Barry Saltzman and the Theory of Climate

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ABSTRACT

Barry Saltzman was a giant in the fields of meteorology and climate science. A leading figure in the study of weather and climate for over 40 yr, he has frequently been referred to as the "father of modern climate theory." Ahead of his time in many ways, Saltzman made significant contributions to our understanding of the general circulation and spectral energetics budget of the atmosphere, as well as climate change across a wide spectrum of time scales. In his endeavor to develop 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, including the progenitor of Lorenz's famous chaos model. In applying his own dynamical-systems approach to long-term climate change, he recognized the potential for using atmospheric general circulation models in a complimentary way. In 1998, he was awarded the Carl-Gustaf Rossby medal, the highest honor of the American Meteorological Society "for his life-long contributions to the study of the global circulation and the evolution of the earth's climate." In this paper, the authors summarize and place into perspective some of the most significant contributions that Barry Saltzman made during his long and distinguished career. This short review also serves as an introduction to the papers in this special issue of the *Journal of Climate* dedicated to Barry's memory.

1. Introduction

Professor Barry Saltzman began his academic career at the highly prestigious Bronx High School of Science, from which he graduated in 1949. He then attended the City College (of New York) where he earned a B.S. in physics in 1952. Barry did his graduate work at the Massachusetts Institute of Technology (MIT), where he obtained an S.M. in meteorology in 1954 and a Ph.D., also in meteorology, in 1957, the latter under the guidance of Professor Victor Starr. As a graduate student, and later a research scientist, Saltzman quickly established an excellent reputation while participating 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, set out 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 a more complete theory of how the atmosphere works.

Victor Starr served not only as a mentor to Barry Saltzman, but also as a role model for how to become a complete scholar. Barry's inherent interest in history was further stimulated and encouraged by the example set by the well-rounded Starr. Later Saltzman's own students would greatly benefit from this early influence on Barry's career. Saltzman was also significantly influenced by other participants of the General Circulation Project including Edward Lorenz and Robert White.

The MIT General Circulation Project sparked the development of the complex computer models used for

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nearly all climate and weather prediction studies today (Phillips 1956). During these early days of his career, Saltzman was also 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 rigorously use atmospheric energetics as a key tool in understanding how the atmosphere works. His methods for doing this are still widely used today.

In 1961 after very productive years at MIT, Saltzman took a job at the Travelers Research Center in Hartford, Connecticut, a move prompted by Robert White. The position at Travelers afforded Saltzman the opportunity to continue fundamental research on the atmosphere. During his seven years at Travelers, he cemented 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 that it would be a good idea to hire a meteorology/climatology faculty member. Karl Turekian, who had known Bob White for many years, asked him for his opinion on a good candidate for the job. With no hesitation he said that Barry Saltzman would be a perfect fit. Shortly thereafter George Veronis, who happened to attend a scientific meeting that Saltzman also attended, invited Barry to give a talk at Yale. Subsequently, Saltzman accepted a position and moved to Yale in 1968, where he served as Professor of Geophysics for the rest of his life. Barry made the move back into the academic world because he felt an obligation to train students in addition to doing research.

While at Yale, Saltzman's interests shifted once again, now 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. His pursuit of a theory of climate change involved a hierarchy of models that subsequently resulted in Saltzman becoming a leader in the use of complex GCMs of climate in understanding how climate change occurs; these were the very models he helped develop during his early years at MIT.

While it is difficult to quantify the contribution of any given scientist, one commonly accepted indicator is the number of times his or her publications are cited. The available citation data for Saltzman are shown in Fig. 1. His publications have been cited an average of 20 times each, with early and enduring influence; for example, Saltzman and Vernekar (1972) was cited 32 times between 1974 and 2000, of which only 7 citations were by either of the cited authors.

2. Meteorology

a. *Turbulent energetic models of "semipermanent" patterns*

In his Ph.D. thesis and early publications (Saltzman 1957 to 1970), Saltzman introduced to the meteorological community the use of spatial Fourier analysis to quantify nonlinear dynamical interactions between zonal scales. This seminal work created a bridge to meteorology from the contemporary theory of turbulence that relied on Fourier analysis, as described, for example, by Batchelor (1953), Fjørtoft (1953), Kolmogorov (1941b,a), and others. Saltzman generalized the famous Reynolds (1894) decomposition of an arbitrary spatial field $u(x)$ into its domain mean $\overline{u}$ and deviation $u^*(x) \equiv u(x) - \overline{u}$, to derive a more detailed wavenumber ($m = 0, \pm1, \pm2, \ldots$) decomposition: $\overline{u} = \hat{u}_0$, $u^*(x) = \Sigma_{m\neq0}\hat{u}_m e^{2\pi imx}$. Whereas previous authors (e.g., Lorenz 1955) had used the ($\overline{u}$, u^*) decomposition to analyze interactions between the *global scale* $\ell_1 \equiv 2\pi a \cos \varphi$ (where a is the earth radius and φ is latitude) and the *collection* of all smaller scales, Saltzman's "wavenumber energetics" provided detailed interactions among *each individual* scale, defined by wavelengths $\ell_m \equiv \ell_1/|m| (m \neq 0)$.

Saltzman (1957, 1959) was one of the first to connect the recent observation that atmospheric eddies u^* collectively transfer their kinetic energy to the mean flow $\overline{u}$ with the result from turbulence theory that modes $\hat{u}_m$ can transfer energy to *lower* as well as to higher wavenumbers. Thus, he suggested a physical mechanism for maintaining the "semipermanent centers," that is, localized quasi-stationary pressure patterns. Notably, the energetics of semipermanent centers was eventually further pursued by Hansen and Chen (1982), Hansen and Sutera (1984), and Tanaka (1991), and with further generalization from Fourier to wavelet methods by Fournier (1995, 2003, 2005) and Hasegawa and Tanaka (2002). Fournier approximately spatially localizes wavenumber bands around points $x_{j,k} \equiv 2^{-j}k$, using the orthogonal wavelet expansion

$$\sum_{|m|=2^j}^{2^{j+1}-1} \hat{u}_m e^{2\pi imx} \approx 2^{j/2} \sum_{k=0}^{2^j-1} \tilde{u}_{j,k} W(2^j x - k).$$

Saltzman's atmospheric energetics was applied and generalized by numerous investigators for a wide range of atmospheric phenomena, many of which are collected in the textbook by Wiin-Nielsen and Chen

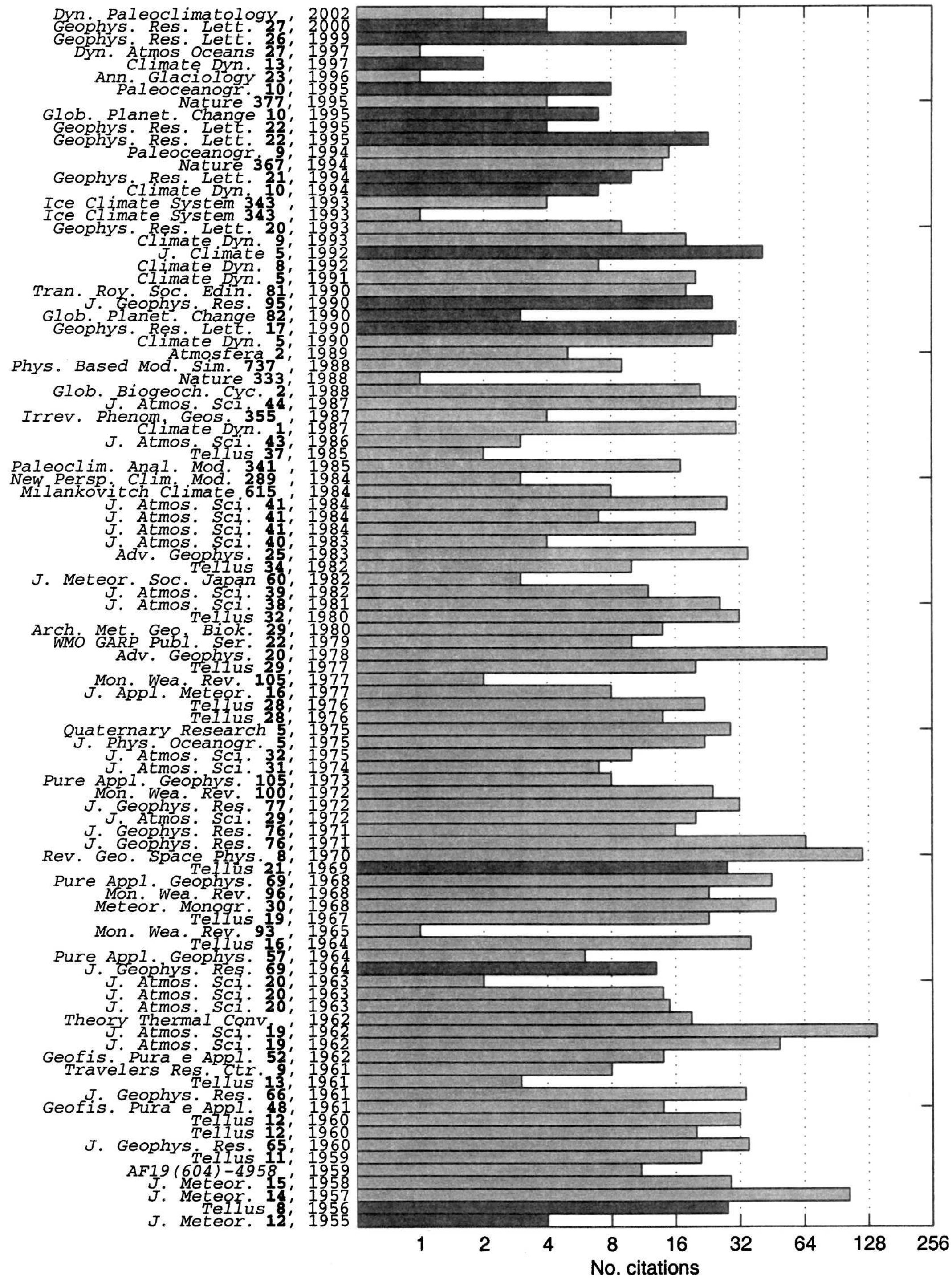

FIG. 1. Number of citations (abscissa, log scale) for Saltzman publications (ordinate) as counted by the Institute for Scientific Information (ISI) Web of Science Cited Reference Search on 31 Aug 2004. Lighter gray indicates primary authorship.

(1993). For example, Steinberg et al. (1971) extended Saltzman's work by applying his available-potential-energy Fourier spectral stock and transfer formulas to observational data and by generalizing his spectral kinetic-energy formulas to enstrophy. Furthermore, Kanamitsu et al. (1972; aided by B. Saltzman 1971, personal communication) generalized Saltzman's energetics formulation to zonally bounded open domains, while Baer (1972) generalized it from zonal Fourier wavenumbers m to spherical Laplace wavenumbers: $\hat{u}_m(\varphi) = \Sigma_{n \geq |m|} \hat{u}_{m,n} P_{m,n}(\sin\varphi)$. Boer (1994) generalized it to time-average and transient interactions: $\hat{u}_{m,n}(t) = \langle \hat{u}_{m,n} \rangle + \hat{u}'_{m,n}(t)$. Each generalization followed Saltzman's original thesis of using appropriate, rigorous decomposition of meteorological patterns to better understand their mutual interactions.

b. Discovery of low-order irregular, nonperiodic flow

Saltzman (1962) is his most cited, and, on average, second-most frequently cited paper, after Saltzman (1970). In this historically pivotal work, Saltzman approximated the 2D Oberbeck (1879)–Boussinesq (1903) PDEs governing roll convection between two isothermal free surfaces, by a seventh-order system of ODEs in time. He again used the Fourier representation, in 2D wavevectors m, to approximate the fields of vertical streamfunction $\psi(t, \mathrm{x})$ and deviation temperature $\theta(t, \mathbf{x})$ by their complex-valued components $\hat{\psi}_{\mathrm{m}}(t)$ and $\hat{\theta}_{\mathrm{m}}(t)$. Upon numerically integrating his ODE system, he discovered that for sufficiently supercritical Rayleigh numbers, four of the seven modes tended to zero, while the order-three subsystem $\mathbf{X} = (\Re\hat{\psi}_{1,1}, \Im\hat{\theta}_{1,1}, \Im\hat{\theta}_{0,2})$ underwent irregular, nonperiodic fluctuations. Around this time, his colleague Ed Lorenz (Lorenz 1962) had found nonperiodic solutions of a similar quasi-meteorological ODE system of order 12, and "was anxious to use an even simpler system . . . to demonstrate exactly what was happening" (Lorenz 1993). Lorenz (1993) recalls that he had "tried to simplify the model . . . with no luck" and so he was "indebted to Dr. Barry Saltzman for bringing to his attention the existence of nonperiodic solutions of the convection equations" (Lorenz 1963). Indeed, with Saltzman providing such a low-order system ["whose existence Lorenz had begun to doubt" (Lorenz 1993)], Lorenz (1963) was able to perform a thorough analysis and obtain seminal results, including (i) what later would be widely known as a pitchfork and a subcritical Hopf bifurcation w.r.t. Rayleigh number, (ii) instability (in the sense of Lyapunov, which is what would later be called "chaos"), and (iii) the first rough sketch of the complicated branched manifold structure in 3D **X**-space ("an infinite complex of surfaces"), which would later be known as a "butterfly" or "strange attractor." One can hardly overstate the eventual and ongoing significance of these discoveries. Even the briefest review of the subsequent work of Lorenz, not to mention countless other investigators who started from these roots, is well beyond the present scope. However, we will see below how Saltzman would eventually return to low-order nonperiodic systems like the one he discovered in 1962, in order to combine fundamental physical principles and an inductive process to construct explicit dynamical models of climate change.

3. Theory of climate

Barry Saltzman was ever so careful in defining "climate," decomposing measures of the climate state into a steady equilibrium, or diagnostic component, and the transient departures from that equilibrium, or the prognostic (time dependent, predictive) component. He carefully accounted for all the potentially relevant physical processes (hypothesized by him or others) using explicit representations where possible and purely symbolic representations where sufficient detailed understanding was still lacking. This required extensive lists of symbols; when the Greek and Roman alphabets proved insufficient he was forced to use characters from the Hebrew alphabet! Only after all possible processes were represented would he attempt to reduce them to a more manageable number via scale analysis. Two works of his particularly capture the emphasis of this work—chapters in *Advances in Geophysics* (Saltzman 1978, 1983). His ultimate views on a comprehensive theory of climate are detailed in *Dynamical Paleoclimatology*, the book he completed only weeks before his death (Saltzman 2002).

a. Equilibrium climate

Saltzman's work on understanding equilibrium climate began during his graduate and postdoctoral days and continued throughout his career. Originally, his interests lay in distinguishing climatic phenomena from shorter-term weather, or meteorological, phenomena. He later turned to studies emphasizing climate on explicit monthly to seasonal climatic time scales.

1) Energy balance and statistical dynamical climate models

During the 1960s, Saltzman did important work aimed at developing parameterizations for energy balance models (EBMs). In the most notable of these (Saltzman 1967), he attempted to fully account for all processes responsible for determining the earth's surface temperature. Very quickly, however, he realized that EBMs were severely hampered in fully describing climate by a lack of dynamics, including the very crucial hydrologic cycle. This led him to introduce and develop a class of models called statistical dynamical models (SDMs), attempting to extend the EBMs to include parameterizations for zonal representations of dry atmospheric dynamics and the hydrologic cycle. Saltzman considered the SDM to be 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 that are subsequently aggregated to yield climate statistics in the same manner as done with daily weather observations). His seminal works in this regard are detailed in two papers written with Vernekar (Saltzman and Vernekar 1971a, 1972). Saltzman (1978) remains the definitive review of these models, though he continued to refine key parameterizations, notably those concerning the hydrologic cycle (e.g., Saltzman 1980).

Saltzman attempted to use his SDM to address problems of climate change (Saltzman and Vernekar 1971b), an important precursor to his later work on ice age oscillations. Much later, Oglesby and Saltzman (1990a) used the SDM to explore problems of pre-Pleistocene climate. In this latter study, the emphasis was on the role of subsurface temperatures, especially in the ocean (the "T_d question" in Saltzman's parlance), a theme he expressed frequently throughout his career and that he helped further develop in some of his last work. At Saltzman's encouragement, Mann (1998) sought to parameterize stationary eddy (gyre scale) ocean heat fluxes in the context of a simplified, zonally averaged model of the ocean, in a manner analogous to that in which Saltzman (e.g., Saltzman 1967) had sought to parameterize atmospheric eddy flux contributions.

2) General circulation models

Most of Saltzman's GCM work (subsequent to early development for the MIT project) involved use of these models in hierarchal theories of climate change and paleoclimate and is discussed below. A few studies, however, were aimed more at the general theme of equilibrium climate. Hu et al. (2000), Saltzman's last published paper during his life, examined the radiative role of water vapor and the ability of the GCM to capture this, with implications for potential future climate change. This work is explored more fully in Hu et al. (2005). Finally, in a posthumous paper, Oglesby et al. (2005) used a GCM to explore climatic ramifications of subsurface ocean temperatures (T_d) using a mixed layer model developed by Stephens et al. (2005).

b. Climate change and paleoclimate

Long-term climate changes occur on time scales ranging from millennia to millions of years. Saltzman broke the problem into three basic parts, for which different methods need be applied to construct a complete theory for how it all works (Saltzman 1990). On tectonic time scales (10–100 Myr), the movement of continents and building of mountains has a profound influence on the global climate. Ice ages occur roughly every 200–300 Myr in coincidence with continental collision and subsequent uplift of mountains. On this ultralong time scale, Saltzman reasoned that the climate system would be in equilibrium with the very slow tectonic forcing.

In the early Cenozoic (mid-Eocene) period, the Earth was much warmer than at present. Gradual cooling over the last 50 million years led to what is commonly referred to as the late Cenozoic ice age. Prior to around 2.5 Ma, there was little Northern Hemisphere ice. Since then, it is evident that on earth-orbital time scales (20–100 kyr) the global climate oscillates between glacial and interglacial conditions. Between 2.5–1.0 Ma glacial–interglacial cycles of around 40 kyr occurred. After about 900 ka, a near 100-kyr cycle came to dominate the paleoclimate record. 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 argued that any complete theory for the ice age must at a minimum account for the onset of glaciation, along with these transitions in the character of glacial–interglacial cycles.

On millennial time scales (1–10 kyr), rapid shifts in global climatic conditions during the last glacial–interglacial cycle occur on two characteristic time scales, roughly 1–3 and 5–10 kyr. On earth-orbital and millennial time scales, 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.

Saltzman considered all of this information on climate change as his guide for constructing dynamical-systems models for global climate change. These models, which are a closed set of equations governing the time-dependent variations of climate variables (i.e., global ice mass, atmospheric CO_2, ocean circulation, etc.), represent his theory for climate change on geologic time scales ranging from thousands to millions of years.

1) Statistical dynamical models

Saltzman's use of climate models for the purpose of developing a complete theory for ice ages started with SDMs. Along with Anandu Vernekar, he used the newly available Climate Long-Range Investigation Mapping and Prediction (CLIMAP) reconstruction (CLIMAP 1976) of last glacial maximum (LGM) boundary conditions to obtain the SDM solution for zonally averaged climate at 18 ka (Saltzman and Vernekar 1975). It was also around this time that GCMs were first used to try to simulate climate conditions at the LGM (e.g, Gates 1976; Manabe and Hahn 1977). These model experiments, however, only provided an equilibrium "snapshot" of what climate conditions may have been like during the LGM. What Saltzman was really after was the time-dependent behavior of the climate system. Clearly recognizing that GCMs could not feasibly be used as a prognostic tool for the purpose of long-term climate change, he turned to developing his own nonequilibrium, time-dependent models.

Feedbacks between sea ice extent, ocean temperature, and CO_2 were explored by developing a time-dependent SDM of climate change (Saltzman 1978; Saltzman and Moritz 1980; Saltzman 1982). This model describes the fundamental dynamic energy exchanges between the ocean, atmosphere, and sea ice. Its prognostic state variables are bulk ocean temperature and sea ice extent. Variations in both prognostic variables are determined by heat fluxes. The ocean can gain or lose heat (and hence change temperature) through the sea ice, at the sea ice margin, and across the ocean–air interface. The extent of sea ice varies solely as a function of the freezing (melting) at its margin, envisioned as a flux of latent heat to (from) the ocean.

Within the range of plausible solar variability and greenhouse forcing, Saltzman's model predicted the possibility of 1–2-kyr oscillations. The now well-known millennial-scale oscillations known as Dansgaard/Oeschger cycles would not become mainstream in the literature for at least another decade. In effect, Saltzman had modeled millennial climate oscillations many years before widespread interest in climate change on this time scale developed in the paleoclimate community.

2) Low-order dynamical system climate models

Following the development of this time-dependent SDM, it became apparent to Saltzman that a simpler form of model equations, which retain some representation of the important physics included in the more complicated model, would serve as a more useful way to illustrate, and explore, the many positive feedbacks involved in low-frequency climatic variability. From the SDM of the sea ice–ocean system, Saltzman et al. (1981) developed a low-order model in which the prognostic, or time dependent, variables were expressed as departures from equilibria. These equilibria, determined from boundary conditions, are not directly involved in the feedback dynamics. Hence, unlike the statistical–dynamical model of Saltzman and Moritz (1980), which used the *full* values of the prognostic variables, this low-order model focused solely on the feedback dynamics that produce variability *about* the full system's equilibria.

With this prototype model, Saltzman provided an eloquent illustration of the advantages provided by a dynamical systems approach to developing a theory of time-dependent paleoclimate change. With this distilled version of the more complex SDM, he was able to explore the individual feedbacks in terms of the structural stability of the model solution. Over a plausible range of model parameter values, both steady-state, damped oscillatory and auto-oscillatory solutions were obtained. With this model he was also able to clearly make the important point that model solutions are more realistic with the inclusion of stochastic forcing. In fact, he argued that stochastic forcing is actually a necessary component of models including variables averaged over a significant amount of periodic fluctuation and that stochastic forcing may also be necessary to produce low-frequency oscillations by sustaining damped periodic modes, or by stochastic resonance.

At this point, Saltzman's primary attention shifted to the problem of explaining the near 100-kyr cycle that has dominated global climate change over the last 900 kyr. At the most fundamental level, Barry believed that all climatic variability is due to either 1) changes in external forcing (e.g., Milankovitch earth-orbital changes) or 2) instability of the internal system that would arise even in the presence of steady external forcing. He noted that all indications point to the probability that a complex combination of both of these possibilities is involved in producing the observed paleoclimatic variability. Being so familiar with the baroclinic theory for midlatitude storms, it was natural for Barry to consider the possibility that instability within the climate system could lead to auto-oscillatory behavior on long time scales. At the time, however, this concept met considerable resistance. Saltzman stood virtually alone with regard to the idea that the near 100-kyr ice age cycle may be the result of internally driven oscillations due to positive feedbacks in the climate system. In the 1980s, 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.

Classic Milankovitch theory states that high-latitude (~65°N) summer insolation variations give rise to glacial cycles. More specifically, at times when summer temperatures remain cool enough for the previous winter's snow to survive the warm months, an ice sheet can form and grow. Saltzman reasoned that if near-surface air temperature was the critical factor in building an ice sheet that one needs to know how temperature in high-latitude regions is related to insolation, along with greenhouse forcing, ocean temperature, and the ice sheets themselves. His models included time dependence of global ice volume as a function not only of insolation, but also of these other relevant climate variables. The challenge to Saltzman was to discover laws that govern the time-dependent evolution of global ice volume over the past few million years. He cast these governing laws as a set of equations forming a closed system in which the long-term changes in global climate are projected onto the dynamical behavior of only a few prognostic variables to which the fast-response variables governed by a GCM are equilibrated. This system constitutes what Saltzman called a "paleoclimate dynamics model" (PDM).

During his last twenty years, Saltzman made significant progress toward meeting this challenge. In this body of his work, he clearly articulated the need for using an inductive approach. The reason for this is that the fluxes of energy involved in climate change on long time scales were so small. For example, the amount of energy required to melt the great Northern Hemisphere ice sheets of the last glacial maximum was only on the order of 10^{-1} W m^{-2}. Likewise, the energy flux involved in observed glacial–interglacial change in deep ocean temperature was also only on the order of 10^{-1} W m^{-2}. Guided by rapidly accumulating empirical evidence for paleoclimate change, Saltzman constantly refined his theory by including the climate system components implicated by the most up-to-date view of past climate conditions. He methodically explored those feedbacks likely to play an active role in paleoclimate change.

A brief summary of Saltzman's low-order PDMs begins with a modification to the Saltzman and Moritz (1980) model. Reinterpreting sea ice as floating marine ice (Saltzman et al. 1982), and subsequently the addition of a third variable, yielded a model solution with a much longer periodicity, closer to 100 kyr (Saltzman et al. 1984b). With subsequent modifications, this model was used to explore potential climate instability due to marine ice sheets, as proposed by Denton and Hughes (1981). The cryosphere was split into continental ice sheets and marine ice sheets and dynamically linked with the deep ocean in a three-component PDM that exhibited near 100-kyr free oscillations generated by feedbacks within the climate system (Saltzman and Sutera 1984). That earth-orbital forcing was a necessary condition for ice age cycles to occur was an unanswered question that never left Barry's mind. He did, however, always believe that such forcing was important in that it served to phase lock the solution. Using this model, Saltzman et al. (1984a) clearly illustrated the "pacemaker" role of external forcing.

Well into the late 1980s, Barry Saltzman led the revival of the theory that variations of atmospheric CO_2 are a significant driver of long-term climate change. He clearly recognized the importance of greenhouse forcing prior to the time when direct evidence for variations of CO_2 (and CH_4) became available from ice core records. As a true scholar, Salzman remained keenly aware of the historical ideas put forth concerning the impact of CO_2 on climate (e.g., Arrhenius 1896; Callendar 1938; Plass 1956). Further development of his dynamical-systems approach led to the explicit inclusion of atmospheric CO_2 as a prognostic variable (Saltzman 1987, 1988). The idea that there were potentially many positive feedbacks within the carbon cycle was discussed in detail by Saltzman and Maasch (1988a). This model produced an asymmetric, saw-toothed near 100-kyr free solution, with a phase relationship between paleoclimate proxies for global ice mass and atmospheric CO_2 over the last 500 kyr, consistent with available paleoclimate records of these variables (Saltzman and Maasch 1988a,b). The idea that inclusion of a long-term tectonically forced decrease in atmospheric CO_2 can lead to a bifurcation of the system from a steady-state to a near 100-kyr auto-oscillation was illustrated by Maasch and Saltzman (1990) and Saltzman and Maasch (1990, 1991).

While the carbon cycle instability continued to play a significant part in Saltzman's ice age theory, he also considered the possibility that other instabilities may also contribute to observed climate variability. Throughout the 1990s, he methodically explored the potential impact of an active cryosphere in the ongoing refinement of his theory. Along with Mikhail Verbitsky, he added bedrock depression as a prognostic variable to his PDM (Saltzman and Verbitsky 1992, 1993). In addition to the possibility for a near 100-kyr cycle, still driven by the carbon cycle instability, this model also included a possible solution with a near 40-kyr periodicity driven by a conditional instability due to an ice calving mechanism during times when large ice sheets are present.

Following up on paleoclimatically important aspects such as an active cryosphere, and possible instabilities within this component of the climate system, Saltzman and Verbitsky systematically explored the theoretical aspects of the millennial-scale variations known as Heinrich events. Occurring only during glacial times, Heinrich events (or oscillations) are roughly spaced at between 5 and 12 kyr. As many paleoclimatologists do, Saltzman considered it likely that the internal physical behavior of ice sheets is a significant driving mechanism for Heinrich oscillations. In essence, when basal temperature reaches the pressure melting point, a layer of liquid water forms that can lead to sliding or surging at the periphery of an ice sheet, usually in the form of ice streams. Using a scale analysis, Verbitsky and Saltzman (1994) found that basal temperature is controlled by the geothermal flux, basal boundary friction, and internal advection of cold upper-surface ice to the basal boundary layer.

With their dynamical model based on the fundamental thermo-mechanical properties of an ice sheet, Verbitsky and Saltzman (1995) and 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.

3) General circulation models

After having developed by midcareer a reputation as a "critic" of GCMs (a tag he never liked as he felt he was only trying to better define what they could and *could not* do), by the end of his career Saltzman was known as a leading worker (and proponent) in their use for problems of paleoclimate. Most of this work was done with his then Ph.D. student Bob Oglesby, to whom Saltzman gave as a specific charge the task of learning how to use these models. They subsequently worked together to apply GCMs to numerous problems of paleoclimate. Some of these involved processes relevant to the climate of a particular past time period. For example, Oglesby et al. (1989) and Maasch and Oglesby (1990) evaluated the role of cooling of the Gulf of Mexico during deglaciation. Most of their studies, however, involved evaluating the *fast components* in Saltzman's theories of climate change, notably atmospheric carbon dioxide and solar luminosity (Oglesby and Saltzman 1990b, 1992; Marshall et al. 1994). A key feature of these studies was investigation of model sensitivity to a wide range of parameter values, as opposed to exhaustive study of model response to a single change (e.g., evaluating the response of systematic carbon dioxide variations from 100 to 1000 ppm rather than just the more conventional doubling of carbon dioxide). Because Saltzman envisioned these models as providing stationary (i.e., equilibrium) parameters in a theory of climatic change, he was also very interested in the sensitivity of the GCM to its initial state. In other words, he wanted to know if they could be used to obtain a well-defined equilibrium (Oglesby et al. 1997; Saltzman et al. 1997).

4. Summary

The list of Barry Saltzman's contributions is long. One way to summarize them is in terms of his publications. Barry had a significant impact on many important aspects of the fields of meteorology, climatology, and paleoclimatology. This impact may be quantified by examining the number of citations of his work (as shown in Fig. 1). He produced a steady stream of papers across almost five decades. Some of the more outstanding honors bestowed upon Barry 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), and serving numerous editorships on prestigious scientific journals and on numerous visiting and advisory committees. Saltzman was also awarded the Carl-Gustaf Rossby Medal in 1998 by the American Meteorological Society (the highest honor bestowed by the AMS).

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