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The Saltzman–Lorenz Exchange in 1961: Bridge to Chaos Theory

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ABSTRACT: A single-day meeting between two theoretical meteorologists took place in 1961 at the Travelers Research Center (TRC) in Hartford, Connecticut. The two scientists were Barry Saltzman and Edward Lorenz, former proteges of V. P. Starr at Massachusetts Institute of Technology (MIT). Several years before this meeting, Lorenz discovered the following profound result: extended-range weather forecasting was not feasible in the presence of slight errors in initial conditions. The model used was the geostrophic form of a two-level baroclinic model with 12 spectral variables. These results were presented a year earlier at the first symposium on numerical weather prediction (NWP) in Tokyo, Japan, and met with some skepticism from the NWP elite, dynamical meteorologists, and pioneers in operational NWP. Lorenz held faint hope that Saltzman's recently developed model of Rayleigh–Bénard convection would produce the profound result found earlier. One of the numerical experiments executed that eventful day with Saltzman's seven-mode truncated spectral model produced an unexpected result: inability of the model's seven variables to settle down and approach a steady state. This occurred when the key parameter, the Rayleigh number, assumed an especially large value, one associated with turbulent convection. And further experimentation with the case delivered the sought-after result that Lorenz had found earlier and now convincingly found with a simpler model. It built the bridge to chaos theory. The pathway to this exceptional result is explored by revisiting Saltzman's and Lorenz's mentorship under V. P. Starr, the authors' interview with Lorenz in 2002 that complements information in Lorenz's scientific autobiography, and the authors' published perspective on Salzman's seven-mode model.

SIGNIFICANCE STATEMENT: Although Edward Lorenz is known as the father of chaos theory, few know about the 1-day meeting between Lorenz and Barry Saltzman in 1961 at the Travelers Research Center (TRC) in Hartford, Connecticut, a meeting that built the bridge to chaos theory. This history paper explores results found that day through numerical experiments with Saltzman's recently developed seven-mode Rayleigh–Bénard convection model. Several years earlier, Lorenz discovered that slight inaccuracy to initial conditions in a deterministic model led to the impossibility of extended-range forecasting. He was looking for a more convincing and simpler model that would exhibit the same result. He held faint hope that Saltzman's model would exhibit this result. However, when the model was executed in a high Raleigh-number regime, the hoped-for result was apparent. In this regime, the seven-mode spectral model was reduced to a three-mode model, Lorenz's classic three-mode butterfly model.

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1. Introduction

Barry Saltzman, a research meteorologist at the Travelers Research Center (TRC)[1] in Hartford, Connecticut, and Edward Lorenz, a professor of meteorology at Massachusetts Institute of Technology (MIT), met on an afternoon in 1961 at TRC. The purpose of the visit was to examine computer output from Saltzman's spectral model of Rayleigh–Bénard convection (Bénard 1900; Rayleigh 1916). Lorenz had found a profound result several years earlier: extended-range weather forecasting was not feasible in the presence of slight errors in initial conditions. The geostrophic form of a two-level baroclinic model with 12 spectral components produced this result. He was in search of a simpler model well founded physically. Lorenz hoped that Saltzman's model would deliver this same sensitivity, but the hope was faint since he had spent several years searching for such a model. Surprisingly, a numerical experiment with Saltzman's seven-mode spectral model, an experiment with a relatively large Rayleigh number, exhibited an aperiodic flow regime that would not settle down to a steady state. Further experiments revealed the extreme sensitivity to initial conditions.

The steps that led to this scientific discovery are explored by 1) examining the mentorship of these two meteorologists under Victor Paul ("V. P.") Starr, 2) a brief review of results from Lorenz's two-level baroclinic model, 3) the part played by events at the 1960 numerical weather prediction (NWP) symposium in Tokyo, Japan, 4) details of the critical numerical experiment with the seven-mode model, and 5) a perspective on the seven-mode model based on the present authors published paper on the subject.

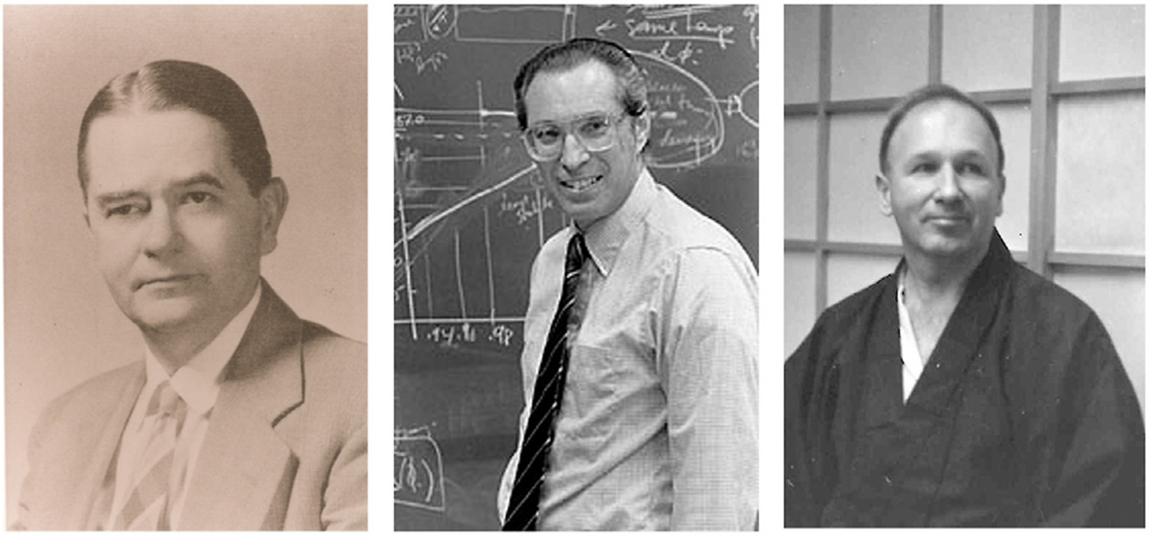
The three theoretical meteorologists central to this study are V. P. Starr, Barry Saltzman, and Edward Lorenz. They are pictured in Fig. 1. They were primarily professors during their careers: Starr at University of Chicago from 1941 to 1947 and at MIT from 1947 to 1974; Saltzman at Yale University from 1968 until his death in 2001; and Lorenz at MIT from 1954 to 1987. These scientists were also winners of the prestigious Carl-Gustaf Rossby Research Medal. Years of their awards: Starr 1961; Lorenz 1969; and Saltzman 1998.

[1] The Travelers Weather Research Center, later named the Travelers Research Center (TRC), was the first privately owned research institute for scientific study of weather, emphasizing statistical methods. This organization was closely linked to MIT through Tom Malone and Robert White in the 1950s and 1960s. Both men became TRC directors after leaving MIT—Malone in 1955 and White in 1960.

2. Saltzman's and Lorenz's Mentorship under V. P. Starr at MIT

a. Starr at University of Chicago. Victor Starr began his career in meteorology after receiving his master of science degree from MIT in 1938. He spent several years working for the U.S. Weather Bureau (USWB) before joining Carl-Gustaf Rossby in 1941 as an assistant professor of meteorology at the Institute of Meteorology, University of Chicago (U of C).[2] This institute was created along with four other academic institutions in the United States to train weather forecasters in support of aviation during World War II (WWII) (see Harper 2012, chapter 3). Starr demonstrated clarity and precision in his approach to

[2] Starr's position at U of C and the courses he taught are based on two lists: Officers of Instruction and Courses of Instruction, Institute of Meteorology, University of Chicago, Academic Year 1943/44 (Courtesy of University of Chicago Archives 1991).



Victor Paul (V. P.) Starr Barry Saltzman Edward Lorenz

Fig. 1. Photos of Starr (1909–76), Saltzman (1931–2001), and Lorenz (1917–2008) where the dates in parentheses are years of birth and death. Lorenz is pictured in a kimono at the NWP symposium, Tokyo, Japan, in 1960, and Saltzman is shown teaching class at Yale (date unknown).

teaching Dynamic Meteorology (Meteorology 316) and Introductory Meteorology (Meteorology 201). He was soft spoken and reserved, with few wasted words while lecturing, showing evidence of advance preparation.

Besides his teaching and advising assignments, he played an important role in supervising Rossby's doctoral students when Rossby was called away from the U of C for extended periods during the war years. Further, Rossby called on Starr to work with Dave Fultz in establishing a hydrodynamics laboratory at U of C, a laboratory used for instruction after the war years and under Fultz's direction from the late 1940s to the 1980s. Laboratory experiments conducted at this laboratory were central to understanding the dynamics of the atmosphere's general circulation.

Starr steadily made headway on his doctoral research under Rossby, and he became a key member of the Institute's research staff investigating jet stream dynamics. Shortly before the jet stream paper was published (Staff Members of the Department of Meteorology of the University of Chicago 1947),[3] Starr received his doctor of philosophy under Rossby with a dissertation titled: A Quasi-Lagrangian System of Hydrodynamic Equations (Starr 1945). The theme of the dissertation was an innovative method of combining Eulerian and Lagrangian systems of equations—an approach still used today at operational weather prediction centers worldwide. In 1947, Starr left U of C and accepted a professorship at MIT.

[3] Starr was 1 of 10 meteorologists listed among the "Staff" authors of this paper.

b. Starr at MIT. Lorenz came under Starr's influence after receiving his doctorate at MIT in 1948, under Professor James Austin, dissertation titled: A Method of Applying the Hydrodynamic and Thermodynamic Equations to Atmospheric Models. Saltzman's mentorship under Starr began in 1952 when he entered graduate school at MIT. Thus, Lorenz and Saltzman were at different levels in graduate school when they first met, one a beginning graduate student and the other a postdoctoral student. But more importantly, they were both working on Starr's eminently successful General Circulation Project sponsored by the U.S. Air Force.

Both young meteorologists were theoretically inclined, yet they were assigned to research projects that used observed atmospheric general circulation data: angular momentum and kinetic and potential energy budgets to investigate climate-scale circulations. Their work was accomplished under the guidance of Starr's primary postdoctoral assistant, Robert M. White. During his years at MIT and his association with Starr's General Circulation Project, White demonstrated his independence by publishing six single-authored papers in major journals between 1949 and 1954 (White 1949, 1950, 1951a,b,c, 1954). His managerial skills were apparent while he supervised graduate students, but these skills would blossom after leaving MIT in 1960 to assume the presidency of TRC, and while serving in that position, President John F. Kennedy named him Chief of the USWB in 1963. His career from that point onward was as politically and scientifically important as any meteorologist in the history of the United States—serving as the head of government meteorological organizations and the National Academy of Engineering until his retirement in 1995.

Lorenz remembered his work on the general circulation project: "After finishing my doctorate at MIT in 1948, I stayed on as a research associate under Victor Starr on general circulation research. He was a wonderful person to work with and I learned a lot more meteorology other than forecasting while working with him than I did while a student" (E. N. Lorenz 2002, personal communication). Lorenz's classic paper on available potential energy was published while a member of Starr's General Circulation Project (Lorenz 1955). Saltzman's research experience under Starr led to an important dissertation in 1957—use of wavenumber space to investigate atmospheric turbulence (Saltzman 1957). This research experience was fundamental to his analysis of Rayleigh–Bénard convection in the spectral domain (Saltzman 1962). Saltzman also came under the influence of Robert White, and they collaborated on a theoretical paper related to potential and energy conversion on the climatic scale (White and Saltzman 1956).

3. Profound result from the 12-variable model

In 1955, Lorenz was hired as assistant professor of meteorology at MIT. He filled the chair left vacant by tenured Professor Tom Malone who resigned to direct the weather research center at TRC in Hartford, Connecticut. Lorenz also inherited Malone's Statistical Research Project. This was a fortunate event since it led Lorenz, a dynamicist, into statistical meteorology where he immediately faced a dilemma. Many statistical meteorologists contended that linear regression could yield a weather forecast as good as NWP. Lorenz doubted this contention after a year of studying the existing methods of statistical weather prediction, and he set out to disprove the conjecture. As he said in his scientific autobiography (Lorenz 1993), "Needless to say, many of the devotees to statistical forecasting disagreed with my findings. Possibly they looked at me as an infiltrator from the numerical weather prediction camp."

To disprove the conjecture, Lorenz needed a nonlinear aperiodic model and a computer, although the personal computer was a rare commodity in the mid-1950s. Who suggested he buy a computer? None other than his supervisor/teacher in Starr's General Circulation Project, Robert White. The computer he purchased had storage of 4 kilobytes, $4 \times 2^{10} = 4096$ bytes, and a computational speed 1000 times faster than a desk calculator. The computer Lorenz purchased was the Royal-McBee LGP-30. It was built within the Royal McBee division of Royal Typewriter Company, first manufactured in 1956, and sold for $47,000 (equivalent to $510,000 today).

The model he chose was described as follows: "it seems logical to choose for our deterministic equations one of the simpler models used in numerical weather prediction . . . the geostrophic form of the two-layer baroclinic model [where][4] we have appended linear terms, representing heating, proportional to the difference between the existing temperature field and the standard temperature field, skin friction, proportional to the flow in the lower layer; and

[4] Information within brackets inserted by authors.

friction at the surface separating the layers, proportional to the vertical shear" (Lorenz 1962).[5] Three empirical proportionality constants were associated with appended physical processes. Twelve spectral amplitudes governed flow in the two layers, and the model resembled the general circulation model developed by one of Lorenz's students at MIT, Kirk Bryan, who credited Lorenz for suggesting the problem and acknowledged help from V. P. Starr (Bryan 1959).

[5] This work was completed in 1959 but published in 1962 since it was a contribution to the NWP symposium in 1960 with proceedings published in 1962.

In 1959, Lorenz used the 12-variable model to disprove the statistical linear regression hypothesis. But, by chance, he also discovered the extreme sensitivity of the forecast to slight changes in the initial conditions. After ruling out machine error, he realized that this result had serious consequences for extended-range prediction by any deterministic model. Key results are recounted in Lorenz (1993, chapter 4). We briefly summarize these results:

> To examine the model output in more detail, Lorenz stopped the integration, typed in a line of numbers that it had printed out earlier, and set the model running again. The numbers printed out were nothing like the old ones. He realized the numbers he typed into the program were not the exact values—they were rounded-off values (third decimal place round-off)—errors in the initial conditions.

When the model was set in motion again, these errors steadily amplified until they dominated the solution.

In the presence of these results from the numerical experiment, Lorenz had an epiphany: extended-range weather prediction was not feasible because initial conditions for our NWP models are not measured that accurately. Considering these results: 1) the refutation of the linear regression hypothesis and 2) the extreme sensitivity to initial conditions, he decided to submit a paper for presentation at the 1960 NWP symposium in Tokyo, Japan (Syono 1962). The paper was accepted.

4. The first numerical weather prediction symposium, Tokyo, Japan, 1960

To set the stage for the first symposium on NWP, we briefly return to events between the late 1940s and 1960, the period between the first successful NWP forecasts at Princeton's Institute for Advanced Study—1949—to the 5-yr anniversary of operational NWP in the United States and Sweden—1960. For discussion and reviews of events associated with early operational NWP, we refer readers to the paper by Wiin-Nielsen (1991) and the book by Harper (2012).

The barotropic one-level model tested at Princeton was the workhorse at the two operational centers beginning in 1955. However, alongside the 72-h forecasts made every day from the single-level model, tests were made with two-level baroclinic models, one alongside the operational single-level model at the United States's operational center (see Wiin-Nielsen 1987) and another at the USWB's General Circulation Research Section (GCRS) under the directorship of Joseph Smagorinsky (see Harper 2012, p. 137). These baroclinic models could not outperform the robust one-level barotropic model.

Reading the various contributions in the proceedings of the first symposium on NWP (Syono 1962) and following the recorded panel discussions, one is left with optimism about the advances that had been made over the approximate 10-yr span, but one is also left with a sense of troubling problems that remained. For example: 1) theoretical problems related to the choice of the predictive model, the filtered barotropic model, or an unfiltered baroclinic model and 2) impact of errors in the initial fields and problems with longer-range predictions (beyond a few days)—discussed by Arnt Eliassen in Panel Discussions (Syono 1962, p. 645).

Lorenz's contributed paper (Lorenz 1962) exclusively focused on the refutation of the statisticians' belief that forecasts using linear regression were just as good as NWP forecasts.

However, in the discussion that followed Lorenz's presentation, Bert Bolin, a newly appointed director of the International Meteorological Institute (IMI) in Stockholm, asked a critically important question: "Did you change the initial condition just slightly and see how much different results were in the forecasting in this way?" (Syono 1962, p. 635). This gave Lorenz the chance to discuss the profound results from the 12-variable model. In Lorenz's 160-word response, he briefly described results obtained in the numerical experiment previously discussed (section 3), but he put his answer in the context of the numerical experiment's extended-range forecast. Lorenz's answer ended with the sentence: "Thus by these dynamical methods if you assume you have an observational error whatever to begin with, eventually the error predominates" (Lorenz 1962, p. 635). As he remembered in his oral history discussion with Philip Thompson: "I mentioned the results [at the Tokyo symposium]. These small errors of three decimal places had amplified so much that in the course of two months [simulated time] they drowned out the signal. And I found this very exciting because this implied that if the atmosphere behaved this way, then long-range forecasting was impossible because we certainly don't measure things as accurate as that" (Thompson and Lorenz 1986, 9–10).

In the symposium's milieu of excitement about NWP and its future, it is not hard to imagine that Lorenz's pessimistic view of extended-range prediction met with skepticism. In his oral history interview with the authors (E. N. Lorenz 2002, personal communication), he felt that his conjecture about the impossibility of extended-range weather forecasting was accepted in response to his answer to Bolin's question. However, the following reaction from Akio Arakawa's gives an alternate view: "The reaction of the audience including myself was perhaps best summarized by Charney at the end of his speech presented at the Panel Discussion of the Symposium: 'What happens in a system of this character if there are many degrees of freedom' although he [Lorenz] clearly had the point he later elaborated upon in the 1960s, the results with Saltzman's model were more influential" (A. Arakawa 2002, personal communication).

The exact quote from Charney referred to by Arakawa follows:

> We have seen from Lorenz's study that it is possible to discuss the predictability of atmosphere-like systems, or should I say, Lorenz-like systems? And the question I would like to ask is: What happens in a system of this character if there are many degrees of freedom? That is, to what extent does the predictability of the system depend on the number of degrees of freedom and also the variety of energy sources? (Charney 1962, p. 641).

5. The meeting at Hartford, Connecticut

In 1961, Ed Lorenz made a 100-mile trip from his institution, MIT, to the TRC in Hartford, Connecticut. The purpose of the trip was to discuss results from Saltzman's recently developed spectral model of Rayleigh–Bénard convection.

Although Saltzman's spectral model was developed for 52 spectral components (23 streamfunction components and 29 temperature departure components), he concentrated on a seven-mode system discussed in Saltzman (1962, section 7)—three streamfunction modes and four temperature modes. The numerical experiments were executed with relatively small Rayleigh parameters, $\lambda \sim 2 - 5$, λ measuring the ratio of the Rayleigh number to the critical Rayleigh number (the value when convective cellular motion begins). The small range of Rayleigh numbers used in laboratory experiments is discussed in Chandrasekhar (1961, chapter 2). The other nondimensional number, the Prandtl number, was set to 10 (approximate value for water at 20°C).

The seven-mode system was explored when Lorenz visited Saltzman at TRC. Lorenz was intrigued by one of the numerical experiments where a particular set of initial conditions led to an unusual result: a convective regime that would not settle down to a steady state.

The experiment necessarily had to be executed for a value of $\lambda > 24.74$, the critical Rayleigh parameter for instability of steady convection as found in Lorenz (1963, sections 6 and 7). The unusual result was associated with a turbulent regime of convection. Lorenz remembered the event in his scientific biography:

> He [Saltzman] was interested in periodic solutions and had obtained several of them, but he showed me one solution that refused to settle down. I looked at it eagerly and noted that four of the seven variables soon become very small. This suggested that the other three were keeping each other going, so that a system with only these three variables might exhibit the same behavior. Barry gave me the go-ahead signal, and back at MIT the next morning I put the three equations on the computer, and sure enough, there was the same lack of periodicity that Barry had discovered. Here was the long-sought system whose existence I had begun to doubt (Lorenz 1993).

Lorenz called Saltzman from MIT and reviewed these results: steady state never reached for the three surviving amplitudes and small perturbations to the initial conditions led to large differences in the amplitudes. Saltzman was surprised and stated: "I think it [the result] is a quirk, nothing important" (E. N. Lorenz 2002, personal communication). That was a reasonable reaction from Saltzman since he had concentrated on "lower" Rayleigh parameters λ in his numerical experiments where all 7 amplitude components approached steady state in finite time as shown in Saltzman (1962, section 7, Fig. 3).

As Lorenz looked back on the exceptional results that came from the meeting, he felt fortunate:

> I was lucky in more ways than one. An essential constant in the model is the Prandtl number—the ratio of the viscosity of the fluid to the thermal conductivity. Barry had chosen the value 10.0 as having the order of magnitude as the Prandtl number of water. As a meteorologist, he might well have chosen to model convection in air instead of water, in which case he would probably have used the value 1.0. With this value, the solutions of the three equations would have been periodic, and I probably would never have seen any reason for extracting them from the original seven (Lorenz 1993).

6. Details on results found by Saltzman and Lorenz

We duplicate results found by Saltzman and Lorenz at their meeting in 1961. Spectral amplitudes are represented by variables $(x_1, x_2, x_3, x_4, x_5, x_6, x_7)$ where the first three components are streamfunction and the last four components are temperature departure (departure from the linearly decreasing temperature profile in the fluid heated from below). Hereafter, we simply refer to this departure temperature as temperature. The initial condition is the same as used in Lorenz (1963): the three-horizontal wave temperature $x_4(0) = 1$ while all other six components vanish. The Rayleigh parameter $\lambda = 28$ and the Prandtl number = 10, again parameter values assumed in Lorenz (1963). The time-dependent evolution of the seven spectral amplitudes is shown in Fig. 2.

Note that amplitudes $x_2, x_3, x_5, x_6 \to 0$ at $t \cong 6$. This three-mode system is found in Lorenz (1963). His notation for the three-mode system is $(X, Y, Z) = (x_1, x_4, x_7)$.

When Lorenz had a chance to plot the amplitudes in phase space as shown in Lorenz (1963, Fig. 2), the similarity between "butterfly wings" and the solution curves is apparent. As studied by Hilborn (2004), this resemblance to butterfly wings is only one of multiple theories regarding the origin of the metaphor. Reading Hilborn (2004) along with studies that complement it, Sorensen and Zobitz (2012) and Saravanan (2022), adds a valued visual component to problems in physics and geophysics such as found in Lorenz (1963).

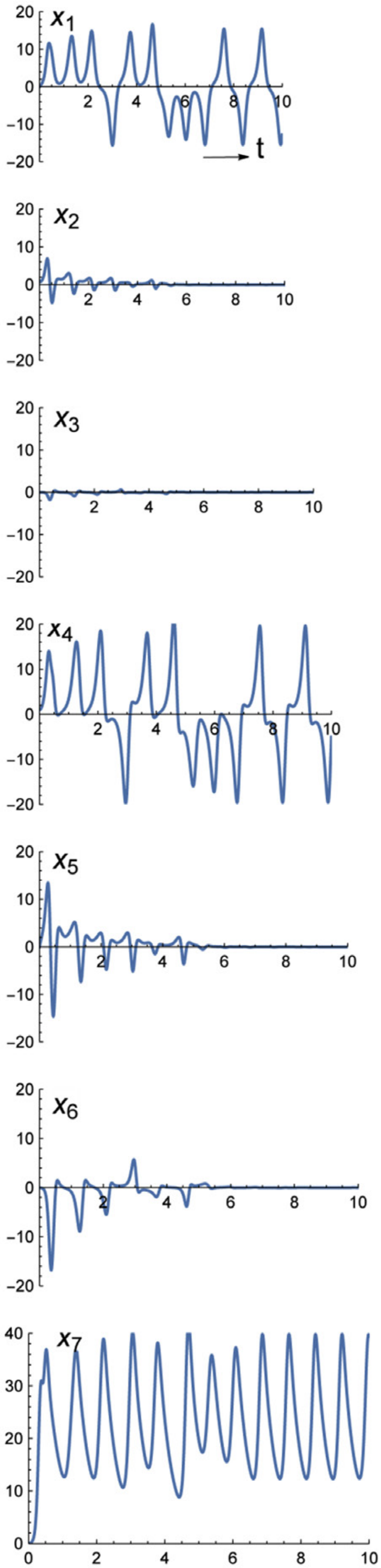


Fig. 2. Time-dependent spectral amplitudes found from solution to Saltzman's seven-mode model with $\lambda = 28$, Prandtl number = 10, and initial conditions: $x_4 = 1$ and other spectral components 0.

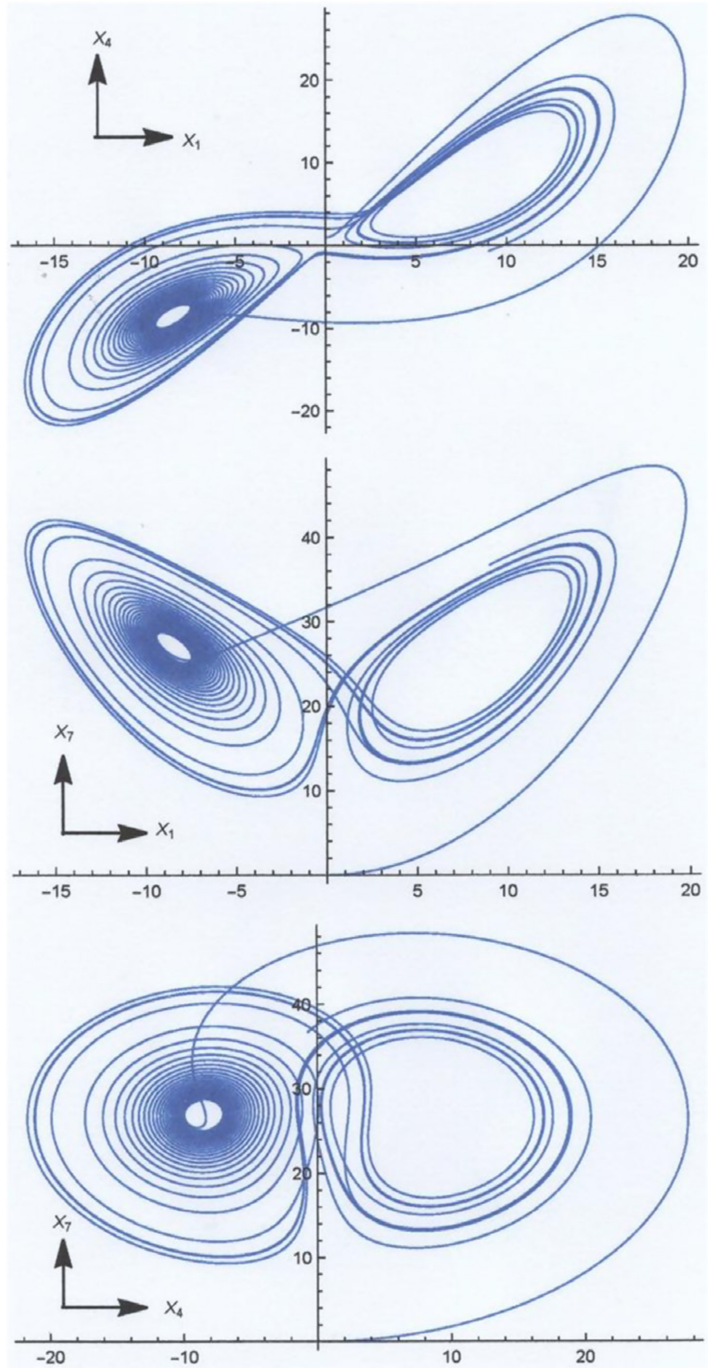


Fig. 3. Phase–space diagram of amplitudes in the x_1–x_4, x_1–x_7, and x_4–x_7 planes over the nondimensional time interval [0, 25] when $\lambda = 28$.

We executed Lorenz's three-mode model and plotted amplitudes in phase space. They are found in Fig. 3: (top) x_1–x_4 plane (X–Y plane in Lorenz's notation), (middle) x_1–x_7 plane (X–Z plane in Lorenz's notation), and (bottom) x_4–x_7 (Y–Z plane in Lorenz's notation). Phase space amplitude plots in the X–Y plane and Y–Z planes are found in Lorenz (1963, Fig. 2). Each phase space plot exhibits two equilibrium points, centers of attraction, that appear to attract and repel the solution curve as it moves from its initial point to the final resting places, as $t \to \infty$.

7. Further exploration of the seven-mode model

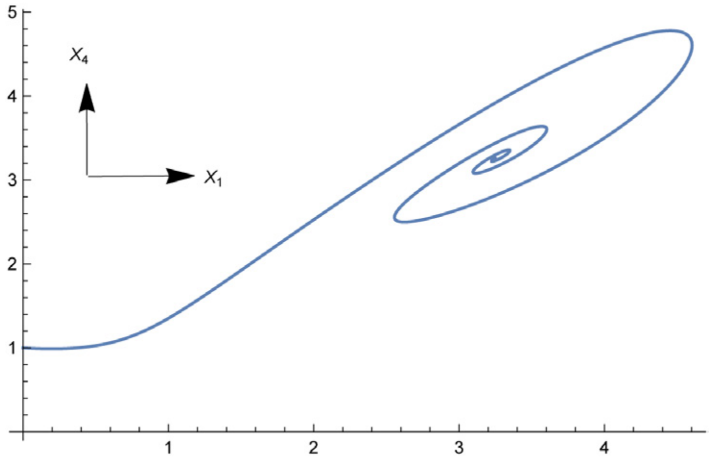


Fig. 4. Phase–space diagram of amplitudes in the x_1–x_4 plane over the nondimensional time interval [0, 5] when $\lambda = 10$.

The recent paper by Lakshmivarahan et al. (2019)—referred to as LLH hereafter—presented a complete characterization of Saltzman's seven-mode low-order model, referred to as S-LOM (7). LLH shows that S-LOM (7) admits to a natural decomposition into a union of three invariant subspaces, called IS_1, IS_2, and IS_3. A subspace is an invariant subspace if the energy in the initial condition is confined to this subspace, and this in turn guarantees that the solution lies in that subspace for all times. These three low-order models involve the following variables: $IS_1 = (x_1, x_4, x_7)$, $IS_2 = (x_2, x_5, x_7)$, and $IS_3 + (x_3, x_6, x_7)$. In these subspaces, four of the components go to zero as follows: IS_1: $x_2, x_3, x_5, x_6 \to 0$; IS_2: $x_1, x_3, x_4, x_6 \to 0$, IS_3: $x_1, x_2, x_4, x_5 \to 0$. See Fig. 3 where $x_2, x_3, x_5, x_6 \to 0$.

The three-mode subsystems in IS_1 and IS_2 exhibit the same chaotic structure for large values of $\lambda \geq 24.74$ while IS_3 is a trivial, stable, dissipative dynamic model. Refer to LLH for details. In short, by using the same initial condition as stipulated by Saltzman (1962, section 7) and setting $\lambda = 28$ it is shown that two chaotic subsystems simultaneously co-exist in IS_1 and IS_2, each exhibiting its own butterfly structure. For small Rayleigh parameters, the solutions do not possess the instability as shown in Fig. 4. In this case, convective motion is periodic with steady-state amplitudes near 3.5 for x_1 and x_4 (X and Y in Lorenz's notation).

8. Conclusions

A key statement is found in the conclusions section of Lorenz (1963): "When our results concerning the instability of nonperiodic flow are applied to the atmosphere . . . they indicate that prediction of the sufficiently distant future is impossible by any method, unless the initial conditions are known exactly. In view of the inevitable inaccuracy and incompleteness of weather observations, precise very-long range forecasting would seem to be non-existent . . . There remains the question as to how long is 'very-long range.' Our results do not give the answer for the atmosphere." The question still awaits an answer.

When Lorenz was asked by the authors (E. N. Lorenz 2002, personal communication) if there was commentary and discussion in the meteorological community following publication of the paper, he simply said: "No, only from Norman Phillips who was the assigned Journal of Atmospheric Science editor; but letters from mathematicians started coming." And it was Editor Norman Phillips who suggested that Lorenz change the title of the paper from "Deterministic Turbulence" to "Deterministic Nonperiodic Flow" since the equations lacked some of the properties that we generally associate with turbulence (Lorenz 1993).

Saltzman and Lorenz approached the solution to the Rayleigh–Bénard convection problem from different angles—Saltzman interested in steady-state convection while Lorenz was searching for a model, simpler than his two-layer baroclinic model that would exhibit the same sensitivity to initial conditions that he had found earlier. The numerical experiment that would not settle down, an "outlier" compared to the other solutions that had been examined that day, was the treasure Lorenz was seeking.

Indeed, the result found that day with Saltzman's low-order spectral model of convection built the bridge to chaos theory, a theory that is actively investigated to this day, not only in meteorology but also in the sciences generally.

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Data availability statement. No data sets were generated or analyzed during the current study. Software (other than typesetting) was not used in this research.

References

Bénard, M., 1900: Les tourbillons cellulaires dans une nappe liquide. *Rev. Gen. Sci. Pures Appl.*, **11**, 1261–1271, 1309–1328.

Bryan, K., 1959: A numerical investigation of certain features of the general circulation. *Tellus*, **11** (2), 163–174, https://doi.org/10.1111/j.2153-3490.1959.tb00017.x.

Chandrasekhar, S., 1961: *Hydrodynamic and Hydromagnetic Stability.* Oxford University Press, 652 pp.

Charney, J. G., 1962: Introductory speaker for panel discussions. *Proc. Int. Symp. on Numerical Weather Prediction*, Tokyo, Japan, Meteorological Society of Japan, 641 pp.

Harper, K. C., 2012: *Weather by the Numbers: The Genesis of Modern Meteorology.* MIT Press, 308 pp.

Hilborn, R. C., 2004: Sea gulls, butterflies, and grasshoppers: A brief history of the butterfly effect in nonlinear dynamics. *Amer. J. Phys.*, **72**, 425–427, https://doi.org/10.1119/1.1636492.

Lakshmivarahan, S., J. M. Lewis, and J. Hu, 2019: Saltzman's model. Part I. Complete characterization of solution properties. *J. Atmos. Sci.*, **76**, 1587–1608, https://doi.org/10.1175/JAS-D-17-0344.1.

Lorenz, E. N., 1955: Available potential energy and the maintenance of the general circulation. *Tellus*, **7** (2), 157–167, https://doi.org/10.3402/tellusa.v7i2.8796.

——, 1962: The statistical prediction of solutions of dynamical equations. *Proc. Int. Symp. on Numerical Weather Prediction*, Tokyo, Japan, Meteorological Society of Japan, 629–634.

——, 1963: Deterministic nonperiodic flow. *J. Atmos. Sci.*, **20**, 130–141, https://doi.org/10.1175/1520-0469(1963)020<0130:DNF>2.0.CO;2.

——, 1993: *The Essence of Chaos.* The University of Washington Press, 319 pp.

Rayleigh, L., 1916: LIX. On convection currents in a horizontal layer of fluid, when the higher temperature is on the under side. *London Edinburgh Dublin Philos. Mag. J. Sci.*, **32**, 529–546, https://doi.org/10.1080/14786441608635602.

Saltzman, B., 1957: Energetics of the larger scales of atmospheric turbulence in the domain of wavenumber. *J. Meteor.*, **14**, 513–523, https://doi.org/10.1175/1520-0469(1957)014<0513:EGTEOT>2.0.CO;2.

——, 1962: Finite amplitude free convection as an initial value problem – I. *J. Atmos. Sci.*, **19**, 329–341, https://doi.org/10.1175/1520-0469(1962)019<0329:FAFCAA>2.0.CO;2.

Saravanan, R., 2022: *The Climate Demon: Past, Present, and Future of Climate Prediction.* Cambridge University Press, 379 pp.

Sorensen, J., and J. Zobitz, 2012: CHAOS in context behind the scenes of the Lorenz model. *Math Horiz.*, **20**, 25–28, https://doi.org/10.4169/mathhorizons.20.1.25.

Staff Members of the Department of Meteorology of the University of Chicago, 1947: On the general circulation of the atmosphere in middle latitudes: A preliminary summary report on certain investigations conducted at the University of Chicago during the academic year 1946–1947. *Bull. Amer. Meteor. Soc.*, **28**, 255–280, https://doi.org/10.1175/1520-0477-28.6.255.

Starr, V. P., 1945: A quasi-Lagrangian system of hydrodynamic equations. *J. Meteor.*, **2**, 227–237, https://doi.org/10.1175/1520-0469(1945)002<0227:AQLSOH>2.0.CO;2.

Syono, S., Ed., 1962: *Proceedings of the International Symposium on Numerical Weather Prediction in Tokyo.* Japan Meteorological Agency, 656 pp.

Thompson, P. T., and E. N. Lorenz, 1986: *Dialogue between Phil Thompson and Ed Lorenz on 31 July 1986*. N. Gauss, Moderator, Amer. Meteor. Soc., Tape Recorded Interview Project, 19 pp. [Available from NCAR Archives, P.O. Box 3000, Boulder, CO 80303.]

White, R. M., 1949: The role of mountains in the angular momentum balance of the atmosphere. *J. Meteor.*, **6**, 353–355, https://doi.org/10.1175/1520-0469(1949)006<0353:TROMIT>2.0.CO;2.

——, 1950: A mechanism for the vertical transport of angular momentum in the atmosphere. *J. Meteor.*, **7**, 349–350, https://doi.org/10.1175/1520-0469(1950)007<0349:AMFTVT>2.0.CO;2.

——, 1951a: On the energy balance of the atmosphere. *Trans. Amer. Geophys. Union*, **32**, 391–396, https://doi.org/10.1029/TR032i003p00391.

——, 1951b: The meridional eddy flux of energy. *Quart. J. Roy. Meteor. Soc.*, **77**, 188–199, https://doi.org/10.1002/qj.49707733204.

——, 1951c: The meridional flux of sensible heat over the Northern Hemisphere. *Tellus*, **3** (2), 82–88, https://doi.org/10.3402/tellusa.v3i2.8619.

——, 1954: The counter-gradient flux of sensible heat in the lower atmosphere. *Tellus*, **6** (2), 177–179, https://doi.org/10.3402/tellusa.v6i2.8724.

——, and B. Saltzman, 1956: On conversions between potential and kinetic energy in the atmosphere. *Tellus*, **8** (3), 357–363, https://doi.org/10.1111/j.2153-3490.1956.tb01233.x.

Wiin-Nielsen, A., 1987: Interview with Aksel Wiin-Nielsen. Interviewers: J. Tribbia, W. Washington. A. Kasahara, Amer. Meteor. Soc., Tape Recorded Interview Project, 62 pp. [Available from NCAR Archives, P.O. Box 3000, Boulder, CO 80303.]

——, 1991: The birth of numerical weather prediction. *Tellus*, **43B**, 36–52, https://doi.org/10.3402/tellusb.v43i4.15397.