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Thermal stratification vs. water vapor content in the upper troposphere

A. P. Ferreira[1], J. M. Castanheira[2], L. Gimeno[3]

University of Vigo

(1)(3) Environmental Physics Laboratory, Faculty of Sciences, University of Vigo, Orense, Spain
(2) CESAM, Department of Physics, University of Aveiro, Aveiro, Portugal

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Lapse rate - water vapor relationship in the UT

Starting point

Using the two-stream gray atmosphere IR radiative transfer model of Goody (1964), and by further assuming that the UT region is close to radiative equilibrium below an optically thin stratosphere, we arrived at a direct relationship between the lapse rate and the water vapor pressure (on the right) after taking into account that water vapor is the dominant radiatively active species in the IR bands. The underlying constant of proportionality depends essentially on the absorbing mean properties of water vapor over the IR spectrum. Such a relationship is expected to hold in the uppermost part of the troposphere, e.g. near the tropopause, insofar as the IR equilibrium prevails there and also the upward IR radiative flux largely exceeds the downward flux.

$$-\frac{\partial T}{\partial z} \propto (water\ vapor\ pressure)$$

Goal

In order to test the relationship depicted above we plot the water vapor pressure against the lapse rate as derived from upper air data (1) within a 1000 m depth just bellow the tropopause or (2) at the UT levels 300 hPa and 400 hPa. Two sources of data are employed: (1) data reports of the water vapor vertical soundings conducted by the NOAA/ESRL Global Monitoring Division and (2) radiosonde data taken from the Integrated Global Radiosonde Archive (IGRA).

Test 1: a mid-latitude layer near the tropopause

Data selection and calculations

Our study collected pressure, temperature and water vapor mixing ratio observations from a set of NOAA/CMDL water vapor vertical profiles within 1980-2009 at the first 8 locations of Table 1, and 1964-1980 at the last one. Data are unevenly distributed in time, its vertical resolution is 250 m and mixing ratio is measured by some version of a frost point hygrometer. Water vapor pressures and lapse rates were evaluated at all altitude levels reported at a distance ≤ 1000 m from the first tropopause, which amounts to 2048 pair of values distributed among 490 soundings. Most of the profiles are from Boulder (69%) and Washington (26%). The lapse rate was calculated using the central-difference formula of $O(h^2)$. The tropopause heights were calculated following the WMO convention. On average, our UT layer lies in between 11.0 and 11.9 km.

Table 1

LOCATIONS OF NOAA/CMDL VERTICAL SOUNDINGS		
Boulder, CO	40 N	105 W
Crows Landing, CA	37 N	121 W
Dagett, CA	35 N	121 W
Edwards AFB, CA	32 N	123 W
Laramie, WY	45 N	105 W
Lauder, New Zealand	45 S	169 E
Palestine, TX	32 N	96 W
Platte Valley, CO	40 N	105 W
Washington, DC	39 N	78 W

Water vapor pressure vs lapse rate

The mean and median values of water vapor pressure at different lapse rate bins 0.5 K/km wide is shown in Fig. 1a; Fig. 1b presents the corresponding PDF. Bins with very scarce data (less than 9 observations) are not shown. A few observations for the lowest latitudes were excluded in a part of the year, in compliance with our definition of mid-latitudes (explained later in Test 2). A direct proportionality between either of the two water vapor statistical quantities and the lapse rate is fairly apparent over the range of the most frequently observed lapse rates. The curves deviate greatly from linearity as static stability becomes improbably small.

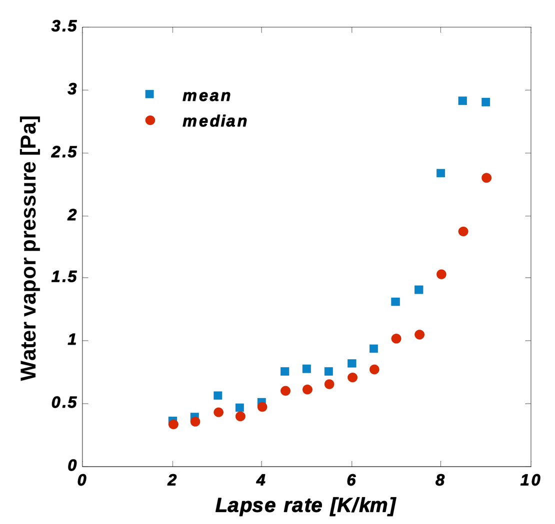


Figure 1a

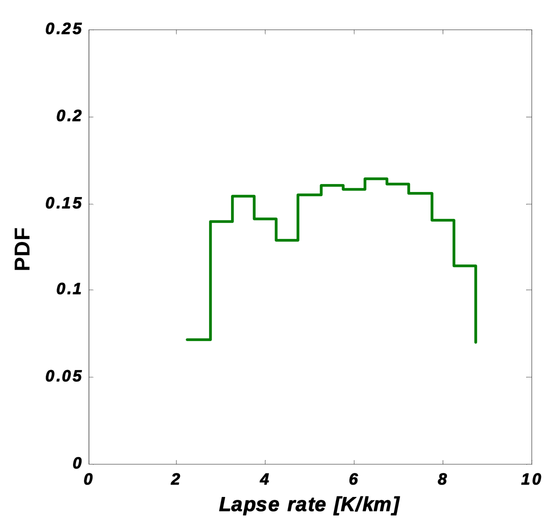


Figure 1b

Test 2: two fixed UT pressure levels

Data selection and calculations

Water vapor pressures and lapse rates at 300 hPa and 400 hPa were calculated from all radiosonde data (IGRA) in the period 1979-2008 taken from 800 stations distributed around the world. The selection of the 800 stations was based on a ranking of all IGRA stations in terms of the integral number of humidity data (dew point depression) found in the UT region extending from 500 hPa up to the long term average tropopause level at each location. About half the stations are located between 35°S and 35°N; the main part of the extratropical half is in the North Hemisphere. To avoid gross errors in computing the lapse rate, an *had-hoc* criterion was imposed for the 2nd order numerical scheme (based on Taylor expansion and hydrostatic equilibrium) in the vicinity of the studied pressure level: the vertical distance between the neighbor levels reported around the mandatory level of interest could not exceed 2000 m; otherwise the data were discarded. Moreover, to ensure that the calculations do not included some stratospheric upper level, which could compromise the accuracy of the lapse rate computation, only the cases in which the temperature decreased with height at the reported levels were considered. All in all the input comprised about 1.3 million of observations at 400 hPa and 1.0 million at 300 hPa.

Water vapor pressure vs lapse rate

Several plots of the mean and median values of water vapor pressure at lapse rate bins 0.5 K/km wide are shown in Fig. 2a, along with the PDFs in Fig. 2b, for each level and region: M for the mid-latitudes, P for the polar region, S for the subtropics and T for the tropical zone. In all cases data from both hemispheres are included. Polar regions are bounded by the 60° circles of latitude, while the lower [upper] bound of mid-latitudes [tropical zone] varies with season, following the definition of subtropics given in Table 2. This aims a separation of the tropical region from the extratropics bearing in mind the seasonal shift of the tropical belt. In all cases, an almost linear behavior is found for the most frequent and more stable thermal stratifications. Linearity breaks down as the lapse rate gets closer to static instability, when radiative equilibrium is no longer expected. Deviations from linearity for the smallest lapse rates may well arise from loss of precision in estimating the lapse rate (for that reason, vapor pressure is not plotted bellow 1.5 K/km). If one focus on the median part of the water vapor curves - which presumably gives a better picture of the average water vapor pressure, since humidity observations from radiosondes are noisy at the levels considered - the linear part of the curves intercept the origin, as predicted, except for the 400 hPa-(sub)tropical cases, i. e. the cases where the troposphere is thicker, the "over world" is less optically thin and complicating factors like clouds and moist convection might be important. The PDF picks around 8.5 K/km in the tropical and subtropical 300 hPa level are very close to the all-data average of the saturated adiabatic lapse rate that we have estimated for both cases at that level: 8.3 K/km in the tropics, 8.7 K/km in the subtropics. The study of some higher level for those regions is prohibitive, because humidity data at very low temperatures are not reliable and vertical resolution becomes too poor to calculate the local lapse rate.

Table 2

Subtropics extent			
Dec-Feb	Mar-May	Jun-Aug	Sep-Nov
20-30 N 30-40 S	25-35 N 25-35 S	30-40 N 20-30 S	25-35 N 25-35 S

Figure 2a

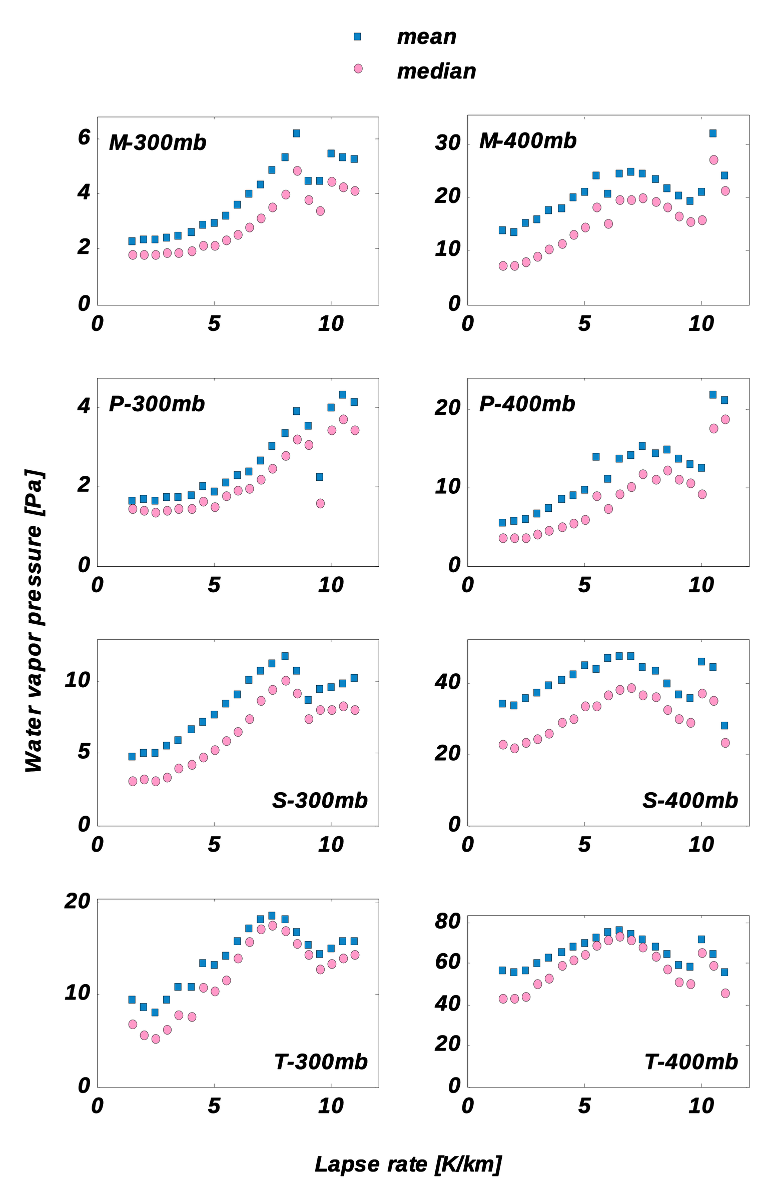
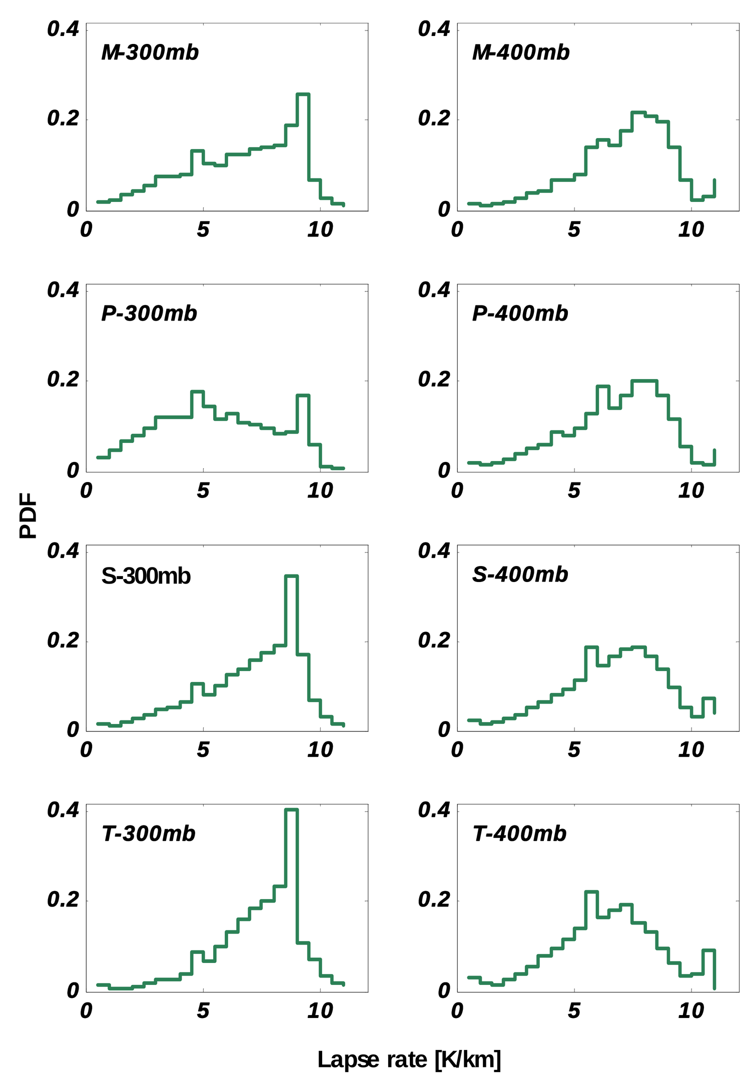


Figure 2b



Conclusion and remarks

The study presented here points out to a long-term proportionality between water vapor pressure and local lapse rate in the UT on average static stability conditions, notably in the vicinity of the mid-latitude tropopause. Such a relationship relies on the approximate IR radiative equilibrium in the uppermost UT in an idealized semi-gray atmosphere. Results obtained through the NOAA/CMDL water vapor vertical data profiles for a thin layer immediately below the tropopause at mid-latitudes (where the number of soundings is large enough to allow a long-term analysis) deserve special attention because water vapor data are more accurate and present much better vertical resolution, despite the modest number of observations available. On the other hand, results obtained through regular radiosonde data at 300 and 400 hPa, using a large collection of data at many latitudes, are somewhat questionable in view that radiosond humidity observations at about 400 hPa or higher levels are known to be doubtful. However, both results proved to be fairly consistent.