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Doppler Lidar Wind Statistics Profiles Value-Added Product

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ARM

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Acronyms and Abbreviations

ACF	autocovariance function
AGL	above ground level
ARM	Atmospheric Radiation Measurement
CBH	cloud-base height
DLPROF-WSTATS	Doppler Lidar Wind Statistics Profiles VAP
DLWSTATS	Original name of Doppler Lidar Wind Statistics Profiles VAP
DOE	U.S. Department of Energy
ECOR	eddy correlation flux measurement system
MET	surface meteorological instrumentation
netCDF	Network Common Data Form
NAN	not-a-number
PPI	plan-position-indicator
QC	quality control
SGP	Southern Great Plains
SNR	signal-to-noise ratio
VAP	value-added product

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1.0   Introduction

Height-resolved measurements of clear-air vertical velocity variance, skewness and kurtosis are crucial to understanding turbulent mixing in the atmospheric boundary layer, convective initiation, and cloud life cycles. Instrumented towers can provide accurate measurements of these quantities, but their vertical coverage is generally limited to a small fraction of the lower boundary layer. By contrast, ground-based remote sensors, such as Doppler lidars, can provide height-resolved measurements of vertical velocity through the depth of the atmospheric boundary layer with more than sufficient resolution to observe the inertial subrange of turbulence.

The U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) user facility currently operates several Doppler lidars at sites around the globe. These instrument produce range-resolved measurements of radial velocity, signal-to-noise-ratio (SNR), and attenuated backscatter. The SNR is the ratio of the energy contained in the signal portion of the Doppler spectrum to energy contained in the noise floor over the passband of the receiver, and is useful in identifying poor-quality radial velocity data.

The ARM Doppler lidars are operated with a fixed scan schedule consisting of vertical stares and plan-position-indicator (PPI) scans. The PPI scans are performed once every 10 or 15 minutes (depending on the site), and take about 40 seconds to execute. The rest of the time is spent staring vertically, providing measurements of clear-air vertical velocity profiles in the lower troposphere with a temporal resolution of about 1 second and a height resolution of 30 minutes. These raw measurements are processed to yield height-resolved estimates of vertical velocity variance, skewness, and kurtosis.

The Doppler Lidar Wind Statistics Profiles (DLPROF-WSTATS) value-added product (VAP) contains height- and time-resolved estimates of vertical velocity variance, skewness, and kurtosis as computed from the raw 1-second data. Additionally, the VAP also contains estimates of cloud properties, including cloud-base height, cloud fraction, cloud-base vertical velocity, and cloud-base updraft fraction. This report documents the methods used in deriving these quantities.

2.0   Input Data

The DLPROF-WSTATS algorithm reads in data from the following ARM datastreams:

- *<site>*dlfpt*<facility>*.b1
- *<site>*ceil*<facility>*.b1
- *<site>*30ecor*<facility>*.b1 or *<site>*ecorsf*<facility>*.b1
- *<site>*met*<facility>*.b1

Specific variables that are used from each of these datastreams are listed in Tables 1 through 4.

Table 1.   Variables and global attributes from the *<site>*dlfpt*<facility>*.b1 datastream used by the DLPROF-WSTATS algorithm.

Variable Name	Description	Units
base_time	seconds since 1970-1-1 0:00:00 0:00	s
time_offset	Time offset from base_time	s
range	Distance from Lidar to center of range gate	m
elevation	Beam elevation	deg
azimuth	Azimuth relative to true north	deg
attenuated_backscatter	Attenuated backscatter	1/(m sr)
radial_velocity	Radial velocity	m/s
Iintensity	Intensity (signal-to-noise-ratio + 1)	unitless
alt	Altitude above mean sea level	m
dlat (global attribute)	Lidar latitude in double precision	deg
dlon (global attribute)	Lidar longitude in double precision	deg

Table 2.   Variables and global attributes from the *<site>*ceil*<facility>*.b1 datastream used by the DLPROF-WSTATS algorithm.

Variable Name	Description	Units
detection_status	Detection status	unitless
first_cbh	Lowest cloud-base height detected	m
lat	Ceilometer latitude	deg
lon	Ceilometer longitude	deg
alt	Ceilometer altitude	m

Table 3.   Variables and global attributes from the *<site>*30ecor*<facility>*.b1 or *<site>*ecorsf*<facility>*.b1 datastreams used by the DLPROF-WSTATS algorithm.

30ecor Variable Name	ecorsf Variable Name	Description	Units
mean_t	sonic_temperature	30-min averaged temperature	K
mean_q	h2o_molar_density	30-min averaged water vapor density	$mmol/m^3$
var_rot_u	variance_u	Variance of easting velocity component	m^2/s^2
var_rot_v	variance_v	Variance of northing velocity component	m^2/s^2
var_rot_w	variance_w	Vertical velocity variance	m^2/s^2
ustar	friction_velocity	Friction velocity	m/s^1
skew_w	skew_w	vertical velocity skewness	unitless
kurt_w	kurt_w	vertical velocity kurtosis	unitless
cvar_rot_wt	covariance_w_ts_cov	covariance of vertical velocity and temperature	$(K\ m)/s^1$
cvar_rot_wq	covariance_w_h2o_cov	covariance of vertical velocity and water vapor density	$mmol/(m^2\ s^)$
lat	lat	ECOR latitude	deg
lon	lon	ECOR longitude	deg
alt	alt	ECOR altitude	m

Table 4.   Variables and global attributes from the *<site>*met*<facility>*.b1 datastream used by the DLPROF-WSTATS algorithm.

Variable Name	Description	Units
atmos_pressure	Atmospheric pressure	kPa
qc_atmos_pressure	QC results for Atmospheric pressure	
pwd_precip_rate_mean_1min	PWD 1-min mean precipitation rate	mm/hr
qc_ pwd_precip_rate_mean_1min	QC results for PWD 1-min mean precipitation rate	
rh_mean	Relative humidity mean	%
qc_rh_mean	QC results for Relative humidity mean	
temp_mean	Temperature mean	degC
qc_temp_mean	QC results for Temperature mean	
wdir_vec_mean	Wind direction vector mean	deg
qc_wdir_vec_mean	QC results for Wind direction vector mean	
wspd_vec_mean	Wind speed vector mean	m/s
qc_wspd_vec_mean	QC results for Wind speed vector mean	
lat	MET latitude	deg
lon	MET longitude	deg
alt	MET altitude	m

3.0   Algorithm and Methodology

The DLPROF-WSTATS algorithm reads in vertical staring data from the *<site>*dlfpt*<facility>*.b1 datastream and computes vertical velocity and cloud statistics using a 30-minute averaging interval. For a given site, the algorithm processes one 24-hour period at a time and produces a single netCDF output file per day. Although the algorithm uses a 30-minute averaging period, it reports results at 10-minute intervals. Thus, the resulting profiles are oversampled by a factor of 3 (i.e., every third sample is independent). No averaging is performed in the height dimension; thus the height resolution of the VAP is equal to that of the raw data in the *<site>*dlfpt*<facility>*.b1 datastream, which is typically 30 minutes.

It is worth mentioning that the algorithm screens the staring data to ensure that the beams are in fact vertical. In general, the *<site>*dlfpt*<facility>*.b1 datastream may contain either vertical or slant-path staring data from the Doppler lidar. Although slant paths are not routinely performed, they may be performed occasionally. It is therefore good practice to verify that the beam elevation angle is within about 0.2º of 90º.

The ARM Doppler lidars operate in the near infrared and are sensitive to scattering from aerosol and relatively insensitive to molecular scattering. As a result, reliable clear-air radial velocity measurements are usually constrained to the lower troposphere where aerosol concentrations are typically much higher. The DLPROF-WSTATS algorithm is therefore configured to process clear-air vertical velocity statistics up to a maximum height of 4 km. By contrast, strong scattering from cloud bases enables reliable estimates of cloud-base vertical velocities up to the maximum sensing height of 10 km.

3.1   Vertical Velocity Variance

Noise fluctuations in the radial velocity measurements can have a significant impact on higher-order statistical moments. The noise generally increases with increasing range and decreasing signal-to-noise

ratio (SNR). To deal with the noise, the DLPROF-WSTATS algorithm applies a noise correction procedure in the computation of the vertical velocity variance.

For a given range gate, a 30-min time series of vertical velocity is extracted from the *<site>*dlfpt*<facility>*.b1 datastream. The observed vertical velocity can be written

$$\hat{w} = w + n \tag{1}$$

where w is the true vertical velocity, and n is the noise. If the noise is random and correlated with w, then the observed "total" variance is given by

$$\sigma_{\hat{w}}^2 = \sigma_w^2 + \sigma_n^2 \tag{2}$$

where σ_w^2 is the true atmospheric variance, and σ_n^2 is the variance of the noise. The DLWSTAT algorithm estimates the noise variance, σ_n^2, for each range gate and averaging interval and then subtracts that from the observed variance to obtain the noise-corrected atmospheric variance, i.e., $\sigma_w^2 = \sigma_{\hat{w}}^2 - \sigma_n^2$.

The noise variance (also known as precision) is computed using the technique described by Lenschow et al. (2000) and Pearson et al. (2009). In this method, the noise contribution to the total variance is estimated from the autocovariance function (ACF) of the 30-minute vertical velocity time series. The ith lag of the ACF is given by

$$ACF_i = \frac{1}{N-i} \sum_{j=0}^{N-1-i} w_j w_{i+j}, \tag{3}$$

where *N* is the number of samples in the time series. The ACF is useful for distinguishing between the noise and atmospheric contributions because random uncorrelated noise in the signal manifests itself as a delta function spike in the zeroth lag of the ACF.

Computation of the ACF requires that the data be evenly sampled in time. In practice, gaps exist in the vertical staring data record because the lidar periodically performs other scans. Thus prior to computing the ACF, these gaps are filled with uniformly spaced not-a-number (NAN) samples. These NAN samples help to preserve the spacing between samples.

The DLPROF-WSTATS algorithm computes the first six lags of the ACF. The variance due to atmospheric motion is estimated by extrapolating the ACF in lags one through five to the zeroth lag, as illustrated in Figure 1. This extrapolation is done by fitting a straight line to the ACF in lags one through five. The noise contribution to the total variance is then obtained by simply taking the difference between the zeroth lag and the extrapolated atmospheric variance. The DLPROF-WSTATS algorithm saves these noise estimates, and the corresponding median SNR values (for the same 30-minute time series) to the final VAP output file.

(a)

w

Time

(b)

ACF_i

Noise contribution

Observed Total Variance

Atmospheric contribution

Lag, i
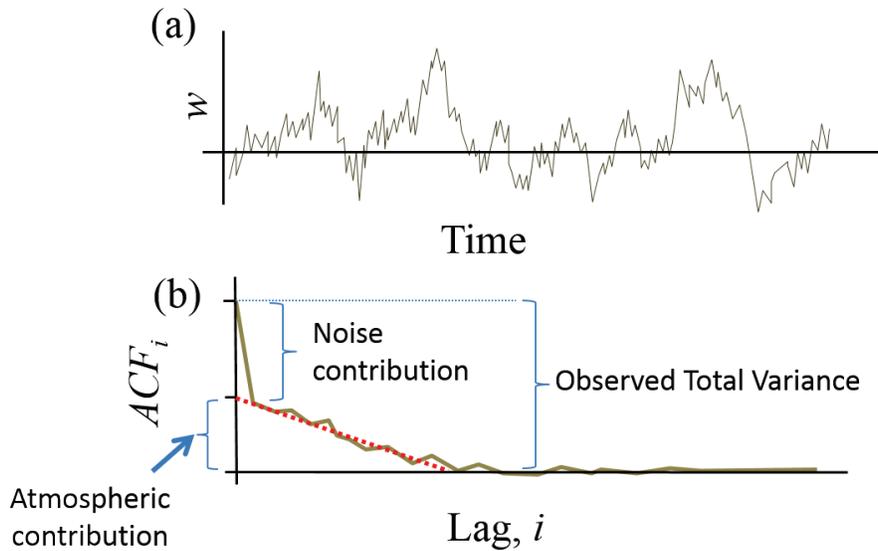
Figure 1. The process for estimating the atmospheric and noise contributions to the observed total variance. Panel (a) shows the raw time series; panel (b) shows the corresponding ACF. The dotted red line in (b) represents the straight-line fit to lags 1 through 5.

The noise generally increases with decreasing SNR up to the limit imposed by the receiver bandwidth. Figure 2 shows estimates of the radial velocity noise standard deviation (i.e., radial velocity precision) as a function of the median SNR for the Doppler lidar at the ARM Southern Great Plains (SGP) site Central Facility (Halo Photonics StreamLine, S/N 0710-07) on 9 June 2015. The median SNR is computed for the same 30-minute averaging interval as the ACF. We note that all of the ARM Doppler lidars exhibit very similar behavior in terms of noise versus SNR.

Velocity precision versus SNR for sgpdlfpt 20150609

RK Newsom, Wed Jun 10 09:04:50 2015
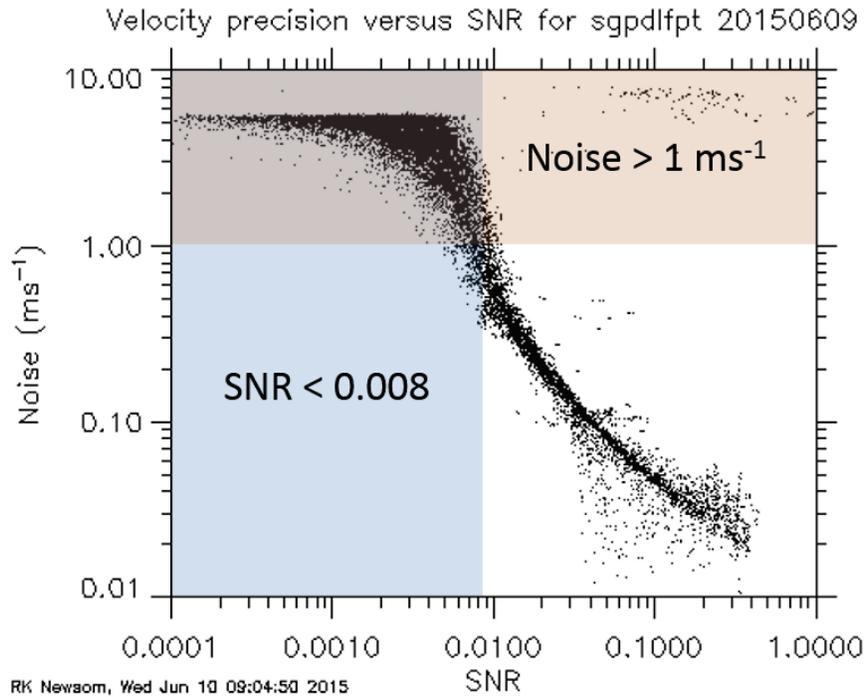
Figure 2.   Radial velocity noise standard deviation (i.e., precision) estimates as a function of SNR for the Doppler lidar at the SGP Central Facility. Also indicated are regions with SNR<0.008 and noise>1 ms^{-1}. Data that fall into these regions should be rejected.

The DLPROF-WSTATS VAP contains the noise, median SNR, and the non-quality-controlled corrected variance fields. To apply quality control to the data, users should filter the corrected variances based on either the noise or the median SNR fields, or both. Figure 2 shows those regions (SNR<0.008 and/or noise>1.0 ms^{-1}) where data should be rejected. We typically use an SNR threshold of around 0.008, and/or a noise threshold of about 1 ms^{-1}. These thresholds are effective at removing most of the poor-quality measurements.

Figure 3 displays examples of the total variance, noise, and atmospheric (noise-corrected) variance during a three-day period at the SGP site. The effect of the noise correction is clear by comparing Figures 3a and 3c. The atmospheric variance field shown in Figure 3c has been filtered using a noise threshold of 1 m s^{-1}.
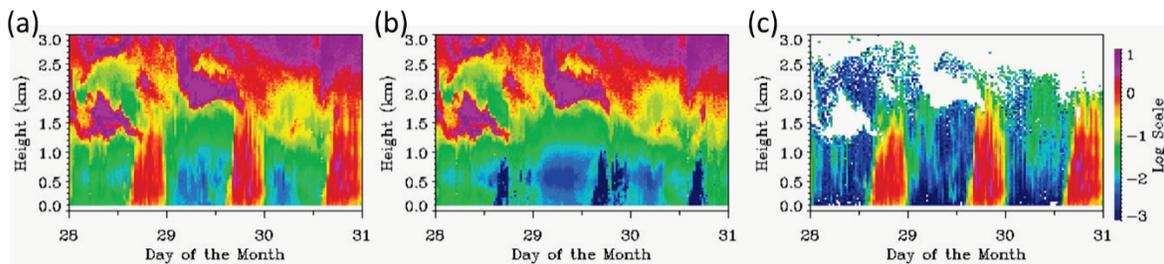
Figure 3.   Time-height displays showing the (a) total variance, (b) noise variance, and (c) corrected atmospheric variance at SGP over a three-day period from 28 through 30 August, 2012. The atmospheric variance field (c) has been filtered to remove data corresponding to noise variances greater than 1 m^{2}s^{-2}.

3.2 Vertical Velocity Skewness and Kurtosis

The vertical velocity skewness and kurtosis are the normalized third- and forth-order moments, respectively. Skewness is defined by

$$S = \frac{\overline{(w - \bar{w})^3}}{\sigma_w^3},$$ (4)

and kurtosis defined by

$$K = \frac{\overline{(w - \bar{w})^4}}{\sigma_w^4}.$$ (5)

The sign of S can indicate whether turbulence is driven by surface heating or cloud-top cooling. When the boundary layer is driven by surface heating, S tends to be positive. Positive S implies that updrafts tend to be narrower and more intense than the broader, weaker downdrafts (Hogan et al. 2009).

Kurtosis quantifies the frequency with which extreme values occur relative to a normal distribution. A normal distribution is defined by $K=3$. When $K>3$ the distribution produces more extreme outliers than a normal distribution. The vertical velocity kurtosis is therefore useful for studying turbulence intermittency.

Estimates of S and K are computed from the same 30-minute time series used in the variance calculation. However, in contrast to the variance calculation, the effects of noise are mitigated by first filtering out vertical velocity measurements corresponding to low SNR. Typically the SNR threshold is set to 0.008. The actual SNR threshold used in the calculation is saved in the VAP. The S and K fields therefore contain missing values in regions where the SNR is below the prescribed threshold. Additionally, users can impose further quality control by increasing the SNR threshold.

3.3 Cloud Statistics

The DLPROF-WSTATS algorithm also computes cloud-base height (CBH), cloud-base vertical velocity, cloud frequency, and cloud-base updraft fraction over each 30-minute averaging period. The cloud frequency is the fraction of time that a cloud is detected at any altitude, and the cloud-base updraft fraction is the fraction of time that positive cloud-base vertical velocities are observed during a given averaging period.

CBH estimates are obtained by locating the heights of sharp spikes in the 1-sec range-corrected SNR profiles, as illustrated in Figure 4. To minimize false detections, the CBH algorithm uses a method based on the first derivative of the range-corrected SNR. When a cloud is present in the profile, the first derivative shows a strong positive peak immediately below and a strong negative peak immediately above the cloud base. We require the magnitude of these peaks to exceed 0.1 km, and vertical separation between peaks to be between 2 and 15 range bins. If these conditions are met, then the algorithm locates the maximum in the range-corrected SNR between the two extrema in the first derivative. The height of

this maximum then determines the CBH. This process is then repeated for all 1-second profiles acquired during a given 24-hour period. Additional checks are then applied to minimize false detections by rejecting temporally isolated CBH estimates. This is done by computing the absolute difference in CBH at a given time and CBH values immediately before and after in time. If both differences exceed 1 km, then that CBH value is rejected. Once the CBH values have been located, the cloud-base vertical velocity is determined from the vertical velocity at the CBH.

The DLPROF-WSTATS algorithm reports the median value, 25th and 75th percentiles of the 1-second CBH values and cloud-base vertical velocities over a given 30-minute averaging interval. Also, for each averaging interval the algorithm reports the fraction of profiles in which a cloud is detected at any height (cloud frequency), and the fraction of profiles in which the cloud-base vertical velocity is positive (cloud-base updraft fraction).
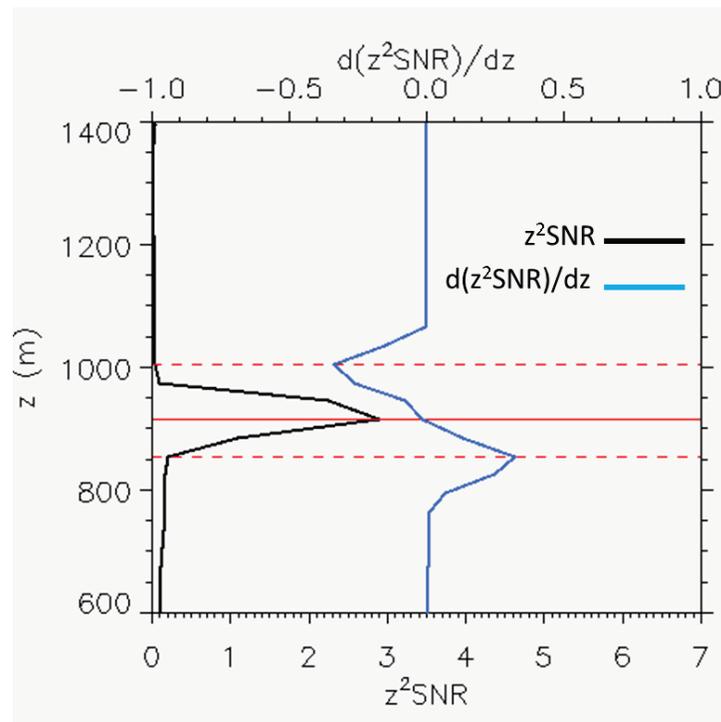
Figure 4. Illustration of the cloud-base detection method used by the ARM Doppler lidars. The solid black curve is the range-corrected SNR, and the blue curve is the first derivative of the range-corrected SNR. The CBH (solid red line) is located by finding the maximum value of the range-corrected SNR between the heights corresponding to the minimum and maximum of the derivative (red dashed lines).

3.4 Additional Data Products

In addition to those parameters derived from the DL measurements, the DLPROF-WSTATS VAP also incorporates cloud-base height data from the Vaisala ceilometers, surface turbulence measurements from the eddy correlation system (ECOR), and precipitation rate measurements from the surface MET station. Cloud-base height data from the Vaisala ceilometers are obtained from the *<site>*ceil*<facility>*.b1 datastream. As in the case of the Doppler lidar, the final reported cloud-base height for the ceilometer is given by the median value during the 30-minute averaging period, and the final reported cloud frequency

is the fraction of profiles for which a cloud is detected at any height during the 30-minute averaging period. In addition to the median values, the VAP also reports the 25th and 75th percentile values in the ceilometer cloud-base heights.

The DLPROF-WSTATS VAP also includes turbulence and surface meteorological measurements from the *<site>*30ecor*<facility>*.b1 or *<site>*ecorsf*<facility>*.b1, and *<site>*met*<facility>*.b1 datastreams. The 30-min data from *<site>*30ecor*<facility>*.b1 are interpolated to the time grid of the DLPROF-WSTATS VAP. Measurements include the surface temperature, water vapor density, vertical velocity variance, skewness and kurtosis, turbulent kinetic energy, and kinematic sensible and latent heat flux. The 1-minute precipitation rate measurements from *<site>*met*<facility>*.b1 are averaged within each 30-minute averaging time interval. The mean, maximum, and minimum precipitation rate for each 30-minute averaging period are also included in the VAP.

4.0   Output Data

The primary Doppler lidar-derived variables in the DLPROF-WSTATS VAP are listed in Table 5

Table 5.   Primary Doppler lidar-derived variables in the DLPROF-WSTATS VAP.

Variable name	Description	Dimensions
w_variance	Noise-corrected vertical velocity variance	Height and time
w_skewness	Vertical velocity skewness using SNR threshold	Height and time
w_kurtosis	Vertical velocity kurtosis using SNR threshold	Height and time
w	Median vertical velocity	Height and time
w_25	Vertical velocity 25th percentile	Height and time
w_75	Vertical velocity 75th percentile	Height and time
dl_cbh	Median Doppler lidar cloud base height	Time
dl_cbh_25	Doppler lidar cloud base height 25th percentile	Time
dl_cbh_75	Doppler lidar cloud base height 75th percentile	Time
cbw	Median Doppler lidar cloud-base vertical velocity	Time
cbw_25	Median Doppler lidar cloud-base vertical velocity 25th percentile	Time
cbw_75	Median Doppler lidar cloud-base vertical velocity 75th percentile	Time
dl_cloud_frequency	Fraction of time that a cloud is detected during averaging period from DL	Time
cbw_up_fraction	Doppler lidar cloud-base vertical velocity updraft fraction	Time
noise	Variance of random noise in vertical velocity	Height and time
snr	Median signal-to-noise ratio	Height and time
snr_threshold	Minimum SNR used in skewness and kurtosis calculation for the Doppler lidar	scalar

4.1   Other Output Data

The DLPROF-WSTATS VAP also includes several variables that are derived from non-Doppler lidar datastreams. These include: ceil_cbh (Ceilometer cloud-base height), ceil_cloud_frequency (Fraction of time that a cloud is detected by the ceilometer during averaging period), ecor_temp (temperature from eddy correlation system), ecor_h2o (water vapor density from eddy correlation system), ecor_tke (turbulence kinetic energy from eddy correlation system), ecor_ustar (friction velocity from eddy correlation system), ecor_w_var (w variance from eddy correlation system), ecor_w_skew (w skewness from eddy correlation system), ecor_w_kurt (w kurtosis from eddy correlation system), ecor_wt (wt covariance from eddy correlation system), ecor_wq (wq covariance from eddy correlation system), smet_spr_mean (Mean surface precipitation rate from surface meteorological instrumentation [MET]).

This ancillary information can be used to assess the quality of the lidar-derived vertical velocity statistics. For example, precipitation may bias the vertical velocity statistics. For this reason, the VAP includes measurements of precipitation rate from the surface MET station. Also, the surface measurements of vertical velocity variance, skewness, and kurtosis from the ECOR provide a valuable sanity check on the lidar results.

5.0   Summary

The Doppler Lidar Wind Statistics Profiles (DLPROF-WSTATS) VAP provides height- and time-resolved measurements of vertical velocity variance, skewness, kurtosis, cloud-base height, cloud-base vertical velocity, cloud-base updraft fraction, and cloud fraction. These statistics are computed from 1-second vertical staring data from the Doppler lidar. The temporal resolution of DLPROF-WSTATS VAP output is 30 minutes and the temporal sampling interval is 10 minutes; thus every third profile is independent. The height resolution of the output is equal to the height resolution of the raw Doppler lidar data, which is typically 30 minutes. The minimum height of the lidar-derived vertical velocity statistics is approximately 100 m, and the maximum height varies based on the atmospheric conditions. Typically, under clear-sky conditions, and in a mid-latitude convective boundary layer, the maximum height will be roughly equal to the depth of the boundary layer (i.e., 1 to 3 km AGL). On the other hand, cloud-base statistics may be computed as high as 10 km AGL.

The DLPROF-WSTATS VAP includes the SNR and the standard deviation of the random noise (called "noise" in the VAP). These two fields are included to enable users to apply their own quality control. The variance field in particular should be filtered to remove estimates corresponding to high noise (noise > 1 ms-1) or low SNR (SNR < 0.008). The skewness and kurtosis fields already contain missing values in regions of low SNR; however, users can impose further quality control by applying a higher SNR threshold. The SNR threshold used in the skewness and kurtosis calculation is included in the VAP.

The (DLPROF-WSTATS) VAP also includes several variables that are derived from non-Doppler lidar datastreams. These data are useful for assessing the quality of the lidar-derived vertical velocity statistics. For example, surface measurements of vertical velocity variance, skewness, and kurtosis from the ECOR provide a valuable sanity check on the lidar results, and precipitation rate data from the surface MET station is useful for identifying periods when the lidar results may be biased by the precipitation.

6.0   Example Plots
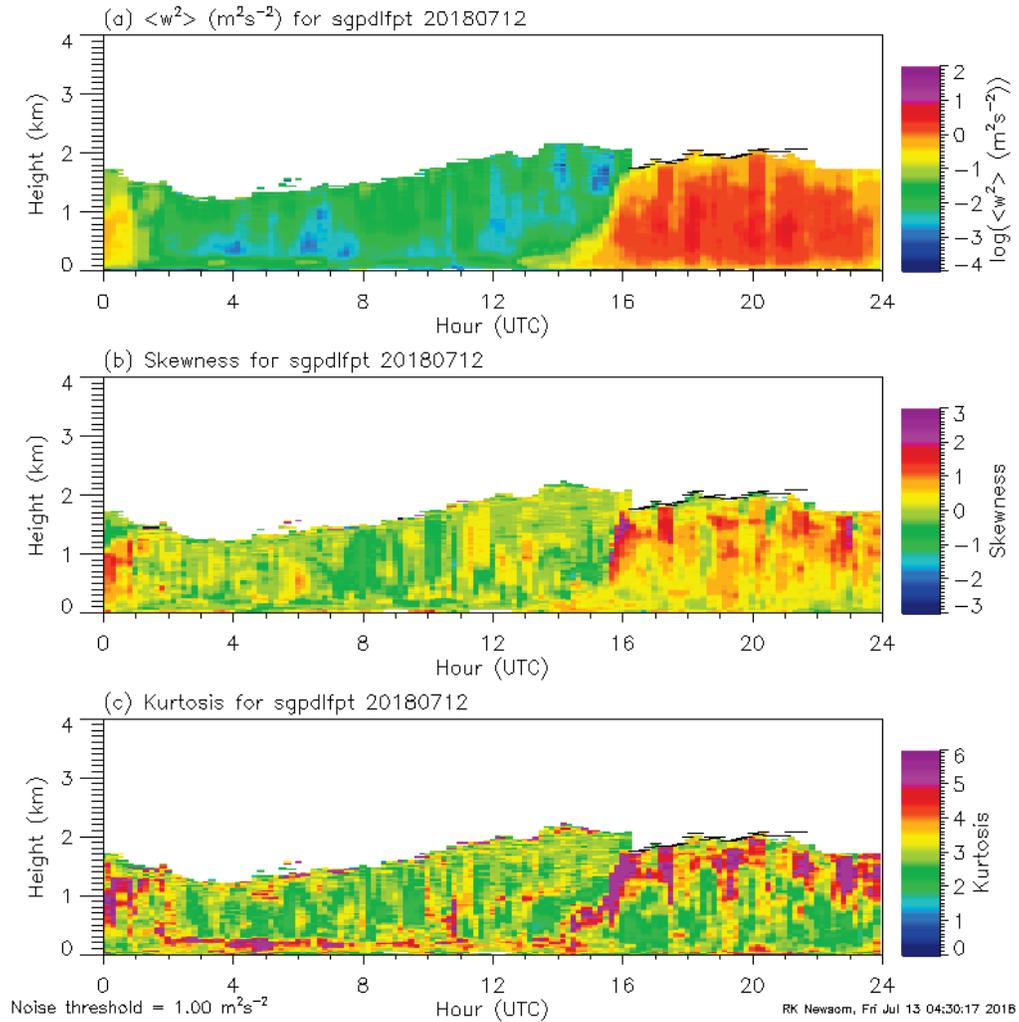
Figure 5.   Height-time displays of (a) the log10 of the vertical velocity variance, (b) skewness (b) and (c) kurtosis computed from Doppler lidar data at the SGP site for 12 July 2018. The variance has been filtered to remove data corresponding to noise standard deviation greater than 1.0 ms^{-1}. Cloud-base height estimates are indicated by the black dashes.
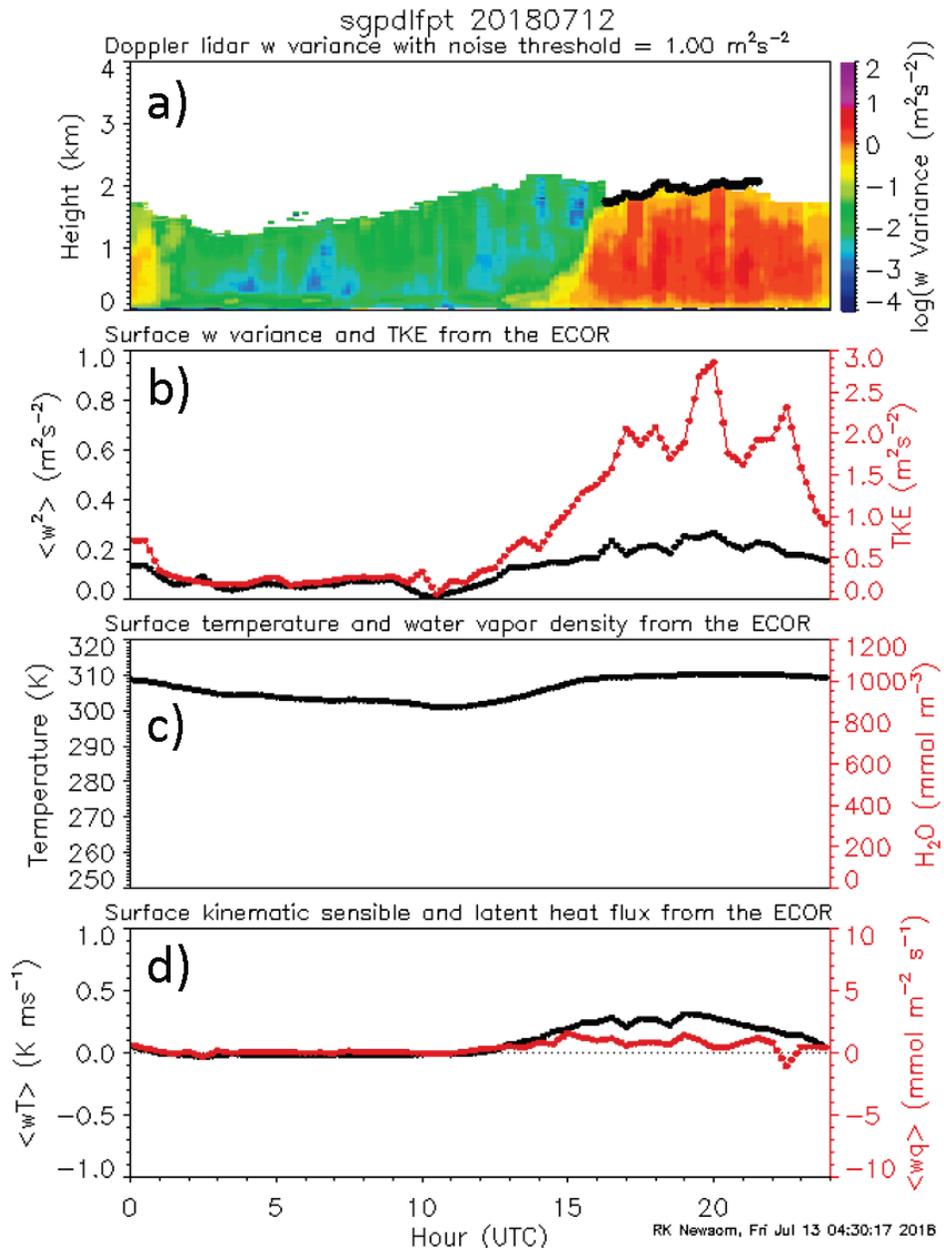
Figure 6.   DLPROF-WSTATS results for SGP on 12 July 2018 showing a) the log10 of the vertical velocity variance and cloud-base height (black dots); b) ECOR vertical velocity variance (black) and turbulence kinetic energy (red); c) ECOR temperature (black) and water vapor concentration (red); d) ECOR kinematic vertical heat flux (black) and vertical water vapor flux.
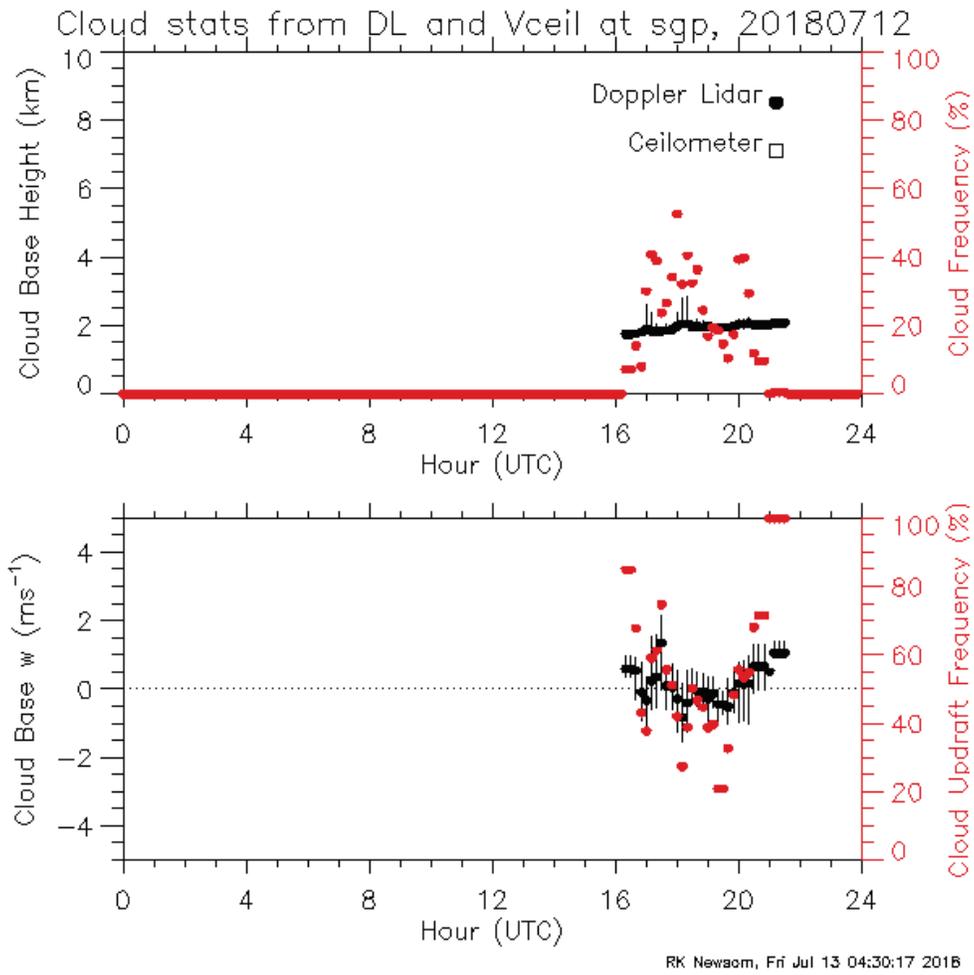
Figure 7. DLPROF-WSTATS results for SGP on 12 July 2018. The top panel shows the Doppler lidar-derived cloud-base heights (black) and cloud frequencies (red). The bottom panel shows the Doppler lidar-derived cloud-base vertical velocity (black) and updraft fraction (red).
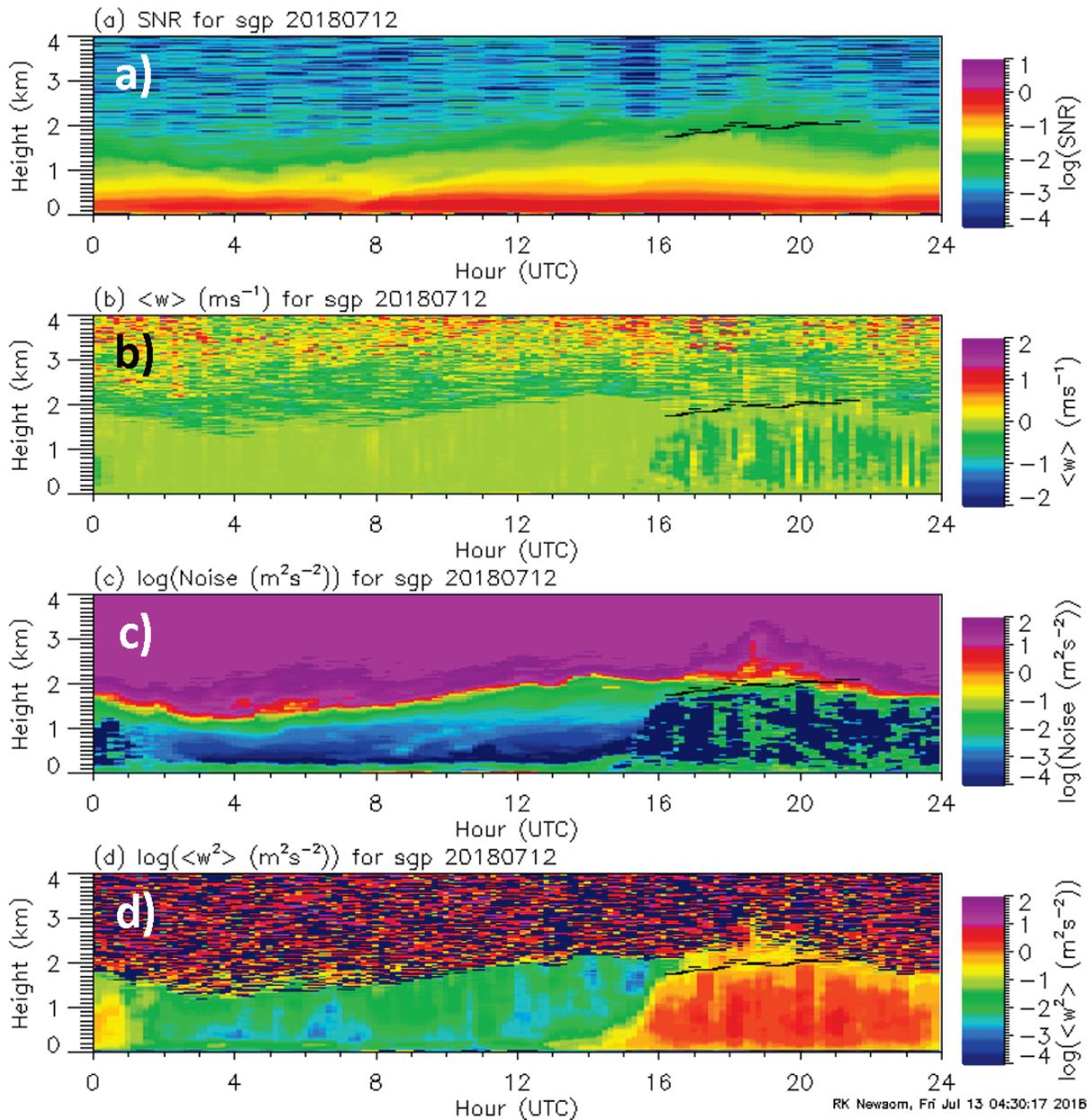
Figure 8.   DLPROF-WSTATS results for SGP on 12 July 2018 showing a) log10 of the SNR, b) median vertical velocity with no QC, c) log10 of the vertical velocity noise, d) log10 of the vertical velocity variance with no QC.

7.0   References

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