Estimation of the Ocean/Atmosphere Boundary Layer Height of Water Vapor from Space

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Abstract -- A new retrieval technique has been developed which resolves some of the vertical structure of lower tropospheric water vapor over oceans from space. The relationship is demonstrated by comparisons between direct measurements of the water vapor profile, by radiosondes, and coincident estimates of the horizontal turbulence structure of Integrated Water Vapor, using the TOPEX Microwave Radiometer (TMR). Correlation is highest between the turbulence structure and the lower, boundary layer, component of the water vapor profile. The relationship is next applied to a two year time series of TMR data at Wake Island in the tropical Pacific. Both TMR and the Wake Island radiosondes indicate a periodic variation in the water vapor height which is consistent with the Madden and Julian Oscillation (MJO).

INTRODUCTION

Estimation from space of the vertically integrated water vapor burden (IWV) in the atmosphere over open ocean has reached a mature and operational level [1]. Measurements by a microwave radiometer of the upwelling brightness temperature near the 22 GHz water vapor line are used. Use of the relatively weak 22 GHz line results in robust estimates of IWV that are largely insensitive to variations in cloud cover, sea surface roughness and temperature, and the height distribution of the water vapor [2]. Global maps of IWV are routinely produced by satellite radiometers, including the SSM/I on board the DMSP platforms, the TMR on board the TOPEX/Poseidon satellite, and the microwave radiometers on board ERS-1 and ERS-2. The ability to infer some additional information about the vertical distribution of the water vapor from the global IWV images would add significantly to their value.

A relationship has been determined between the spatial correlation structure of the horizontal variations in IWV and the vertical distribution of the water vapor profile. The relationship can be explained by first considering the point-to-point correlation structure of the three dimensional water vapor density field. The structure function for this field is given by

$$D_\rho(s) = \left\langle \left[\rho(\vec{r}) - \rho(\vec{r}+\vec{s})\right]^2 \right\rangle \quad (1)$$

where s is the magnitude of the separation between points, $\rho(\vec{r})$ is the water vapor density at $\vec{r}$, and the expectation is over all realizations of the random function $\rho(\vec{r})$. If the separation, s, is assumed to lie within the inner and outer scales of isotropic turbulence, then Kolmogorov turbulence theory predicts a relationship of the form

$$D_\rho(s) = C_\rho s^\alpha \quad (2)$$

where C_ρ, the structure constant of the turbulence, scales according to the magnitude of the water vapor variability and α, the power law exponent, is a measure of the rate at which the water vapor distribution decorrelates with separation distance [3]. For the case of isotropic turbulence in three dimensions, α=2/3 [3]. If the separation, s, is larger than the outer scale (typically in the tens of meters), then (2) will not be strictly obeyed. For example, D_ρ will become independent of s at separations so widely spaced that the water vapor is essentially uncorrelated. Eqn. (2) can be considered a local model for the behavior of the correlation structure in different regions of the separation, with α considered a region dependent variable. For separations between the inner and outer scales of isotropic turbulence, α=2/3. For very large separations, α=0. In between these two extremes, we expect α to decay from 2/3 to 0.

Measurements of IWV are related to $\rho(\vec{r})$ by

$$IWV(\vec{x}) = \int_0^\infty \rho(\vec{r} = (\vec{x}, z))dz \quad (3)$$

where $\vec{x}$ denotes the two dimensions of horizontal variability of the IWV field and z is the height. The spatial correlation structure function for the IWV field is defined, in the same manner as the three dimensional field, as

$$D_{IWV}(s) = \left\langle \left[IWV(\vec{x}) - IWV(\vec{x}+\vec{s})\right]^2 \right\rangle. \quad (4)$$

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If the separation, s, lies within the inner and outer scales of isotropic turbulence for the water vapor field, then Kolmogorov theory predicts a relationship of the form

$$D_{IWV}(s) = C_{IWV} s^{\beta} \tag{5}$$

where the power law exponent is given by β=5/3 [3]. We can locally fit the actual behavior of D_{IWV} to (5) for separations beyond the outer scale. We expect β to roll off from 5/3 to 0 as s increases to very large separations.

The behavior of β as a function of separation is also influenced by the finite vertical extent of the water vapor distribution. Even for the case of isotropic turbulence on all horizontal scales, separations which are an appreciable fraction of the vertical extent of the bulk of the water vapor will result in two dimensional structure functions for which β is reduced below 5/3. This aspect of the dependence of β on separation has been recognized and studied by several investigators [4, 5]. Armstrong and Sramek [4] estimate the dependence of β on separation directly from sets of phase differences between radio interferometer pairs with the Very Large Array in Socorro, New Mexico. They note a range of values $0.84<\beta<1.95$ for separations in the range 1-10 km. Treuhaft and Lanyi [5] corroborate this behavior with numerical simulations which predict a smooth, monotonic transition of β from 5/3 to 2/3 as the separation is varied from much less than to much greater than the height of a slab of water vapor which is isotropically turbulent on all scales in the horizontal direction. Note that their model does not incorporate the additional roll off of β with separation due to the finite outer scale in the horizontal direction.

TMR AND RAOB DATA PROCESSING

The IWV data used in this study were measured by the TMR [2]. TMR measures the brightness temperature in the nadir direction at 18, 21, and 37 GHz and estimates the path delay, PD, due to water vapor. Because the PD is nearly linearly proportional to the IWV [6], we use its turbulence structure to estimate the power law dependence, β, of the water vapor distribution. TMR data are recorded every 5.8 km along the satellite ground track. In our study here, we determine the structure function, D_{IWV} (s), by using sequential measurements of PD within a specified interval and approximating the expectation operator in (4) by an average over the data in that interval.

An estimate of the power law dependence, β, is made using a log/log linear regression of the structure function versus separation. We include only estimates of D_{IWV} (s) over the range $11.6<s<29.0$ km in our regression fit. This range has been found to produce a good correlation between β and coincident estimates of the water vapor scale height, as measured by the radiosondes.

Coincident radiosonde measurements were assembled as part of the TMR flight validation program [2]. Radiosondes provide a direct measure of the vertical profile of absolute humidity. One measure of the characteristic height of the water vapor, which we use here, is the fractional height, H(f). H(f) is defined as the height below which some fraction, f, of the total water vapor burden lies.

The flight validation program for TMR involves daily collection of radiosonde data from 24 island launch sites which lie within 50 km of the satellite ground track [2]. We have selected the subset of radiosonde launches which occurred within 100 min of a satellite overpass. Corresponding TMR data are selected which lie within a specified radius of the radiosonde launch site. This radius is determined independently for each overpass so that the standard deviation of path delay samples within the radius remains approximately the same. This controls for large changes in the statistics of the vapor field over the ensemble of data from which the turbulence structure is estimated. The average value for the radius was 500 km and results in a path delay standard deviation of ~2.0 cm.

TMR/RADIOSONDE INTERCOMPARISON

Scatter plots of H(f) versus the turbulence parameter β are shown in Figure 1. Fractional heights are shown with f = 10% and 50%. In both cases, the general trend is as expected. Higher rates of decorrelation with separation (higher values for β) generally correspond to lower characteristic heights of the water vapor profile. The correspondence appears stronger for the 10% fractional height. We conjecture that this may be due to the stronger correspondence between the lower fractional height and the thickness of the water vapor in the ocean/atmosphere boundary layer. This boundary layer water vapor is better mixed and, hence, more representative of three dimensional isotropic turbulence than are the higher regions of the profile.

A second comparison between the radiosonde height and β is possible by examining a continuous time series of the two values at a common location. The TMR-derived estimates of β are based on an ensemble of data from an entire orbit cycle (9.9 days), using all satellite ground tracks with closest approach points within 150 km of the launch site. The radiosonde heights, which are generally available twice daily, have been smoothed by a triangular running average of ±10 days to approximate the effective time average imposed by the TMR processing. A sample of the results is shown in Figure 2 for the Wake Island

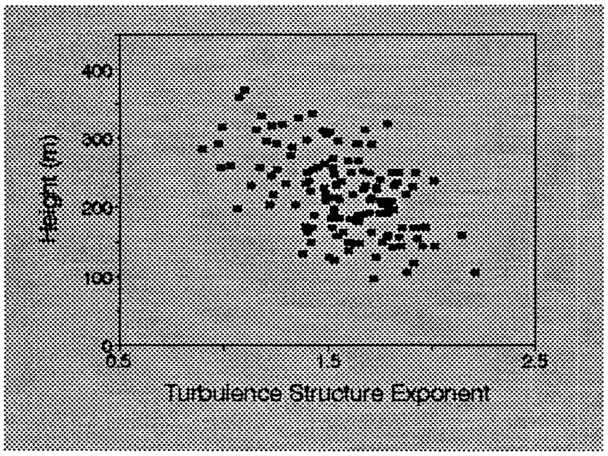

Figure 1a. β vs. 10% height of water vapor profile.

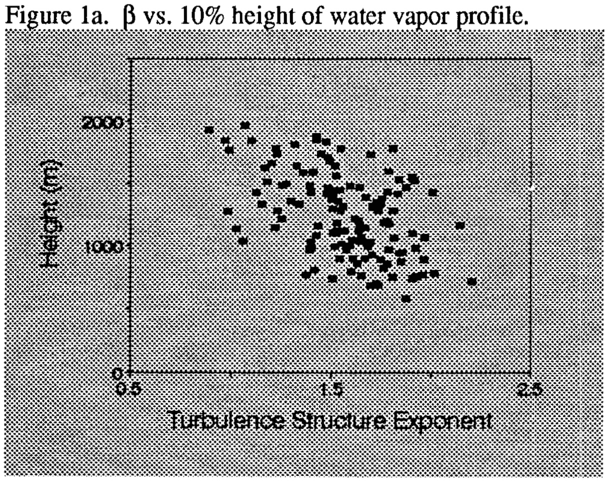

Figure 1b. β vs. 50% height of water vapor profile.

radiosonde station (latitude 19.28 North, longitude 166.65 East). Both radiosonde height and β time series' display an oscillating behavior which is consistent with the MJO period of 40-50 days [7]. The phase coherence between the two time series' suggests that they are responding to correlated characteristics of the water vapor profile. In addition to the similar MJO signatures, both time series' also have a similar response to the seasonal variation in the height of the water vapor profile. Higher levels are noted during the 1994 and 1995 summers in both the radiosonde height and the turbulence scale height which can be inferred from β.

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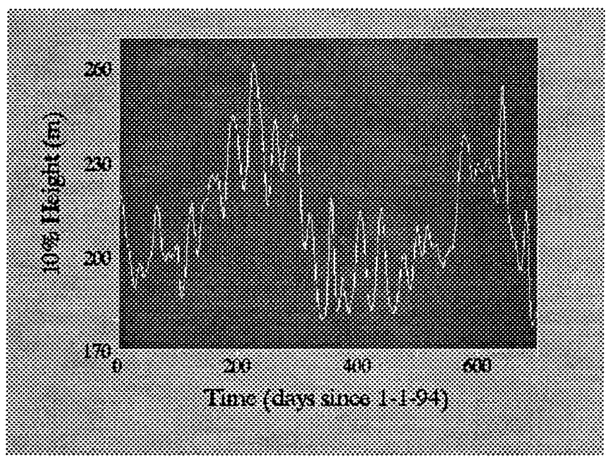

Figure 2a. Height of first 10% of water vapor at Wake Island - derived from RaOb profiles.

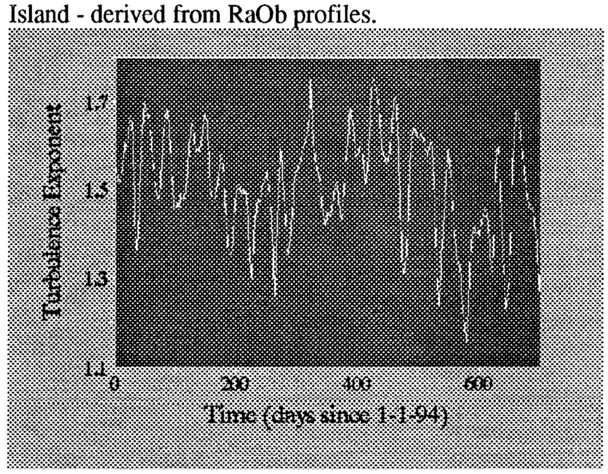

Figure 2b. TMR derived β at same site (Wake Island).