Ann. Geophysicae 11, 119–127 (1993) © EGS – Springer-Verlag 1993

Annales Geophysicae

The unified scaling model of atmospheric dynamics and systematic analysis of scale invariance in cloud radiances

S. Lovejoy [1], D. Schertzer [2], P. Silas [1], Y. Tessier [1], and D. Lavallée [3]

[1] Physics Department, McGill University Montreal, Que., H3A 2T8 Canada
[2] LMD, boite 99, Université Pierre et Marie Curie, 4 Pl. Jussieu, F-75252 Paris Cedex 05, France
[3] Earth Science Research Group, University of California, 5276 Hollister ave., suite 260 Santa Barbara, CA, 93111, USA

Received March 20, 1992; revised October 5, 1992; accepted October 20, 1992

Abstract. The unified scaling model of the atmosphere links the large and small scale dynamics by a single scaling but anisotropic regime, rather than distinct isotropic two- and three-dimensional turbulent regimes as posited in the standard model. We argue that the study of mesoscale clouds is a particularly stringent test for the standard model and we present (perhaps the first) systematic analysis of the scaling of energy spectra of satellite radiances over five wavelength channels and spanning the range of scales from 160 m to 4000 km (the entire mesoscale). The study mostly involved 15 consecutive scenes of AVHRR data (1.1 km resolution, 512 × 512 pixels) taken over the same location at the same local time in February 1986. This data was chosen because it was expected to provide a very sensitive indicator of the mesoscale break in the scaling predicted by the standard model of atmospheric dynamics (the "mesoscale gap"). Over the entire range, with surprisingly little scene-to-scene variation, the (isotropic) energy spectrum ($E(k)$) was found to follow the scaling form $E(k) \approx k^{-\beta}$ where k is a wavenumber, and β is the spectral exponent. This type of behaviour is exactly as predicted by the unified scaling model of the atmosphere as the outcome of anisotropic nonlinear cascade dynamics. It is hard to see how these results can be reconciled with the standard model.

1 Introduction

There are two principle approaches to understanding atmospheric dynamics. The first is a statistical, turbulent approach conventionally based on the assumption of a small scale isotropic three-dimensional turbulence and large scale isotropic two-dimensional turbulence. The second, the "dynamic meteorology" approach, starts with a phenomenological classification of structures and seeks deterministic understanding of corresponding idealized flows. The two approaches have never been satisfactorily reconciled because (until recently) the turbulence approach has not been able to statistically explain the existence of "coherent" atmospheric structures, while the dynamic meteorology approach has not been able to demonstrate its compatibility with ubiquitous power law spectra and other statistical manifestations of scaling predicted by turbulence theory.

In a series of papers (Schertzer and Lovejoy, 1983, 1984, 1985a and b, 1989a and b, 1991; Lovejoy and Schertzer, 1985, 1986), we and our colleagues have criticized both approaches and proposed the outlines of a synthesis which can potentially reconcile the statistics with the (coherent) structures, while accounting for the observations. The unified scaling model is a synthesis based on the dramatic advances in scaling notions that have occurred over the last 10 years. Two distinct advances are paramount here. The first is the recognition that the general framework for scaling *fields* – and hence dynamics – is multifractals rather than fractals (which are only adequate for treating scaling geometric *sets*). Multifractals are complex superpositions of singularities of various orders, and thus intrinsically involve coherent structures of all sizes. The general canonical multifractals (associated with the turbulent atmospheric cascade processes) not only generate such coherent structures on each realization, but have the (realistic) property that high-order singularities (corresponding to violent, intense events) exist which will almost surely be absent on an individual realization, but which will (almost surely) exist in a sample of a sufficiently large number of realizations. In meteorological terms, this corresponds to the appearance of different "synoptic conditions" on each realization without any artifically imposed non-stationarity in the basic dynamical mechanism. The discovery of universal multifractals (Schertzer and Lovejoy, 1987a and b, 1989b, 1991; Schertzer *et al.*, 1991; Brax and Peshanski, 1991), makes multifractals even more appealing as a framework for the dynamics since the properties of the cascades will depend on only three fundamental parameters – most of

Correspondence to: S. Lovejoy

their details will be "washed out" in the limit of a large number of interacting structures.

The second major advance was the discovery of "generalized scale invariance" (GSI) (Schertzer and Lovejoy, 1983, 1985a and b, 1988, 1989a, 1991; Lovejoy and Schertzer, 1985, 1986; Lovejoy *et al.*, 1992; Pflug *et al.*, 1991, 1993), which provides the general framework for defining the notion of scale and scale transformations in scale invariant systems. It answers the question as to what are the minimum (most general) conditions under which the large and small scales of a system can be related to each other only by their respective scale ratios, without reference to their actual sizes. In atmospheric (as in many other geophysical systems), the physical justification for scale invariance is the absence of a well-defined (and strong enough) mechanism that can break the scale invariance symmetry respected by the basic physical laws as expressed in the dynamical equations. Indeed, when analyzed in detail, the standard model's prediction (see e.g. Monin, 1972 or Lesieur, 1987) of fundamentally distinct dynamics at large and small scale is *not* based on the identification of *any* dynamical scale breaking mechanism whatsoever! It is rather an indirect theoretical inference resulting from the adherence to outmoded restrictive scaling ideas which identify scaling with isotropy, and which deduces a scale break from the evident lack of isotropy (as evidenced particularly by the large scale stratification of the atmosphere). The final inference concerning the distinct dynamics is based on the fact that 2D isotropic and 3D isotropic turbulence are fundamentally different because of the existence of vortex stretching in the latter but not in the former. The overall result of this chain of reasoning is that the standard model predicts very different regimes with different power law energy spectra (k^{-3}, $k^{-5/3}$ respectively), separated by a sharp (Schertzer and Lovejoy, 1985a) "dimensional transition" in the mesoscale. The alternative 2.555... (23/9)-dimensional unified scaling model of atmospheric dynamics proposed by Schertzer and Lovejoy (1983, 1985a) simply retains the assumption of scaling and dynamical cascades, but drops the ad hoc assumption of isotropy. Rather than requiring injection to occur over a narrow range of (large) scales, it is expected to occur in a scaling way over a wide range, corresponding to the observed scaling modulation of the solar radiation by clouds. The primary boundary conditions such as topography are also (multiple) scaling (e.g. Lovejoy and Schertzer 1990b; Lavallée *et al.*, 1993), and will not break the scaling of the dynamics.

A final piece of evidence supporting the unified scaling model comes from analyses of the vertical structure of the atmosphere. While it is true that the mean pressure decays exponentially with altitude, the dynamically important fluctuations in the horizontal velocity appear to be of the scaling form $k^{-\beta}$ over at least the range from 50 m to 15 km in the vertical (Endlich *et al.*, 1969; Adelfang, 1971; Schertzer and Lovejoy, 1985a), with β not too far from the value 11/5 predicted by dimensional analysis based on considerations of the buoyancy force variance. Furthermore, there does not appear to be any part of this range (which includes virtually the entire thickness of the atmosphere) where the spectrum is close to either the $k^{-5/3}$ or the non-scaling forms predicted respectively for the three- and two-dimensional isotropic ranges of the standard model. A similar result for rain comes from radar studies (using functional box-counting) which show that rain is also scaling over the vertical range 1–8 km (Lovejoy *et al.*, 1987).

However, no model, no matter how simple and theoretically appealing it may be, can be adopted without systematic and extensive empirical tests. This is especially true when the model plays a fundamental role in our understanding and conceptualization of reality. In this paper, we present new analyses of satellite cloud radiances which we believe are particularly strong endorsements of the unified scaling model, and indicate new, subtle forms of bias. From the perspective of distinguishing the standard 2D/3D model from the unified scaling model, this has several unique strengths:

1. By studying the readily accessible cloud radiance fields, large samples spanning wide ranges of scale are available. This makes robust studies of the scaling possible.
2. Unlike the vector wind field, study of the cloud field has the advantage that it is potentially a very sensitive indicator of mesoscale scaling breaks. This is because the cloud density is a scalar (not vector) quantity, hence it will have only one associated quadratic invariant, and a single scaling regime which will correspond to the regime in which the energy (not enstrophy) cascade is dominant. A break separating an enstrophy flux from an energy flux dominated cascade would therefore be much more pronounced than for the wind field, which might only display a change in its spectral slope and thus be harder to detect.
3. Our study concentrates on the critical range 1–512 km spanning scales much smaller to much larger than the ≈10 km scale height where the 2D/3D break is expected. It is very difficult to get adequate statistics in this region from any in situ source. A more limited number of METEOSAT and LANDSAT images supplement this so that the overall range covered by this study is from ≈4000 km to 160 m.
4. Selection bias based on the meteorological situation is largely avoided; here all (15) satellite pictures taken during February 1986 from the NOAA 9 satellite over the same region (off the Florida coast) at the same local time (1400 hrs ± 20 min) are used. Violent weather systems are not systematically avoided as they are by in situ aircraft measurement platforms and data are not screened to contain only "interesting" meteorological situations. Of course climatological bias could still be present; although it is unlikely to break the scaling, it might alter estimates of the exponents.
5. The raw radiances are sampled on a near rectangular grid so that minimal reprocessing is required. There are no sparse network problems (e.g. Lovejoy *et al.*, 1986), no need for "objective analysis" or other complex-to-analyze data processing procedures.
6. By confining ourselves to the use of energy spectra, we use a method of testing scaling which is familiar to geophysicists, and whose limitations and strengths are fairly well known. Although we have argued elsewhere (especially in Lovejoy and Schertzer, 1991, 1993; Tessier

et al., 1993) in favour of the use and development of new techniques – which we believe to be more powerful for studying scaling – these are less familiar, and their statistical (e.g. sampling) properties are not yet well established.

2 Empirical scaling and some reported breaks

Since the GSI model was proposed, other empirical studies of various atmospheric fields have been performed using a variety of analysis techniques, many of which have confirmed the scaling hypothesis, sometimes over astonishingly large ranges of scale (for a critical survey see Lovejoy and Schertzer, 1991). As concerns the dynamical velocity field, direct observations of its spectrum have improved considerably since the original evidence for the "mesoscale gap" was proposed by Van der Hoven (1957). Starting with Pinus (1968) and Vinnechenko (1969) using single-point measurements in time, Brown and Robinson (1979) using conventional network data, and Nastrom and Gage (1983) using commercial aircraft, many investigators have failed to find evidence for a spectral break and have found that a $k^{-5/3}$ law well describes the spectrum to wavenumbers corresponding to at least hundreds of kilometers (see also Lilly, 1983; Van Zandt 1982 and Balsley and Carter 1982). The Nastrom and Gage study is particularly pertinent since it is based on a fairly large sample size in the critical 100–1000 km region. At the lowest wavenumbers (corresponding to hundreds of kilometers) there is apparently a slow bend which the authors interpret as evidence of a k^{-3} regime. However, the effect is sufficiently small so that it will be hard to rule out the possibility that it is due to selection biases. For example, pilots know that even small detours around storms and the centres of depressions can result in significantly calmer rides. By systematically avoiding regions with high energy at medium and high wavenumbers, the spectrum will be artificially depressed at the corresponding wavenumbers, giving the appearance of a low-frequency spectral steepening; perhaps as observed. Although some have found comfort for the 2D/3D model in this slight apparent steepening of the spectral slope, even if it is not an artifact, it should not obscure the fundamental fact that *no dimensional transition is observed.* Indeed, we are not aware of any investigators who still take the mesoscale gap seriously (at least not in its original version as a dull energy sink). Attention has focused on speculations about ad hoc (scale dependent) mechanisms that could somehow "fill the gap" while only imperceptibly modifying the $k^{-5/3}$ scaling spectrum and making the fundamental 2D/3D dichotomy virtually invisible (e.g. Gage, 1979).

Since all the atmospheric fields are strongly dynamically coupled, a break in the scaling in one of them will necessarily make its presence felt in the others. This result is likely to be very general, and follows from the fact that scaling is a symmetry principle which will be respected unless specific symmetry breaking mechanisms exist. The results of numerous studies of the scaling of other atmospheric fields are therefore relevant. Studies of the well-measured rain (and rain reflectivity) and cloud radiance fields are particularly abundant. Recent surveys may be found in Lovejoy and Schertzer (1991, 1993) respectively, and cover (using a variety of methods including blotting paper, lidar, radar, satellites, and in situ measurements) the range of scales from 1 mm to 4000 km. The authors conclude that no obvious breaks in the scaling occur, but that far more data must be analysed to determine the exact type of scaling and its limits.

Lovejoy and Schertzer (1991) (and to a lesser degree Lovejoy and Schertzer, 1990a) also address a few loudly proclaimed but isolated and limited results purporting to find breaks in the scaling. These claims typically follow studies involving only one or a handful of empirical samples. Such breaks can be spuriously generated in several ways. One particularly trivial way of finding apparent breaks in the scaling is to fail to recognize that scaling is a statistical symmetry *which is necessarily broken on individual realizations*, and that the variability (intermittency) is so large that we expect large numbers of samples to be necessary to obtain adequate approximations to the ensemble statistics. A more subtle way of artificially introducing breaks is by lack of care when using monofractal analysis techniques on multifractal fields. Lovejoy and Schertzer (1990a, 1991) discuss several examples in considerable detail.

3 The data and analysis

In order to initiate systematic study with large sample sizes, we analysed data obtained from the NOAA-9 satellite. We made use of all 5 channels of the AVHRR sensor. These pictures were obtained with the sensor centred at a longitude of 70° west and a latitude of 27.5° north. This point is situated over the Atlantic Ocean, east of Florida. The 15 scenes were each taken at about 1400 ± 20 local time during the month of February, 1986 (the exact dates are the 10^{th}–20^{th}, 22^{th}, 24^{th}, 25^{th} and 27^{th} of February). The resolution of the sensor is 1.1 km at nadir. The five channels used were sensitive to the following ranges of wavelength: channel 1: 0.5 to 0.7 μm, channel 2: 0.7 to 1.0 μm, channel 3: 3.6 to 3.9 μm, channel 4: 10.4 to 11.1 μm and channel 5: 11.4 to 12.2 μm.

Although data from all five channels were used, study was concentrated on the visible and one of the thermal infrared channels (channels 1 and 4 respectively). For a given scene, the images for the various channels are essentially coincident in time. To give an idea of the large sample-to-sample variability, the visible channel images are displayed consecutively in Fig. 1. As expected, the meteorological conditions (including the total cloud cover) vary considerably from case to case.

To test the scale invariance predicted by the unified scaling model, we used standard spectral analysis, anticipating that the energy at wavenumber k will be of the scaling form $E(k) \approx k^{-\beta}$ where β is the spectral exponent (we ignored slowly varying factors such as powers of logs which would also be compatible with scaling). Recall that the energy spectrum is both the ensemble-averaged and angle-integrated squared modulus of the Fourier transform of the image. Although the cloud fields are aniso-

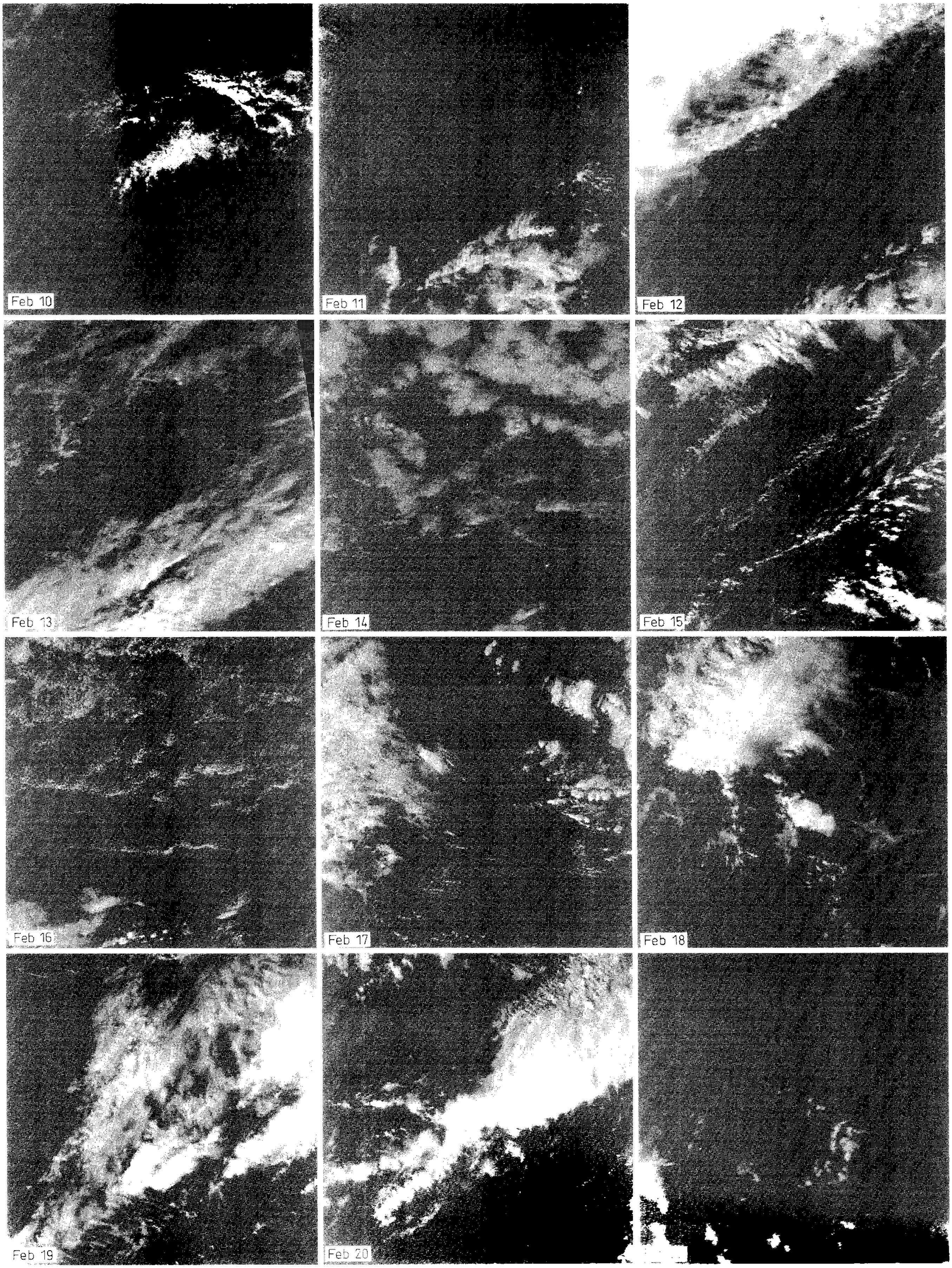

Fig. 1. Satellite images contained in the visible channel (channel 1): visible images of the NOAA 9 AVHRR sensor centred over the Atlantic Ocean. Each image is 512×512 pixels in size, see details in the text

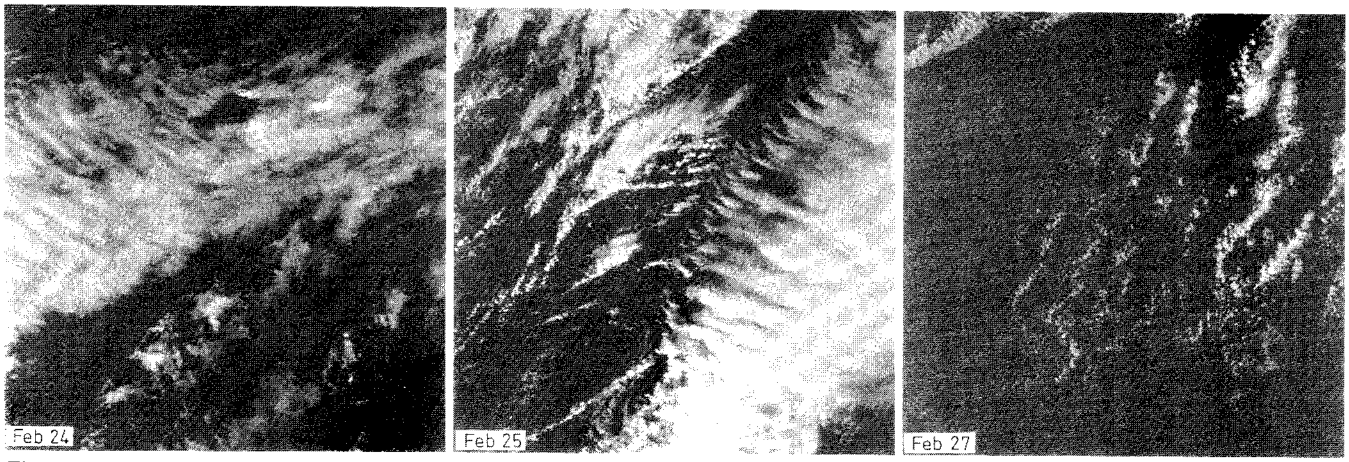

Fig. 1. (Continuation)

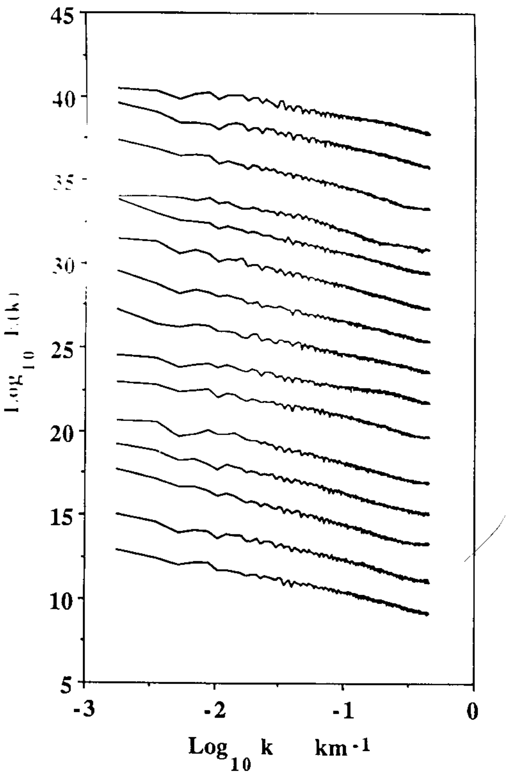

Fig. 2. Energy spectra corresponding to the visible images contained in channel 1 (512 × 512 pixels). For purposes of comparison, the spectra are superimposed and displaced from their true energies (energy in arbitrary units). The spectra are ordered chronologically starting from the lower end of the graph. Each spectrum is displaced by two orders of magnitude from the last so that while the first spectrum (*lower end of the graph*) is not displaced at all from its true enery values, the energy of the second spectrum is off by two orders of magnitude, the third spectrum off by four orders of magnitude and so on

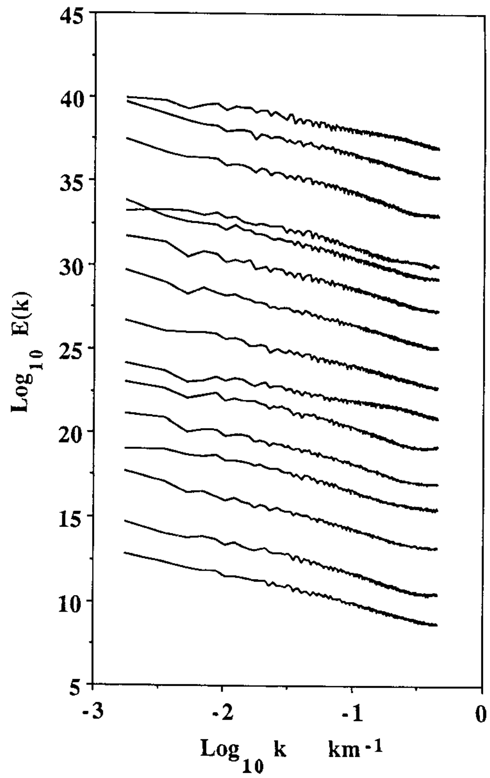

Fig. 3. Same as Fig. 2 but for the infrared images of channel 4

tropic (see Pflug *et al.*, 1993 for an anisotropic generalization of the spectrum based on GSI), most of the anisotropy (unless it is quite extreme) will be "washed out" by the angle integration. As discussed by Pflug *et al.*, 1993 for satellite cloud radiances, this is unlikely to lead to large deviations from the power law form. Although we anticipate that the power law form will not hold exactly on any finite sample, it is still of interest to examine the scaling of each individual image. This is shown for both the visible (see Fig. 2) and infrared channels (see Fig. 3).

To quantify the variability, we fit power laws to the energy spectrum of each picture, $E(k)=E_1\,k^{-\beta}$, by performing linear regressions of $\log E$ versus $\log k$. In the case of the visible channel (channel 1), the mean and standard deviation of the spectral slopes for each of the 15 images is $\bar{\beta}_1 = 1.71 \pm 0.20$ and the standard deviation of $\log_{10} E_1$ is 0.42. The corresponding values obtained for the infrared channel (channel 4) are $\bar{\beta}_4 = 1.85 \pm 0.20$ and 0.38. The case-to-case variation in spectral slopes is therefore quite small; it is a little larger than the difference between the mean visible and infrared channel exponents. Furthermore, the scene-to-scene variation in the exponents for each channel is highly correlated; the average difference $\beta_1 - \beta_4 \approx 0.15 \pm 0.09$ has a much smaller scatter than that which would be expected if the exponents were independent (assuming that the error variances add for independent processes yields a scatter of $\approx \pm 0.28$).

To obtain a more accurate estimate of the exponents, they were estimated for each of the two channels by performing a spectral analysis on the ensemble-average spectra of the 15 images. The resulting spectra are shown in Fig. 4 with $\beta_{1a} = 1.67$ and $\beta_{4a} = 1.91$ (where the subscript "a" indicates that the estimate is from an average). The corresponding scaling exponents for the other infrared channels (2, 3, 5) were very similar as Fig. 5 shows ($\beta_{2a} = 1.67$, $\beta_{3a} = 1.49$, $\beta_{5a} = 1.85$). This is not surprising since the visible channel is virtually entirely dominated by scattering processes whereas the thermal infrared channel is almost entirely dominated by thermal emission and absorption. The other channels have intermediate physics (some scattering, some emission/absorption). It is interesting to note that in spite of its fairly small magnitude, the differences in spectral slope may indeed be the most fundamental statistical difference between the two image types. This is because Tessier *et al.* (1993), using the same data, showed that the images corresponding to different wavelengths can be fit by universal multifractals with quite similar universal exponents describing the sparseness of the mean and the degree of multifractality (however, the exponents were not measured very precisely). It is possible that the third exponent which determines the degree of non-stationarity (and the spectral slope) may be the only one which is in fact different. These findings have important implications for the modeling and analysis of cloud radiances, especially since preliminary results of Borde *et al.* (1992) show that radiative transfer from multifractal clouds does indeed mostly affect the spectral slopes of the radiances: it apparently preserves the basic index of multifractality.

For comparison, also shown in Fig. 5 are various spectra from METEOSAT (geostationary) satellites at ≈ 8 km resolution and LANDSAT MSS data at 160 m resolution. The combined data from all sources covers the range ≈ 4000 km to 160 m; the only hint of any characteristic length scale being the slow bend at wavenumbers corresponding to scales smaller than ≈ 300 m in the LANDSAT data. However, the three LANDSAT pictures used in the analysis all had significant "saturation" problems (roughly 30% of these mostly cloud-covered images were at the maximum measurable intensity) so that not much internal cloud structure was discernable. The high wavenumber part of the spectrum could therefore be biased. Indeed, Welch *et al.* (1988) used area-

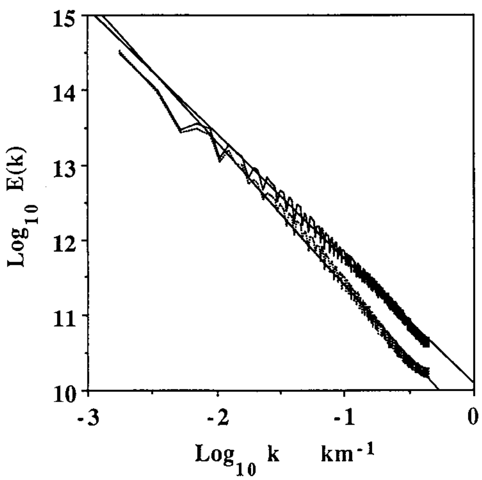

Fig. 4. Comparison of the ensemble-averaged energy spectra of channels 1 and 4 (512 × 512 pixels). The *solid line* corresponds to the visible channel. The *dotted line* corresponds to the infrared channel

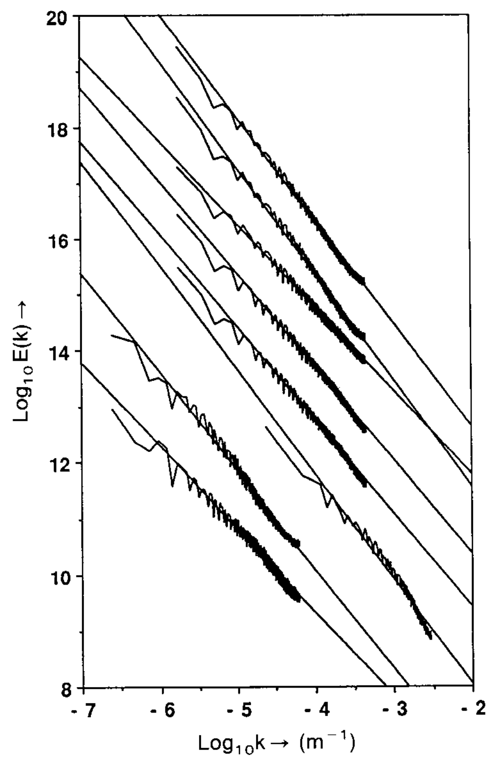

Fig. 5. In order to cover a wider range of scales, we compared our results with those of Tessier *et al.* (1993) who analysed three images (512 × 512 pixels) from METEOSAT and three images (512 × 512 pixels) from Landsat. From the METEOSAT satellite we used pictures which were brought to an 8-km resolution for both visible (0.7–1.0 μm) and thermal infrared (10.5–12.5 μm) channels. With these images, which were taken over a region of the Atlantic west of Spain, we could cover the range of scales from 8 km to 4000 km. We also used images from the MSS sensor aboard Landsat over wavelengths of 0.49–0.61 μm. This time the three photos used were from the tropical Pacific. From bottom to top, the curves correspond to METEOSAT (visible and infrared), LANDSAT and NOAA 9 (channels 1–5)

perimeter relations (which will not be sensitive to this problem) on LANDSAT cloud perimeters and found reasonable power laws over the entire range from ≈ 100 m to 25 km; see Lovejoy and Schertzer (1990a) for a discussion. Much more data needs to be analysed before accepting 300 m as a genuine break in the scaling. In any event, the comparison of these AVHRR images with the larger and smaller scale METEOSAT and LANDSAT images confirms that there is no break in scale anywhere near the mesoscale.

4 The effect of subjective image selection

Based on the phenomenological idea that structures with different appearances are associated with fundamentally different physics, meteorologists frequently select sub-regions of satellite pictures which have special meteorological properties that are "homogeneous" in some meteorological sense (for example, regions containing "uniform" marine stratocumulus). We sought to investigate how such selection procedures might bias the spectrum away from the ensemble averaged result found above. In order to get an idea of how drastic such a bias might be, we chose (in consultation with a synoptic meteorologist) the most "meteorologically homogeneous" 64×64 pixel sub-region from each scene. The size of each subregion is one sixteenth of the size of the original image, so this allows for considerable selection possibilities. After this subjective selection process was complete, an energy spectrum was obtained from the ensemble average of the 15 sub-regions for both channels 1 and 4.

Figures 6 and 7 display the comparison of these ensemble-averaged spectra at the two scales for the visible (channel 1) and infrared (channel 4) respectively. Note the flattening of the spectral slope of the selected sub-regions when compared with the full images. The main effect of the selection seems to be to change the spectral slope, although there is some evidence for the introduction of a slight break in the scaling at the lowest frequencies. This is especially apparent in the case of the infrared channel. Such a break might be associated with the tendency of the selection process to eliminate large scale cloud "edges" separating cloudy and non-cloud regions. To investigate the selection bias more fully, the ratio of the full scene and sub-scene energy spectra were taken for each channel. Figure 8 illustrates the comparison of the two ratios. The straight line regressions indicate that the bias is indeed reasonably scaling, leading to a bias in the exponents ($\Delta\beta = \beta_{\text{subregion}} - \beta_{\text{image}}$) of ≈ -0.33 and -1.34 for the visible and infrared scenes respectively. The bias, especially for the infrared, is quite large and should be carefully considered when attempting estimates of β, especially since satellite data is often prescreened to consist only of "interesting" meteorological situations.

The fact that the energies of the sub-regions are higher, and the slopes of the selected regions lower, means that selection has the effect of selectively increasing the high frequencies, i.e. it is the opposite of smoothing which would *decrease* the spectral energy at high wavenumbers. This can be understood when it is recalled that full scenes contained considerable (smooth) cloud-free zones; the selection singled out sub-regions with mostly cloud or broken cloud. Finally, the fact that sub-regions of single realizations can have locally varying scaling parameters is predicted by general (canonical) multifractal cascade models since local exponent estimates will be dominated by the (random) presence (or absence) of specific local orders of singularities (note that cascade multifractals are not geometric, their singularities are only partially localized; see Schertzer and Lovejoy 1992). Indeed, Garbriel *et al.* (1988) and Lovejoy and Schertzer (1990a, 1991), have empirically shown over various ranges of scale that cloud radiances are multifractal.

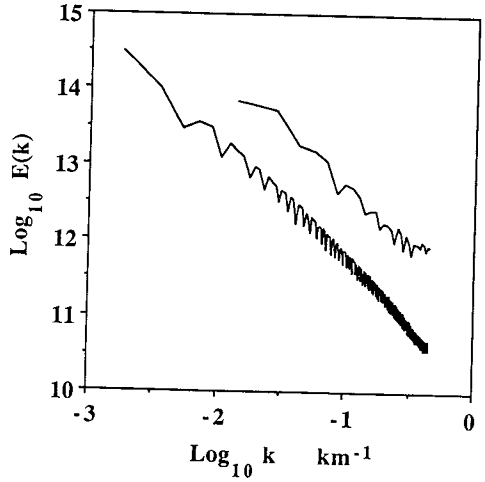

Fig. 6. Comparison of the ensemble-averaged energy spectrum obtained for the full size images contained in the visible channel and the ensemble-averaged spectrum obtained for the corresponding "homogeneous" sub-regions (64×64 pixels)

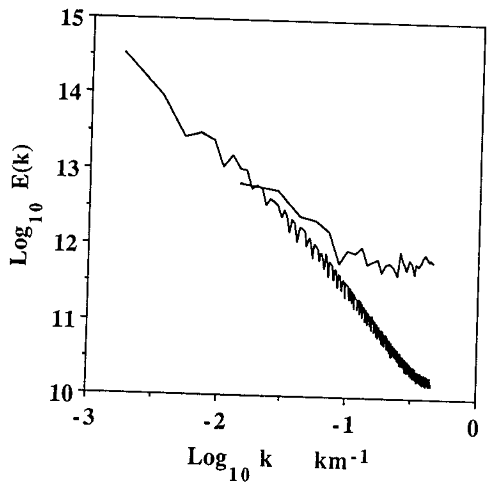

Fig. 7. Same as Fig. 6 but for the infrared channel (channel 4)

5 Conclusions

We have reported on the first systematic spectral analysis of cloud data from an unbiased statistical ensemble of 15

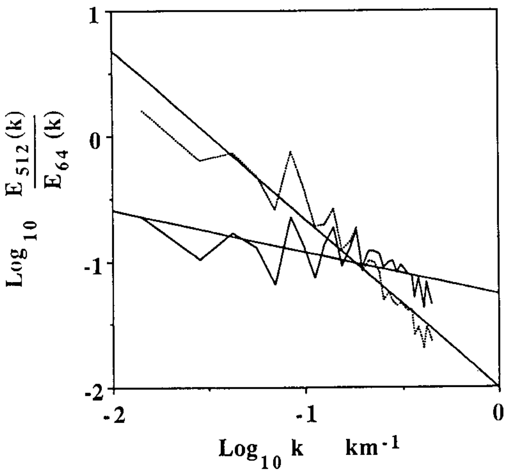

Fig. 8. Ratios of the energy spectrum of the ensemble-averaged images (512 × 512 pixels) to that of the ensemble-averaged subregions (64 × 65 pixels) for channels 1 and 4. The *solid line* is this ratio for the visible channel. The *dotted line* corresponds to the infrared channel. The *straight regression lines* have slopes ($=\Delta\beta$) of -0.33 and -1.34 respectively

satellite scenes with five wavelength channels and for scales spanning the entire mesoscale. For all the wavelengths and scenes, the spectra were remarkably close to the power law forms predicted by a unified scaling model of the atmosphere, with surprisingly small scene-to-scene variability in the (isotropic) spectral exponent. This finding will be very difficult to explain using the standard model of atmospheric motions which involves a dimensional transition in the mesoscale (the famous meso-scale "gap"). Indeed, theoretically, passive scalar clouds and their associated radiance fields would have a drastic meso-scale break corresponding to the transition between turbulent regimes dominated by enstrophy fluxes and energy fluxes. Although real clouds are not passive scalars, and we analyze the associated radiance rather than the liquid water field, we still expect the presence/absence of scaling to be a sensitive indicator of the basic scaling of the dynamics. The unified scaling model of coupled anisotropic scaling cascade dynamics was given additional support by the comparison with METEOSAT and LANDSAT spectra which extended the range of observed scaling to significantly larger and smaller scales.

Considering the theoretical simplicity and mounting empirical support in favour of the unified scaling model, there is a surprising sense of complacency in the meteorological community about the standard model. This complacency has roots both in myth and in certain uncritically absorbed data analyses. We outlined the two components of the myth. First, the unfounded idea that phenomena which *look* quite different at different scales *are* necessarily quite different. Generalized scale invariance (the general framework for studying scaling), especially when nonlinear, clearly shows how appearances (texture, aspect ratios, orientations, etc.) can change drastically with scale even though from the point of view of the physical processes involved there is a single (albeit highly nonlinear) dynamical mechanism at work. A second myth is the idea that a statistical theory (such as the unified scaling model) is incapable of accounting for either the tremendous variation in intensity of phenomena, or their structures (including large scale synoptic weather patterns). Multifractals (especially of the general, "canonical" variety produced by turbulent cascades) can easily provide the required extreme variability, their singularities being associated with specific structures whose morphology can change with scale because of the anisotropy.

Ten years ago scaling was associated only with (relatively uninteresting) isotropic monofractal fields, the latter being variants of Brownian motion. Today, rather than being a theoretical straightjacket, scaling is known to be of great generality. It can profitably be compared to the more familiar symmetries embodied in the principles of conservation of energy and momentum which are fundamental but not overly restrictive. Further progress will require the use of both other (dynamical) symmetries and empirical knowledge to determine the exact types and limits of the scaling of the various atmospheric fields (including their mutual interactions; it is interesting in this regard that to our knowledge, not even the full set of symmetries of the three-dimensional Navier-Stokes equations is known). It will then be possible to exploit scaling (for example by using the implied long-range correlations) to make stochastic multifractal forecasts or for performing "multifractal objective analyses" (Lovejoy and Schertzer 1993). Multifractal forecasts would in principle make maximum use of all the available information (including that from remotely sensed platforms) to make theoretically optimum forecasts (including error estimates). This is an attractive potential alternative to current approaches based on deterministic, partial differential equations. Similarly, multifractal objective analyses would replace the regularity and homogeneity assumptions of standard objective analyses (such as Kriging) by scaling (heterogeneity) assumptions. Applications are currently being explored.

In our discussion of our spectral analyses, we made allusion to a tendency to uncritically accept certain isolated claims of empirical breaks in the scaling. Several instances were discussed in Lovejoy and Schertzer (1990a). We did not repeat these in detail here; such a discussion would have perhaps missed the point. What is remarkable is that in spite of the fact that we are discussing the most fundamental aspects of atmospheric dynamics, and that much data is available, there have been virtually *no systematic studies of scaling or its limits in any of the atmospheric fields*. The present study – which is a very modest contribution in this regard – is the first of which we are aware to attempt a systematic sampling and analysis, and it could have been performed twenty or more years ago. We hope that many more will follow. In the meantime, basic scientific methodology ("Okham's razor") incites us to adopt the simplest theory that fits the data. Complications should only be added when absolutely required. On this count, the unified scaling model must at least be considered as our best current working hypothesis.

Acknowledgements: We thank A. Bellon for help with the meteorological classification (Section 4). We also acknowledge discussions with R. Cahalan, A. Davis, P. Gabriel, C. Gautier, B. Kerman, G. Lewis, D. Lilly, A. Marshale, R. Pierrehumbert, V. Ramanathan and W. Wiscombe. Support for this work was partially provided by Atmospheric Radiation Measurement program contract #DE-FG03-90ER 61063.

References

Adelfang, S. I., On the relation between wind shears over various intervals, *J. Atmos. Sci.,* **10,** 138, 1971.

Balsley, B. B., and D. A. Carter, The spectrum of atmospheric velocity fluctuations at 8 km and 86 km, *Geophys. Res. Lett.,* **9,** 465–468, 1982.

Borde, R., D. Schertzer, S. Lovejoy, B. Watson, and A. Davis, Multifractal relationships between cloud and radiation singularities: exact and asymptotic results, *Ann. Geophysicae Suppl. II,* Vol. **10,** Abstract book Gen. Ass. EGS, Edinburgh April 6–10, 1992, p. c344.

Brax, P., and R. Pechanski, Levy stable law description of intermittent behaviour and quark-gluon phase transitions, *Phys. Lett. B,* 225–230, 1991.

Brown, P. S., and G. D. Robinson, The variance spectrum of tropospheric winds over Eastern Europe, *J. Atmos. Sci.,* **36,** 270, 1979.

Endlich, R. M., R. C. Singleton, and J. W. Kaufman, Spectral analyses of detailed vertical wind speed profiles, *J. Atmos. Sci.,* **26,** 1030–1041, 1969.

Gabriel, P., S. Lovejoy, D. Schertzer, and G. L. Austin, Multifractal analysis of resolution dependence in satellite imagery, *Geophys. Res. Lett.,* **15,** 1373–1376, 1988.

Gage, K. S., Evidence for a $k^{-5/3}$ law inertial range in mesoscale two-dimensional turbulence, *J. Atmos. Sci.,* **36,** 1950–1954, 1979.

Lavallée, D., S. Lovejoy, D. Schertzer, and P. Ladoy, Nonlinear variability and Landscape topography: analysis and simulation, in *Fractals in Geography,* Eds. L. De Cola and N. Lam, 1993 (in press, Prentice-Hall, New York).

Lesieur, M., *Turbulence in Fluids,* Martinus Nijhoff, Dordrecht, 1987.

Lilly, D. K., Mesoscale variability of the atmosphere, in *Mesoscale Meteorology – Theories, Observations and Models,* Eds. D. K. Lilly and T. Gal-Chen, D. Reidel, Hingham, 13–24, 1983.

Lovejoy, S., and D. Schertzer, Generalized scale invariance in the atmosphere and fractal models of rain, *Water Resour. Res.,* **21,** 1233–1250, 1985.

Lovejoy, S., and D. Schertzer, Scale invariance, symmetries, fractals and stochastic simulations of atmospheric phenomena, *Bull. Amer. Meteor. Soc.,* **67,** 21–32, 1986.

Lovejoy, S., D. Schertzer, and P. Ladoy, Fractal characterisation of inhomogeneous measuring networks, *Nature,* **319,** 43–44, 1986.

Lovejoy, S., D. Scherzter, and A. A. Tsonis, Functional box-counting and multiple elliptical dimensions in rain, *Science,* **235,** 1036–1038, 1987.

Lovejoy, S., and D. Schertzer, Multifractals, universality classes and satellite and radar measurements of cloud and rain fields, *J. Geophys. Res.,* **95,** 2021–2034, 1990a.

Lovejoy, S., and D. Schertzer, Our multifractal atmosphere: A unique laboratory for nonlinear dynamics, *Phys. Can.,* **46,** 62–71, 1990b.

Lovejoy, S., and D. Schertzer, Multifractal analysis techniques and the rain and cloud fields from 10^{-3} to 10^{6} m, in *Scaling, Fractals and Non-linear Variability in Geophysics,* Eds. D. Schertzer and S. Lovejoy, Kluwer, Dordrecht, 111–144, 1991.

Lovejoy, S., and D. Schertzer, Multifractals and Rain, *New uncertainty concepts in hydrology and hydrological models,* Ed. A. W. Kundzewicz, Birkhäuser, 1993 (in press).

Lovejoy, S., D. Schertzer, and K. Pflug, Generalized scale invariance and differentially rotating cloud radiances, *Physica A,* **185,** 121–127, 1992.

Monin, A. S., *Weather Forecasting as a Problem in Physics,* MIT Press, Cambridge, 1972.

Nastrom, G. D., and K. S. Gage, A first look at wavenumber spectra from GASP data, *Tellus,* **35,** 383, 1983.

Pflug, K., S. Lovejoy, and D. Schertzer, Generalized scale invariance, differential rotation and cloud texture, in *Nonlinear Dynamics of Structures,* Eds. R. Z. Sagdeev, U. Frisch, S. Moiseev, and N. Erokhin, World Scientific, pp. 71–80, 1991.

Pflug, K., S. Lovejoy, and D. Schertzer, Generalized Scale Invariance, Differential Rotation and Cloud Texture: analysis and simulation, *J. Atmos. Sci., 1993* (in press).

Pinus, N. Z., The energy of atmospheric macro-turbulence, *Izv. Atmos. Ocean. Phys.,* **4,** 461, 1968.

Schertzer, D., and S. Lovejoy, Elliptical turbulence in the atmosphere, in *Proc. of the 4th Symposium on Turbulent Shear Flows,* Eds. L. J. S. Bradbury, F. Durst, B. E. Launder, F. W. Schmidt, and J. H. Whitelaw, Springer, Berlin Heidelberg New York, 1983.

Schertzer, D., and S. Lovejoy, On the dimension of atmospheric motions, in *Turbulence and Chaotic Phenomena in Fluids,* Ed. T. Tatsumi, Elsevier North Holland, New York, 505–508, 1984.

Schertzer, D., and S. Lovejoy, The dimension and intermittency of atmospheric dynamics, in *Turbulent Shear Flow 4,* Eds. L. J. S. Bradbury, F. Durst, B. E. Launder, F. W. Schmidt, and J. H. Whitelaw, Springer, Berlin Heidelberg New York, 7–33, 1985a.

Schertzer, D., and S. Lovejoy, Generalized scale invariance in turbulent phenomena, *J. of Physico-Chemical Hydro.* **6,** 623–635, 1985b.

Schertzer, D., and S. Lovejoy, Singularités anisotropes et divergence de moments en cascades multiplicatifs, *Ann. Math. Que.,* **11,** 139–181, 1987a.

Schertzer, D., and S. Lovejoy, Physical modeling and analysis of rain and clouds by anisotropic scaling multiplicative processes, *J. Geophys. Res.,* **92,** 9693–9714, 1987b.

Schertzer, D., and S. Lovejoy, Multifractal simulation and analysis of clouds by multiplicative processes, *Atmos. Res.,* **21,** 337–361, 1988.

Schertzer, D., and S. Lovejoy, Generalized scale invariance and multiplicative processes in the atmosphere, PAGEOPH, **130,** 57–81, 1989a.

Schertzer, D., and S. Lovejoy, Non-linear variability in geophysics: Multifractal simulations and analysis, in *Fractals: Physical Origin and Consequences,* Ed. L. Pietronero, Plenum, New York, 49–79, 1989b.

Schertzer, D., and S. Lovejoy, Non-linear geodynamical variability: multiple singularities, universality and observables, in *Scaling, Fractals and Non-linear Variability in Geophysics,* Eds. D. Schertzer and S. Lovejoy, Kluwer, Dordrecht, 41–82, 1991.

Schertzer, D., S. Lovejoy, D. Lavallée, and F. Schmitt, Universal hard multifractal turbulence, theory and observations, in *Nonlinear Dynamics of Structures,* Eds. R. Z. Sagdeev, U. Frisch, F. Hussain, S. S. Moiseev, and N. S. Erokhin, World Scientific, 213–235, 1991.

Schertzer, D., and S. Lovejoy, Hard and Soft Multifractal processes, *Physica A,* **185,** 187–194, 1992.

Tessier, Y., S. Lovejoy, and D. Schertzer, Universal multifractals in rain and clouds: theory and observations, *J. Appl. Meteorol.,* **32,** 223–250, 1993.

Van der Hoven, I., Power spectrum of horizontal wind speed in the frequency range from 0.0007 to 900 cycles per hour, *J. Meteorol.,* **14,** 160–164, 1957.

Van Zandt, T. E., A universal spectrum of buoyancy waves in the atmosphere, *Geophys. Res. Lett.,* **9,** 575–578, 1982.

Vinnichenko, N. K., The kinetic energy spectrum in the free atmosphere – 1 second to 5 years, *Tellus,* **22,** 158–166, 1969.

Welch, R. M., K. S. Kuo, B. A. Wielicki, S. K. Sengupta, and L. Parker, Marine stratocumulus cloud fields off the coast of Southern California observed by LANDSAT imagery, Part I: Structural characteristics, *J. Appl. Meteorol.,* **27,** 341–362, 1988.