**FINAL REPORT: THEORETICAL CLOUD RADIATION
STUDIES IN SUPPORT OF THE ATMOSPHERIC RADIATION
MEASUREMENT PROGRAM**

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1. Project Goals

Our ARM research project has as its ultimate goal the improvement of theoretical understanding of radiation processes in real clouds. Our strategy is to use remote and *in situ* cloud observations to inform fractal models that elegantly capture the enormous spatial heterogeneity of real clouds. The project was motivated by the great importance assigned to the cloud-radiation problem in understanding climate, and by the recognition that GCM predictions of grid-box-average liquid/ice water (the most we can probably expect) are insufficient to assign cloud radiative properties. The project was designed to have the following logical progression:

- analyze cloud observations, using statistical methods developed in turbulence theory, non-linear dynamics, and the study of multifractals;
- based on these analyses, develop models, mainly with a multi-fractal origin, for the spatial distribution of cloud water
- study the radiative properties (reflectivity, mainly) of these model clouds using the Monte Carlo method.

2. Project Development: Short Synopsis

The project was intended to be carried out largely by two postdocs. (Almost all the funding was used for postdoc salaries, equipment, and travel; Drs. Wiscombe and Cahalan, being civil servants, drew project funds only for ARM travel.) The project got off to a delayed start due to a mixup in first-year funding. Thus it was not possible to advertise for the first postdoc till spring of 1991. Following worldwide advertising, Dr. Alexander Marshak was hired in August 1991; he is an applied mathematician trained in the former USSR, with recent experience in Monte Carlo and fractal approaches to radiative transfer in plant canopies. Dr. Anthony Davis was hired in October 1992; he is a physicist just graduated from McGill University, where his thesis (under Prof. Shaun Lovejoy, an expert in fractal analysis of geophysical data) involved theoretical radiation transport in scale-invariant media.

During the first year of the project, Dr. Marshak "got his feet wet" learning about clouds, cloud data, and multifractal analysis techniques, as well as mastering the U.S. computer and networking environment. He began by studying liquid water content (LWC) aircraft data and liquid water path (LWP) microwave data from the FIRE stratocumulus experiment in 1987, and by developing various multifractal models consistent with this data.

Following the arrival of Dr. Davis, the project expanded into the development of new analysis techniques for the existing data sets, new models for cloud water, and more recently into entirely new data sets including the Gerber LWC and droplet surface area data from the ASTEX experiment and the ARM microwave LWP data.

Concurrently, Dr. Cahalan continued to develop his ideas and methods concerning stratocumulus albedo as measured during FIRE and as calculated from Monte Carlo radiative transfer using bounded multifractal models of cloud liquid spatial distribution that he invented.

The last year was one of intensive journal-article writing and extensive presentation of results at scientific conferences. It was clear that multifractal and other related analysis techniques had not achieved much penetration into the atmospheric community, and thus considerable effort was expended in developing simple examples and writing papers, posters and talks that would be accessible and persuasive to atmospheric researchers.

A list of publications and conference presentations is appended to this report [numbers in square brackets refer to this list]. In the following, we try to give some flavor of the work accomplished without being overly technical.

3. Scale-Invariant Cloud Data Analysis

Consider any signal $\phi(x)$ where x is time or a spatial coordinate. For our work $\phi(x)$ is typically a time series measured in a cloud or from the surface, or radiances from a cloudy scene. We are interested in the *invariant* statistical properties of $\phi(x)$ at some given scale r — those properties which don't change from one cloud to the next. Multifractal analysis techniques aim at finding statistical properties of

$\varphi(x)$ which are *independent of scale r* . Generally, $\varphi(x)$ is "scale-invariant," meaning that its statistics follow power-laws in r over at least 1-2 decades of r values.

In order to discern these power-laws, it is necessary to derive non-negative quantities $\xi_{\varphi}(r;x)$ from $\varphi(x)$ which are somehow degraded to scale r (by differencing, averaging, or otherwise applying a moving window function of width r to $\varphi(x)$). Then we seek $A(q)$ in

$$\langle \xi_{\varphi}(r;x)^q \rangle \equiv \langle \xi_{\varphi}(r)^q \rangle \propto r^{A(q)} \quad (1)$$

where $\langle \cdot \rangle$ denotes an ensemble average and where the identity applies only if ξ_{φ} is stationary. q corresponds to the moment number in standard Gaussian statistics, except that it is a real variable which can be negative as well as positive. $A(q)$ is derived as the slope of the fitted straight line (if it is straight!) on the graph of $\log(\langle \xi^q \rangle)$ vs. $\log(r)$. The range of r over which the line is straight is denoted by $[\eta, R]$ in the following.

Such power-law behavior is expected from geophysical systems governed by strongly nonlinear dynamics. Thus, in contrast with standard (e.g. Gaussian) statistical techniques, scale-invariant ones are physically based and so have proven invaluable in all of nonlinear science. They are still vastly under-exploited in atmospheric science, largely due to a lack of good introductory material, doubts as to their utility, and misconceptions about their mathematical difficulty. Thus we have taken considerable pains in [2] to give a step-by-step tutorial on the two most popular multifractal analyses applicable to a non-stationary signal, namely "Structure Functions" and "Singular Measures". Here, we illustrate these analyses using liquid water path data from the microwave radiometer at the Southern Great Plains ARM site; the ensemble-average is taken over 41 one-day time series free of suspicious behavior (e.g., missing data, unphysically large values, too many negative values, rain and dew). Samples of several days of this data are shown in Fig. 1. The ensemble-average power spectrum is shown in Fig. 2(a) and exhibits nearly a 5/3 power-law in wavenumber.

Figure 1: ~~4~~ samples of cloud vertically-integrated liquid water path (LWP) retrieved from passive microwave radiometry at the Oklahoma ARM Central Site.

- Structure Functions. Here the operation on the data consists merely in taking differences across scale r :

$$\xi_{\varphi}(r;x) = |\Delta \varphi(r;x)| \equiv |\varphi(x+r) - \varphi(x)|$$

Figure 2(b) is a log-log plot of $\langle \Delta \varphi(r)^q \rangle$ vs. r showing a "scaling range" $[\eta, R]$ of almost 3 decades. In this scaling range, we fit straight lines to the points, for multiple q values, and so obtain the exponent

$$A(q) = \zeta(q) = q H(q) \geq 0 \quad (\text{for } q \geq 0)$$

(adopting notations from the turbulence/physics literature). $\zeta(q)$ is plotted in Fig. 3; it is concave and smooth with $\zeta(0)=0$. Note that, although the microwave LWP data rarely appear *differentiable*, the fact that $\zeta(1)$ is positive reveals a tendency toward *continuity* since $\Delta \varphi \rightarrow 0$ as $r \rightarrow 0$.

- Singular Measures. Here the operation on the data consists in taking

$$\xi_{\varphi}(r;x) = \varepsilon(r;x) = \text{spatial averages of } |\Delta \varphi(\eta;x)| \text{ over } r\text{-sized intervals}$$

where η is the lower end of the scaling range. Figure 2(c) is a log-log plot of $\langle \varepsilon(r)^q \rangle$ vs. r showing roughly the same scaling range as Fig. 2(a). Fitting straight lines, as before, gives the exponent

$$-A(q) = K(q) = (q-1) C(q)$$

$K(q)$ is plotted in Fig. 3; it is convex and smooth with $K(0) = K(1) = 0$ in general. The non-increasing function $D(q) = 1 - C(q)$ has been used to quantify the underlying *intermittency* of $\varphi(x)$ in turbulence studies; another well-known interpretation of $D(q)$ is as the "generalized dimension".

A particularly attractive feature of these analyses is that the exponents $\zeta(q)$ and $K(q)$ are smooth functions, whereas the original data is wildly vacillating. Also, time series that "look" very different are often revealed to have similar $\zeta(q)$ and

Figure 2: *Scale-Invariance of the Statistical Properties of LWP measured at the Oklahoma ARM site.* An ensemble of 41 daily datasets with 20-sec resolution was used to obtain these results. (a) Power spectrum $E(k)$ vs. wavenumber k in log-log axes; the slope defines the exponent $\beta \approx 1.69$. (b) log-log plot whose slope gives Structure Function exponent $\zeta(q)$, for $1 \leq q \leq 5$; the scale-invariant regime η to R is indicated. (c) log-log plot whose slope gives Singular Measures exponent $K(q)$, for $1 \leq q \leq 5$.

Figure 3: The $\zeta(q)$ and $K(q)$ Exponent Functions for LWP measured at the Oklahoma ARM site. An ensemble of 41 daily datasets with 20-sec resolution was used to obtain these results. The curvature of these two functions establishes the multifractality of the horizontal distribution of liquid water in the atmosphere. The range of scales involved is 200 m to 100 km (assuming a 5 m/s cloud speed and Taylor's frozen turbulence hypothesis to time to space). The mean exponents H_1 and C_1 are highlighted and carried into Fig. 4.

$K(q)$, thus revealing a hidden kinship.

The functions ξ_φ are simple special cases of wavelets. Both $\zeta(q)$ and $K(q)$ can also be derived using the simplest wavelet transforms, and we discussed this in [6], which evolved from a presentation at an AGU session on the use of wavelets in geophysics. We have explored alternative wavelet-based approaches to both data analysis and model synthesis in [7,13].

We have studied possible $K(q) \leftrightarrow \zeta(q)$ connections (much discussed in the turbulence field) for cloud datasets in [5,6]. As one aspect of such connections, and in order to classify cloud datasets and compare them both with each other and with model calculations, we have proposed [2,5,11,16] the "mean multifractal plane" as a simple and universal diagnostic device. In this plane, a dataset becomes a point with x-coordinate $H_1=H(1)$ and y-coordinate $C_1=C(1)$. H_1 measures stationarity, or, alternatively, the fractal dimension of the data graph; C_1 measures intermittency, which is, loosely speaking, the 'spikiness' of the data graph.

Figure 4 shows the (H_1, C_1) plane with points for the ARM microwave LWP data and for the FIRE and ASTEX LWC data. These points do not correspond to either of the simplest random models: neither additive models like fractional Brownian motion, nor multiplicative cascade models like those used for turbulent dissipation. This points up the need for a new class of stochastic models for LWC and LWP.

4. Stochastic Modeling of Cloud Liquid Water Fields

Our main goal in the data analysis procedures described above is to single out a small number of representative statistical parameters, in order to develop simple yet realistic stochastic models of cloud liquid water. These models enable us to simulate not only the measurement itself (which is generally 1-D) but also the liquid water field in 2-D and 3-D, making certain assumptions about statistical isotropy.

Cascade models are the current paradigm in turbulence studies. These models try to reproduce the observed intermittency in the kinetic-energy dissipation field.

Figure 4: The "Mean Multifractal Plane." H_1 is plotted along the x-axis and measures amount of graph smoothness (from completely discontinuous at $H_1=0$ to smooth at $H_1=1$); its physical interpretation is in terms of stationarity. C_1 is plotted along the y-axis and measures amount of intermittency or "spikiness" (from none at $C_1=0$ to a field of delta-functions at $C_1=1$). Both have interpretations in terms of generalized dimensions: H_1 in terms of graph dimension D_g , C_1 in terms of "information dimension" D_1 . Geophysical signals tend to live inside the unit square while the standard "multiplicative" and "additive" models live on the axes.

A typical construction is as follows: set the field $\equiv 1$ on the unit interval, then multiply the field in one half of the interval by W , in the other half by W' , where W and W' are unit-mean non-negative random variables drawn from the same distribution; repeat this procedure on smaller and smaller scales.

In Fig. 5, the leftmost inset shows the result (after 10 cascade steps) of selecting $W = 1 \pm (1-2p)$ and $p=0.35$ (so $W=0.7$ or 1.3) with equal probability, with W' taking the non-selected value (this is an optional constraint of stepwise rather than statistical conservation). The range is unbounded as the model is iterated to infinity, hence it is called a "singular" model. Below the inset is the model's power spectrum power-law exponent β as a function of p ; β is between 0 and 1, indicating a stationary process. In addition, the model is scale-invariant and discontinuous; it falls on the y-axis of the (H_1, C_1) plane and does not correctly simulate any of the cloud liquid water data.

We have studied several empirical modifications of the above cascade model that more correctly simulate the cloud liquid water data. One, called the "bounded" or "Cahalan" model, simply reduces the variance of the W 's at each cascade step n , according to

$$W = 1 \pm (1-2p) r_{n-1}^H \quad (H > 0), \text{ at scale } r_n = 1/2^n$$

Because this model is strictly bounded, its Singular Measures exponent $K(q) \rightarrow 0$ as $n \rightarrow \infty$. In [1], we derived an analytical expression for the residual value of $K(q)$ at $n < \infty$, showed that the Structure Function exponent is

$$\zeta(q) = \min\{qH, 1\}$$

and showed that the power spectrum exponent is

$$\beta = \zeta(2)+1 = 2H+1 \quad \text{if } 0 < H < 1/2$$

(independently of p). $H=1/3$ roughly gives the $\beta \approx 5/3$ observed in cloud liquid water data. In Fig. 5, the middle inset shows a realization of the $H=1/3$ bounded model after 10 cascade steps; the range is much smaller than its singular counterpart in the leftmost inset and "looks" a lot more like cloud liquid water data. The rightmost inset shows a realization for $H=1.7$; it clearly displays the discontinuities

Figure 5: *Power-Spectrum Exponents of Singular and Bounded Cascades.* (a) The field illustrated in the leftmost inset has $K(q) = \log_2[(2p)^q + (2-2p)^q] - 1$ for any real q [1, and references therein] and a residual $\zeta(q)$ function with small values dependent on the finite number of cascade steps; it is stationary since $\beta = 1 - K(2) < 1$. (b) The two fields illustrated in the rightmost insets have $\zeta(q) = \min\{qH, 1\}$ for $q > -1$ and only residual $K(q)$'s; they are non-stationary since $\beta = \zeta(2) + 1 > 1$ [1,3, and references therein].

arising from the construction process, which prevent β from rising above 2, as can be seen in the graph above the inset.

Another class of models that we have used to reproduce observed cloud liquid water data are called "fractionally integrated", which involves Fourier transforming the singular model to wavenumber space, multiplying by a fractional power of wavenumber to get the right β , then Fourier transforming back to real space. We then linear transform the result in order to fit the mean, variance and sign of skewness of LWC time series observed in aircraft soundings. Figure 6 shows an example; the upper panel shows measured LWC from a King hot-wire probe, the bottom panel the corresponding fractionally-integrated linearly-transformed result. Both fields show intense and generally clustered downward spikes (probably related to cloud-top entrainment events). The fact that the model and measurements still don't "look" alike may be important, but we suspect that simply getting the model's fractal statistics right is the most important thing as far as radiative transfer is concerned.

The bounded and fractionally-integrated models are still somewhat *ad hoc*. The analogy with turbulence is rather loose since LWC is an active not a passive scalar. And neither model can predict patchy cloudiness, their LWC values always being non-zero. In an effort to inject more physics, we have developed a third class of model which we call "thermodynamic". The essence of the model is as follows. Cloud top and cloud base air are characterized by their equivalent potential temperature θ_e and total water (liquid + vapor) mixing ratio Q_{tot} . These two quantities are sufficient to determine the LWC. A cloudy parcel is assumed to have θ_e and Q_{tot} values linearly mixed from the corresponding cloud top and bottom properties, with a mixing fraction f derived from a multifractal cascade model. This model allows cloud gaps, and a cascade model is more appropriate for f than for LWC. Our preliminary results using this model to simulate ASTEX LWC data are very encouraging, and we expect it will be vital for modeling ARM microwave LWP.

5. Multifractal Characterization of Cloud Liquid Water Distributions

We have performed extensive spectral and multifractal analyses of LWC

Figure 6: *Stochastic modeling of a typical cloud liquid water signal.* (a) A sample of a LWC time series measured during FIRE'87; the overall length of this segment is ≈ 40 km (for more details, see [15–16]). (b) A fractionally integrated stochastic model with similar (H_1, C_1) values and the same mean, variance and sign of skewness as the signal in (a).

distributions obtained from two sources: first, a King probe flown during the July 1987 FIRE marine stratocumulus experiment off the coast of southern California and, second, a new optical instrument developed by Herman Gerber flown during the Atlantic Stratocumulus Transition EXperiment (ASTEX) in the Azores during June 1992.

Multifractal analyses of the FIRE LWC data are reported in [9,12]. We found this data to be scale-invariant from 20 m to at least 20 km upon ensemble-averaging five long datasets, with interesting violations of scaling in individual datasets. The LWC data are shown to be

- non-stationary with $\beta \approx 1.5$ (somewhat less than LWP where $\beta \approx 5/3$ [3]),
- multifractal with parameters $H_1 \approx 0.29$ and $C_1 \approx 0.08$ (cf. Fig. 4).

The ASTEX data analyzed in [22] is also made of five flight sections, selected to be largely inside cloud and relatively long. This LWC data is scale-invariant from 60 m to 60 km and its mean multifractal parameters (H_1, C_1) are very close to those of the FIRE data (cf. Fig. 4). This argues for a degree of universality in the strongly nonlinear turbulent dynamics that determine the internal structure of marine stratocumulus under rather different climatological conditions.

In [15], we have also compared the spectral responses to natural variability of King and Johnson-Williams hot-wire probes (the latter showing the lag expected from an instrument with more inertia). Similar comparison of King and Knollenberg FSSP probes highlight the inherent digital noise of the latter and its general inutility for studies of the statistics of LWC.

The Gerber instrument also measures "PSA" (Particle Surface Average), which is nearly proportional to radiative extinction coefficient in the shortwave. Our analyses of PSA data reveal it to have almost identical statistical character to the LWC data; this is an important result, showing that LWC may be used as a surrogate for extinction, as far as multifractal statistics go. The ratio LWC/PSA is roughly proportional to "effective droplet radius" (r_{eff}), a quantity which has become of intense interest for climate models because it allows their predictions of LWP to be transformed to the optical depth needed by their radiation subroutines. We are

currently analyzing the PSA data independently and jointly with LWC, as a means to test the robustness of the standard constant- r_{eff} hypothesis.

In Figs. 1-3 we showed some results of our analysis of LWP retrieved from the passive microwave radiometer at ARM's Southern Great Plains site. In Fig. 3, the mean exponents $H_1 \approx 0.37$ and $C_1 \approx 0.08$ are highlighted and carried into Fig. 4 as a point. As expected for a quantity smoothed by vertical integration, we notice that the parameter of non-stationarity H_1 (as well as $\beta = \zeta(2)+1$) is somewhat larger than that of LWC in stratocumulus. At the same time, the corresponding values of the intermittency parameter C_1 are very close, suggesting a certain subtle universality in the mesoscale atmospheric dynamics responsible for cloud formation and maintenance.

6. Radiative Transfer Simulations in Random Fractal Media

Our team, together with various outside collaborators, has reported in [3,8,14,17] a number of new results on the albedo of marine stratocumulus, known to be a major contributor to cloud forcing in climate models. These papers have compared Monte Carlo simulations and "independent pixel approximations" of cloud albedo, assuming a horizontal distribution of optical depth given by the bounded cascade model. The independent pixel approximation consists in neglecting *net* horizontal radiative fluxes across pixel boundaries; each pixel can then be treated as a homogeneous plane-parallel cloud. When this approximation is valid, it represents a considerable reduction in the information a climate model must know in order to calculate accurate cloud albedos.

The two parameters of the bounded model are selected so as to reproduce the $\beta \approx 5/3$ power spectrum exponent and the probability distribution of LWP observed during the FIRE stratocumulus experiment. Then the following major results were obtained:

- (a) independent pixel and Monte Carlo albedos are usually very close, although there can be enormous differences in individual pixels;
- (b) plane-parallel albedo estimates are least accurate when the cloud fraction is nearly 100%, because then stratocumulus liquid water is the most variable; thus

the maximum error in the plane-parallel albedo occurs when the usual climate-model correction, involving only cloud fraction, vanishes.

- (c) for typical sun angle and mean optical thickness, the pixel-mean albedo is substantially less than the plane-parallel estimate (with the same mean optical depth);
- (d) the pixel-mean albedo can be approximated by the plane-parallel estimate for a reduced optical thickness, where the reduction factor is a function of the bounded-model parameter p .

To illustrate results (c) and (d), Fig. 7 shows the pixel-mean albedo vs. the pixel-mean LWP for a plane-parallel model and for the bounded cascade model in the independent pixel approximation. At $LWP=100 \text{ g/m}^2$ (optical depth ≈ 15), the relative bias is 15% and, to obtain the "correct" albedo from a plane-parallel model, 30% less liquid water must be used.

Marshak and Ridgway have imported the Monte Carlo code of Dr. G. Titov of the Institute of Atmospheric Optics in Siberia, who is scheduled to visit us for several weeks in spring 1994. Dr. Titov has been funded by ARM to investigate the radiative effects of broken cloudiness and we are considering joint efforts centered on the thermodynamic model discussed above.

7. Summary

We have applied multifractal analysis techniques to marine stratocumulus liquid water content, and discovered scale-invariance over three decades of spatial scale. The multifractal statistical parameters seem to depend little on the local climatology; similar parameters were found for daily liquid water path data measured at the Oklahoma ARM site.

We have developed new random fractal models that effectively simulate the liquid water data, which in turn fed into Monte Carlo radiative transfer studies of cloud albedo that showed the utility of the "independent pixel approximation".

We have developed the "mean multifractal plane" (Fig. 4) as a diagnostic

Figure 7: *Albedo Bias due to Internal Cloud Variability.* The upper curve is the albedo predicted by a homogeneous plane-parallel model as a function of LWP or optical thickness τ for a sun angle of 60° and an asymmetry factor of 0.85. The lower curve corresponds to our bounded cascade model with parameters $H = 1/3$ (hence $\beta = 5/3$) and $p = 0.25$ (which fits the observed 1-point variance) in the independent pixel approximation.

device to compare datasets and validate models. And we have related our work to the wavelet analysis approach.

A number of papers have been published and submitted on this work, and numerous conference posters and talks have been given (see below).

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LIST OF PUBLICATIONS FROM ARM PROJECT (PI: WISCOMBE)

Journal Papers

- [1] "Bounded Cascades as Non-Stationary Multifractals." A. Marshak, A. Davis, R. Cahalan and W. Wiscombe, **Physical Review E**, to appear in Vol. 49, #1 (Jan. 1994).
- [2] "Multifractal Characterizations of Non-Stationarity and Intermittency in Geophysical Fields, Observed, Retrieved or Simulated." A. Davis, A. Marshak, W. Wiscombe and R. Cahalan, **J. Geophys. Res.** (accepted, January 1994).
- [3] "The Albedo of Fractal Stratocumulus Clouds." R. Cahalan, W. Ridgway, W. Wiscombe, T. Bell and J. Snider, **J. Atmos. Sci.** (accepted, October 1993).
- [4] "Multi-Singular and Multi-Affine Properties of Bounded Cascade Models." A. Marshak, A. Davis, R. Cahalan and W. Wiscombe, **Fractals** (accepted, July 1993).
- [5] "Bi-Multifractal Analysis and Multi-Affine Modeling of Non-Stationary Geophysical Processes, Application to Turbulence and Clouds." A. Davis, A. Marshak and W. Wiscombe, **Fractals** (accepted, July-1993).

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- [6] "Two Dynamically Relevant Multifractal Data Analysis Techniques, A Wavelet-Based Approach." A. Davis, A. Marshak and W. Wiscombe, in **Applications of Wavelet Transforms in Geophysics**, Eds. E. Foufoula-Georgiou and P. Kumar, Academic Press (accepted, Jan. 1994).
- [7] "Inhomogeneities in Marine Stratocumulus Liquid Water Column Amount Using Wavelet Analysis" S. M. Gollmer, Harshvardhan, R. F. Cahalan, and J. B. Snider, in **Applications of Wavelet Transforms in Geophysics**, Eds. E. Foufoula-Georgiou and P. Kumar, Academic Press (accepted, Jan. 1994).
- [8] "Impact of Cloud Structure on Climate." R. F. Cahalan and W. J. Wiscombe, in **IRS'92: Current Problems in Atmospheric Radiation**, Ed. Sirje Keevallik, A. Deepak Publishing, Hampton (Va.), 565+pp, pp. 120-124, 1993.
- [9] "On the Analysis of the Multifractal Properties of Cloud Liquid Water." A. Marshak, W. Wiscombe, and A. Davis, in **IRS'92: Current Problems in Atmospheric Radiation**, Ed. Sirje Keevallik, Deepak Publ., Hampton (Va.), 565+pp, pp. 116-119, 1993.
- [10] "Supercomputer Simulation of Radiative Transfer Inside Multifractal Cloud Models." A. Davis, S. Lovejoy and D. Schertzer, in **IRS'92: Current Problems in Atmospheric Radiation**, Ed. Sirje Keevallik, Deepak Publ., Hampton (Va.), 565+pp, pp. 112-115, 1993.

Papers Submitted but not yet Accepted for Publication

- [15] "The Scale-Invariant Structure of Marine Stratocumulus Deduced From Observed Liquid Water Distributions, 1 - Spectral Properties and Stationarity Issues." A. Marshak, A. Davis, W. Wiscombe and R. Cahalan, **J. Atmos. Sci.** (submitted, Jan. 1994).
- [16] "The Scale-Invariant Structure of Marine Stratocumulus Deduced From Observed Liquid Water Distributions, 2 - Multifractal Properties and Model Validation." A. Davis, A. Marshak, W. Wiscombe and R. Cahalan, **J. Atmos. Sci.** (submitted, Jan. 1994).
- [17] "Bounded cascade clouds: albedo and effective thickness." R. F. Cahalan, **Nonlinear Processes in Geophysics** (submitted, Nov. 1993).
- [18] "Independent Pixel and Monte Carlo Estimates of Stratocumulus Albedo." R. Cahalan, W. Ridgway, W. Wiscombe, S. Gollmer and Harshvardhan, **J. Atmos. Sci.** (submitted, Aug. 1993).

Papers in Progress (Working Titles)

- [19] "Testing the Hypothesis of Multiplicity in the Scaling of Statistical Properties of Geophysical Signals."
- [20] "Bounded Cascade Models, A Paradigm for Phase Transitions Between Multifractal Stationary and Non-Stationary Behavior."
- [21] "Multifractal Stochastic Models for Geophysical Processes, Application to the Internal Structure of Stratocumulus."
- [22] "Multifractal Properties of Liquid Water Path Retrieved From Passive Microwave Radiometry at the ARM Central Great Plains Site."

Conference Papers

- [11] "Two Complementary Multifractal Analysis Techniques for Non-Stationary Atmospheric Processes with an Application to Cloud Liquid Water Content." W. Wiscombe, A. Davis, and A. Marshak, in *Proceedings of the Third Atmospheric Radiation Measurement (ARM) Science Team Meeting*, March 1-5, Norman (Okla.), 1993 (in press).
- [12] "Multifractal Models of Cloud Liquid Water." A. Marshak and W. Wiscombe, in *Proceedings of the 4th. Symposium on Global Change Studies*, January 17-22 1993, Anaheim (Ca.), A.M.S., Boston (Ma.), pp. 220-224, 1993.
- [13] "Wavelet Analysis of Marine Stratocumulus." S. Gollmer, Harshvardhan, R. F. Cahalan, and J. Snider, in *Proceedings of the 11th. International Conference on Clouds and Precipitation*, August 17-21, Montreal (Qc), Canada, pp. 827-831, 1992.
- [14] "Plane-Parallel Albedo Bias." R. F. Cahalan and W. J. Wiscombe, in *Proceedings of the Second Atmospheric Radiation Measurement (ARM) Science Team Meeting*, October 26-30, Denver (Col.), p. 35, 1991.

Contributions to Recent and Upcoming Scientific Meetings

"Scale-Dependent Statistical Analysis of Cloud Structure Observed During ASTEX and a Multifractal Model Incorporating Microphysics." A. Marshak, A. Davis, W. Wiscombe and H. Gerber at *8th AMS Conference on Atmospheric Radiation*, Jan. 24-28, Nashville (Ten.), USA, 1994 (accepted).

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