

Time-series of zenith radiance and surface flux under cloudy skies: Radiative smoothing, optical thickness retrievals and large-scale stationarity

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[1] Cloudy sky zenith radiance time-series covering spatial scales a few meters up to 200–400 km measured by a ground-based photometer at 753 nm are investigated with 2nd-order structure functions, and compared to broad-band short-wave column transmittance. A previously reported scale break occurs at scales on the order of the vertical cloud extension due to radiative smoothing (i.e., lateral photon transport by diffusion in optically thick clouds). We use simulated radiance and flux fields for 3D clouds to explain why optical depths can be extracted with reasonable accuracy from surface fluxes by using 1D radiative transfer theory at large-enough scales. We also show clear evidence of a transition from nonstationary to stationary behavior, i.e., a scale break, occurring at spatial scales of a few tens of kilometers. We argue that this qualitative change in the correlations of remotely observed radiation fields is likely to carry over to the most highly variable inherent cloud property, namely optical depth. **INDEX TERMS:** 0360 Atmospheric Composition and Structure: Transmission and scattering of radiation; 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 3250 Mathematical Geophysics: Fractals and multifractals. **Citation:** von Savigny, C., A. B. Davis, O. Funk, and K. Pfeilsticker, Time-series of zenith radiance and surface flux under cloudy skies: Radiative smoothing, optical thickness retrievals and large-scale stationarity, *Geophys. Res. Lett.*, 29(17), 1825, doi:10.1029/2001GL014153, 2002.

1. Introduction and Context

[2] The scaling behavior of the radiance fields reflected by and transmitted through clouds has recently received considerable attention. If a time-series is “scale-invariant,” or simply “scaling,” then its wavenumber (or energy) spectrum $E(k)$ will follow a power law, i.e., $E(k) \propto k^{-\beta}$, k being the wavenumber and β the spectral exponent. Transition from a scale-invariant regime with one spectral exponent to another is a scale break.

[3] In this context, the following experimental findings on cloudy sky radiative transfer (RT) were important: (a) a scale break due to radiative smoothing [Marshak *et al.*,

1995] in reflected radiance fields observed in LANDSAT imagery at roughly 0.2–0.4 km [Cahalan and Snider, 1989; Lovejoy *et al.*, 1993; Davis *et al.*, 1997]; (b) skylight transmitted through optically thick clouds to the ground also exhibits a break at scales corresponding roughly to the cloud’s vertical extension H [von Savigny *et al.*, 1999]; (c) a possible scale break at a few tens of kilometers [Davis *et al.*, 1997; Austin *et al.*, 1999].

[4] Lovejoy *et al.* [1993] investigated the scaling of the radiance fields from variably cloudy satellite images either reflected at visible and near-IR wavelengths or emitted at thermal IR wavelengths; they found evidence for scale-invariance in energy spectra for a variety of instrument-dependent ranges covering 0.16 to 4000 km. More importantly, Lovejoy *et al.* find no breaks at the “meso-scale” (around the scale-height of the atmosphere at 8 or so km) where it had been argued that atmospheric dynamics could transition from 2D to 3D turbulence.

[5] In contrast, Davis *et al.* [1997] mention a large-scale transition in the wavenumber spectrum of a LANDSAT/TM scene of marine stratocumulus (Sc) that completely fills the LANDSAT swath. This transition occurs at scales of about 10 km. The spectral exponent changes from $\beta \approx 2$ to $\beta \approx 0$ at larger scales; however, Davis *et al.* point out that the scale break may not be robust due to the inherently poor sampling of large scales. However, Austin *et al.* [1999] recently reported a similar scale break occurring at approximately 10 km in many AVHRR images of marine Sc.

2. Instrumentation and Ancillary Data

[6] The radiometer consists of a zenith pointing telescope, an interference filter (753.2 nm, FWHM = 9.7 nm), and a Si-photodiode for light detection. A 16-bit AD-converter reads out the detector at a frequency of 2 Hz. The full viewing angle is 0.86°.

[7] The zenith radiance time-series used here were taken during CLARE 98 at the Chilbolton Observatory in South England in October 1998. All zenith radiance time-series were divided by the running value of μ_0 , the cosine of the solar zenith angle (SZA). Examples of the normalized narrow-band zenith radiance time-series are shown in Figure 1. Broad-band (BB) short-wave (SW) transmittance obtained from surface flux measured with an Eppley PSP radiometer is also shown in Figure 1 but averaged over 1-minute intervals. Three of the four days were completely overcast with at least an unbroken low dense cloud layer. But, Oct. 20 had periods with no low clouds and, generally speaking, more variability in the cloudiness at all levels.

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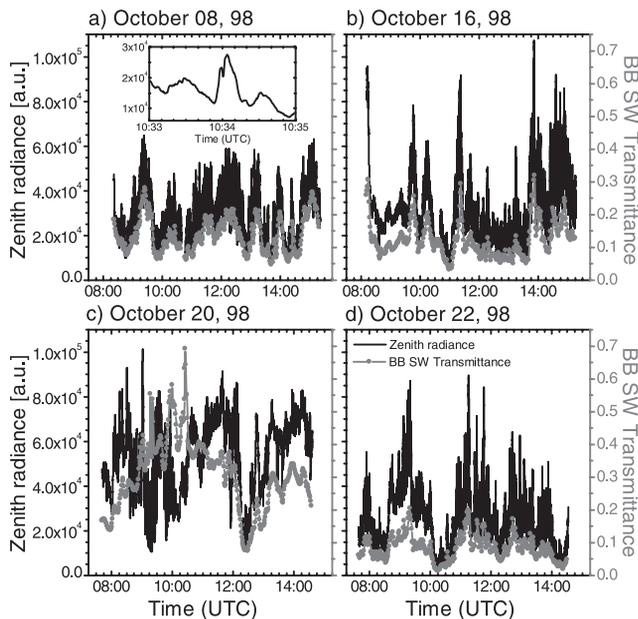


Figure 1. Time-series of narrow-band zenith radiance in arbitrary units but divided by $\mu_0 = \cos(SZA)$ and of broadband atmospheric transmittance observed on four days during CLARE’98. The inset illustrates the radiatively smoothed regime in radiance sampled at 2 Hz.

[8] Cloud base height was simultaneously measured with a ceilometer operated by the University of Reading. Wind speed profiles were available from radiosondes launched every 2 hours as well as from the ECMWF and UKMO models and were used to convert time intervals into spatial scales by applying Taylor’s frozen turbulence hypothesis.

3. Methodology and Terminology

[9] The observed zenith radiance time-series were analyzed with 2nd-order structure functions (SF). SF analysis of a signal $\phi(n)$ of length N seeks scaling in statistical moments of “increments,” i.e., $\Delta\phi(r; n) = |\phi(n+r) - \phi(n)|$, ($n = 1, \dots, N-r$) over scales r that can vary between 1 (sample) and an upper limit not so close to N that the sampling suffers. In mathematical terms, one expects a power-law dependence $\langle \Delta\phi(r; n)^2 \rangle \propto r^{\zeta_2}$ with $\langle \cdot \rangle$ denoting spatial/temporal average over n . For a *nonstationary* scale-invariant random process with stationary increments we have $0 < \zeta_2 < 1$, and this relation translates theoretically to $\beta = \zeta_2 + 1$, hence $1 < \beta < 3$. In practice, finite-sample size effects create a small systematic difference between β and $\zeta_2 + 1$.

[10] For $\beta \leq 1$, the scaling time-series itself is stationary and this leads in principle to $\zeta_2 = 0$, i.e., scale-independence of the variance of the increments. In practice however, there is often a residual trend in the SF. For $\beta \geq 3$, the scale-invariant time-series is nonstationary and so are its increments; in physical space the change in ϕ is so slow that it is everywhere continuous and almost everywhere differentiable and this leads in principle to $\zeta_2 = 2$.

4. Results and Discussion

[11] Figure 2 shows the SF diagrams for the time-series presented in Figure 1. Three distinct scale-invariant regimes

are obvious for zenith radiance I_{zen} and at most two for normalized surface flux, column transmittance T_{sfc} . For I_{zen} . The first regime ends at $r \approx \eta_I$, the radiative smoothing scale in transmission [von Savigny *et al.*, 1999]. Statistically speaking, it is nonstationary with nonstationary increments. For scales greater than η_I an intermediate regime follows where the time-series are nonstationary but have stationary increments, $\zeta_2 \approx 1/2$. Finally, at a scale L of few tens of kilometers the scale invariance breaks again and an essentially stationary (small ζ_2) regime follows. For T_{sfc} in all but one case (Oct. 20), we see the same transition to stationarity at the same scale, but the nonstationary exponent is always larger than for I_{zen} .

4.1. Large-Scale Transition to Statistically Stationary Behavior

[12] Is there any reason to believe this new scale break is for radiation fields but not for the inherent cloud properties? To make this call, we first need to assign a more physical meaning to our normalized zenith radiance (I_{zen}/μ_0) data. We relate I_{zen} to BB SW transmittance (T) using 1D RT theory. At a given μ_0 , if T is high then the cloud’s optical thickness τ is low, therefore I_{zen} is small but increasing with τ . If T is low, then τ is necessarily large, and hence the zenith radiance is again small and getting smaller as τ increases. For moderate T , τ is intermediate (on the order of $1/(1-g)$, with the asymmetry factor g and I_{zen} goes through a maximum. Now, if T fluctuates highly and frequently assumes essentially all possible values within its natural limits, then I_{zen} also frequently assumes all possible values within its natural limits.

[13] Figure 3a shows a scatter-plot of normalized zenith radiance and SW transmittance for the time-series shown in

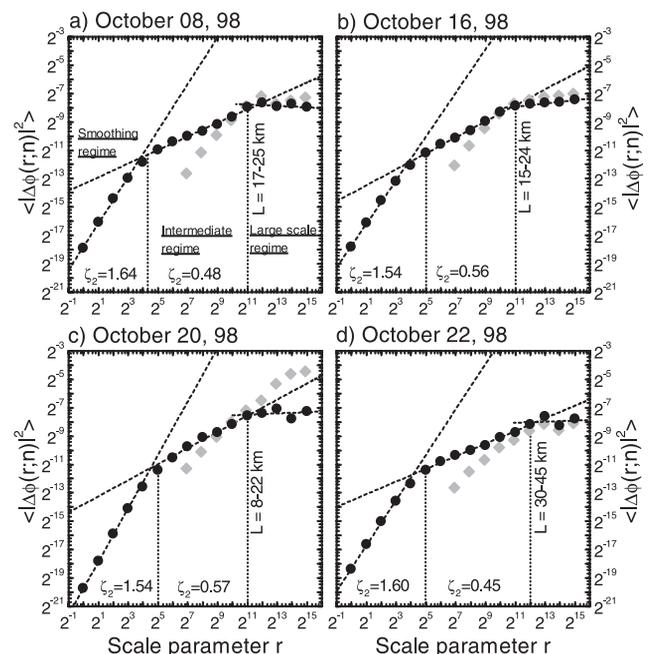


Figure 2. Log-log plots of structure functions of the day-long time-series pairs presented in Figure 1. Three distinct scaling regimes are clearly discernible for zenith radiance ($\phi = I_{zen}/\mu_0$, black circles) while transmittance ($\phi = T_{sfc}$, grey diamonds) shows at most two.

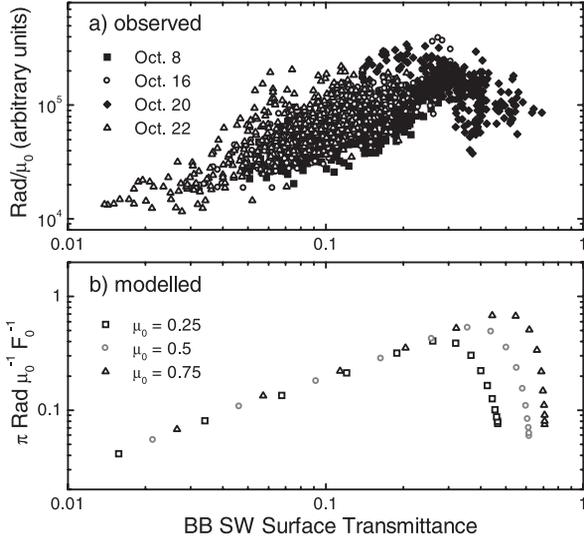


Figure 3. Relationships between (a) I_{zen}/μ_0 averaged over 1-minute intervals and T_{sfc} from Figure 1, and (b) normalized zenith radiance and BB SW transmittance for different μ_0 in 1D radiative transfer theory (F_0 is solar irradiance in $\text{W}/\text{m}^2/\text{cm}^{-1}$ at 753 nm). Cloud optical depth τ decreases from left to right.

Figure 1. Note that we use ground-level transmitted flux as a surrogate for flux at cloud base; since it contains far more geometrical averaging of radiance or flux than the zenith-pointing radiometer, its range of variability, if anything, is somewhat under-estimated. Figure 3b shows plane-parallel model results for a wide range of τ and different μ_0 . The important features of Figure 3 are: (1) the measured transmittances indeed cover the range of possible values; (2) I_{zen}/μ_0 exhibits the expected maximum for moderate transmittances (mainly October 20); (3) for low T (diffusive regime) I_{zen}/μ_0 increases with T , as expected, and for high T (optically thin regime) it decreases with further increase in T ; (4) there is typically an order-of-magnitude of scatter in the data at any radiance or transmittance level due to 3D transport effects discussed further on. Since transmittance T covers the range of possible transmittance values, we can confidently conclude that the range of possible zenith radiances is also exhausted. Furthermore, we observe in our data with the widest spread in T (Oct. 20) in Figure 1 an obvious decoupling with I_{zen}/μ_0 due to the non-monotonic relation between them in 1D RT theory (Figure 3b) as well as in reality at the coarsest level of analysis (Figure 3a). This decoupling is also apparent in the SFs in the corresponding panel in Figure 2 at large scales.

[14] It is now tempting to argue that the radiance signal will become stationary beyond sufficiently large scales simply because increments can no longer grow. However, this is not the case. The IPA works well for unbroken clouds at these large scales and makes no assumption about pixel-scale; so the computations used in Figure 4 from 25 m to 13 km could also be for 0.5–250 km. This is for a given scaling exponent and overall variance which was taken to be sufficient to cover the diurnal variability in τ for marine Sc (over a factor of 10). It is well-known that even highly nonlinear mappings such as $\tau \mapsto I_{\text{zen}}$ do not break the scaling but will change the prefactor.

[15] We therefore conclude that the scale break we observe in transmitted radiation fields has a counterpart in an inherent cloud property, most likely optical depth. We can extend this argument to reflected radiances captured in satellite images of fully cloudy scenes since albedo $R = 1 - T$ and nadir radiance is monotonic in τ for the IPA. So the large-scale transition to stationarity at scales of a few tens of kilometers observed for satellite images of extensive cloud decks [Davis *et al.*, 1997; Austin *et al.*, 1999] likely reflects a similar transition in optical depth.

[16] These various observations of scale-breaks at 10 or a few 10s of km contrast with reports of scale-invariance in reflected radiance fields extending from planetary scales (10^{3+} km) down to 1 km [Lovejoy *et al.*, 2001], or even less [Lovejoy *et al.*, 1993]. However, these are studies of vast ensembles including partially cloudy skies, and the radiometric variability of the broken cloud scenes will naturally dominate the ensemble. Also, these analyses are largely based on the singularity properties of derived fields: absolute pixel-scale gradients. Radiative smoothing processes control these gradients in the bulk of extended clouds but not under general (mixed cloudiness) conditions. So the strong gradients at cloud edges naturally dominate the transition to reduced variability observed so far only in fully cloudy scenes and kindred time-series. Thus Lovejoy *et al.*'s “grand-ensemble” sampling strategy will preserve nonstationarity up to scales on the order of the horizontal extent of the largest clouds, which are indeed planetary. This strategy serves their main point which is the absence of a “meso-scale break” at 10 or so km. Our conclusions are

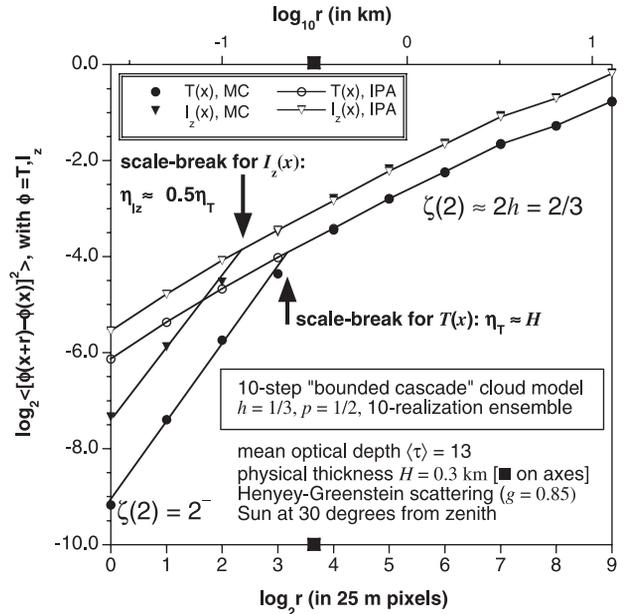


Figure 4. Log-log plot of structure functions of the zenith radiance and transmitted flux fields (conservative scattering) for an ensemble of 2-parameter “bounded cascade” models that mimic realistic Sc. The scaling parameter h prescribed the large-scale exponent of $2h = 2/3$ and the variance parameter p captures the variability for the full daily cycle. The IPA fields scale just like the simulated τ field but the Monte Carlo results show the effect of radiative smoothing at small scales.

of more limited scope in terms of cloud type but will hopefully lead to future insights about the formation and maintenance of the Earth's largest clouds.

4.2. Ground-Based Optical Depth Retrievals in the Presence of Radiative Smoothing

[17] Within this regime the variation of I_{zen} is smoothed by horizontal photon diffusion in optically thick clouds. This smoothing is specifically with respect to the local independent pixel approximation or "IPA" [Cahalan *et al.*, 1994]. So, at non-smoothed scales $r > \eta_l$, the IPA models the 3D RT reasonably well by using the locally-averaged optical depth field (over a scale $\approx \eta_l$) in a 1D RT computation. Figure 4 shows SFs for both $\phi = \pi I_{\text{zen}}/\mu_0$, normalized zenith radiance, and $\phi = T$, normalized flux at cloud base, for an ensemble of realistically variable bounded cascade cloud models [Cahalan *et al.*, 1994; Marshak *et al.*, 1994]. Both monochromatic Monte Carlo (MC) simulations and IPA results are shown for conservative scattering. The IPA follows quite closely the same nonstationary/stationary-increment trend as the simulated τ field. Transmittance is smoothed at scale $\eta_T \approx H$ as predicted by the detailed diffusion computations by Davis and Marshak [2002] with pre-asymptotic corrections. This scale is larger than its counterpart for zenith radiance, $\eta_I \approx \eta_T/2$, which is not surprising since downwelling flux integrates radiance over 2π sr.

[18] It is now common practice [e.g., Min and Harrison, 1996] to derive τ from T_{sfc} and a local IPA, i.e., 1D RT theory. From the above analysis of 3D RT results, one does not expect this to work at all scales. Furthermore, the difference in nonstationary exponents obtained for radiance and flux in Figure 2 raises concerns about the verisimilitude of the retrievals based on surface flux. However, the proposed methods use an effective averaging scale well within the IPA regime and almost into the stationary regime. First, the prescribed 5–10 minute time-averages are well above the smoothing scale and bordering on the large-scale break. Second, the instantaneous T_{sfc} is different from T at cloud base since it integrates via angular acceptance over many values of the radiance field. The weighting in $\cos\theta$ of this geometrical smoothing tells us that the integral is dominated by distances out to at least $\tan 60^\circ = \sqrt{3}$ times the cloud base height on either side of zenith. This also leads to the differences in the nonstationary regime exponents ζ_2 between the modelled cloud-bottom flux SFs (Figure 4) and the observed surface flux SFs (Figure 2). Due to the geometrical smoothing flux-based retrievals have a certain immunity from 3D RT effects under overcast conditions, but radiance-based methods would be an improvement since the effective temporal sampling could be increased almost to the critical value controlled by diffusive smoothing.

5. Conclusions

[19] We present two main results for cloudy-sky radiative transfer based on (a) structure-function analyses of all-day

zenith radiance time series, (b) collocated column transmittance, and (c) Monte Carlo simulations of 3D radiative transfer in realistic stochastic models of Sc. First, we refine radiative smoothing phenomenology in transmission and use it to reappraise the performance of operational (1D RT-based) optical depth retrievals from surface flux measurements. Second, we confirm the existence of a scale break of radiation fields escaping extended stratiform clouds at tens of km and reconcile this finding with the absence of a scale break, when mixed cloudy conditions are considered. We find no reason to believe this transition from nonstationary to stationary behavior does not carry over to the cloud's optical depth field.

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