Geophysical Research Abstracts
Vol. 15, EGU2013-7580, 2013
EGU General Assembly 2013

Height-resolved Scaling Properties of Tropospheric Water Vapour based on Airborne Lidar Observations

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Two-dimensional vertical water vapour cross sections of the free troposphere between altitudes of 2 and 10 km, measured by nadir-viewing airborne differential-absorption lidar with high spatial resolution, were analyzed using structure functions up to the fifth order. We found scale invariance, i.e. a power-law dependency of structure function on length scale, for scales between 5 and 100 km, for the horizontal time series of water vapour mixing ratio. In contrast to one-dimensional in situ measurements, the two-dimensional water vapor lidar observations allow height-resolved analyses of power-law scaling exponents at a vertical resolution of 200 m. The data reveal significantly different scaling properties above and below an air-mass boundary. They stem from three very dissimilar aircraft campaigns: COPS/ETReC over middle and southern Europe in summer 2007, T-PARC around Japan mostly over sea in late summer 2008, and T-IPY around Spitsbergen over sea in winter 2008. After discarding flight segments with low lidar signals or large data gaps, and after averaging horizontally to a resolution of between 1 and 5 km to obtain a high signal to noise ratio, structure functions were computed for 20 flights at various heights, adding up to a length of more than 300,000 km.

The power-law scaling exponents of the structure functions do not show significant latitudinal, seasonal or land/sea dependency, but they do differ between air masses influenced by moist convection and air masses aloft, not influenced. A classification of the horizontal water vapour time series into two groups according to whether the series occurred above or below the level of nearby convective cloud tops could be performed by detecting the cloud top height from the lidar backscatter signal in the corresponding flight segment. We found that the scaling exponents can be divided into two groups depending on the respective air mass: The smoothness of the time series, expressed by the first-order scaling exponent, varies from less than 0.5 in the low-level convectively influenced air masses to values greater than 0.5 and most frequently near 0.6 in the higher-level air above the convective cloud tops. The time series' intermittency, expressed by the variation of the scaling exponent with increasing order, is larger in convectively influenced air masses. These differences in variability strongly suggest that convection provides a source of moisture variability on small scales. Our results show that the high horizontal and vertical resolution of lidar observations allows a characterisation of the scale dependency of the water vapour field at scales close to and smaller than the smallest resolved scales in modern weather and climate models. This provides both a reference for validation of high resolution models and a basis for the design of stochastic or pdf-based parameterisations of clouds and convection.