COMPLEXITY IN CLIMATE PHENOMENA

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Contents

Summary

In the present work we have attempted to illustrate the complex nature of the climate on time scales which cover about half of man's lifetime. We have restricted our attention to the atmosphere, i.e. the component of the climate system that is not particularly able to store heat. Moreover, we have seen that, in order to model reasonably the first few moments of the observed circulation, the dynamical nature of the solution must have a distinct complex character with a long-term variability. In our modeling effort, we have taken an approach closer to the one adopted to analyze a mechanistic process. In fact, we have singled out a particular climatic phenomenon, selected a particular scale of motion, described a rather fast instability mechanism, neglected a few variables of the climate, ignored any other interactions, and grossly reduced the number of degrees of freedom. Nevertheless, the equilibrium statistics are far from showing any simple behavior. Apparently, even in the limiting case here considered, the external input has been integrated by the system to generate an output where the few components considered seem to remain untwined. Further attempts at untwisting the motion in simple dynamical rules appear extremely difficult, perhaps impossible. Nevertheless, the dynamics preserves a few recognizable features, which may be studied and, therefore, their sources found. The observations reported in the present paper have given support to the model results and have somewhat enlarged the significance of the model's conclusion for the real world.

At this stage we owe a deep apology to the many authors who have given major contributions on the aspect of climate behavior here illustrated but have not been quoted in the paper. Unfortunately, space limitation does not allow a scholarly presentation even of the most recent literature. Thus, we have had to leave this task for other occasions.

We cannot end the present paper without reiterating the many assumptions which have been made in deriving our model. Throughout, it has always been far from our intention to present a realistic appraisal of the method of climatic modeling. However, it is commonly felt that a fully formulated realistic climate model is not merely a complicated system but rather a complex one.

1. Introduction

The word “climate” derives from the Greek word “clima-ata,” referring to the slope of the earth from equator to pole. This implies the concept of a spherical world, which is attributed to the Greek philosopher Pythagoras in the sixth century BC. Parmenides stipulated five zones on the surface of this spherical world (one torrid, two temperate, and two frigid) and stated that the central torrid zone was not amenable to life because of the heat from the direct rays of the sun (Harley and Woodward, 1987).

The Greek idea of climatic zones merely dependent on latitude persisted despite the fact that the geographical explorations, at the beginning of the fifteenth century, showed that the lands in the new world had climates that were by no means simple extrapolations of European climates. Highly irregular areas exhibiting contrasts in moisture supply as well as temperature appeared to be a new prominent feature. The zonal system continued to be shown on maps because of a lack of quantitative climatic information. With the development of meteorological instruments such as the thermometer in the late eighteenth century in Europe, regular climatic observations began to be taken.

The German scientist Wladimir Koeppen made the first quantitative classification of world climates in 1900. Koeppen was trained as a plant physiologist and realized that plants could serve as synthesizers of the many climatic elements. He chose as symbols for his classification the five vegetation groups of the French botanist De Candolle, which were based on the climate zones of the Greeks. These groups are: A, the plants of the torrid zone; C, the plants of the temperate zone; D and E, the plants of the frigid zone, while the B group represented plants of the dry zone. A second letter in the classification expressed the moisture factor (an Af climate is tropical and rainy). Modern atlases and geography textbooks continue to use the 100-year old Koeppen classification of climates, which was based on de Candolle’s vegetation groups.

The brief history, just outlined, of climate classification shows the common perception that the observed climatic conditions of a particular geographical position entwine (or twist together) at least three widely different elements: sun inclination at the horizon, moisture supply and evapotranspiration. A system whose parts are twisted together is better translated in Latin as "complexum" which, in turn, may be transliterated as a complex system.
However, climate, as fas as measuring its components is concerned, lends itself to be

studied by the scientific method. Thus, a pertinent definition of a complex system should be given, and tested for advantages gained in describing the behavior of our data. Although, at present, there is no universally-agreed definition of a complex system, work has been done suggesting (e.g. Badii and Politi, 1997) that such a system should have at least three salient traits.

First, it should consist of many components interacting significantly on all scales of the system. Next, each component should lead to irregular behavior. Finally, the overall evolution should manifest different length and/or time scales.

That climate system possesses these traits is easily documented. In fact, it is the end result of the interactions among the atmosphere, the crio-sphere and the ocean-sphere. Each component has spatial scale, ranging from global to a few kilometers. Regarding the time scales, paleoclimate data (Imbrie, 1992) show variability from few days up to million of years, while the overall patterns display some degree of regularity embedded on a highly fluctuating background.

Having given arguments supporting the consideration of the climate as a complex system, we must consider the tools that would be most suitable for the successful study of its behavior, By its own definition, a complex system appears unsuitable for an approach following the mechanistic paradigm. In fact, within this framework, the system would be reduced to isolated objects without internal structure obeying external, invariant laws. Climate, instead, manifests its own capability to integrate the input into unpredictable output. Such a behavior shows clearly that the inner non-linearity of the system hardly allows its effective handling within a mechanistic framework.

On the other hand, the notions discussed so far may lead to the somewhat erroneous impression that a complex system is necessarily expressible by means of complicated equations. Although this is often the case, sometime a complicated set of mathematical statements does not lead to a complex behavior. Maxwell equations in the vacuum are an example of complicated equations leading to simple behavior, while, as shown by Lorenz (1963), a system consisting simply of three variables may lead to a complex evolution. Thus, the degree of complexity may not be defined by just looking at the complicated nature of its governing equations but rather by the complicated structure of their solutions.

Certainly, climate is described by complicated sets of mathematical statements but its complexity arises from mathematical structures describable in terms of a few degrees of freedom.

Approaching the climate as a complex system surely requires effort to solve the equations of motion in their full formulation; however, we should not forget that the other equally important task is to extract from these equations the relevant variables that lead to the climate complex behavior.

To be more specific, the climate system is a heat engine, which is driven essentially by the radiation provided by the sun. The absorbed solar radiation is re-emitted to outer space by the earth’s surface and the atmosphere as infrared radiation. However, the latitudinal dependence of the solar flux reaching the earth causes temperature gradients that drive the atmospheric circulation. The atmospheric winds, in turn, drive the ocean currents. These circulation systems counteract the differential warming. Energy and mass fluxes between the oceans, the atmosphere, plants on land and the water in all its physical states, govern the inner dynamics of the climate system on a broad range of time scales from hours to millennia. On still longer geological time scales, movements of the continents, formation of mountains and variations of the earth's orbit parameters also influence climate. Despite the nature of these interconnections requiring a complicated mathematical description, their behavior might be accounted for through a hierarchical set of models, which may be of various difficulties.

The present paper intends to consider a few of these models by showing how a class of them may be reduced to a simple mathematical form with complex behavior. In particular, we will discuss some of the processes that may govern the long-term average of the atmospheric circulation. These processes adjust the instabilities caused by the differential heating (both vertically and horizontally dependent) created by the atmospheric composition and the earth curvature. We will illustrate these processes by means of rough simplifications of the governing equations, losing details, but gaining, at least in our opinion, some understanding of how complexity characterizes climate behavior.

The outline of a consistent theory of the atmospheric general circulation has a long history going back to Hadley (1735) (see Lorenz, 1967 for an excellent review both of the historical background and the physical basis of the theory). It is a task of dynamic meteorology to combine the physical principles into a mathematical theory from which to deduce the behavior of the earth's atmosphere. In the present work we set out on a possible approach to the problem by applying it to a highly idealized model. We will try to develop some sets of principles which, by now, may be accepted with a certain degree of confidence:

i) An axially-symmetric radiative equilibrium exists, because of earth's spherical geometry and its rotation, where the external source of energy is balanced by earth's radiation;

ii) This radiative equilibrium is unstable for convective motion. The instability is readily equilibrated (in a few hours) to an adjusted state that is usually known as a radiative-convective equilibrium.

These two points have reached a fair consensus among the scientific community and they will be illustrated in section 2. The open questions concern mainly the stability properties of the circulation satisfying the previous statements. Namely, the equator-to-pole temperature gradient associated with the radiative-convective axially symmetrical circulation may be unstable with respect to perturbations acting as eddy elements. The latter may both distort the zonal mean flow through Reynolds stresses and conduct heat upgradient. The net effect may be one of modifying the equator-to-pole temperature difference which, in turn, is forced by the steady heat source to restore a radiative-convective equilibrium. Whether the resulting statistically-equilibrated, zonally-averaged circulation remains subcritical, with respect to other baroclinic disturbances, is debated. As a matter of fact, the observed poleward temperature gradient is about 40 ^{o}K and whether such a gradient suffices to generate further baroclinic activity is unclear.

However, baroclinic instability is a scale-selective process, with maximum instability on synoptic scales (say 1000 *km* or so). It follows that there is yet a wide spectrum of planetary scale eddy motion that may be less prone to generation by the ordinary baroclinic instability of the pole to equator temperature gradient. These eddies, instead, may be excited by the interaction between the axially symmetric zonal wind (associated with the equilibrated meridian temperature gradient) and the non-homogeneous nature of the earth's surface. The result may be a zonally asymmetric circulation. However, these stationary fields may be unstable with respect to perturbations of other planetary scale eddies. Therefore studies should focus on the kind of equilibration that may be reached and its contribution to the zonally averaged circulation. Observations, to be shown later, suggest that, on the monthly basis, a great deal of the observed intraseasonal and interannual variance is associated to the planetary eddies fields. Therefore, they may be important contributors to the longtime climatic statistics. , This example of the nature of these fluctuations shows how complexity arises even in the simplest model -- an important feature of climatic behavior.

The process is of a dynamical nature; therefore the desired theory is one that accounts for the statistical equilibrium implied by the outlined physical mechanism. The underlying problem may be stated in hydro-dynamical terms as follows:
Given a distributed heat source decreasing in intensity from equator to pole, a slowly varying circulation is set up, interacting with the earth's surface. The resulting circulation may be unstable for planetary wavelike disturbances which, therefore, grow in amplitude. The properties of the final state of motion should be calculated and, if possible, the nature of the perturbation.

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Biographical Sketches

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