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VERTICAL TRANSPORT IN THE TROPO-STRATOSPHERE BY INTERMITTENT TURBULENCE: A SIMULATION STUDY

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1. INTRODUCTION

The possibility of a slow depletion of stratospheric ozone in reactions with pollutants inadvertently released in the lower atmosphere has received considerable attention over the past decade (see e.g. Kruger and Setlow, 1982). Production and loss processes alone cannot be used to account for budgets of minor constituents in the stratosphere. Processes that affect their transport also need to be included.

In the simplest and most widely employed one-dimensional (1-d) aeronomic models, transport coefficients are obtained from the observed profiles of a constituent whose chemistry is presumably well understood. In more sophisticated two and three dimensional models, transport by advection with atmospheric circulation is considered, but the effect of motions at scales smaller than some grid size are included only in a parametrized form. Estimates of transport coefficients, based on direct observations of the underlying physical processes such as turbulence, are relatively scarce and have so far provided conflicting results.

From in situ observations of turbulence with instrumented aircrafts Lilly et al. (1974) inferred that the contribution of turbulence to transport is small compared to that by advection. Rosenberg and Dewan (1975) analyzed smoke-trail observations of atmospheric wind shears and obtained transport coefficients comparable to 1-d models. Similar results were recently obtained by Woodman et al (1981) from the observations of turbulence with the sensitive Arecibo radar. These observations reveal intermittent, stratified layers of turbulence (Woodman, 1980; 1981)

Dewan (1981) has shown that the transport by a homogeneous ensemble of intermittent, stratified layers of turbulence can be modelled as a random-walk process. In this paper we consider extensions of this work to non-homogeneous situations, specifically to diffusion in the tropo-stratosphere.

2. SIMULATION METHOD

Consider an ensemble of intermittent, stratified turbulent layers which are randomly distributed in height. The layer thickness is assumed to have a Gaussian distribution. We consider only independent realizations of such layers obtained at discrete steps T of time that is large compared to the time required for mixing within the layers. In each realization, therefore, mixing and transport is induced locally within the layers. For such an ensemble the effective transport coefficient K_e can be obtained by two different methods.

In the first method, the ensemble is used to obtain the mean-square layer thickness ℓ^2 and the mean time τ between the recurrence of layers (in units of T) at each level. For the assumed statistical properties of the ensemble, the effective transport coefficient K_e is obtained as a theoretical diffusivity $K_e = \ell^2/12\tau$.

In the second method, we treat K_e as a proportionality constant relating the flux and the gradient of some hypothetical passive scalar. Consider an initial scalar density profile with unit gradient. The simulated (or observed) ensemble of turbulent layers is then allowed to mix this profile. The flux of the scalar at any level is obtained by integrating the difference between the final and initial profiles upto that level. This

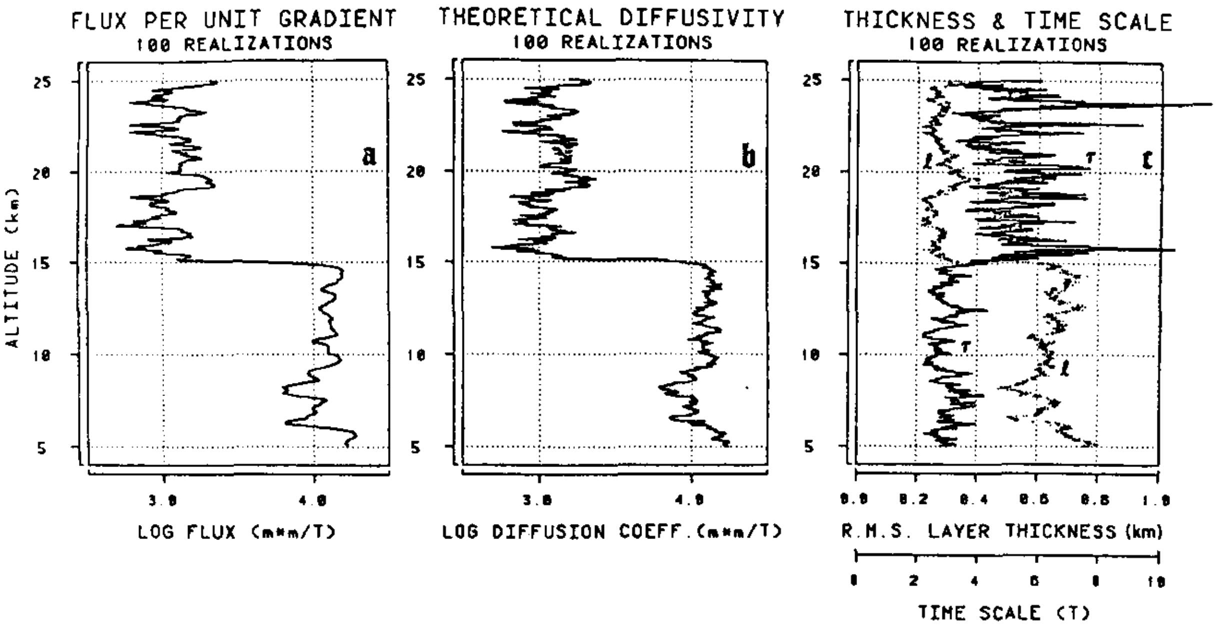

Figure 1. Transport-coefficient profiles obtained for an ensemble of 100 realizations of turbulent layers (a) as a flux per unit gradient for a hypothetical passive scalar, and (b) as a theoretical diffusivity from the actual r.m.s. thickness and time scale shown in (c). It is assumed that the realizations are statistically independent and are sampled at time steps T.

flux then directly gives the effective transport coefficient K_e.

Both the methods are amenable to computer simulation. Moreover, nonhomogeneous cases, e.g. when K_e changes with altitude, can be easily considered by varying the statistical properties of the ensemble.

3. SIMULATION RESULTS

We present here some typical results for simulations of transport in the tropo-stratosphere. These simulations cover an altitude range of 5-25 km, with an average of one layer per km. The layer thickness is assumed Gaussian with a mean thickness of 200 m and a standard deviation of 50 m. The layers are allowed to overlap and their minimum thickness is set to 50 m. To account for an enhanced transport in the tropesphere, the layer thickness is doubled below an assumed tropopause height of 15 km.

Figure 1 shows a comparison between the transport-coefficient profiles obtained by the two methods for an ensemble of 100 realizations. The flux per unit gradient is shown in Fig. 1a. The theoretical diffusivity profile in Fig. 1b is obtained from the r.m.s layer thickness ℓ and the mean time τ between the recurrence of turbulence shown in Fig. 1c for the ensemble. Doubling the layer thickness below the tropopause reduces τ. Despite the small ensemble size, the transport-coefficient profiles obtained by the two methods are in excellent agreement.

The flux method yields a smoother profile. This is to be expected since the flux is obtained as an integral. The discontinuous nature of the length and time scales in Fig. 1c indicates that these scales cannot be easily inferred from an observed ensemble, and suggests that the flux method may actually be easier to use.

In order that an observed ensemble may have a large number of independent realizations, the observations must cover a sufficiently long interval. For example, if the time step T between independent realizations is 1 hr, an ensemble size of 100 would require 100 hr of observations. Observations of turbulence over such long intervals are not usually available. We consider therefore the effect of an even smaller ensemble size, say of 10 realizations. For such small ensembles, the time and length scales cannot be properly inferred from the obervations. The flux method would yield a very sporadic transport-coefficient profile with

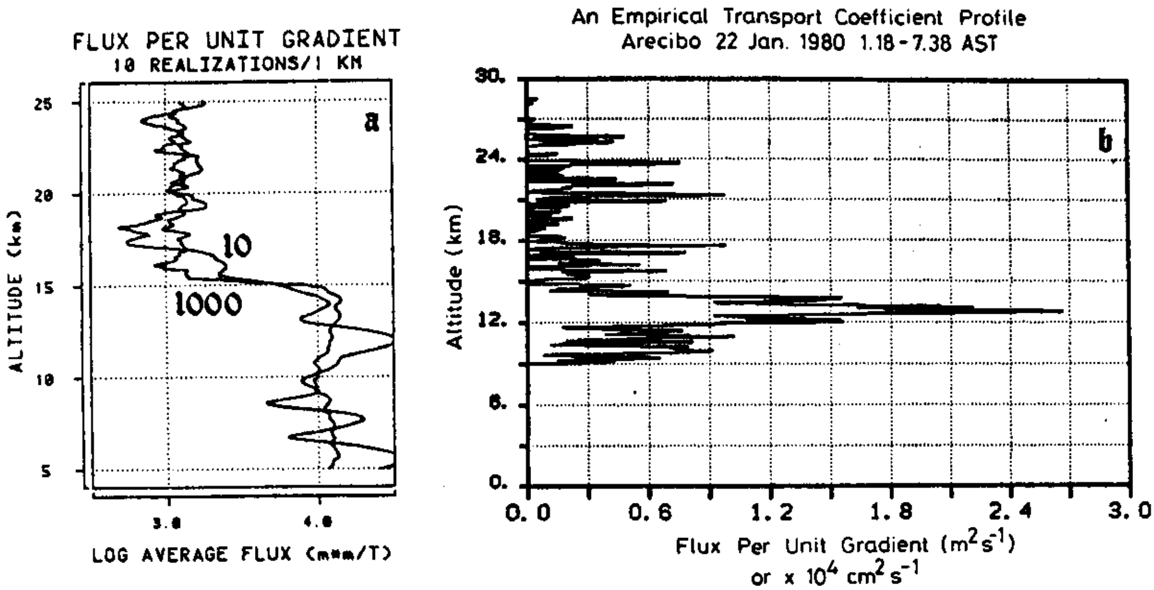

Figure 2. (a) Transport-coefficient profile obtained by the flux method for an ensemble size of 10 with a 1-km height averaging; for comparison a profile for 1000 realizations is also shown. (b) An empirical transport-coefficient obtained by the flux method from a 7-hr segment of radar observations at Arecibo [Woodman et al., 1981]. The sporadic nature of this profile is due to the short observation interval. The values of 0.1 to 0.3 m*m/s are typical of those used in one-dimensional stratospheric models.

frequent excursions to zero in regions devoid of turbulence. However, an integration of this profile with a suitable height window can still provide meaningful values for the transport coefficients. Fig. 2a shows a profile of K_e obtained with the flux method for an ensemble size of 10 after smoothing with a 1-km window. For comparison a flux profile for an ensemble size of 1000 is also shown. The smoothed profile has indeed a large variance, but provides reasonable estimates of the values of K_e below and above the tropopause.

4. DISCUSSION

The flux method discussed above has been used by Woodman et al (1981) to estimate stratospheric transport coefficients from fine altitude resolution (150 m) observations with the Arecibo radar for a 6-7 hr interval. Their flux profile is shown in Fig. 2b. As discussed above, the sporadic nature of this profile is a consequence of the short observation interval. The average shape of the profile, however, is similar to the simulation examples in Figs. 1 and 2a. The values 0.1 to 0.3 m^2s^{-1} may be considered typical of the stratospheric transport coefficients. These values are comparable to those used in 1-d models and imply that turbulence can be effective in vertical transport in the stratosphere.

The simulation examples discussed above suggest that radar observations of stratospheric turbulence over reasonably long intervals, possibly 3-4 days, should be useful in obtaining empirical profiles of vertical transport coefficients.

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