Chaos and Atmospheric Predictability

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"Atmosphere Chaos" or "Deterministic Chaos"?

This article's principal objective is to demystify the confusion between the expressions 'atmospheric chaos' and 'deterministic chaos'. The expression 'atmospheric chaos' led to the belief that nothing could be made to extend meteorological predictability beyond two weeks, because the 'atmospheric chaos' imposes an 'intrinsic' physical limitation on predictions. This confusion between the two expressions lead to an erroneous conclusion: if the atmosphere is 'chaotic', nothing could extend the forecasts beyond two weeks, because this was a limitation physically imposed by the atmosphere itself. The arguments presented here took a different line of thought: the models to predict atmospheric behavior are 'chaotic' due the nonlinear character of its equations. Due to this characteristic, very small input changes in initial values lead to great divergence in the outputs some days later, and these changes are associated with the difficulty to know what is the 'real atmospheric state'. We suggest that possibly 'better models' and 'better observational data' could lead to more accurate atmospheric simulations and predictions, including extending the limit of useful forecasts to beyond two weeks.

Chaos - Not a Disincentive for Research

In the beginning of the numerical weather prediction, linear models were used to simulate atmospheric behavior, but advection terms were not considered. Lorenz (1963), using a model based on an approximate system of nonlinear ordinary differential equations, discovered that two runs of the model starting from slightly different initial conditions gave surprisingly divergent responses after a non-long period of integrations. Lorenz called this unexpected result 'deterministic chaos'. This study revisits the question of atmospheric predictability, suggesting that the research community should invest its effort in two approaches. Firstly, researches should endeavor to find modeling strategies that better reproduce the realistic ways large-scale interact with the small-scale in geophysical fluid systems, especially the atmosphere. Secondly, what is more evident to the meteorological community, we should strongly invest in obtaining better information about the actual atmospheric state and also in more effective forms to assimilate this information in models.

Improving Atmospheric Predictability

Nowadays it is well accepted that the actual models used to predict the weather are 'chaotic' with only a finite predictability. Since high-resolution global modeling approaches have become a current trend for weather prediction and climate projection, Shen (2014) propose numerical experiments with the objective to understand the role of the increased resolutions in the predictability of the models. Numerical tests proposed by Shen (2014) with different Lorenz models lead to conclude that the inclusion of new modes introduces terms that have collective impact on the increase of solution stability. While Lorenz (1963) demonstrated the association of the nonlinearity with the existence of the nontrivial critical points and strange attractors, Shen (2014) emphasizes the importance of the nonlinearity in enabling subsequent negative feedback to improve solution stability. He concluded that the chaotic responses that appear in the Lorenz's models could be suppressed by the inclusion of additional modes, producing stable solutions. Branstator (2014) presents modeling evidences supporting the notion that when considering the influence of tropical rainfall anomalies on the extratropical conditions, this influence on midlatitudes overcomes the two-week limit. He found that for typical pulses of tropical heating of transient events, its effect persists for at least two weeks and is even longer in certain regions. As a consequence, the adequate assimilation of the tropical heating produced by observed rainfall can lead to enhanced predictability in midlatitudes. Therefore, if one took observed tropical precipitation in account during data assimilation, the initial conditions would be better and the predictions in extra-tropics would improve.

Downscale or Upscale Propagation ?

To better understand how different atmospheric motion scales should ‘interact', reproducing in the models what nature probably does, Rotunno & Snyder (2008) have generalized the Lorenz model using a two-dimensional vorticity equation and equations of quasi-geostrophic dynamics at the surface. Later the Rotunno & Snyder (2008) model was modified by Durran & Gingrich (2014) using a smoother nonlinear saturation approach to investigate the error growth from different initial error distributions. Durran & Gingrich (2014) concluded that “initial small-scale errors, including those at length scales far larger than the size of ‘butterflies' do not matter when minor relative errors are present in the largest scales.” The basic explanation for the difference between their experiments is that downscale error propagation in turbulence is much faster than upscale propagation. The relative non-importance of small scale errors were actually included in Lorenz (1969), but seem it has been largely overlooked both in his conclusions and in some subsequent research.

Butterflies Are Not Important for Weather

The impact of large-scale initial errors in the ensembles implemented by Durran & Gingrich (2014) suggests that more extensive use of well-calibrated ensemble forecasts may provide one way of addressing the ‘uncertainty' associated with initial errors at all scales. It is well known the large-scale flow presents some different kinds of wave motions, basically the low-frequency Rossby waves. Because in middle and high latitudes most part of the energy of the large-scale motions is in quasi-geostrophic modes, many initialization methods used in global models of primitive equations filter out inertio-gravity oscillations, and other schemes attempt to separate the solutions into slow and fast modes. Raupp & Silva Dias (2010) made several studies to understand how Rossby slow waves can ‘interact' with fast waves and also if these slow modes can be significantly affected by the propagating fast modes. Based on arguments from the fluid dynamic resonance theory, they demonstrate that the only way for a Rossby mode to ‘interact' with fast waves is by entering in resonance with two inertio-gravity waves with nearly equal or opposite temporal frequencies. They also show in this sort of resonant ‘interaction' that the Rossby mode essentially acts as a catalyst for the energy exchanges between the two high-frequency modes, in the sense that it enables the resonance conditions to be satisfied and controls the ‘interaction' period through its amplitude, although the slow waves energy (amplitude) is not significantly affected by the fast propagating waves.

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