The CSU sodium lidar facility: Current observation capability and science

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Abstract:

Lidar (Light Detection And Ranging) is one of the most powerful atmospheric remote sensing techniques for atmospheric research. A novel narrowband lidar, probing the florescence of atmospheric Na atoms has been deployed in Fort Collins, CO for over a decade. Starting in the late 80', the Na lidar group in Colorado State University has been observing the mesopause region (80-110km in altitude, called the "ignorosphere" in the past for lack of observations) of the earth's atmosphere by probing the motions of naturally occurring atmospheric Na atoms. After a number of upgrades and innovations, this advanced lidar system can now measure temperature and horizontal wind on 24-hour continuous basis during campaigns, weather permitting. Based on these measurements, we can study this region of the atmosphere in an unprecedented manner. In this paper, we first discuss our system and measurement methods, followed by a number of selected, interesting and important atmospheric phenomena that we observed over Fort Collins, CO (40.6^{o}N, 105^{o}W). We present the counter-intuitive thermal structure with summer cooler than winter. Then we report a mesospheric bore (solitary wave) event also observed by an OH imager in nearby Platteville, CO (40.2^{o}N, 104.8^{o}W). Our 9-day continuous observations are shown which reveal solar tides clearly with little data analysis. Also, our local observations are not only substantiated globally by the recently available the NASA/TIMED satellite data, but also provided essential local-time coverage (not available in the TIMED data) for the study of tides and tidal variability.

1. Introduction

The Colorado State University (CSU) Na-lidar system located at Fort Collins, CO (40.6^{o}N, 105^{o}W), first deployed in August, 1989 [1] for observing the mesopause region of the earth's atmosphere (Fig. 1). It consists of Transmitter and Receiver (Fig.2). The Transmitter sub-system has 4 lasers (The seeder beam is generated by Coherent 899-21 Ring-Dye laser which is pumped by a Spectra-Physics Millennia-V YAG laser; other two are for transmitted power amplification with Spectra-Physics Quanta-Ray PDA-1 pumped by injection-seeded Spectra-Physics Quanta-Ray Pro-230 pulsed YAG laser), one Acoustic Optic Modulator to convert laser light to three predetermined frequencies within the Doppler-broadened width of the Na D_2 transition, and one frequency monitor based on Doppler-free spectroscopy. The continuous light beam at these frequencies is sequentially used to seed a pulsed dye amplifier, whose output is sent into the atmosphere. The home-constructed frequency monitor (by using Doppler-Free spectroscopy) helps us locate and lock the seed frequency to the Na D_{2a} transition peak within 1-2 MHz. The Receiver has two channels; one pointing east, the other pointing north (both tilted 30º from zenith direction). Each channel has a 14" telescopes to collecting the back scattering, one narrow band interference filter (~3nm FWHM) and one ultra-narrow Faraday Filter with 2 GHz, FWHM for daytime background noise rejection, and one Photo Multiplier Tube to convert the detected photons into electrical signal in the photon-counting mode, sent to the data taking computer, and the time dependence of the signal gives a vertical profile that is saved in the computer. By measuring the altitude-resolved relative Na florescence backscattering signals at the 3 pre-chosen frequencies, we can determine thermal broadening and Doppler shift of the Na fluorescence spectrum, thereby temperature and line-of-sight wind. Equation (1) is the lidar equation. To utilize the Na florescence we discussed earlier, we calculate two ratios (Equation 2) formed by the normalized signal intensity at the three frequencies. The $\mathbf{R_T}$ is calculated by the average of the two shifted frequencies intensity divided by the intensity at the peak frequency, thus sensitive to thermal broadening and mesopause region temperature. The $\mathbf{R}_W$ is calculated from the difference in intensity at the two shift frequencies divided by the peak frequency intensity, thus sensitive to Doppler shift and the line-of-sight (LOS) wind. Of course, the wind and temperature ratios are coupled, so both ratios must be used together to retrieve temperature and LOS wind from basic principle of atomic spectroscopy.

$$N(z) = \left(\frac{P_L \tau}{hc/\lambda}\right)(\eta T_A^2)(\sigma_{Na} n_{Na}(z)\Delta z) \times \left(\frac{A_R}{4\pi z^2}\right) T_{up} T_{down} + N_B R\tau \quad (1)$$

$$R_T = (I_+ + I_-) / 2I_a \quad (2a)$$

$$R_W = (I_+ - I_-) / I_a \quad (2b)$$

2. Selected science studies in the mesopsue region with Na-Lidar observations

The mesopause region has numerous "abnormal" features, and one of the most well known is the counter intuitive temperature annual variation. It is cold in the summer, and warm in the winter, suggesting dynamics domination over radiative balance in atmospheric circulation. Figure 3 shows Fort Collins climatology of temperature (left) and Na density (right) based on eight-year nocturnal observation of mesopause region, smoothed over 3.7 km and 1 month [2]. The Na density, on the other hand, reaches its minimum during the summer, making the summer signal relatively weaker. The CSU Na-lidar system is capable of daytime operation after the upgrade of the narrow band Faraday filter to reject the daylight sky background. Since May 2002, the CSU lidar system began mesopause region temperature, zonal and meridional winds over full diurnal cycles [3]. This diurnal cycle observation has led to the study of seasonal variation of diurnal tides in temperature, zonal and meridional winds [4]. A 14-day campaign in second half of September 2003 with a 9-day continuous observation provided data for tidal variability study, with clear evidence of planetary wave oscillations and tidal-gravity wave interactions [5]. Figure 4 represents the contour plots of temperature (top), east wind (middle) and north wind (bottom) measurements during this continuous 9-day observation. One can easily observe the 12-hour and 24-hour oscillations in this hourly averaged data. Though no dominant heating source in the mesopause region, these two oscillations are solar thermal tides that are generated by atmospheric absorption of the solar radiation (mainly infra-red radiation absorbed by H_2O in the troposphere, and ultraviolet radiation by O_3 in the stratosphere) below and propagate upward adiabatically with enhanced amplitudes. The blank parts on the top of the contour plots are due to low signal to noise ratio during the daytime when the Faraday filter must be employed.

With these lidar observations, we can also calculate the vertical temperature gradient and wind shear, for the determination of atmospheric stability in the mesopause region. For example, collaborated with OH imager (all sky CCD camera with proper filter) in nearby Platteville CO (~50 miles away from CSU Na-lidar station. Fig.5), the lidar data can be used to assess atmospheric conditions when interesting features are observed by the imager. One example is the study of mesospheric bore in October 2002 [6]. Up to this point, bore events have been captured a number of times by OH imagers. The concurrent lidar data confirm, for the first time, the existence of a collocated temperature inversion layer to serve as the ducting region for bore propagation, as required by the simple theory [7] proposed by Dewan and Picard 6 years ago. Figure 6 shows the time sequence of an undular bore propagating from south-east towards north-west. Continued lidar observation after the bore event reveals that the ducting region may be controlled by a long-period wave, most likely related to a semidiurnal tide, and the atmospheric dynamic instability occurs simultaneously with the destruction of the wave train associated with the bore. This captured event is most likely the first observation of the transition from an undular to a turbulent, or foaming, internal bore.

CSU Na lidar also provides complementary data set to TIMED/SABER observation. For example, the temperature inversion observed during the bore event in October 2002, SABER not only observed temperature inversion with the same magnitude in the overpass flights, but also suggested the extent of the temperature inversion covered a North-South distance of more than 5000km [Richard Picard, Private communication]. Another example is the temperature inversion observed by CSU lidar in day 267 in Fig. 4, over pass SABER observed comparable temperature inversion as shown in Fig. 7 [8]. Temperature climatology with lidar/SABER comparison based on 2003 observation has been carried out recently [9], with general agreement.

3. Conclusion and outlook

Over the past 15 years, the narrowband Na lidar has evolved from a proto-type instrument into a robust work horse for observing mesopause region temperature and horizontal wind on 24 hour basis, weather permitting. The nocturnal temperature observation has now completed 15 years, a record long enough to entertain investigation of solar cycle effect [10] and possibly even anthropogenic effect on mesopause temperature. Observations of mesopause region temperature and horizontal wind over full diurnal cycles have been continued for 4 years, permitting a comprehensive climatology study of not only mean temperature, and horizontal wind, but also of the associated diurnal and semidiurnal tides.

The CSU lidar supported correlative airglow investigation of mesopause region [11]. The Na density data are being used for performance evaluation of laser guide star for the Thirty Meter Telescope Project [Paul Hickson, Private communication]. Case studies of dynamics are being conducted in collaboration of colleagues with modern modeling skills concentrating on the investigation of tidal variability, tide-gravity wave and planetary wave interactions, as well as signatures of instability and wave breaking [12]. Data from multi-day continuous observation are particularly useful in this connection.

The observatory is in the process of upgrading receiving telescopes, going from 14” diameter to 30” diameter. The enhanced signal will allow momentum flux measurements in winter nights, when Na signal is strongest. Along with diurnal cycle temperature horizontal wind observation, the planned momentum flux measurements should provide fundamental information on tidal-gravity wave interactions.

Acknowledgement:

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4. Figures

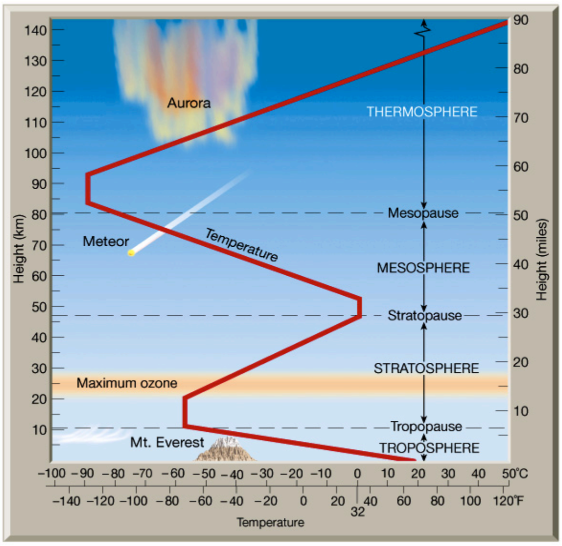

Fig.1. Earth atmospheric layers

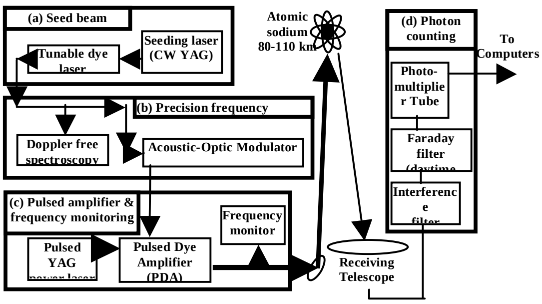

Fig.2. CSU sodium lidar system

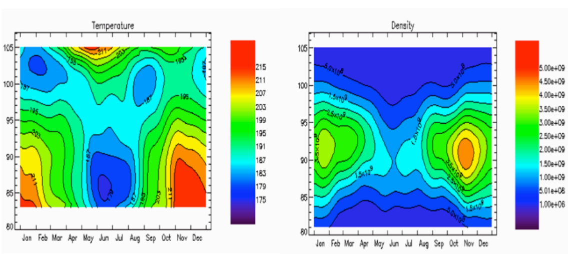

Fig.3. Monthly mean mesopause region nocturnal temperature (left) and Na density, showing seasonal variation [From Ref. 2]

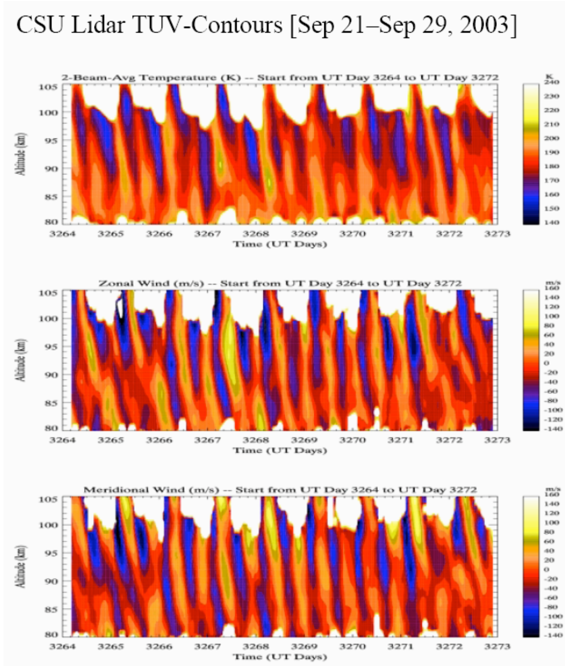

Fig.4. Contours of hourly mean temperatures (top), zonal wind (middle) and meridional wind (bottom) between Sep. 21 and Sep. 29, 2003

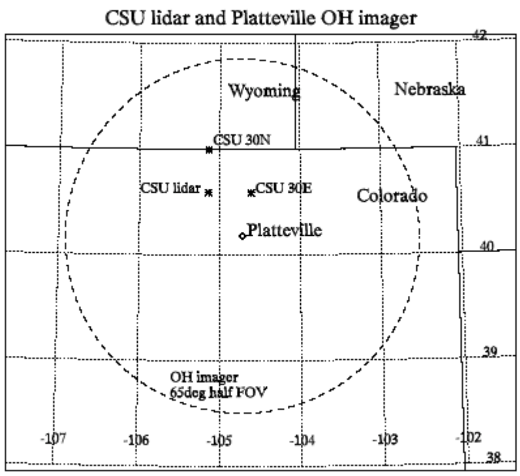

Fig.5. Geographical locations of CSU lidar station, and its 30° off zenith north and east beam viewing positions in the mesopause region. The location of all sky OH imager in Platteville, CO. [From Ref. 6]

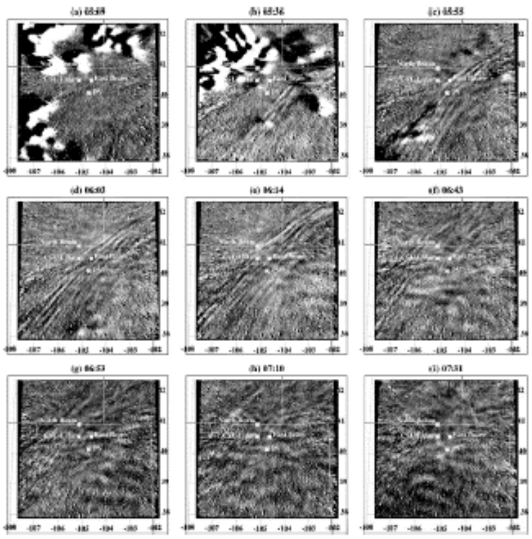

Fig.6 OH imager snap shots of flat-fielded difference images restricted to within 5°x5° of Platteville, CO, taken on the night of 6/7 October 2002 at about 0509, 0536, 0555, 0603, 0614, 0643, 0653, 0710, and 0731 UT, showing the (a) bore onset, (e) front propagation to the north beam, (g) disintegration of bore undulation, (h) appearance of a single propagating bore front followed by a turbulent (foaming) bore. [Taken from Ref. 6].

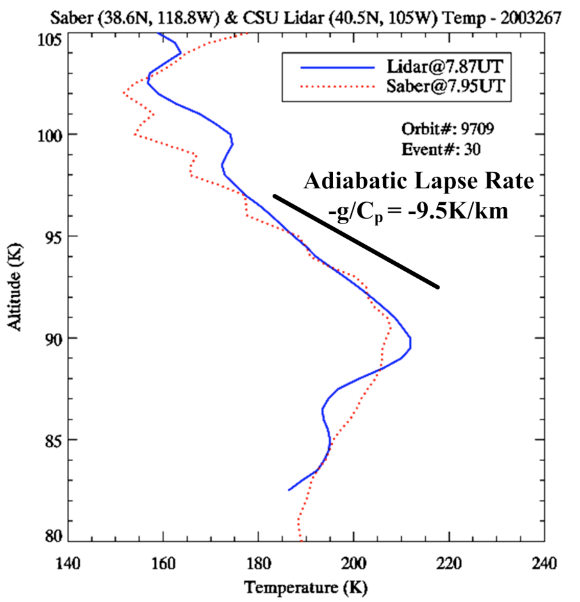

Fig.7. SABER (red dot line) and CSU Na-Lidar (blue solid line) concurrent observation of vertical temperature profiles around UT 8:00 am over Fort Collins on day 267, 2003. [Taken from Ref. 8].

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