

Vertical Wind Measurements with High-Resolution Lidars & Impacts on Antarctica Upper Atmosphere Studies

Xinzhao Chu^(a), Xianxin Li^(b), Jackson Jandreau^(a), and Yingfei Chen^(a)

^(a) University of Colorado Boulder, CIRES, 216 UCB, Boulder, CO 80309, USA

^(b) Institute of Oceanographic Instrumentation, Qilu University of Technology, Qingdao, China

E-mail address: xinzhao.chu@colorado.edu

Abstract: Direct measurements of vertical winds in the upper atmosphere present a grand challenge to the lidar research field. However, information of vertical winds is crucial to many science explorations in the upper atmosphere and its important interactions with the plasma space, which play key roles in protecting the life on Earth from the harmful solar winds. In this paper we present a very sophisticated resonance-fluorescence Doppler lidar that has successfully made the direct measurements of vertical winds with high resolutions at McMurdo Station (77.84°S, 166.67°E) in Antarctica. Technical considerations on both this Na Doppler lidar transmitter and its receiver are discussed in terms of their influences on the vertical wind measurements and calibrations. Simultaneous measurements of vertical winds, temperatures, and metal species are presented to illustrate new discoveries in vertical flux measurements. Time-mean vertical winds are discussed in terms of unexplained discoveries, suggesting gaps in our understanding of the global meridional circulation.

1. Introduction

Direct measurements of vertical winds in the mesosphere and thermosphere present a grand challenge to the lidar field. This is because the vertical wind magnitudes are $\sim 2-3$ orders of magnitude smaller than horizontal winds and the $1/R^2$ factor in the lidar equation causes return signals being much smaller than those from the lower atmosphere.

Information of vertical winds is crucial to many science explorations in the Earth's atmosphere-space system, such as the vertical transport of species, heat, and momentum across multiple regions and scales, the global meridional flow, and the space-atmosphere interactions.

Pursuing vertical wind measurements will not only enable new science endeavors but also push the lidar technology envelope. Here we report the lidar progress, which has led to direct detection of vertical winds, temperatures, and metal species in Antarctica, discuss technical challenges, and demonstrate impacts on the upper atmosphere and space studies [1].

The CLRC and ILRC conferences provide an excellent opportunity to synthesize resonance-fluorescence Doppler with coherent and other direct-detection wind lidar technologies for advancing global wind lidar measurements.

2. Three-Frequency Doppler Lidar

The University of Colorado Na resonance-fluorescence Doppler lidar was developed in Boulder with high-efficiency receiver [2] and then installed at Arrival Heights Observatory at McMurdo, Antarctica in 2017–2018 season [3]. Its transmitter employs a Master Oscillator Power Amplifier (MOPA) configuration, i.e., a DL-TA-SHG 589-nm CW laser injection-seeds a Pulsed Dye Amplifier (PDA) that is pumped by a frequency-doubled Nd:YAG laser at 50-Hz repetition rate. This CW 589-nm laser is frequency locked to Na D_{2a} Doppler-free peak [4], and then shifted by dual double-pass acousto-optic modulators (AOMs) among the peak and wing frequencies (± 750 MHz) [5].

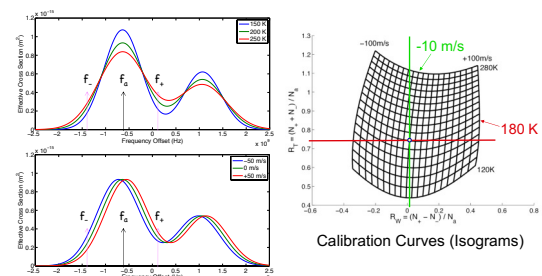


Figure 1. Multi-frequency ratio technique for simultaneous measurements of temperature and LOS wind with Na Doppler lidar [5].

Meteoric Na atoms in the upper atmosphere—a very large “Na vapor cell” on Earth—function as a frequency discriminator in Na Doppler lidar so that Doppler broadening and Doppler shift are inferred with narrowband laser beams and used to derive temperature (T) and line-of-sight (LOS) wind (W) simultaneously. Using the 3-frequency channels of lidar signals, T and W metrics [5] are formed as, e.g.,

$$R_T = \frac{N_+ + N_-}{N_a} \quad R_W = \frac{N_+ - N_-}{N_a} \quad (1)$$

Calibration curves are calculated and illustrated in Figure 1, with which temperature and LOS wind are inferred simultaneously from such isogram mesh. Na density is calculated from the lidar signals using inferred T and W [4,5].

3. Vertical Wind Measurements

Major technical challenges in vertical wind measurements include, but not limited to,

- 1) Vertical pointing of telescope
- 2) Stable laser frequency locking
- 3) Pulsed laser chirp issue
- 4) Sufficient signal-to-noise ratios.

During the installation in Antarctic summer, an 81-cm diameter prime-focus optical telescope (parabolic primary mirror) was aligned to pointing zenith with four vertical-pointing laser levelers and a plumb line (plumb bob). These levelers were verified with reflections from a leveled water surface. The resulted pointing was within ± 1 mrad from the zenith direction.

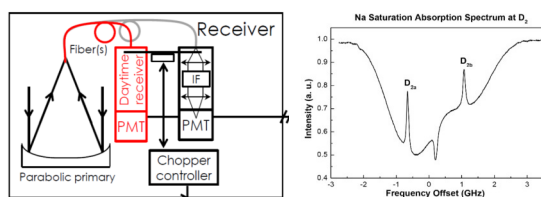


Figure 2. (left) Zenith pointing prime-focus telescope. (right) Na D_2 saturation-absorption spectroscopy for CW laser frequency locking.

The Toptica 589-nm TA-SHG laser is locked to Na D_2a peak using lock-in amplifier (phase sensitive detection) techniques to better than ± 0.5 MHz [4,5]. After injection seeding to PDA, the chirp of PDA output pulses (offset from the CW laser frequency) is $\sim 1\text{--}7$ MHz. In post processing, the chirp-induced offset in vertical winds is removed by subtracting a vertical mean of 85–100 km, which helps reveal the rich spectrum of atmospheric waves.

The high signal-to-noise ratios (SNRs) required for vertical wind measurements are achieved with high-efficiency receiver architecture [2], high output power of PDA and narrow laser linewidth, accurate frequency locking to Na absorption peak, and relatively large primary mirror with a prime focus configuration [5]. Larger primary mirrors are of course desired to extend the vertical wind measurements further into the thermosphere.

4. High-Resolution W and T Results from McMurdo, Antarctica

The raw data of Na Doppler lidar are saved at fundamental resolutions of 4.5 s (1.5 s per freq.) and 24 m. In post processing, W , T , and $[Na]$ are retrieved at $\Delta t = 2.5$ min, $\Delta z = 0.96$ km. Figure 3 show two lidar runs of measured vertical winds and temperatures over 12 hr in June and nearly 50 hr in July 2020 at McMurdo during Antarctica winter (long dark nights).

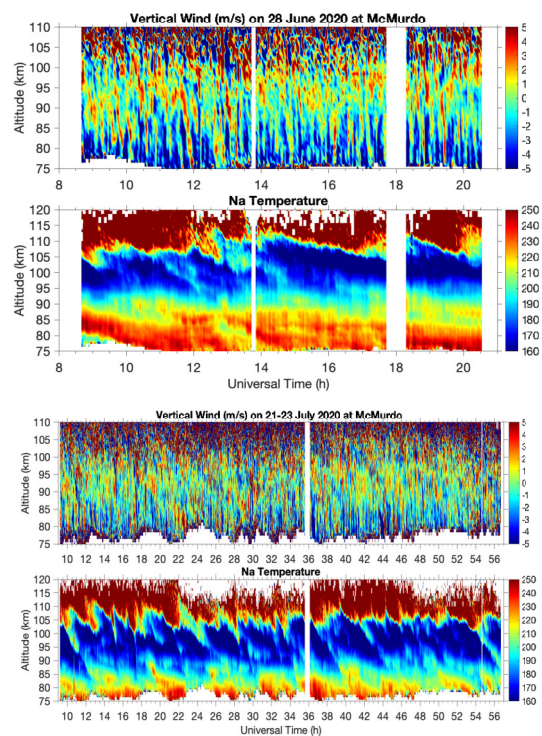


Figure 3. Vertical winds and temperatures measured at McMurdo, Antarctica. The data resolutions are 2.5 min and 960 m.

High-frequency waves with periods of 5–30 min and tilted downward phase progress are prominent features from the vertical wind contours, while they are visible but minor on temperature contours that are dominated by near inertial-period persistent gravity waves [1]. These features are consistent with expectations

from the polarization relations of gravity waves [6], demonstrating that real vertical winds were measured by the Na lidar in Antarctica.

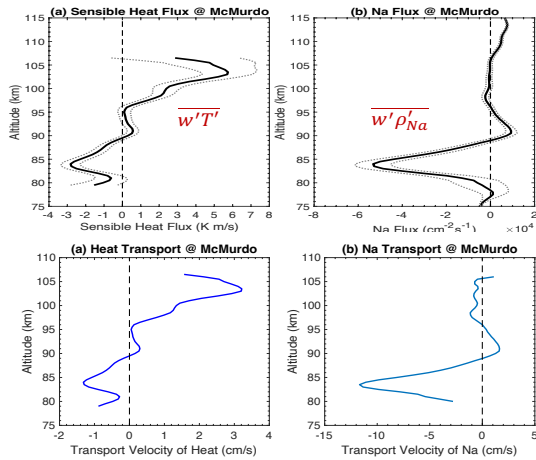


Figure 4. Vertical fluxes & transport velocities of sensible heat and meteoric Na measured in late May 2020 (reproduced from [1]).

The lidar data enabled the first measurements of vertical fluxes of sensible heat and meteoric Na in Antarctica, leading to a new discovery of upward heat flux that helps correct a long-held misunderstanding in wave dynamics [1].

5. Mystery of Mean Vertical Winds

Averaging over many hours (> 10 hr) removes various gravity waves so revealing the mean vertical winds. A surprising result is shown in Figure 5 for McMurdo. That is, the mean vertical winds have positive slopes from ~ 80 to 100 or 105 km, i.e., $d\bar{W}/dz > 0$, in stark contrast to the expectation of nearly zero \bar{w} .

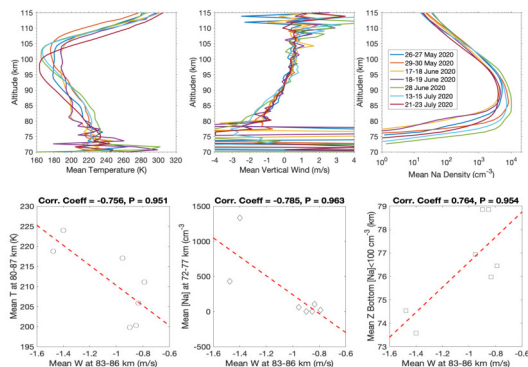


Figure 5. (Top) Dataset-mean \bar{T} (left), \bar{W} (middle), and Na density (right) profiles in late fall and winter 2020 at McMurdo, Antarctica. (Bottom) Mean vertical wind at 83–86 km correlates statistically with mean T, [Na], and Na bottom altitude. All three correlation coefficients have confidence levels $P > 95\%$.

The zonal-mean vertical winds associated with the so-called residual (meridional) circulation are expected on the order of a few cm/s, nearly two orders of magnitude smaller than the time means shown here. These time-mean profiles are representative, however, in the lidar runs in late fall and winter at McMurdo. That is, the vertical winds are upward (+) / downward (-), respectively, above / below certain altitude (~ 90 km). The typical values are about +0.5 m/s to -1.0 m/s near the two ends, leading to a positive slope of ~ 1.5 m/s changes over ~ 20 km altitude.

Interestingly, larger magnitudes of downward vertical winds (\bar{W} at 83–86 km) are correlated with warmer temperatures (\bar{T} at 80–87 km), higher Na density at bottom side ($[\bar{Na}]$ at 72–77 km), and further downward extension of Na layer bottom (Z_b at $[Na] < 100$ cm^{-3}). The linear correlation coefficients between \bar{W} and \bar{T} , $[\bar{Na}]$, and Z_b are over 75% with confidence levels $P > 95\%$.

What causes large magnitudes of downward mean vertical winds? Are they geophysical or possible artifacts from imperfect experiments? We have examined potential issues associated with temperature nonlinearity, discriminator and PMT nonlinearity corrections, and laser linewidth and PDA chirp inaccuracy, but none of them could cause such large and tilted line-of-sight (LOS) wind profiles. The potential horizontal wind leakage to non-strictly vertical beam is also very unlikely because even at a very unlikely 10 mrad large offset from zenith (while the receiver FOV is within 1 mrad and the telescope pointing is within ± 1 mrad from zenith), 1 m/s mean LOS wind means at least 100 m/s mean horizontal winds, which were not observed by a collocated meteor radar [7].

Ruling out experimental artifacts basically, we examine evidence for being geophysical. The mean vertical wind profiles became vertical around zero without tilting slopes during the peak time of sudden stratospheric warming (SSW) event on 9 and 10 Sept 2019. The corresponding mean temperature (~ 85 km) became much colder, the Na layer peaks at much higher altitude (~ 90 km) with its bottom contracted upward substantially than those on 14 Aug 2019 which served as the baseline before the SSW. The dataset-mean \bar{W} on this baseline day showed similar positive slope as in Figure 5 while on 16 Sept 2019 (passing the SSW peak time) showed positive but smaller

slope (*SSW figures will be shown at CLRC*). Therefore, the Na Doppler lidar has measured the real geophysical changes of time-mean vertical winds. That is, the typical downward \bar{W} associated with the residual circulation near the winter pole were significantly weakened or reversed by the SSW event. Consequently, the adiabatic warming related to downwelling \bar{W} was weakened or even replaced with the adiabatic cooling associated with upwelling \bar{W} , leading to the cooler temperature and upward shift of Na layer as the lidar observed.

Except the magnitudes on the order of m/s (instead of cm/s), the vertical wind signs and its correlations to \bar{T} , Na density & bottom altitude observed are all consistent with theoretical expectations of residual meridional circulation. A possible explanation to the large magnitudes of lidar-observed \bar{W} is that time means at a single location may not be equivalent to zonal means. In other words, the zonal-mean residual circulation may not be applicable to the local mean vertical winds. Sato et al. (2021) have proposed a 3-D residual flow theory, suggesting a longitudinal dependence of the poleward flow [8]. The McMurdo lidar observations lend support to such a theory. There could also be a localized/regional flow around McMurdo being responsible for the measured \bar{W} . Further studies with observations, theories, and modeling are crucial to understanding the lidar observations.

6. Conclusions and Outlook

High-resolution direct measurements of vertical winds in the MLT region have been achieved with a 3-freq. Na Doppler lidar in Antarctica. Along with simultaneous measurements of temperatures and metal species, such high-quality lidar data have enabled sophisticated studies like the first vertical fluxes of sensible heat and meteoric metals as well as the first direct observations of high-frequency gravity waves in Antarctica. The resulted discovery of upward sensible heat flux is surprising but helps correct a long-held misunderstanding in the wave dynamics [1]. Many more investigations using vertical wind data are on the way.

The mean vertical winds in the Antarctic winter MLT usually show tilted profiles with ~ 1.5 m/s increases over 20 km range from 80 to 100 km. The mean slope $d\bar{w}/dz$ is ~ 7.5 cm s⁻¹ km⁻¹. Such tilted mean vertical winds became vertical during the 2019 sudden stratospheric warming

in Sept. The downward winds are correlated to elevated temperatures and downward shifts of metal layers. We conclude through multiple analyses that the observed time-mean vertical winds are geophysical, not experimental artifacts, though the explanations still await brainstorming in the science community.

Direct measurements of vertical winds in the upper atmosphere are far from being matured as further improvements are desired. For example, producing chirp-free pulsed lasers for the lidar transmitter, star-map-verifications of vertical-pointing telescopes, and super-stable laser frequency control in the outgoing lidar pulses are several key topics to address. Obtaining sufficient signal-to-noise ratios is also crucial to vertical wind measurements. More importantly, collaborations between the upper atmosphere lidar and the lower-atmosphere wind lidar communities will likely transform global wind lidar technologies for many decades to come.

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