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TEMPERATURE EFFECT ON WATER VAPOR MEASUREMENTS WITH CO_2 DIFFERENTIAL ABSORPTION LIDARS

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INTRODUCTION

Water vapor concentrations are routinely measured in the atmosphere with differential absorption lidars (DIAL) in the CO_2 laser transition lines (9-11μm). In the DIAL technique, two laser wavelengths are chosen to be spaced as closely as possible so that the only difference between the two measurements will be the effect of water vapor absorption. The CO_2 transition line 10R20 (10.247 μm) exhibits the strongest absorption coefficient in the 9- to 11-μm wavelength range and thus is the preferred choice for the first wavelength. The second wavelength is commonly chosen to be the transition line 10R18 (10.260 μm) or the transition line 10R22 (10.233 μm), for low-to-moderate water vapor concentrations over reasonably short paths.

In a recent critical review paper on water vapor absorption coefficients in the infrared, Grant[1] pointed out that while there are plenty of data on the absorption coefficients at temperature between 20°C and 27°C, few reliable data exist on the temperature dependence of water vapor absorption coefficients for temperature <20°C. Thus determining the effect of temperature on atmospheric transmission for temperatures <20°C is problematic at present. The temperature and pressure dependence of the transition lines 10R22, 10R20 and 10R18 were measured in a laboratory experiment at temperatures -10°C, 0°C and 10°C by Loper et al.[2], and the transition line 10R20 was measured at temperatures between -20°C and 37°C by Hinderling et al.[3]. This paper presents moderate-range lidar field measurements of the temperature dependence of water vapor differential absorption coefficients for the wavelengths pair (10R20,10R18) and (10R20,10R22) for temperatures between -0.5°C and 20°C.

MEASUREMENTS

In this experiment, a CO_2 lidar system transmitted two groups of wavelengths at a repetition rate of 3.3 groups per second. Each group contained 10 wavelengths spaced at intervals of 5 ms. Among these wavelengths the laser transition lines 10R20 and 10R18 were each transmitted twice and the laser transition line 10R22 was transmitted once. For each trial, four records, each containing an average of twenty pulses for each of the wavelengths, were stored. Results of a total of one hundred trials at different temperature conditions were accumulated from a field test conducted at Dugway Proving Ground, Utah, during October 1992. All the trials were conducted under a clear sky with the same hard target and over the same path length over a dry desert terrain with very low and sparse vegetation. Simultaneous dry and wet bulb temperatures were measured with a psychrometer a few meters away from the lidar location and at a height of 1.5 m above the ground (approximately the height of the laser beam).

The error in the psychrometer measurements is estimated to be less than 0.2oC for which the error in the water vapor partial pressure is less than 3%. It should be noted that the lidar measurements are path-integrated data while the psychrometer data are local measurements. The standard deviation of the lidar return signals was computed to be less than 3% for all the different trials.

The water vapor absorption coefficients for the transition lines 10R18, 10R20 and 10R22 are the average values[1] $7.127*10^{-6}$, $8.477*10^{-5}$ and $1.012*10^{-5}$ (mb^{-1} m^{-1}) respectively at a temperature T_o of 27°C and at a water vapor partial pressure of 10 torr. These absorption coefficients, $\alpha(T_0)$, are taken as reference values at the reference temperature 'T_o' throughout this study. The water vapor partial pressure P_L computed from the lidar measurements is given by

$$P_L(T) = \frac{\ln\left[\frac{S_{\lambda_2}(T)}{S_{\lambda_1}(T)}\right]}{2R[\alpha_{\lambda_1}(T_o) - \alpha_{\lambda_2}(T_o)]} \qquad (1)$$

where R is the range to the target, S(T) is the measured reflected signal at a dry bulb temperature T, and (λ_1, λ_2) are the wavelengths of the transition line pair (10R20,10R18) or the pair (10R20,10R22). It is assumed in Eq. (1) that the absorption coefficients α are linearly dependent on water vapor partial pressure. Measurements by several authors show that the absorption coefficient is almost linearly dependent on water vapor partial pressure for the transition line 10R20 and has linear and quadratic dependence on water vapor partial pressure for the transition lines 10R22 and 10R18.

The cross correlation between the water vapor computed from the lidar measurements and the meteorological data measured by the psychrometer is almost identical to the autocorrelation curve of the psychrometer measurements, and thus demonstrates that the path-integrated lidar measurements are closely related to the local psychrometer measurements. The maximum value of the cross correlation is 0.9967 for the pair (10R20,10R18), and 0.9968 for the pair (10R20,10R22).

ANALYSIS AND DISCUSSION

Laboratory measurements[2,3] show a positive temperature dependence of the water vapor absorption coefficient for transition line 10R20 (i.e. the absorption coefficient increases with increased temperature), while for most other weak CO_2 transition lines, including lines 10R22 and 10R18, the temperature dependence is negative (i.e. the absorption coefficient decreases with increased temperature). It should be noted that in his review paper, Grant[1] indicated the possibility of contamination by impurities at 27°C in the data given by Loper et al.[2] and some inconsistency in the continuum absorption temperature dependence in the data from Hiderling et al.[3].

Present measurements show that the partial pressure of the water vapor computed from the lidar measurements for temperatures <20°C with the absorption coefficients at 'T_o' is always lower than the water vapor partial pressure measured by the psychrometer. This suggests that the value of the differential absorption coefficients used in Eq. (1) should be decreased and thus is given by

$$\alpha_{\lambda_1}(T) - \alpha_{\lambda_2}(T) = [\alpha_{\lambda_1}(T_o) - \alpha_{\lambda_2}(T_o)] * [1 + X(T) * (T - T_o)]$$

where the empirical temperature correction, X(T) for the wavelength pair (λ_1, λ_2) is

$$X(T) = \frac{\frac{P_L(T)}{P_M(T)} - 1}{T - T_o}$$

Figures 1 and 2 show the empirical

temperature correction X(T) of the differential absorption coefficients for wavelength pairs (10R20,10R18) and (10R20,10R22) respectively. In these figures a least squares curve fit (solid line) in the form $X(T)\ [1/°C] = a_0 + a_1 T + a_2 T^2$ (T in °C) was used to fit the data points (circle symbols). The curve fit coefficients (a_o, a_1, a_2) are ($1.64*10^{-2}$, $-4.33*10^{-4}$, $6.76*10^{-5}$) and ($1.32*10^{-2}$, $-4.09*10^{-5}$, $2.98*10^{-5}$) for the wavelength pair (10R20,10R18) and (10R20,10R22) respectively.

For an error ϵ of 3% in lidar measurements S(T), the uncertainty $\Delta X(T)$ in X(T) is estimated by

$$\Delta X(T) = \frac{\ln\left(\frac{1\pm\epsilon}{1\mp\epsilon}\right)}{P_M(T)\, 2R\, [\alpha_{\lambda_1}(T) - \alpha_{\lambda_2}(T)]\, (T - T_0)}$$

The normalized uncertainty $\Delta X(T)/X(T)$ in computing X(T) is shown in the figures (dotted line). The temperature coefficient X(T) for T=10°C and 10 torr water vapor partial pressure and for T=0°C and 3.2 torr water vapor partial pressure was computed from Loper et al[2]., using their absorption coefficient measurements and their empirical correction for the pressure dependence of the absorption coefficients for these temperature values. Their temperature coefficients are noted by triangle symbols in the figures. The pressure values 10 torr and 3.2 torr for T=0°C and 10°C respectively are close to the psychrometer measurements.

The temperature correction X(T) at a temperature within few degrees of 27°C is given by Grant et al.[4] as 2.1 %/°C for the transition lines (10R20,10R18). The results presented here (Fig. 1) show the temperature correction to be about 3.5 %/°C at 20°C. It should be noted that the temperature correction X(T) [1/°C] computed from the lidar and psychrometer measurements may be biased higher than the "true" temperature correction X(T) as T approaches T_o for which the denominator approaches zero while the numerator due to error in measurements is never equal to zero. However, the total temperature correction $X(T)*(T_o-T)$ decreases with increasing temperature as is shown in Fig.3 where the empirical least square quadratic fit for the transition line pairs (10R20,10R18) (solid line) and (10R20,10R22) (dashed line) are used.

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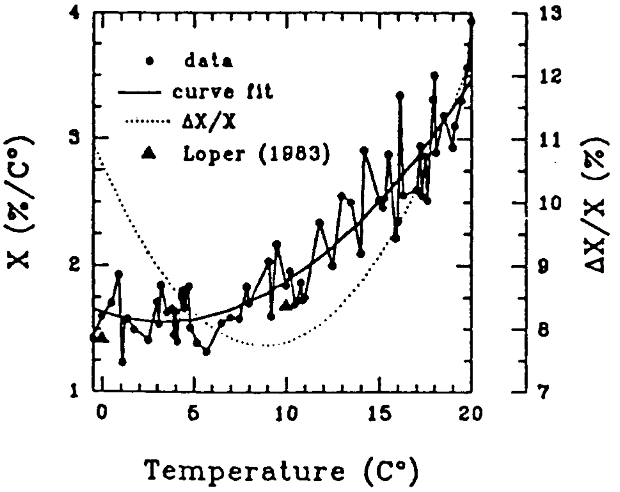

Fig. 1 - Empirical Temperature correction X(T) of the differential absorption coefficients for the transition line pair (10R20, 10R18) as a function of dry bulb temperature

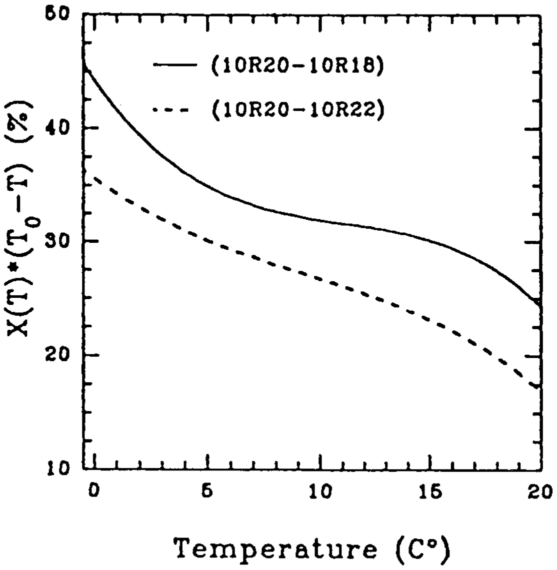

Fig. 3 - Cumulative temperature correction $X(T)^*(T_0-T)$ for the transition line pair (10R20, 10R18) (solid line) and for the transition line pair (10R20, 10R22) (dashed line) as a function of dry bulb temperature

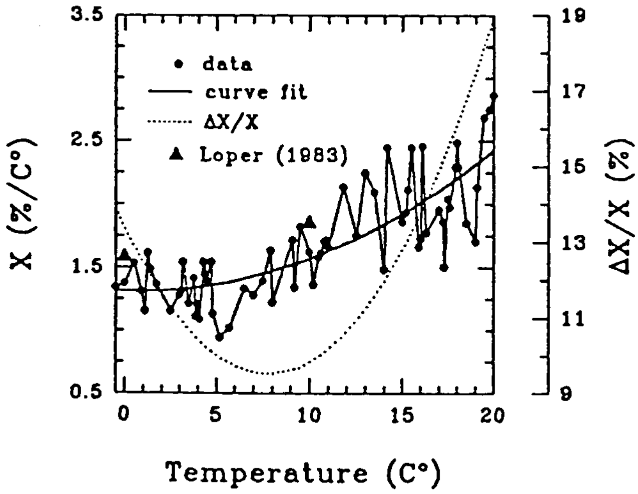

Fig. 2 same as Fig.1 but for the transition line pair (10R20, 10R22)