

The Index Cycle is Alive and Well

Edward N. Lorenz

Massachusetts Institute of Technology

Some thirty-five years ago Namias presented a theory of the major variations of the zonal index. Interest in the index cycle declined during the ensuing years of increasing enthusiasm over numerical weather prediction, and some studies appeared to indicate that the variations of the index were random. The index cycle is now recognizable as a manifestation of chaos rather than randomness.

Laboratory and numerical models have produced index cycles with varying degrees of irregularity. Interest in the index cycle and related phenomena such as blocking has recovered as numerical weather prediction has come of age. In one numerical model the index cycle plays an essential supporting role in producing very-long-period climatic variations.

One of the prominent features of the circulation of the atmosphere is the presence of a broad belt of westerly winds in middle latitudes of either hemisphere. As a long-time observer of worldwide weather patterns and their day-to-day, week-to-week, and month-to-month variations, Jerry Namias always took a keen interest in the behavior of the westerlies.

Nearly fifty years ago, in what has become one of the best known meteorological papers ever published, Rossby and collaborators (1939)—Namias was one of the key collaborators—introduced the average wind in the belt between 35°N and 55°N , measured geostrophically as the pressure difference between 35° and 55° , as a conveniently computed index of the strength of the zonal westerlies. Originally defined at sea level, the “zonal index”, as it came to be called, was soon afterward evaluated at upper levels also. The same paper introduced Rossby’s famous formula, expressing a direct relationship between the strength of the westerlies, i.e., the zonal index, and the speed of progression of the secondary systems.

As recounted by Willett (1948)—another key collaborator—it soon became apparent that the zonal index as defined was sensitive to the latitude as well as the strength of the westerly current, and that, quite aside from displacement rates, the weather structures typically found during periods of high zonal index differed systematically from those characteristic of a low index. It therefore appeared that a good forecast of the zonal index ought to be a useful first step in the preparation of an extended-range forecast.

Although Rossby and his collaborators had used the term “index cycle” to describe the changes which took place as the zonal index fell from a high to a low value and then returned to a high value, it was Namias (1950) who first systematically examined the index cycle with an attempt to determine a physical explanation for its principal features. For the winter season, he found such an explanation in the accumulation of a reservoir of cold air at high latitudes, which would ultimately be released in the form of cold outbreaks. Such outbreaks could be of extended duration, and they would inhibit

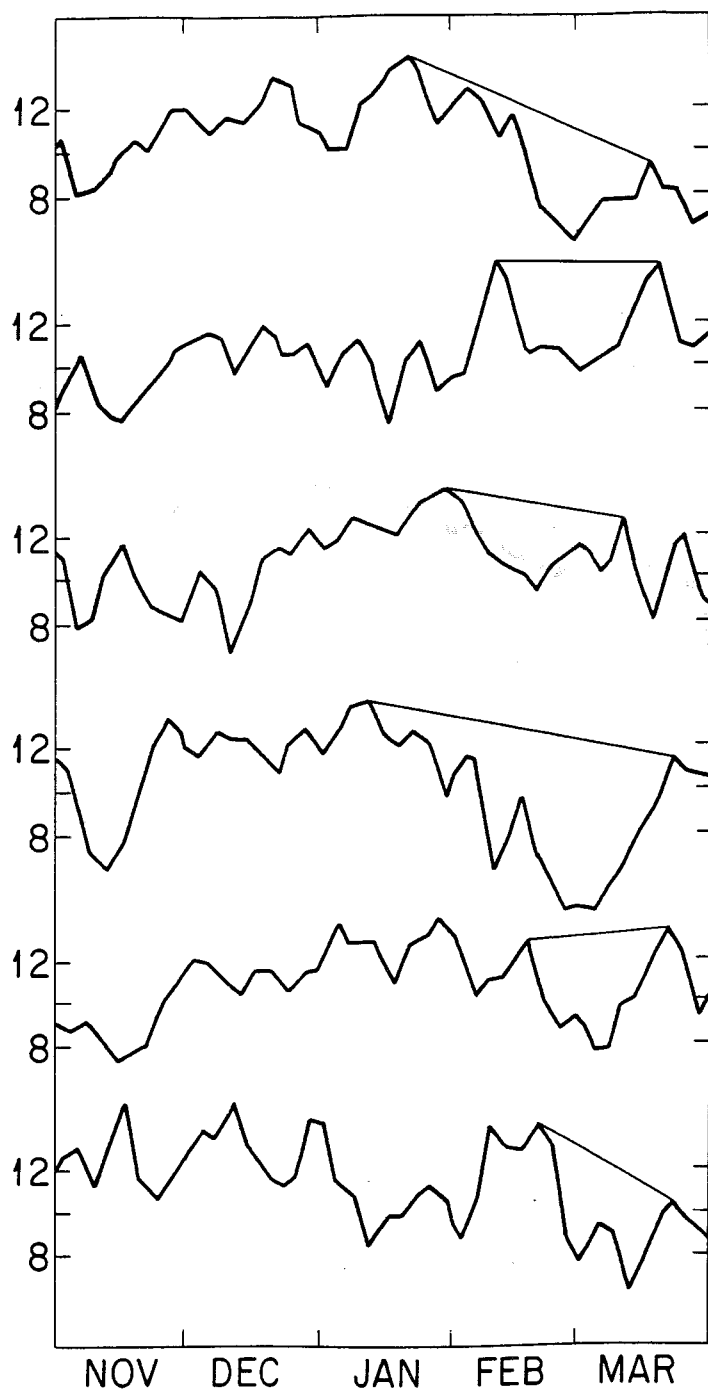


Figure 1. The 5-day averaged 700-mb zonal index, in m s^{-1} , from November through March during the six successive years 1943-44 to 1948-49. The thin line segments connect the beginning and end of the principal index cycle in each year, as identified by Namias. The figure is based on Fig. 1 of Namias (1950).

a strong eastward flow, thus producing a low value of the index. A striking finding was the tendency for the index cycle to occur at the same time in different years; Fig. 1, which is condensed from one of the figures which Namias presented, shows the variations of the 700-millibar zonal index during six successive winter periods, and reveals a tendency for the low point in the most pronounced cycle to occur in late February or early March— a time when the supply of cold air is abundant.

During the ensuing years I saw Jerry on frequent occasions, and our conversation would often turn to the zonal westerly winds and the distinctive features of their fluctuations. Thus, when I was recently invited to speak at this symposium on some topic related to Jerry's interests, I more or less automatically turned to the index cycle.

My own interest in the zonal westerlies as a possibly predictable phenomenon began while I was working with Victor Starr, who was at that time investigating the angular-momentum balance of the atmosphere. Starr (1948) had noted that a dominating process in changing the relative angular momentum, proportional at any latitude to $[u]$, was the convergence of the poleward transport of angular momentum, proportional to $-\partial[uv]/\partial y$, and he had hypothesized that the larger-scale eddies might account for a major fraction of the transport. Here u and v are the eastward and northward wind components, y is distance northward, and brackets denote an average about a latitude circle. If such was the case, $[uv]$ could be estimated fairly well from pressure-height observations, using the geostrophic approximation, and measurements of the virtually unmeasurable departures from the geostrophic wind would be unnecessary. When sufficient data became available, I found significant lag correlations between $[uv]$ and $[u]$ at various latitudes (Lorenz, 1952). At U.C.L.A., similar ideas were being pursued by Jacob Bjerknes, and Mintz was conducting studies parallel to mine (Mintz and Kao, 1952).

As a further step in establishing a procedure for predicting $[u]$, I sought to learn what accounted for the changes in $[uv]$. Here any expressions that I could derive involved departures from the geostrophic wind, and no simple physical interpretation appeared to be at hand. I soon found myself concentrating on other matters.

It was just at this time that numerical weather prediction was beginning to reveal its potentialities. In the same year that Namias published his study of the index cycle, Charney, Fjörtoft, and von Neumann (1950) described a moderately successful numerical integration of the barotropic vorticity equation, and the meteorological world became aware that numerical weather prediction was here to stay. The popularity of the new method soon led to a perhaps predictable side effect, however. In making a numerical forecast, one takes a set of numbers representing the initial wind, pressure, and temperature fields, and, regardless of what synoptic structures may be present in these fields, plugs the number into the same program, obtaining another set of numbers representing the forecast. Inevitably the attitude arose that fields rather than structures or phenomena, such as cyclones and fronts or cyclogenesis and frontogenesis, were the essence of the atmospheric state. Whether or not many meteorologists actually changed their views, the views of the meteorological world as a whole did change, because that world was being rapidly augmented by younger scientists who were trained with the new methods and exposed to the new attitudes. In particular, the perceived importance of the zonal index and the index cycle declined. Since Jule Charney, probably more than anyone else, was responsible for making numerical weather prediction a reality, I feel compelled to add that he did not share the attitude of some of his contemporaries toward structures; in fact, his introduction of the geostrophic filtering

approximation was prompted by the realization that synoptic forecasters made reasonably good forecasts, based upon the location of structures, without any indication of the departures from the geostrophic wind. Later on he worried because the sets of numbers representing the weather patterns could not resolve fronts, which he regarded as essential elements.

As it became more and more evident that the equations of numerical weather prediction gave fair approximations to reality, I suddenly realized that I had an answer to my problem; to find an expression for the time derivative of $[uv]$ which did not involve geostrophic departures, it was sufficient to use the equations of numerical weather prediction to find the derivatives of u and v , and hence of uv , at each longitude, and then integrate over longitude. Almost simultaneously, however, I realized that my success was somewhat empty; if the zonal index was to be predicted as an aid to predicting the weather pattern, and if one first had to predict the weather pattern in order to predict the zonal index, why bother to predict the zonal index?

The status of the zonal index and the index cycle was probably not elevated by a subsequent study by Enger (1957), who examined 25 years of daily sea-level zonal-index values, and found that they very closely fit a first-order Markov process, with a one-day lag correlation of about 5/6. Such a process was suggestive of randomness. In attempting to assess Enger's results a few years later (Lorenz, 1964), I found that an artificially constructed first-order Markov process with a similar one-lag correlation "looked like" a zonal-index time series; it was hard to tell by inspection which series was which.

In the light of more recent work, it is now apparent that in looking at the index cycle we were not looking at randomness, in the classical sense. What we were seeing was chaos, as recently defined. The term "chaos", formerly used with a number of connotations, is now used extensively to refer to any deterministically evolving process which may appear to be evolving randomly, particularly if it is observed at rather infrequent intervals. A rapidly increasing body of knowledge now exists, and many examples have been described (cf. Guckenheimer and Holmes, 1983). Quite a few examples come from meteorology. Close inspection of a chaotic time series often reveals certain regularities, even though the series is not periodic. Tests for distinguishing between chaos and pure randomness have been developed; these do not include classical spectral analysis.

Evidence that regularity in the index cycle constituted a physically reasonable assumption was actually accruing well before the apparent randomness received attention. Fultz (1953) had already found that water in a suitably heated rotating cylindrical container in the laboratory would acquire a circulation rather similar to that of the atmosphere, and apparently resulting from similar causes, but the "vacillation" discovered by Hide (1953) in his experiments immediately suggested an index cycle. Vacillation is a phenomenon where the flow pattern, instead of exhibiting the seeming irregularity found in the atmosphere, develops a chain of identical waves superposed on the zonal westerlies, whereupon these waves, in addition to progressing eastward, undergo regular periodic changes in their shape or intensity, completing a cycle in a few simulated days or weeks. The transport of angular momentum effected by these waves necessarily varies with a similar period, and produces periodic variations of the zonal index.

Vacillation did not invariably occur in Hide's apparatus, and different rates of rotation or different amounts of heating would lead to different regimes with various

degrees of regularity or irregularity. If the real atmosphere was obviously in a less regular regime than vacillation, there was still no *a priori* reason why it had to be completely irregular.

A few years later I succeeded in producing chaotic "index cycles" with a simple numerical model (Lorenz, 1962). The model was derived by severely truncating the equations of the familiar two-layer geostrophic model so popular in numerical forecasting at that time, and it consisted of 12 coupled ordinary differential equations, whose 12 variables—six representing the 500-milibar wind field and six representing the temperature field—were supposed to capture the gross features of the general circulation. The external heating driving the model circulation varied with latitude and longitude but not with time.

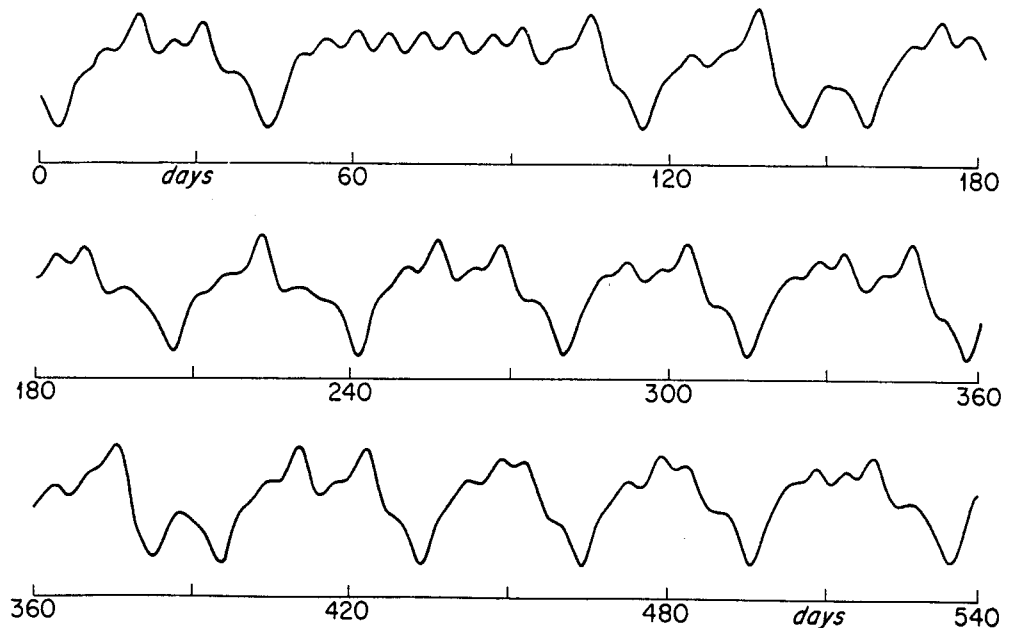


Figure 2. Variations of the "zonal index" in the 12-variable model of Lorenz (1962) during 18 consecutive months.

Fig. 2 shows the variations during an 18-month period of one variable, which represents the contrast between the speeds of the westerlies in high and low latitudes; a positive value indicates that the westerlies are displaced northward. Since the real atmosphere zonal index depends upon the latitude as well as the intensity of the westerlies, it seems permissible to call this variable a zonal index. We see some obvious regularities despite the absence of periodicity; this is typical of the simpler examples of chaos. There are episodes of high index, lasting a month or longer, separating briefer periods of low index. The separate episodes share many features, including a rapid initial rise from low index, superposed shorter-period oscillations while the index is high, and a rapid final fall to low index. An unanticipated feature, which hints that "synoptic" methods of forecasting the model's behavior could have been developed, is the occurrence of a second minimum, about two weeks after a first minimum, whenever there has been a very smooth descent from a high maximum to the first minimum; this feature appears twice in Fig. 2.

Numerous "global circulation" models have appeared in more recent years. Some are even simpler than the 12-variable model which we have described, while others, including the largest models used in operational weather forecasting, possess several hundred thousand variables. These models produce their own index cycles. Not surprisingly, the cycles in some instances are as regular as vacillation, and in others are seemingly as irregular, and perhaps actually as irregular, as the real atmospheric index cycle. They are nevertheless manifestations of chaos rather than pure randomness, and regularities may be present even when they are not obvious. The real index cycle appears to exhibit some regularities, including the seasonal preference noted by Namias, and it is not unreasonable to conjecture that additional regularities might be revealed by suitable analysis schemes.

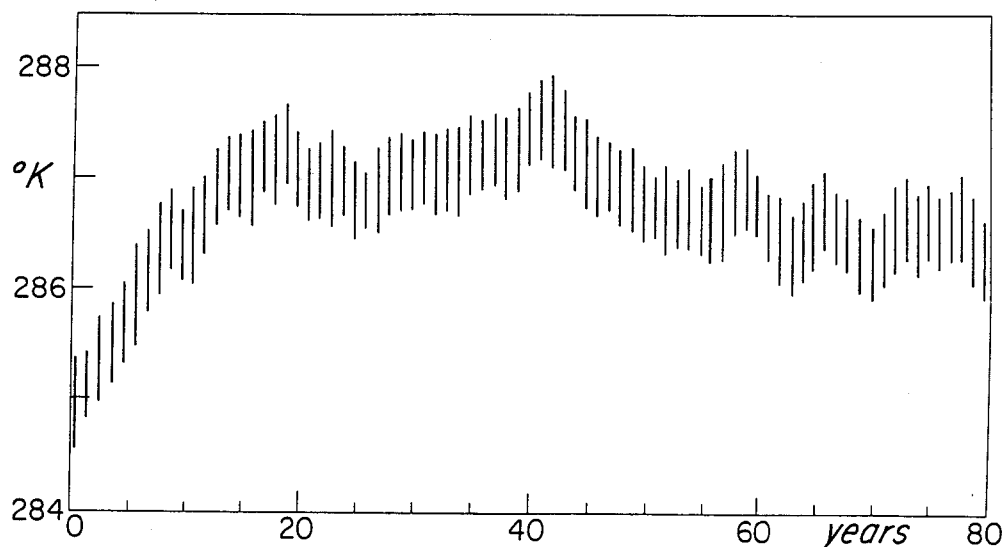


Figure 3. Ranges of the globally averaged temperature in the 27- variable model of Lorenz (1984) during 80 consecutive years, starting from sub- equilibrium conditions. The numerical values of the constants are those used in Tables 2-4 of Lorenz (1984), except that the lapse rate is 7/10 of the dry- adiabatic, the heat capacity of the oceanic layer is 10 times that of the atmosphere, and $T^* = 273.0 + 10.0\phi_3$.

Along with the coming of age of numerical weather prediction has come the realization that further improvements may depend more and more on skillful engineering and less and less on new scientific breakthroughs. Scientific studies which have not avoided numerical methods altogether have therefore tended to take already-developed models and apply them to specific problems. Inevitably many of the recent studies have dealt with structures and phenomena.

One phenomenon which has received much attention in the past few years is blocking. This has traditionally been considered a low-index phenomenon, and its occurrence is presumably linked in some manner to the index cycle. One may argue as to whether the low index is primarily a cause or an effect. Nevertheless, as a phenomenon which may be observed in the atmosphere, and produced and controlled in the laboratory and the computer, the index cycle appears to be quite healthy.

Let me conclude by describing a numerically produced phenomenon in which the index cycle seems to play a crucial supporting role. This is the long-period variabil-

ity of the globally averaged temperature as observed in a 27-variable model. The model, described elsewhere in detail (Lorenz, 1984), is an extension of the 12-variable model which produced Fig. 2, and, in addition to a thirteenth variable T_0 representing the globally-averaged sea-level temperature, contains seven variables representing the moisture field and seven representing the sea-surface temperature. A key feature is the use of the total dew point—the value which the dew point would assume if all the water were converted to vapor—as the moisture variable; an auxiliary equation determines the apportionment of the water between vapor and liquid, and guarantees that supersaturation will not occur. The model includes viscous and thermal damping, evaporation and precipitation, and radiative heating and cooling. The cloud cover is a preassigned function of the relative humidity, and the albedo depends in turn upon the cloud cover.

A feature which was not intentionally introduced and not anticipated is a cloud-albedo feedback process; a positive temperature disturbance produces a drying of the atmosphere, which reduces the cloud cover and the accompanying albedo and allows the sun to produce further heating. As a consequence the approach to equilibrium from an unbalanced state is an extremely slow process, often requiring several years. The rather high heat capacity of the upper oceanic layer contributes to the slowness.

In Fig. 3 the vertical bars show the ranges of T_0 during 80 consecutive years, in a solution beginning with a sub-equilibrium temperature. Baroclinic activity of variable intensity occurs throughout the period, and is carried explicitly in the model, which is integrated in 90-minute time steps. Although the ranges in successive years show considerable overlap, there is a gradual progression toward apparent equilibrium, lasting about 20 years. After year 40 a gradual downward progression develops, suggesting that equilibrium may not have been reached after all.

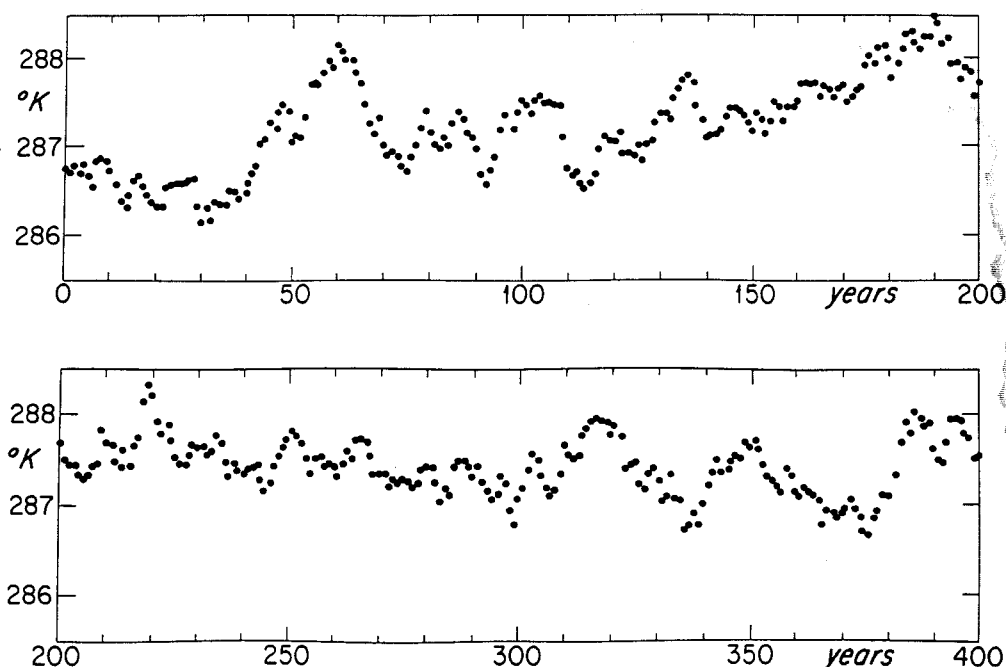


Figure 4. Annual mean values of the globally averaged temperature during 400 consecutive years in a continuation of Fig. 3. The initial state follows the initial state of Fig. 3 by 50 years.

Fig. 4 shows annual mean values of T_0 for a 400-year period; the first 30 years are the final 30 years of Fig. 3. Evidently the downward trend does not continue, and is followed by a rise of more than two degrees to an ultimate peak 160 years later. Thereafter fluctuations continue, and no unequivocal equilibrium value of T_0 can be identified.

A one- or two-degree local temperature change is not a spectacular event. The significance of Fig. 4 is that the globally and annually averaged temperature is changing by this amount, and corresponding changes in the real atmosphere seem to be of comparable magnitude. In all likelihood an overall warming or cooling of the real atmosphere resembling what appears in Fig. 4, say from year 30 to year 60, year 115 to year 135, or year 350 to year 375, would, once detected, be interpreted as a climatic change by many observers, and attempts would be made to determine the cause.

In Fig. 4 the changes simply represent the model's natural variability; there are no variations in external conditions. However, the nonlinearity associated with the moist processes leads to weak interactions between the mean temperature and the cross-latitude temperature gradient. If these interactions were suppressed, T_0 would in due time approach equilibrium. It appears, then, that the variability of the temperature gradient and its associated westerly wind current, i.e., the index cycle, is acting as a weak quasi-random forcing upon the mean temperature, producing the "climatic" variations.

What does this result tell us about the real atmosphere? Certainly it does not say that real climatic fluctuations are produced by a cloud-albedo feedback process; we do not even know whether such a process actually takes place. It does tell us that the very-long-period fluctuations may depend upon features which seem so secondary that they are often omitted in theoretical investigations. Instead of clouds, the key feature might be ice, or perhaps vegetation. It might even be some feature which we have not yet dreamed of examining.

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