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Estimation of the turbulent heat flux in the lower stratosphere from high resolution radar measurements

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[1] Two estimates of the turbulent diffusivity (i.e., the heat flux per unit gradient) in the lower stratosphere are inferred from high-resolution radar measurements and compared. First, the local heat flux (within the turbulent patches) is evaluated from the dissipation rate of turbulent kinetic energy ϵ_k under the basic assumptions of local homogeneity and stationarity of the fluctuations. We then estimated the effective heat flux per unit gradient as the time-averaged flux for a given altitude during the measurement period (six hours), taking into account the observed turbulence intermittence. The time-averaged heat flux per unit gradient is found to be $\sim 2 \times 10^{-2}$ m^{2}s^{-1} typically, in good agreement with some of the weakest estimates of diffusivity already published. The observed ratio between the local and the time averaged fluxes can reach about one order of magnitude. This last result stresses the fact that turbulent diffusivity inferred from MST radars measurements cannot generally be directly interpreted as an effective diffusivity, since radar estimates, in most cases, do not take into account the turbulence intermittence. **Citation:** Wilson, R., F. Dalaudier, and F. Bertin (2005), Estimation of the turbulent heat flux in the lower stratosphere from high resolution radar measurements, *Geophys. Res. Lett.*, *32*, L21811, doi:10.1029/2005GL024124.

1. Introduction

[2] The actual impact on vertical transport of small scale turbulence in the lower stratosphere is at present controversial. The major difficulty comes from the large heterogeneity of turbulence within stratified fluids. Numerous observations have revealed the intermittent behavior of atmospheric turbulence [e.g., *Sato and Woodman*, 1982; *Barat and Bertin*, 1984]. On an other hand, a recent theoretical study, following the pioneering work of [*Dewan*, 1981], showed that the overall effect on vertical transport of patchy turbulence can be parametrized as an ordinary diffusive process in the long-time limit [*Vaneste and Haynes*, 2000].

[3] Various estimates of turbulent diffusivity in the lower stratosphere show large discrepancies, over about two orders of magnitude. From in situ observations *Lilly et al.* [1974] inferred an effective diffusivity for heat, $K_\theta \approx 10^{-2}$ m^2/s. Such an estimation was based on evaluations of the heat flux (from the dissipation rate of turbulent kinetic energy (TKE)) at a considered level, thus taking into account the time-and-space intermittence of turbulence. MST radar estimates of K_θ in the lower stratosphere usually range from 10^{-1} to 1 m^2/s typically [e.g., *Sato and Woodman*, 1982; *Woodman and Rastogi*, 1984; *Fukao et al.*, 1994; *Kurosaki et al.*, 1996; *Nastrom and Eaton*, 1997; *Rao et al.*, 2001]. Combining microstructure measurements with a stochastic model *Alisse et al.* [2000] inferred an effective vertical diffusivity of $\sim 2 \times 10^{-2}$ m^{2}s^{-1}. Others estimates for K_θ were inferred by combining observations of tracers and mesoscale models [*Balluch and Haynes*, 1997; *Legras et al.*, 2003]. By observing (from instrumented aircraft) the time evolution of stratospheric filaments submitted to both large scale advective stirring and small scale turbulent mixing *Balluch and Haynes* [1997] found $K_\theta \approx 10^{-2}$ m^{2}s^{-1} typically. Following a different approach, *Legras et al.* [2003] evaluated K_θ from the comparison of observed ozone profiles with a stochastic-dynamical reconstructions. These authors found $K_\theta \approx 10^{-1}$ m^{2}s^{-1}.

[4] The object of the present study is to evaluate the effective transport due to small scale turbulence by using very high resolution ST radar data. The PROUST radar (PROUST is a French acronym for Prototype de Radar d'Observation Uhf de la Stratosphère et Troposphère) is a UHF radar (961 MHz), located in St Santin, France (44°39′N, 2°12′E). The vertical range resolution is 30 m, the angular resolution being better than 1°, the integration time being reduced to 51 s [*Delage et al.*, 1996]. The PROUST radar data allow to estimate both the turbulent velocity variance, v^2, as well as the structure constant of refractive index C_n^2, from respectively the measured Doppler broadening Δf and reflectivity η, the estimation of η requiring a radar calibration [*Hocking*, 1985].

[5] The inference method for the turbulent heat flux is presented in section (2). Data are described in section (3), results being shown in section (4). Some conclusions are drawn in the last section.

2. Method

[6] Under the basic assumption that small scale turbulence is locally homogeneous and stationary, the dissipation rate of velocity variance ϵ_k is related to the buoyancy flux [e.g., *Tennekes and Lumley*, 1972, pp. 95–98]:

$$-\left(\frac{g}{\overline{\theta}}\right)\overline{w'\theta'} = \frac{R_f}{1 - R_f}\epsilon_k = \gamma\epsilon_k \qquad (1)$$

where w is the vertical velocity, θ the potential temperature, R_f being the flux Richardson number, g the acceleration due to gravity. Primes and overbars denote fluctuations and mean quantities, respectively. The ratio $R_f/(1 - R_f) \equiv \gamma$ is frequently labeled as the mixing efficiency (discussions about γ by *Hocking* [1999] and *Wilson* [2004]). The

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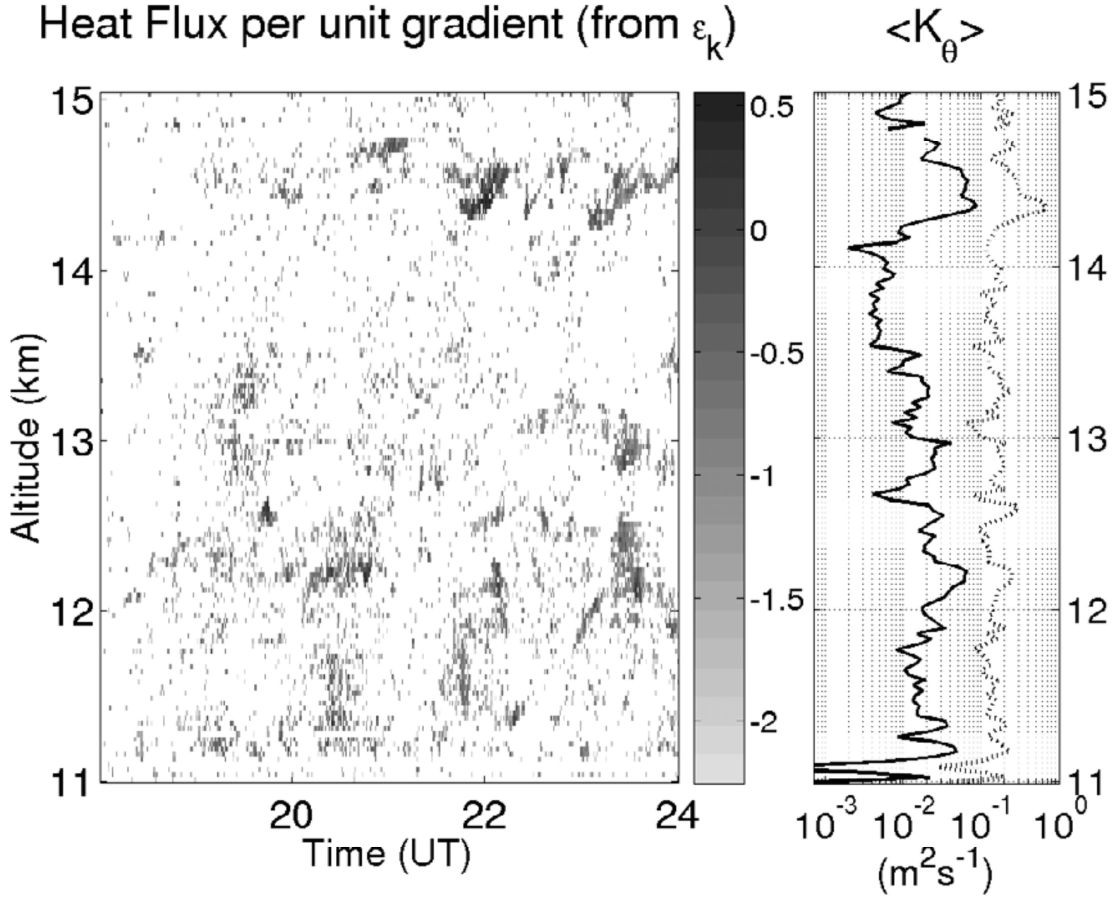

Figure 1. (left) Turbulent diffusivity of heat within turbulent patches in the lower stratosphere (logarithmic scale) on April 27, 1998. (right) The averaged heat flux per unit gradient (i.e., K_θ), taking into account the non–turbulent periods (continuous) and during the turbulent events only (dotted).

retained value for γ is usually 1/3 (corresponding to $R_f = 0.25$) [e.g., *Fukao et al.*, 1994; *Nastrom and Eaton*, 1997] although recent experimental works suggest that γ could be slightly smaller ($\gamma \sim 0.2$) [*Alisse and Sidi*, 2000]. The flux per unit gradient, i.e., the local turbulent diffusivity, is defined as:

$$K_\theta = \frac{-\overline{w'\theta'}}{\left(\partial\overline{\theta}/\partial z\right)} \tag{2}$$

By using (1), K_θ reads:

$$K_\theta = \gamma\frac{\epsilon_k}{N^2} \tag{3}$$

where N is the buoyancy frequency. By assuming a Kolmogorov inertial range spectrum, the TKE dissipation rate ϵ_k is related to the mean square turbulent velocity v^2 [e.g., *Hocking*, 1983]:

$$\epsilon_k \approx 3.5\left(v^2\right)^{3/2}/L_m^{2/3} \tag{4}$$

where L_m is the outer scale of turbulence. By further assuming that L_m is proportional to the Ozmidov scale $L_O = (\epsilon_k/N^3)^{1/2}$ [*Weinstock*, 1978; *Hocking*, 1983], i.e., $L_m \approx 3\pi L_O$, ϵ_k reads:

$$\epsilon_k \approx 0.5\left(v^2\right)N \tag{5}$$

[7] The radial velocity variance v^2 is inferred from the radar-measured half-power half-width Δf of the velocity spectrum, the non-turbulent broadening contribution being previously removed [*Hocking*, 1983]:

$$v^2 = \left(\frac{\lambda_r}{2}\right)^2 \Delta f^2/(2\log 2) \tag{6}$$

where λ_r is the radar wavelength.

3. Data Description and Processing

[8] A field campaign combining high resolution balloon and the PROUST radar was conducted during three observation periods on April 27th, 28th and 30th, 1998. During each observation period, instrumented balloons were launched with a time interval of about 3 hours: three balloons during the first and second periods, two during the last one. We present here the data of the first period only,

the results not being significantly different for the two other periods. During this first period, the tropopause height was observed to be at about seven km altitude.

[9] The dissipation rate ϵ_k is estimated from the spectral width Δf (equations (5) and (6)). The heat flux per unit gradient (i.e., K_θ) is then evaluated within each sampling volume from equation (3). Performing a time average of the local flux per unit gradient for a constant height (assuming $K_\theta = 0$ if no signal is detected) gives an estimate the actual (or effective) flux across that considered height due to small scale turbulence.

[10] The buoyancy frequency N is treated as a constant within the considered height range (from 11 to 15 km) as the successive N profiles (from in situ soundings) are totally uncorrelated for such a high range resolution (30 m). We therefore consider N as a random variable, a reasonable estimator of which being the statistical average $\overline{N}$ from the three successive soundings within the overall height domain.

4. Results

[11] The time-height distribution of the turbulent patches observed on April 27, 1800 UT to 2400 UT, from 11 to 15 km height, is shown in Figure 1. Not surprisingly, the turbulence field appears highly inhomogeneous. Intense turbulence patches are observed intermittently between 11 and 13 km and around 14.5 km altitude. On the contrary, almost no turbulence is observed within the 13.5–14 km domain. The turbulent fraction (i.e., the fractional time for which the radar volumes are observed to be turbulent) is ~0.1–0.2 in the average. The plot on the right of the figure shows two averages of the inferred heat fluxes per unit gradient. The dotted curve is an ensemble average of the local diffusivities K_θ, that is the averaged value observed during the turbulent events only, for the considered height. The thick continuous curve shows the time average of the heat flux per unit gradient for the considered height, thus taking into account the non-turbulent periods. Note that the ratio between the two curves is the turbulent fraction during the observation period for the considered height.

[12] The striking feature here is that the time-averaged flux per unit gradient is much smaller than the local turbulent diffusivity, typically from three to ten times. Indeed, the observed diffusivity within the turbulent spots is $\sim 10^{-1}$ m^{2}s^{-1} typically. Such an estimate is in very good agreement with published local diffusivities, inferred either from in situ measurements [e.g., *Bertin et al.*, 1997], or from radar measurements [e.g., *Fukao et al.*, 1994; *Nastrom and Eaton*, 1997]. On the other hand, the effective flux per unit gradient is found to be $\sim 10^{-2}$ m^{2}s^{-1}. Such a weak value for the flux (per unit gradient) due to small scale turbulence is in good agreement with some indirect estimates of diffusivity [*Balluch and Haynes*, 1997] or with direct estimates taking into account the space and time intermittence [*Lilly et al.*, 1974].

[13] Such an evaluation method of an effective diffusivity—through the time averaged heat flux—is basically similar to the one proposed by *Woodman and Rastogi* [1984]. The only differences are (1) that these authors deduced the vertical and temporal distribution of the turbulent layers by a deconvolution of radar reflectivity profiles obtained with a height-time resolution of 150 m–1 min and (2) that they assumed complete mixing within the turbulent layers. *Woodman and Rastogi* [1984] found an effective flux per unit gradient of about 0.2 m^{2}s^{-1}, i.e., one order of magnitude larger than the present estimate. Such a difference likely results from their assumption of complete mixing within the turbulent layers although it can partly be due to the diversity of location and season of the radar observations.

5. Summary and Concluding Remarks

[14] We evaluated the dissipation rates of turbulent velocity variance ϵ_k within turbulent patches in the lower stratosphere from very high resolution radar measurements. From these dissipation rates, and by assuming a likely value for the stratification, we estimated the heat flux per unit gradient within the turbulent patches. Two estimates of the turbulent transport of heat (or mass) are compared: the one characterizing the turbulent events (i.e., local turbulent diffusivity), the other one characterizing the effective flux through a considered height taking into account the non-turbulent periods. The local turbulent diffusivity is observed to be $\sim 10^{-1}$ m^{2}s^{-1}, a value which has been commonly observed, either from in situ measurements or from ST radar measurements. The local flux per unit gradient is observed to be significantly larger than the effective flux, up to one order of magnitude.

[15] Such findings, allowed by the PROUST radar resolution, show that the diffusivity inferred from most ST radars measurements cannot be directly interpreted as an actual (or effective) turbulent diffusivity. Indeed, most of these evaluations rely on Doppler broadening measurements (i.e., TKE estimates). However, the width of the Doppler spectrum is a range-and-reflectivity weighted quantity, that is to say an average over the only turbulent (reflecting) zones within the radar sampling volume [e.g., *Sato and Woodman*, 1982; *Wilson et al.*, 2005]. Therefore, the diffusivity deduced from the Doppler width gives a local value, characterizing the patches of turbulence only and not the entire sampled volume. Although long time recognized [e.g., *VanZandt et al.*, 1978; *Gage et al.*, 1980; *Sato and Woodman*, 1982; *Fukao et al.*, 1994], such an effect does not seem always fully appreciated [e.g., *Alisse et al.*, 2000; *Legras et al.*, 2003].

[16] The time-averaged heat flux is an Eulerian quantity as each estimate is evaluated within a fixed sampling volume (radar volume). Clearly, such a heat flux per unit gradient cannot be directly interpreted as an effective turbulent diffusivity. Indeed, an evaluation of the actual transport due to small scale turbulence should rather be performed from the estimation of the vertical displacements experienced by an air particle, following the particle trajectory, that is a Lagrangian estimate (i.e., the vertical displacement through isentropic surfaces resulting from the encounters with turbulent events) [*Vaneste and Haynes*, 2000]. However, our finding provides an order of magnitude of the difference between local estimates of diffusivity (either inferred from radar or from in situ measurements) and "effective" or "actual" estimates of diffusivity, by taking into account the turbulence intermittence. Finally, the presented result give support to the idea of the weak

impact of small scale turbulence on vertical transport in the stratosphere.

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