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Saltzman, Barry (*b.* New York, New York, 26 February 1931; d. New Haven, Connecticut, 5 February 2001), *meteorology, climatology, paleoclimatology*.

Barry Saltzman was a leading figure in meteorology and climate science research for nearly fifty years. He made significant contributions to both of these fields at their most formative stages. Ahead of his time in many ways, Saltzman contributed to an understanding of the general circulation and the spectral energetics budget of the atmosphere. He also developed a comprehensive theory for climate change across a wide spectrum of time scales, ranging from sub-annual to millions of years. On his path toward a unified theory of how the climate system works he played a role in the development of energy balance models, statistical dynamical models, and paleoclimate dynamical models. He was a pioneer in developing meteorologically motivated dynamical systems. These included the progenitor of Edward Norton Lorenz's (1963) famous chaos model. In applying his own dynamical-systems approach to long-term climate change, Saltzman recognized the potential for using atmospheric general circulation models in the development of a complete theory. In 1998, he was awarded the Carl-Gustaf Rossby Research Medal, the highest honor of the American Meteorological Society, "for his lifelong contributions to the study of the global circulation and the evolution of the earth's climate."

Early Life and Career.

Barry Saltzman was born in New York on 26 February 1931. He grew up in the Bronx, where his parents had settled as immigrants from Eastern Europe in the 1920s. His mother, Bertha Burmil, was from Poland; his father, Benjamin Saltzman, was from Ukraine. They met as workers in the garment district in New York City. Barry had one sibling, his older sister Jean.

As a child Saltzman was interested in history and science. He collected stamps and loved to read the encyclopedia, activities that taught him a lot about these subjects. Saltzman began his academic career at the prestigious Bronx High School of Science. He

also loved sports, and spent as much time as he could at the Polo Grounds watching his favorite baseball team, the New York Giants. Saltzman was an outstanding athlete in high school, particularly in track and field.

Saltzman matriculated at City College of New York in 1949. He majored in physics. By his own account, he was significantly influenced by three faculty members during his undergraduate years: Mark Zemansky in physics, Sherburne Barber in math, and later Richard Rommer in meteorology. Actually, Saltzman decided to become a meteorologist one day when visiting the local public library, where he found a book on dynamical meteorology by David Brunt. This experience prompted him to take his first meteorology class in the geology department at City College with Rommer. Saltzman served as president of the City College branch of the American Meteorological Society. He graduated from City College with a BS degree in meteorology, cum laude, in June 1952.

Later that summer Saltzman started graduate school at the Massachusetts Institute of Technology (MIT). There he specialized in dynamic meteorology, receiving a Master's degree in February 1954. His thesis, jointly written with Richard Pfeffer, was entitled "Large-Scale Rotational Flow in a Fixed Cylindrical Volume of the Atmosphere." Pfeffer, who first met Saltzman at City College, also arrived at MIT in the summer of 1952. Saltzman and Pfeffer were initially assigned to the "Pressure Change" research project under James M. Austin. After their first semester, Pfeffer asked Victor Starr if he could study for his Master's degree with him as Major Professor. Starr reported this request to the department chairman, Henry Houghton. Houghton, who could not distinguish between the two new students from City College, called Saltzman into his office to ask him if he was the one who wanted to be switched from Austin to Starr. Stating that he did not wish to split "salt and pepper," Houghton moved them both to Victor Starr's research project, where they subsequently did their Master's and PhD theses. Saltzman received his PD from MIT in 1957. His thesis was entitled "The Energetics of the Larger Scales of Atmospheric Turbulence in the Domain of Wavenumber."

As a graduate student Saltzman established an excellent reputation as a participant in the General Circulation Project at MIT. This project, initiated by Starr in 1948 and funded by the U.S. Air Force through the late 1950s, aimed to collect, archive, and analyze upper-air data on a global scale. From these data, general circulation statistics were generated and used by the MIT scientists to develop theoretical insights into atmospheric dynamics.

Starr served as a mentor to Saltzman, as well as a role model for how to become a complete scholar. Saltzman's keen interest in history was further stimulated and encouraged by the example set by Starr. Later Saltzman's own students would greatly benefit from this early influence on his career. Other participants of the General Circulation Project including, Edward Lorenz and Robert White, also influenced Saltzman.

The MIT General Circulation Project prompted the development of the complex computer models used for nearly all climate and weather prediction studies into the twenty-first century (Phillips, 1956). Saltzman was a pioneer in the use of computers in the geosciences as well as in the use of spectral analysis in the study of atmospheric phenomena. He was the first to use atmospheric energetics rigorously as a key tool in understanding how the atmosphere works, and his methods are still widely used.

Saltzman moved to Connecticut in 1961 to work as a senior research scientist at The Travelers Research Center in Hartford. He married Sheila Eisenberg on 10 June 1962. Pfeffer was the best man at their wedding. Barry and Sheila had two children, Matthew David and Jennifer Ann. The move to Travelers, prompted by Robert White, afforded Saltzman the opportunity to continue his fundamental research on the atmosphere. During the seven years he spent at Travelers, he solidified his reputation as an outstanding atmospheric scientist and climate theoretician. Along the way his work shifted toward developing a quantitative theory that would account for the observed climatic state.

In 1967 the Department of Geology and Geophysics at Yale University decided to hire a meteorology/climatology faculty member. Karl Turekian, who had known White for many years, asked him for his opinion on a good candidate for the job. With no hesitation he said that Saltzman would be a perfect fit. Shortly thereafter George Veronis invited Saltzman to campus for an interview; he was offered and accepted a position at Yale in 1968, and he served as professor of geophysics there for the rest of his life.

Saltzman was in large part motivated to move back into the academic world because he felt obligated to train students in addition to doing research.

While at Yale, Saltzman's interests shifted once again, into the realm of climate change and the development of a theory of the ice ages. Beginning in the late 1970s, Saltzman pioneered the development of low-order dynamical system models as a tool for understanding the processes by which climate changes on century to millennial (and longer) time scales. In his pursuit of a theory of climate change, Saltzman employed a hierarchy of models, including complex general circulation models (GCMs).

Meteorology.

In his PhD thesis and early publications, Saltzman introduced to the meteorological community the use of spatial Fourier analysis to quantify nonlinear dynamical interactions between zonal scales. This ground-breaking work created a link to meteorology from the contemporary theory of turbulence that relied on Fourier analysis (e.g., Batchelor, 1953; Fjørtoft, 1953; Kolmogorov, 1941a and b). Saltzman generalized the famous Osbourne Reynolds (1894) decomposition of an arbitrary spatial field into its domain mean and deviation, to derive a more detailed way to separate weather patterns into their different spatial scales. While previous authors had used the decomposition to analyze interactions between the global and the collection of all smaller scales, Saltzman's "wavenumber energetics" provided detailed interactions among each individual scale, defined by wavelengths.

Saltzman was one of the first to connect the then-recent observation, that atmospheric eddies collectively transfer their kinetic energy to the mean flow (Saltzman, 1957, 1959). Thus, he suggested a physical mechanism for maintaining localized quasi-stationary pressure patterns.

Low-Order Irregular, Nonperiodic Flow.

It was in 1962 that Saltzman stumbled upon a low-order system of equations that behaved chaotically. Saltzman (1962) developed a seventh-order system of ordinary differential equations (ODEs) to approximate the classic 2D Oberbeck (1879)—Boussinesq (1903) partial differential equations (PDEs) governing roll convection

between two isothermal free surfaces. When this system was numerically integrated, he discovered that for high enough Rayleigh numbers, four of the seven modes tended to zero, while the remaining order-three subsystem underwent irregular, nonperiodic fluctuations. That same year Lorenz (1962) had found nonperiodic solutions of a similar quasi-meteorological ODE system of order 12, and was eager to find a simpler system to demonstrate how this was happening. In his landmark paper "Deterministic Nonperiodic Flow" (Lorenz, 1963), the acknowledgements read that he was "indebted to Dr. Barry Saltzman for bringing to his attention the existence of nonperiodic solutions of the convection equations" (p. 141). With the low-order system provided by Saltzman, Lorenz performed a thorough analysis, obtaining results, including: (i) what would become widely known as a "pitchfork," or subcritical Hopf bifurcation; (ii) instability in the sense of what would later be called "chaos"; and (iii) the first rough sketch of the complicated structure in 3D-space known as a "butterfly" or "strange attractor."

Climate Theory and Models.

Saltzman's work on climate started by distinguishing climatic phenomena from shorter-term weather, or meteorological phenomena emphasizing climate on explicit monthly to seasonal time scales. During the 1960s Saltzman developed parameterizations for energy balance models (EBMs). In the most notable of these (Saltzman, 1967), he attempted to account fully for all processes responsible for determining Earth's surface temperature. Realizing that EBMs, because they lacked dynamics, were severely deficient in describing climate spurred him to develop a class of models called statistical dynamical models (SDMs), which attempted to extend the EBMs by including parameterizations for zonal representations of dry atmospheric dynamics and the hydrologic cycle. To Saltzman the SDM was a "true" climate model in that it solved for relevant quantities directly on monthly to seasonal time scales (as opposed to the widely used GCM, which actually solves for daily weather patterns subsequently averaged to yield climate statistics). His seminal works in this regard were later detailed in two papers written with Anandu Vernekar (Saltzman and Vernekar, 1971, 1972).

He began developing his theory for ice ages using the SDM. Along with Vernekar, he used the newly available Climate: Long-range Investigation, Mapping, and Prediction

(CLIMAP) reconstruction of last glacial maximum boundary conditions to model zonally averaged climate at 18,000 years ago (CLIMAP, 1976; Saltzman and Vernekar, 1975). Others soon followed his lead, using GCMs (e.g., Gates, 1976; Manabe and Hahn, 1977). However, the GCM model experiments only provided an equilibrium "snapshot" of what climate conditions may have been like during the last glacial maximum (LGM). What Saltzman really wanted to understand was the time-dependent behavior of the climate system. Recognizing that GCMs could not feasibly be used as a prognostic tool for the purpose of long-term climate change (because of the small energy fluxes involved), he ultimately turned to developing his own non-equilibrium, time-dependent models. His simpler models were a more useful way to illustrate and explore the many positive feedbacks involved in low-frequency climatic variability. Saltzman called these "paleoclimate dynamics models" (PDMs).

Saltzman was careful in defining climate. Measures of the climate state were separated into a steady equilibrium—or diagnostic—component, and the transient departures from that equilibrium—or the prognostic (time-dependent, predictive)—component. He considered all potentially relevant physical processes (hypothesized by him or others) using explicit representations where possible. After all possible processes were represented, he would then attempt to reduce them to a more manageable number via scale analysis. Two review articles comprehensively summarize this work: "A Survey of Statistical-Dynamical Models of the Terrestrial Climate" and "Climatic Systems Analysis," both published in *Advances in Geophysics* (Salzman, 1978, 1983).

Ice Age Theory.

Saltzman spent the better part of the second half of his career attempting to develop an explanation for the origin of the late Cenozoic ice age. He always maintained that a complete theory for ice ages must at a minimum account for the onset of glaciation, and the transitions in the character of glacial-interglacial cycles observed in climate proxy records. In particular, for the Plio-Pleistocene glacial cycles this meant the near-100,000 year cycle and its sudden appearance at around 900,000 years ago. In his endeavor to construct such a complete theory, Saltzman clearly articulated the need for using an inductive approach for the simple reason that the fluxes of energy involved in climate

change on these time scales were very small. The amount of energy required to melt northern hemisphere ice sheets of the last glacial maximum (LGM) was on the order of 10^{-1} W/m². Likewise, the energy flux involved in observed glacial-interglacial change in deep ocean temperature was also only on the order of 10^{-1} W/m².

Saltzman separated the problem of long-term climate change into three basic parts, each requiring a different approach (Saltzman, 1990). He examined the time dependent evolution of global ice volume over the past several million years using a set of equations that formed a closed system linked to shorter-tem variables in a GCM. Long-term changes in global climate are the result of dynamical feedbacks between only a few prognostic variables to which the fast-response variables (those governed by a GCM) are equilibrated.

Because of orbital variations on time scales ranging from 20,000 to 100,000 years, Saltzman reasoned that the climate system would not be in equilibrium, and that feedbacks within the climate system could potentially give rise to a rich variety of behavior, including damped oscillations or even auto-oscillations.

At the most fundamental level, Saltzman believed that paleoclimatic variability was due to a complex combination of changes in external forcing and instability of the internal system that arose even in the presence of steady external forcing. However, the concept that instability within the climate system could lead to auto-oscillatory behavior on long time scales met considerable resistance. In the 1980s, however, the vast majority of scientists working on the ice age problem believed that earth orbital (Milankovitch) forcing was the ultimate cause of glacial-interglacial cycles. On the other hand, Saltzman felt that positive feedbacks within the climate system could drive a near-100,000 year ice age cycle (Saltzman, Sutera, and Hansen, 1982 and 1984; Saltzman and Sutera, 1984). He reasoned that if near-surface air temperature was the critical factor in building an ice sheet, an account was needed of how temperature can vary in high latitude regions not only as a function of changing insolation, but also as related to variations in greenhouse forcing, ocean temperature, and the ice sheets themselves. While Saltzman did not consider earth orbital forcing a necessary condition for ice age cycles to occur, he did

believe that such forcing served as a "pacemaker" (Saltzman, Hansen, and Maasch, 1984).

Inspired by historical ideas concerning the role of CO₂ in climate change (for example, Arrhenius, 1896; Callendar, 1938; Plass, 1956), Saltzman led a revival of the theory that variations of atmospheric CO₂ are a significant driver of ice age cycles. Saltzman's recognition of the importance of greenhouse forcing came prior to the time when direct evidence for variations of CO₂ (and CH₄) became available from ice core records. In his model, many positive feedbacks within the carbon cycle produced an asymmetric, saw-toothed near-100,000 year free solution, with a phase relationship between paleoclimate proxies for global ice mass and atmospheric CO₂ consistent with available paleoclimate records of these variables (Saltzman and Maasch, 1988a and b). The addition of a long-term tectonically forced decrease in atmospheric CO₂ led to a bifurcation of the system from a steady-state to a near-100,000 year auto oscillation (Maasch and Saltzman, 1990; Saltzman and Maasch, 1990 and 1991).

Saltzman also made extensive use of GCMs in developing his theory of climate change. Most of these studies involved evaluation of the "fast components" of the climate system, most notably changes in energy balance related to atmospheric carbon dioxide and solar luminosity (Oglesby and Saltzman, 1990a, 1990b, and 1992; Marshall, et al., 1994). These studies explored model sensitivity to a wide range of radiative forcing (e.g., evaluating the climate response to systematic carbon dioxide variations from 100 to 1,000 ppm). Because Saltzman envisioned these models as providing stationary (equilibrium) parameters in a theory of climatic change, he was also very interested in the sensitivity of the GCM to its initial state. He wanted to know if they could be used to obtain a well-defined equilibrium (Oglesby, et al., 1997).

Rapid shifts in global climatic conditions during the last glacial/interglacial cycle occur on two characteristic time scales, roughly 1,000 to 3,000 years and 5,000 to 10,000 years. Saltzman explored what he believed to be the most relevant feedbacks on millennial time scales beginning with his time-dependent SDM of climate change, which contained the fundamental dynamic energy exchanges between the ocean, atmosphere, and sea ice (Saltzman, 1978 and 1982; Saltzman and Moritz, 1980). In this model, the

ocean gains or loses heat (and hence changes temperature) through the sea ice, at the sea-ice margin, and across the ocean/air interface. The extent of sea ice varies as a function of the freezing (melting) at its margin, envisioned as a flux of latent heat to (from) the ocean. The model also includes short-wave and long-wave radiation fluxes as a function of solar forcing and atmospheric CO₂. Within the range of plausible solar variability and greenhouse forcing, Saltzman's model predicted the possibility of 1,000- to 2,000-year oscillations. The now well-known millennial scale oscillations, often referred to as abrupt climate change, would not become a mainstream topic of scientific research for at least another decade. In effect, Saltzman had developed a theory for millennial climate oscillations many years before widespread interest in so-called abrupt climate changes developed in the paleoclimate community.

Saltzman also considered other instabilities that have likely contributed to observed climate variability. Through the 1990s he methodically explored the climatic impacts of ice dynamics (Saltzman and Verbitsky, 1992 and 1993). He added to the model bedrock depression and conditional instability due to an ice calving mechanism. He then extended this work to explore systematically the theoretical aspects of millennial scale variations known as "Heinrich events."

During glacial times, climate oscillations also occur about every 5,000 to 12,000 years. These so-called Heinrich events involve massive volumes of ice that discharge from the Laurentide ice sheet into the North Atlantic Ocean. Like most others, Saltzman considered the most likely driving mechanism for Heinrich events to be internal behavior of ice sheets. With their dynamical model based on the fundamental thermo-mechanical properties of an ice sheet, Mikhail Verbitsky and Saltzman (1994, 1995; Saltzman and Verbitsky, 1996) illustrated the essential physical processes governing coupled variations of ice volume, basal water amount, and the surge of ice, clearly exposing the key free parameters likely to be involved in Heinrich oscillations. The instability leading to auto oscillatory behavior of ice sheets is regulated by both cold advection from the upper ice surface along with the much weaker influence of geothermal heating (Verbitsky and Saltzman, 1995; Saltzman and Verbitsky, 1996).

The list of Barry Saltzman's contributions is long. He had a significant impact on many important aspects of the fields of meteorology, climatology, and paleoclimatology. He produced a steady stream of papers across almost five decades. Some of the more outstanding honors bestowed upon Saltzman include membership in Phi Beta Kappa; being a Fellow of the American Meteorological Society; being a Fellow of the American Association for the Advancement of Science; being elected to membership in the Academy of Sciences of Lisbon (Portugal); serving numerous editorships on prestigious scientific journals, and on numerous visiting and advisory committees. Saltzman was also awarded the Carl-Gustaf Rossby Research Medal in 1998 by the American Meteorological Society (the highest honor bestowed by the AMS).

Saltzman's ultimate views on a comprehensive theory of climate are detailed in *Dynamical Paleoclimatology* (Saltzman, 2002). This project actually began with an invitation to Saltzman from Jose Peixoto and Abraham Oort to be a co-author with them on their planned second edition of the *Physics of Climate* (Peixoto and Oort, 1992). That book was never finished because Peixoto died of cancer in 1996. Saltzman had so much time and effort invested into summarizing his work on paleoclimate for the section he was to contribute that he decided to write his own book. Ironically, Saltzman was diagnosed with cancer in 2000. He completed *Dynamical Paleoclimatology* during his final year and died of his illness on 5 February 2001. His book was published posthumously.

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