should represent atmospheric behavior as well as possible. Meteorologists neither demanded nor desired that the predictors know how or where a determined meteorological event originated. It is not important to know which butterfly or where butterflies flap their wings to predict the behavior of a hurricane. We are interested in knowing as much as possible about the progression of a hurricane over the past week, the past two weeks, the past three weeks, and so on.

In summary, the most important thing is not whether the atmosphere or the forecast models are "chaotic" but rather to understand that there is room for improvement in the performance of these models, as opposed to Kalnay (2003), who suggests that the reliability of predictions would be limited to just two weeks. Therefore, we should pursue better responses and longer predictability to reap greater benefits for the users of weather predictions.

Certainly, there are several physical factors that occur in the atmosphere that are not well known or understood and perhaps deserve to be considered due to their importance, including improving our prognostics on climatic changes. It is necessary to emphasize that current physical-mathematical models are no longer a priority; that is, they are much more settled in mathematics than in physics. Considering its scientific importance, this assumption deserves to be studied in the future.

The nonlinear processes existing in the atmosphere are not necessarily identical to the nonlinear processes existing in the models. In nature, the duration and cause of an impacting event depends on the energy involved in the generation of the event. In the models, however, some interactions of mathematical origin can lead to erroneous results, especially if the duration of the integration is sufficiently long. In models, the nonlinearity does not depend on the energy available but on the interaction between terms. In nature, the atmosphere in particular has its own intrinsic self-control; that is, the control of energy growth comes from natural laws. Therefore, when models are used, it is necessary to take caution that the parameters do not extrapolate along the time of integration.

Natural phenomena are frequently represented by mathematical equations that only describe behavior not physical evolution. The effects of nonlinearity begin to appear almost at the start of the integration of the models and increase with time. With the objective of reducing that effect, we could try to add more physics and then advance further in the integration by controlling those nonlinear effects. This could result in good predictions for longer than two weeks. We could advance a few steps more, but it is necessary to conduct experiments with this objective.

The "chaos theory" should not be an obstacle to furthering weather prediction. The Lorenz discovery should act as an ally in the use of the ensemble forecast. In numerical weather prediction, substantial progress has been made through the realization that the "chaotic" behavior of the nonlinear models requires the replacement of a single deterministic forecast with ensembles of forecasts with differences in the initial conditions that realistically reflect the uncertainties in our knowledge of the atmosphere. This realization led to the introduction of operational ensemble forecasting at both NCEP and ECMWF in December 1992.

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