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Journal of Atmospheric and Solar-Terrestrial Physics 68 (2006) 1061–1074

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

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Seasonal variation of mesopause region wind shears, convective and dynamic instabilities above Fort Collins, CO: A statistical study

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Received 20 June 2005; received in revised form 2 December 2005; accepted 17 January 2006
Available online 29 March 2006

Abstract

One thousand three hundred and eleven 15-min profiles of nocturnal mesopause region (80–105 km) temperature and horizontal wind, observed by Colorado State University sodium lidar over Fort Collins, CO (41°N, 105°W), between May 2002 and April 2003, were analyzed. From these profiles, taken over 390 h and each possessing vertical resolution of 2 km, a statistical analysis of seasonal variations in wind shears, convective and dynamical instabilities was performed. Large wind shears were most often observed near 100 km and during winter months. Thirty-five percent of the winter profiles contained wind shears exceeding 40 m/s per km at some altitude. In spite of large winds and shears, the mesopause region (at a resolution of 2 km and 15 min) is a very stable region. At a given altitude, the probability for convective instability is less than 1.4% for all seasons and the probability for dynamic instability (in the sense of Richardson number) ranges from 2.7% to 6.0%. Wind shear measurements are compared with four decades of chemical release measurements, compiled in a study by Larson [2002. Winds and shears in the mesosphere and lower thermosphere: results from four decades of chemical release wind measurements. Journal of Geophysical Research 107(A8), 1215]. Instability results are compared with those deduced from an annual lidar study conducted with higher spatial and temporal resolution at the Starfire Optical Range (SOR) in Albuquerque, NM, by Zhao et al. [2003. Measurements of atmospheric stability in the mesopause region at Starfire Optical Range, NM. Journal of Atmospheric and Solar-Terrestrial Physics 65, 219–232], and from a study by Li et al. [2005b. Characteristics of instabilities in the mesopause region over Maui, Hawaii. Journal of Geophysical Research 110, D09S12] with 19 days of data acquired from Maui Mesosphere and Lower Thermosphere (Maui MALT) Campaign . The Fort Collins lidar profiles were also analyzed using 1-h temporal resolution to compare instances of instabilities observed on different time scales.

Keywords: Lidar; Mesopause; Wind shear; Convective instability; Dynamic instability

1. Introduction

The unique capability of sodium fluorescence lidar to simultaneously measure vertical profiles of temperature and both horizontal wind components in the 80–105 km altitude range permits real-time

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1364-6826/$ - see front matter
doi:10.1016/j.jastp.2006.01.011

measurement of atmospheric parameters that implicate atmospheric stability, such as Brunt–Vaisala frequency, wind shears, and Richardson number. It is well known that convective stability of the atmosphere depends on the vertical temperature profile. From this profile, the square of the Brunt–Vaisala frequency, N^2, can be calculated and used to assess convective stability. The existence of vertical shear in horizontal wind disturbs atmospheric flow. The extent that this causes dynamic instability may be measured by the gradient Richardson number, Ri. They are defined as

$$N^2 = \frac{g}{T}\left(\frac{dT}{dz} + \Gamma_d\right), \quad \text{and} \\ Ri = \frac{N^2}{S^2} = \frac{(g/T)((dT/dz)+\Gamma_d)}{(dU/dz)^2+(dV/dz)^2}, \tag{1}$$

where $\Gamma_d = g/c_p$ is the dry adiabatic lapse rate (~9.5 K/km at mesopause heights), with $g =$ gravitational acceleration (~9.5×10^{-4} km/s^2 at mesopause altitudes) and $c_p =$ specific heat $=$ 1.005 J/K g. In Eq. (1), T, U (positive to east), and V (positive to north) are temperature, zonal, and meridional winds, respectively, and $S = ((dU/dz)^2 + (dV/dz)^2)^{1/2}$ is the magnitude of vertical shear of horizontal wind. The local atmosphere is said to be static or convectively unstable if $N^2 < 0$. One can show that $Ri =$ (gradient) Richardson number > 0.25 is a sufficient condition for dynamic stability (Dutton, 1986). The Richardson number is thus a ratio of the stabilizing effect of (restoring force against) buoyancy divided by the de-stabilizing effect of wind shears. By measuring vertical profiles of temperature and both horizontal wind components, the Richardson number can be computed at each altitude and used to assess dynamic instabilities in the region.

Wind and wind shear measurements in the mesopause region have been carried out by ground-based MF (Manson et al., 1989) and meteor radars (Liu et al., 2002), by radar-tracking of rocket-released falling sphere, and chemical release experiments (Larson, 2002). Without accurate measurement of temperature profiles and Brunt–Vaisala frequency measurements, the degree of atmospheric instability, convective and dynamic, cannot be assessed directly. Although the simultaneous measurement capability of temperature and wind with a narrowband sodium lidar had been demonstrated more than a decade ago (Bills et al., 1991; She and Yu, 1994), only recently has it been used to assess background atmospheric conditions for focused investigations in the mesosphere and lower thermosphere (MLT). These investigations include in situ rocket study of turbulent mixing (Liu et al., 2004) and an imager study of instability layers (Hecht, 2004). Statistical study of convective and dynamic instabilities in the MLT has been rare. To our knowledge, there are only four papers in the literature at this point: three by the University of Illinois (UI) group (Gardner et al., 2002; Zhao et al., 2003; Li et al., 2005c) using data collected at the Starfire Optical Range (SOR), near Albuquerque, NM (35°N, 106.5°W), and those collected from Maui mesosphere and lower thermosphere (Maui MALT), over Maui Hawaii (20.7°N, 156.3°W) and one by the Colorado State University (CSU) group (Sherman et al., 2003) using data collected at the Fort Collins facility, Fort Collins, CO (41°N, 105°W). Though with similar objectives, the measurement resolutions with which these studies were made are quite different. Using a 3-m diameter class telescope for lidar data acquisition, the Illinois studies employed 500-m (1 km) vertical resolution and 1.5-min (24 min) temporal resolution for temperature (horizontal wind) measurements for SOR data, while they employed 0.5-km and 15-min resolution for the Maui MALT data. This of course leads to higher frequency of occurrence in instabilities (in the case of SOR data, more in convective then in dynamic) as compared to the CSU study, which employed two 35 cm telescopes for lidar data acquisition, resulting in 2-km and 15-min resolution to achieve the desired photon-counting statistics for acceptable error bars. For this reason, rather than direct comparison between studies with different resolutions, our emphasis in this paper is on the seasonal dependence of wind gradients and of convective and dynamic instabilities in the mesopause region, at least those occurring on time scales of 15 min or more. We will also compare the frequency and altitude distributions observed using 15-min resolution with those observed during the same time period using 1-h temporal resolution (Section 6). These results can be compared both with one another and with the Illinois data to deduce instability features of varying time scales.

2. Motivation for the study

The nature and time scale of atmospheric instabilities deduced from lidar observations can provide essential information on the local atmosphere that is required to support a theoretical conjecture on dynamical features observed by airglow imagers.