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29/9 dimensional space-time atmospheric stratification of passive admixtures using lidar data

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One of the most fundamental aspects of atmospheric turbulence is its space-time stratification. Over the last twenty years the evidence has accumulated that it is scaling over wide ranges of space-time scales; indeed, the main competing theories are the scaling quasi-linear gravity wave theories which predict horizontal and vertical spectral exponents 5/3, 3; hence the space dimension of the atmospheric motions D_s=7/3, and the anisotropic generalization of Bolgiano-Obukov convectively driven turbulence with D_s=23/9. As is often the case, key breakthroughs come with advent of new technology; in this case, state-of-the-art lidar backscatter data from passive scalars which yielded the estimate D_s=2.55±0.02 [M. Lilley *et al.*, Phys. Rev. E **70**, 036307 (2004)], thus ruling out the competing theories.

The D_s=23/9 model of spatial stratification ((x, y, z) space) implies that space-time ((x, y, z, t) space) is scaling with exponent D_{st}=29/9. Building on the earlier vertical cross-section lidar work, we test this prediction using passive scalar surrogates of aerosol and cirrus clouds from six ground based lidar cross sections (vertical-time) and ten airborne lidar cross sections (vertical-horizontal), thereby directly accessing both vertical and time (or horizontal and vertical) information.

Space-time cross-sections are a bit more complicated than vertical-horizontal cross-sections because the effect of overall advection is to introduce off-diagonal elements in the generator of the group of scaling changing operators which lead to the possibility of three different exponents for 1D temporal spectra (two of which were observed).

In order to test the theoretical predictions for density fluctuations in arbitrary space-time displacements, we developed new Anisotropic Scaling Analysis Technique (ASAT) based on nonlinear coordinate (wave numbers and frequency in Fourier space) transformations. The idea is to use a nonlinear transformation to transform the data into an isotropic space so that the spectra become isotropically scaling (self-similar). The nonlinear transformations allow for visual validation of the theory as well as for quantitative estimate of the stratification exponents. The main advantage of ASAT is that it makes possible data analysis in arbitrary directions (not only orthogonal eigendirections). Combining ASAT with scale invariant generator technique we verified the 29/9D model in all wave numbers and frequency directions for space-time scales ranging around 3 orders of magnitude, estimating $D_{st} = 3.13 \pm 0.16$ in Fourier space. In real space we obtained $D_{st} = 3.21 \pm 0.05$; this value is slightly more accurate since it is based on analysis of statistical moments with a range of order (roughly 0 to 3 using structure functions) rather than only second order (spectral) analysis here. Both results are compatible with the theoretical value.