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Dissipation rates of turbulence kinetic energy in the free atmosphere: MST radar and radiosondes

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ABSTRACT

Our knowledge of the spatio-temporal variability of the dissipation rates of turbulence kinetic energy (TKE) in the free atmosphere is severely limited because of the difficulty and expense of making these measurements globally. A few MST/ST radar facilities that are still in operation around the globe have provided us with valuable data on temporal variability of the dissipation rate in the atmospheric column above the radars but the data covers an extremely tiny fraction of the global free atmosphere. Moreover, there are limitations to these data also, since restrictive hypotheses are necessary for making these measurements. It appears that simple radiosondes launched from the existing global sonde network might be able to provide a much wider coverage, provided the technique for deducing the dissipation rates from overturns detected by the sondes can be calibrated and validated against existing techniques. An intensive field campaign conducted over the Harrow ST radar site located in western Ontario, Canada, during the summer of 2007 provided precisely such an opportunity. In this paper, we report on the comparison of the TKE dissipation rates derived from the PTU measurements made by ozonesondes launched during the campaign with those obtained from direct ST radar measurements. We find encouraging agreement between the two, which suggests that routine measurements of TKE dissipation rates by radiosondes in the global free atmosphere might indeed be feasible.

1. Introduction

Turbulent mixing in the global free atmosphere and its variability are very poorly known at present. This is simply due to the difficulty of making related measurements and consequent dearth of observational data. In situ measurements using turbulence probes mounted on research aircraft are costly, and are made only during dedicated campaigns such as T-REX (Grubisic et al., 2008). A half-a-dozen or so MST/ST radar facilities still in operation around the globe do provide valuable data on temporal variability of the atmospheric column above the radars but cover only a miniscule fraction of the global free atmosphere. Routine monitoring, an important goal of clear air turbulence (CAT) research, has been all but impossible.

Making use of turbulence scaling concepts developed over the past few decades for application to turbulent mixing in the deep ocean, Clayson and Kantha (2008) have recently proposed that conventional radiosondes be used to deduce the dissipation rates of turbulence kinetic energy (TKE) in the free atmosphere. The technique is based on identifying local turbulent overturning regions in the potential temperature profile derived from the radiosonde pressure, temperature and humidity (PTU) measurements and determining the dissipation rates in these regions by the use of turbulence scaling concepts. We will describe briefly the methodology here but for more details, we refer the reader to Clayson and Kantha (2008). However, we will address the measurement noise issue below, in greater detail than in that paper.

The "instantaneous" potential temperature profile, as derived from the radiosonde PTU data is generally statically stable in the free atmosphere (away from the planetary boundary layer), but contains localized regions of overturns (inversions) due to breaking gravity waves and turbulence. Thorpe (1977) came up with a very simple means of estimating the scale of these overturns. The method consists of rearranging the measured potential temperature profile into a monotonic (stable) profile that contains no overturns. Suppose the profile contains n samples of potential temperature and suppose the sample at depth z_n needs to be moved to a depth z_m in order to create a stable profile. The resulting displacement $d_n = |z_m - z_n|$ is known as the Thorpe displacement, whose root mean square value over the overturning region is the Thorpe scale L_T. It is possible to estimate the displacements in the overturn regions using a simple routine to sort the high-resolution potential temperature profile into a stable monotonic profile. For a detailed description of the sorting process, see Thorpe

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(2005, Figure 6.2, page 176). Note however, that the spatio-temporal sampling of the atmospheric column by a sonde is highly complex, since the balloon drifts freely and therefore, generally speaking, the path of the sonde is seldom vertical. Even though free atmospheric turbulence is characterized by thin turbulent layers of large horizontal extent, the oblique path of a sonde must be kept in mind in interpreting the dissipation rates derived from it.

The Thorpe scale is indicative of the local overturning scale in the water column and decades of oceanic microstructure research have shown it to be well correlated with an important turbulence length scale in stably stratified fluids, the Ozmidov scale $L_o=(\varepsilon/N^3)^{1/2}$

$$L_o = cL_T \tag{1}$$

where c is an empirical constant, $N=\sqrt{g/\theta(\partial\theta/\partial z)}$ is the local Brunt–Vaisala (buoyancy) frequency and ε is the TKE dissipation rate. However, plots of observed L_T vs L_o in the ocean show considerable scatter (e.g. Dillon, 1982; Wesson and Gregg, 1994) typical of all oceanic microstructure measurements and therefore, there is considerable uncertainty and variability in the value of c. The variability is due to the fact that the value of c depends on the degree of development of turbulence (see Gavrilov et al., 2005) and near unity only when turbulence is fully developed. Nevertheless, the approximate proportionality between L_T and L_o is well established and beyond dispute.

It follows immediately from the definition of the Ozmidov scale that

$$\varepsilon = C_K L_T^2 N^3 \tag{2}$$

where N is the local buoyancy frequency and $C_K=c^2$. Thus an estimate of the Thorpe scale provides a reliable means of inferring ε, using the background value of local N from the sorted monotonic potential temperature profile (Dillon, 1982; Thorpe, 2005).

In Wesson and Gregg (1994) measurements, c ranged between 0.25 and 4.0, yielding a value ranging between 0.0625 and 16 for C_K! Other values quoted in the literature for C_K: Dillon (1982) -0.64 and Gavrilov et al. (2005) -1.32 from very high-resolution atmospheric temperature data. Clayson and Kantha (2008) used $C_K=0.3$. Note that a particular goal of this paper is to try and ascertain the value of C_K from comparisons with radar derived epsilon values. As far as measuring and understanding the spatio-temporal variability of turbulence in the free atmosphere is concerned, it is our view that epsilon measurements made world-wide using radiosondes, albeit with considerable scatter but known degree of uncertainty, are preferable to no measurements at all.

Knowing ε and N, assuming local equilibrium and hence a balance between production and dissipation terms in the TKE equation, it is possible to infer the turbulent or eddy diffusivity (viscosity) from

$$K = \gamma\varepsilon N^{-2} \tag{3}$$

where γ, the so-called mixing efficiency is most commonly assumed to be about 0.25, although it could assume values anywhere from 0.2 to nearly one (Fukao et al., 1994). Assuming the turbulence is in equilibrium, and the shear production of TKE is balanced by dissipation and buoyancy destruction, it can be shown that $\gamma=\mathrm{Ri}_f/(1-\mathrm{Ri}_f)$, where Ri_f is the flux Richardson number, whose upper bound is $\sim$0.25, for which $\gamma=0.33$.

Because of the considerable uncertainty in the value of C_K, before the technique can be widely used and applied to the free atmosphere, it is necessary to compare the technique with established methods such as the ST radar and estimate the appropriate value for the constant C_K. This is hard to do since co-located simultaneous and independent measurements of epsilon are very rare. Consequently, even though radar measurements are themselves subject to an uncertainty of perhaps a factor of two, it is still quite appealing to try and obtain C_K from comparison with radar data, when data from sondes released in the vicinity of the radar are also available.

It is worth mentioning that use of Eqs. (2) and (3) requires that there be no liquid water present, because the stability cannot then be estimated using PTU measurements only. Thus the technique cannot be used in cloudy portions of the free atmosphere.

2. Measurement noise

There are two important steps in inferring the TKE dissipation rate ε from radiosonde data. The first step is identifying the regions of overturns in the potential temperature profile derived from sonde PTU data. The second step is inferring the Ozmidov scale and determining ε in the overturn regions. Measurement noise is an important issue in identifying the overturn regions, especially when the background stratification is weak. This noise issue has been addressed by many (Thorpe, 1977; Galbraith and Kelly, 1996; Ferron et al., 1998; Alfred and Pinkel, 2000; Piera et al., 2002; Timmermans et al., 2003; Johnson and Garrett, 2004; Gargett and Garner, 2008), mostly in an oceanographic context, since generally speaking, the stratification in deep oceanic regions is quite weak. Comparatively, the stratification in the stratosphere is much stronger. However, stratification can often be weak in the troposphere, and hence the impact of measurement noise on identifying overturn regions in the troposphere through the Thorpe sorting process needs to be addressed.

The principal question is how to identify and eliminate false overturn regions created in the sorting process by measurement noise. Here the background stratification and vertical resolution play an important role. Gargett and Garner (2008) review the methods used in oceanographic context, while Wilson et al. (2010) address the issue specifically in atmospheric context. In the ocean, the density profile determined from the temperature and salinity measured by a conductivity, temperature, depth (CTD) probe is used to determine the overturn regions. Consequently, errors, drift, contamination and spikes in salinity measurements (more difficult to make than temperature measurements and more error-prone) need to be taken into account. For a detailed discussion of the many methods that have been proposed to address the noise issue in oceanographic context, see Gargett and Garner (2008).

In the atmosphere, radiosondes are used to measure the temperature and humidity, and the principal concern here is the noise in temperature measurements, provided regions of liquid water content (clouds) are excluded. Gavrilov et al. (2005) and more recently, Wilson et al. (2010) have examined the impact of instrument noise in atmospheric context.

Of the many approaches that have been proposed so far to address the noise issue (see Gargett and Garner, 2008; Wilson et al., 2010 for a detailed discussion), those proposed by Ferron et al. (1998) and Gargett and Garner (2008), and Wilson et al. (2010) are particularly noteworthy. Thorpe (1977) proposed rejection of displacements that did not exceed a specified noise level. Ferron et al. (1998) and Gargett and Garner (2008) proposed the use of an "intermediate profile" determined by processing the measured profile to make the density (temperature in the atmospheric context) of adjacent points in the profile differ only if the density (temperature) difference between them exceeds the noise level. Wilson et al. (2010) advocate the use of the trend to noise ratio (TNR, defined below) to reject false overturns. A combination of these approaches results in a more robust method to address the noise issue.

Since the background stratification, the vertical resolution and the noise level are all important in identifying true inversions, it is useful to define a parameter that quantifies these effects. Following Galbraith and Kelly (1996) and Wilson et al. (2010), this parameter can be defined as the difference in the values between consecutive