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Energetics of persistent turbulent layers underneath mid-level clouds estimated from concurrent radar and radiosonde data

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ABSTRACT

Two Japanese-French field campaigns devoted to studying small-scale turbulence and instabilities in the lower atmosphere were conducted in September 2011 and November 2012 at the Shigaraki Middle and Upper atmosphere (MU) Observatory (34.85°N, 136.15°E; Japan). The Very High Frequency Middle and Upper atmosphere radar (MUR) was operated with a time resolution of the order of 10 s in range imaging mode allowing echo power measurements at fine range-resolutions (typically, a few tens of meters). In addition, balloons instrumented with RS92G Vaisala radiosondes were launched from the observatory during the radar operations. From the raw data of temperature, pressure and humidity, temperature turbulent layers can be identified from the detection of overturns by using the Thorpe (1977) method. During the two campaigns, both radar and balloon data revealed turbulent layers of about 1.0 km in depth, underneath mid-level clouds and meteorological frontal zones. They persisted for about 10 h in the radar data. The balloon data collected were undoubtedly representative of the conditions met by the radar. Turbulence parameters associated with stably stratified flows were tentatively estimated by using different methods involving both radar and balloon observations for 4 balloon flights. These parameters included the Thorpe, buoyancy, and Ozmidov scales L_T, L_B and L_O, potential and kinetic turbulent energies TPE and TKE, potential kinetic energy dissipation rates ε_P and ε_K and turbulent diffusivities K_θ. The turbulence scales were found to be consistent between each other within a factor of about 2. Energy dissipation rates of 0.6 mW/kg were found for 3 cases and 0.06 mW/kg for one case.

1. Introduction

Soon after their conception, ST (stratosphere–troposphere) VHF radars were used simultaneously with instrumented balloons for measuring atmospheric parameters. Intercomparisons improved our knowledge on the radar backscattering mechanisms at VHF which, in turn, provided informations on atmospheric dynamics and structures at various scales. A variety of methods were then developed for retrieving small-scale turbulence parameters from ST radars (e.g. Hocking, 1999).

The Middle and Upper atmosphere radar (MUR) (Shigaraki MU Observatory, Japan) was upgraded in 2004 for operating in range imaging mode (Hassenpflug et al., 2008) (called Frequency domain radar Interferometry Imaging, FII), allowing a range resolution of radar echo power of several tens of meters at a time resolution of several tens of seconds (Luce et al., 2006). In addition, Wilson et al. (2011) showed that data collected from Vaisala radiosondes have sufficient resolutions for detecting the deepest turbulent layers or patches from the Thorpe (1977) analysis. The method consists in sorting an adiabatically conserved parameter, such as a potential temperature. It was applied to the 1-Hz sampled (raw) profiles of dry potential temperature for clear air or moist potential temperature for cloudy air after a careful treatment of the instrumental noise effects. The detection procedure adapted for including the effects of moisture (water vapor saturation) in cloudy air was proposed by Wilson et al. (2013).

Consequently, the simultaneous use of both radar and balloon techniques can make a significant contribution to the study of turbulent events in both clear air and cloudy conditions in the lower atmosphere. In order to evaluate this contribution, two Japanese-French field campaigns using MUR and RS92G Vaisala radiosondes were carried out in September 2011 and November 2012 at the Shigaraki MU Observatory. In September 2011 and November 2012, the number of radiosondes launched from the observatory was 59 and 5, respectively. Results of comparisons

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between the overall datasets are not the topic of the present work. Here, we focus on two turbulent events occurring underneath mid-level cloud associated with sloping frontal zones in the mid-troposphere. The radar and balloon data revealed turbulent layers of about 1 km in depth or more between the altitudes of 3.0 and 8.0 km. Their signatures in the radar data are enhanced echo power, broadening of Doppler spectrum of the atmospheric signal, and nearly isotropic echoes. Random motions produced by turbulence are important contributors to the width of the Doppler spectrum. Despite the fact that the spectral width measurement is subject to a large variety of non-turbulent contributions that need to be removed or minimized (e.g. Dehghan and Hocking, 2011, for a recent review) quantitative information on the intensity of turbulent motions can be obtained from the measured spectral width after processing the undesirable effects.

The radar data indicated that turbulent events lasted ~7–12 h from the altitude of 7.5 km down to 4.0 km in 2011 and from 6.5 km down to 5.0 km in 2012. Their patterns in the time-height cross-sections of echo power are very similar to those observed at higher altitudes (~9.0 km) in radar data and described by Luce et al. (2010) underneath a deep cirrus cloud base. Moreover, it was recently shown by Kudo (2013) from 3D numerical simulations and aircraft pilot reports that such events can be at the origin of airplane passenger discomfort and hazards. The radiosondes launched from the observatory undoubtedly passed across these layers and very likely provided temperature and humidity profiles indicative of the state of the layers. In the present work, the characteristics of the turbulent layers are described from their signature in the radar and balloon data. Taking advantage that the same turbulent events were resolved by the radar and the radiosondes, turbulence parameters (scales and energetics) were estimated (almost) independently from radar and balloon data so that original comparisons between the estimates could be made.

The radar and balloon datasets used for the present study are briefly described in Section 2. In particular, the radar parameters are listed in Section 2.1 and the balloon operations are described in Section 2.2. Section 3 describes the processing methods applied to the balloon and radar data for retrieving turbulence parameters. In Section 3.1, the method proposed by Wilson et al. (2011, 2013) for retrieving the Thorpe scale L_t (which is a scale of temperature turbulence) from balloon data in subsaturated and saturated air conditions is briefly recalled. In the same section, the two methods introduced by Smyth et al. (2001) for estimating the "bulk" squared Brunt–Väisälä frequency N^2 expected to quantify the stability experienced by eddies in a turbulent layer are also presented. The methods used for estimating the turbulent velocity variance σ_t^2 from radar Doppler spectra are described in Section 3.2. From these three parameters, additional turbulence parameters can be deduced, such as the buoyancy scale L_B, the Ozmidov scale L_O, the turbulent potential energy *TPE*, the turbulent kinetic energy *TKE*, the potential and kinetic energy dissipation rates (ε_p and ε_k), the eddy diffusion coefficients K_θ and the heat fluxes ϕ_θ. The theoretical developments used for deriving their expressions are presented in Section 3.3.

Section 4 describes the structures of the radar and the radiosonde data that indicate the presence of the turbulent layers studied in the present work. The turbulence parameters associated with these events and estimated from the expressions derived in Section 3 are then presented in Section 5. Conclusions are presented in Section 6.

2. Dataset

2.1. MUR data

The MUR is a flexible beam-steering Doppler pulsed radar (Fukao et al., 1990). Its characteristics and the parameters used during the two campaigns are listed in Table 1. It was continuously operated in range imaging (FII) mode during 3 weeks in September 2011 and during 1 week in November 2012. This mode consists in transmitting several closely spaced frequencies switched pulse to pulse (e.g. Palmer et al., 1999; Luce et al., 2001) and aims at improving the range resolution of the radar without increasing the receiver bandwidth. (The bandwidth is generally restricted by the receive system, including antennas and electronic components, and by frequency allocations.) Five equally spaced frequencies from 46.0 MHz to 47.0 MHz (i.e. with a frequency spacing of 0.25 MHz) were used. Because the data were processed with the adaptive Capon method, the range resolution actually obtained is not simply inversely proportional to the maximum frequency spacing used, but is improved, despite its dependence on signal to noise ratio (SNR) of the received echoes (see Palmer et al., 1999; Luce et al., 2001 for more details). With the radar parameters used, a range resolution of a few tens of meters can be typically obtained for SNR larger than ~5–10 dB. Range sampling was performed from 1.245 km up to 20.44 km above sea level (ASL) with an arbitrary step of 5 m. It was demonstrated that the improved range resolution can make easier the identification and interpretation of atmospheric echoes received by UHF and VHF wind profiler radars (e.g. Chilson, 2004; Luce et al., 2006).

In addition, the radar beam was steered into three directions (one vertical, and two oblique directions at 10° off zenith toward North and East) so that winds and horizontal wind shears could be estimated at a range resolution of 150 m. Echo power and Doppler spectral width

Table 1
Parameters of MUR during the two experiments. * and ** refer to the September 2011 and November 2012 experiments, respectively. Note that the effective acquisition times are about 12 and 6 s due to Hanning windowing of the radar time series.

Parameters	Values
Frequencies (MHz)	46.00, 46.25, 46.50, 46.75, 47.00
Bandwidth (MHz)	3.5
Maximum peak output power (MW)	1
Two-ways half-power half-beamwidth (deg)	1.32
Pulse coding	16-bits optimal code
Sub-pulse duration (μs)	1
Time sampling (μs)	1
Interpulse period (μs)	400
Number of coherent integrations	32*/16**
Acquisition time (s)	24.57*/12.28**
Nyquist velocity (m s^{-1})	8.40*/16.80**
Spectral resolution (m s^{-1})	0.1313*/0.2625**
First height (km)	1.245
Gate number	128
Range sampling (m) in FII mode	5