Validation of a UV-to-RF High-Spectral-Resolution Atmospheric Boundary Layer Characterization Tool

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ABSTRACT

This paper demonstrates the capability of the Laser Environmental Effects Definition and Reference (LEEDR) model to accurately characterize the meteorological parameters and radiative transfer effects of the atmospheric boundary layer with surface observations or climatological values of temperature, pressure, and humidity ("climatology"). The LEEDR model is a fast-calculating, first-principles, worldwide surface-to-100-km, ultraviolet-to-radio-frequency (UV to RF) wavelength, atmospheric characterization package. In general, LEEDR defines the well-mixed atmospheric boundary layer with a worldwide, probabilistic surface climatology that is based on season and time of day and, then, computes the radiative transfer and propagation effects from the vertical profile of meteorological variables. The LEEDR user can also directly input surface observations. This research compares the LEEDR vertical profiles created from input surface observations or numerical weather prediction (NWP) data with the LEEDR climatological profile for the same time of day and season. The different profiles are compared with truth radiosonde data, and the differences from truth are found to be smaller for profiles created from surface observations and NWP than for those made from climatological data for the same season and time. In addition, this research validates LEEDR’s elevated aerosol extinction profile vertical structure against observed lidar measurements and details the advantages of using NWP data for atmospheric profile development. The impacts of these differences are demonstrated with a potential tactical high-energy-laser engagement simulation.

1. Introduction

For the purpose of evaluating expected directed-energy-weapon (DEW) system performance, the U.S. Air Force Institute of Technology Center for Directed Energy (AFIT/CDE) has developed several modeling codes to simulate operating conditions. One of these codes, the High Energy Laser End-to-End Operational Simulation (HELEEOS; Bartell et al. 2005; Fiorino et al. 2006), is perhaps the first DEW simulation package to fully incorporate a correlated, probabilistic climatological database. The infusion of such realistic atmospheric effects into the simulations allows HELEEOS to better assess variability/uncertainty in DEW system performance arising from spatial, spectral, and temporal variations in operating conditions (Fiorino et al. 2011; Randall et al. 2011). HELEEOS is intended as a tool for testing engineering-design performance or doing research analysis; AFIT/CDE is currently developing a mission-planning version of HELEEOS, called the High Energy Laser Tactical Decision Aid (HELTDA; Fiorino et al. 2013), that would allow for high-energy-laser (HEL; generally at least 1–2 kW) mission planning with atmospheric effects determined from current or short-term forecast data rather than from climatological information (hereinafter referred to as climatology). A hallmark
feature of HELEEOS and the HELTDA is that the critically important atmospheric boundary layer (BL) is assumed to be well mixed for much of its diurnal cycle (Stull 1988) and can be defined with an acceptably small amount of error on the basis of surface observations only. The primary purpose of this paper is to quantify the improvement in atmospheric definition that one can gain by using surface observations in the BL definition rather than probabilistic surface climatology and to describe the advantages of using actual forecast data for atmospheric profile development. The metric for the amount of improvement is illustrated with root-mean-square differences and a hypothetical HEL simulation using the HELTDA.

The capability to create realistic data profiles of correlated atmospheric effects on electromagnetic energy propagation extends far beyond DEW system performance. Thus, AFIT/CDE has produced a separate atmospheric code, called the Laser Environmental Effects Definition and Reference (LEEDR; Fiorino et al. 2008), that allows the export of first-principles atmospheric characterizations for other DEW simulation codes (such as HELEEOS and HELTDA), military or U.S. Department of Defense mission planners, or even nonmilitary scientific research such as climatic-change impact studies. LEEDR has two primary, up-front purposes: 1) to create correlated, physically realizable vertical profiles of meteorological data and environmental effects such as gaseous and particle extinction, optical turbulence, and cloud-free line of sight (LEEDR’s optical turbulence and cloud-free line-of-sight capabilities are not discussed in this paper) and 2) to allow graphical access to and export of the probabilistic data from the Extreme and Percentile Environmental Reference Tables (ExPERT) database. To create the most realistic correlated, physically realizable vertical profiles that include effects of moisture and humidity on aerosol distributions, LEEDR uses a novel approach to characterize the BL that utilizes fast-calculating dry- and moist-adiabatic relationships (Fiorino et al. 2008). This approach combined with the ExPERT probabilistic data provides the capability to create atmospheric profiles that could actually occur or have actually occurred at the ExPERT sites. AFIT/CDE also incorporated into LEEDR the ability to input limited surface data in the “Ground Level” tab using the most easily obtainable observed data to create a more realistic data profile. This research compares the LEEDR vertical profiles created from input surface observations and surface probabilistic climatology with the radiosonde data collected for Randall et al. (2011) and with numerical weather prediction (NWP) data valid at the same times. The NWP data source used for this study was the Global Forecasting System (GFS) model as obtained from the National Oceanic and Atmospheric Administration National Operational Model Archive and Distribution System (NOMADS).

2. LEEDR description and calculations
To create physically realistic atmospheric profiles, LEEDR requires detailed databases and characterization algorithms for worldwide climatological data, temporally and spatially varying BL definitions, aerosol and hydrometeor descriptions, molecular absorption data, and a capability to input user-specified surface observations. This section describes these aspects of LEEDR.

a. Climatological databases
Worldwide seasonal, diurnal, and geographical spatial–temporal variation in meteorological parameters in LEEDR is organized into databases of probability density function using a variety of available resources, including the ExPERT (Squires et al. 1995) database, the Master Database for Optical Turbulence Research in Support of the Airborne Laser (Bussey et al. 2000), and the Global Aerosol Data Set (GADS; Koepke et al. 1997). GADS provides aerosol constituent number densities on a 5° × 5° grid worldwide (Fiorino et al. 2008). Maritime aerosol environments are characterized using the wind speed–driven Advanced Navy Aerosol Model (ANAM; Gathman et al. 1998). An ExPERT atmosphere can be selected from the world map shown in Fig. 1. The red circles indicate the 573 land surface sites available from ExPERT climatological data in LEEDR. The user can also select one of the nine relative humidity (RH) percentile conditions (ranging from 1st to 99th percentiles) to model, with the default being 50th-percentile conditions, as well as time of day in 3-h local-time blocks for any of these sites. Selection of an ocean site location uses regional data as delineated and shown in Fig. 2. A zoom box or latitude–longitude input fields allow the user to indicate a desired set of coordinates precisely. The six upper-air regions used to characterize meteorological parameters above the atmospheric BL (within the BL, surface data are used to characterize the environment with adiabatic relationships) are also displayed in Fig. 2. In addition to these six upper-air regions—polar north, midlatitude north, tropical, desert, midlatitude south, and polar south—the U.S. Standard Atmosphere, 1976 is a selection (Fiorino et al. 2008).

LEEDR supports any user-defined wavelength from 0.35 μm to 8.6 m and provides vertical profiles of atmospheric data and attenuating effects on electromagnetic propagation from the surface to any user-specified altitude up to 100 km.
b. Atmospheric BL considerations

Surface meteorological data are available in LEEDR for 573 land locations for a 24-h average as well as for eight 3-h local-time blocks throughout the diurnal cycle. If a 3-h time block is selected, the height of the top of the atmospheric BL is dynamically adjusted as indicated in Table 1. The BL height is set at 500 m at all times and seasons over oceanic sites (Fiorino et al. 2008).

Within the BL, the atmospheric conditions are characterized by the ExPERT climatological surface conditions for the selected site or by user-defined surface data input through the Ground Level tab. This is accomplished according to the well-mixed BL and nighttime residual-layer (RL) qualities described in Stull (1988) and by many others. Within the well-mixed BL (and RL) the water vapor mixing ratio, the aerosol number concentration, and the potential temperature are very nearly constant with altitude. While potential temperature (the temperature a parcel of air would have if it is brought dry adiabatically to a pressure level of 1000 hPa) remains constant in the BL, temperature does vary. Temperature throughout the BL can be characterized by the surface temperature, which is allowed to decrease at the dry-adiabatic lapse rate:

\[
\frac{dT}{dz}_{\text{dry}} = -\frac{g}{c_p} = -9.8 \text{ K km}^{-1}.
\]  

(1)

Dewpoint temperature (the temperature at which condensation occurs in a parcel of air when cooled at constant pressure) also varies throughout the BL, even though the water vapor mixing ratio remains constant. The dewpoint temperature lapses with height according to

\[
\left(\frac{dT_d}{dz}\right)_{\text{dry}} = -\frac{g}{s l_v} \frac{T_d^2}{T} = -1.8 \text{ K km}^{-1}.
\]  

(2)

In the above equations, \(T\) is temperature, \(T_d\) is dewpoint temperature, \(z\) is height, \(g\) is the gravitational constant, \(c_p\) is the specific heat of air at constant pressure, \(s\) is the ratio of the molecular weight of water over the molecular weight of dry air, and \(l_v\) is the latent heat (enthalpy) of vaporization of water. Note that the temperature lapses at a far greater rate than the dewpoint; thus, in many cases saturation can occur within the height of the BL specified by the user. In this case the lapse rate of temperature is no longer linear with height and decreases at a rate that is less than the dry-adiabatic rate according to

\[
\left(\frac{dT}{dz}\right)_{\text{moist}} = -\frac{g}{c_p} \frac{1 + l_v}{1 + l_v} \frac{w_s}{R_v T^2}.
\]  

(3)

The variables in (3) are the same as in (1) and (2); \(w_s\) is the saturation mixing ratio of water, and \(R_v\) is the moist-air gas constant. Temperature and dewpoint are also characterized for the RL using the above lapse-rate techniques; low-level inversions associated with nighttime radiative cooling can introduce errors, however. Such errors are discussed in section 4b.
LEEDR allows the BL lapse rates to occur on the basis of surface values for an ExPERT site or user-defined surface data input on the Ground Level tab. Above the BL, LEEDR defaults back to the upper-air regional data on the basis of the location of the site. An important consequence of these lapse rates is that the RH varies dramatically within the BL, usually increasing from the surface to 100% or nearly so. This circumstance has a very strong effect on the aerosol size distribution—as a result of the RH-driven water uptake by water-soluble aerosols—that in turn strongly affects simulated laser propagation through the BL. This effect is not captured when modeling with standard atmospheric data because the moisture (dew-point) does not lapse realistically in standard atmospheres. Thus, RH does not necessarily increase with height in a standard-atmosphere BL. This situation is illustrated when comparing the left and right panels of Fig. 3, which graphically depict absorption and scattering of 1.315 25-μm radiation between the surface and 3000 m for U.S. Standard Atmosphere, 1976 conditions and the LEEDR representation of Wright-Patterson Air Force Base, Ohio (WPAFB), summer conditions [1500–1800 local time (LT)], respectively. In general, many engineering environmental simulations allow attenuating atmospheric effects such as aerosol extinction to decay with height above the surface; this assumption can lead to significant deviations from reality in the case of BL aerosol absorption and scattering. Furthermore, a much better approximation of these BL effects can be made with observed surface meteorological data and surface aerosol concentration (Fiorino et al. 2008).

c. Atmospheric particulate (aerosol and hydrometeor) characteristics

LEEDR calculates an aerosol size distribution for each user-specified scenario, location, altitude, season, and

<table>
<thead>
<tr>
<th>Time of day</th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000–0259</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>0300–0559</td>
<td>500</td>
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</tr>
<tr>
<td>0600–0859</td>
<td>1000</td>
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<td>0900–1159</td>
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<tr>
<td>1500–1759</td>
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<td>1524</td>
</tr>
<tr>
<td>1800–2059</td>
<td>1524</td>
<td>1000</td>
</tr>
<tr>
<td>2100–2359</td>
<td>1000</td>
<td>500</td>
</tr>
</tbody>
</table>
RH. For aerosol scattering and absorption calculations, Mie scattering is assumed. The Mie extinction, scattering, and absorption coefficients are first calculated by assuming a dry environment and then are allowed to vary with increasing RH conditions.

The LEEDR aerosol algorithm calculates dimensionless extinction, scattering, and absorption efficiencies with the Wiscombe Mie-scattering module. Wavelength-specific indices of refraction for the 10 GADS aerosol species are interpolated from either Table 4.3 in d’Almeida et al. (1991) or by using tables derived with values from the Optical Properties of Aerosols and Clouds (OPAC) software package (Hess et al. 1998). The Shettle and Fenn (1979) characterizations are used only when the user specifies one of the three aerosol types from the Moderate Resolution Atmospheric Radiance and Transmittance Model and Code (MODTRAN). The normalized radius-specific particle number density per unit volume \( dN/d(\log r) \) is derived as shown in Hess et al. (1998) for the lognormal distribution:

\[
dN(r)/d(\log r) = \frac{N}{(2\pi)^{1/2} \log(\sigma)} \exp \left[ \frac{(\log r - \log r_M)^2}{2(\log r)^2} \right], \tag{4}
\]

where \( N \) is the total particle number density per unit volume and is normalized to 1. The \( r_M \) value is the modal (or median) radius, and \( \sigma \) is the standard deviation for the aerosol species. LEEDR takes these values from either d’Almeida et al. (1991) or Hess et al. (1998). As was done in d’Almeida et al. (1991), the wavelength-specific normalized extinction, scattering, and absorption coefficients \( \beta_{e,s,a}(\lambda) \) are obtained by integrating over the range of radii using

\[
\beta_{e,s,a}(\lambda) = \frac{Q_{e,s,a}(n, \lambda, r) \pi r^2}{r \ln 10(d(\log r))} \frac{dN(r)}{d(\log r)} dr \\
= \sum_{i=\min}^{\max} \frac{Q_{e,s,a}(n, \lambda, r_i) \pi r_i^2}{r_i \ln 10(d(\log r_i))} \Delta r_i, \tag{5}
\]

where \( Q_{e,s,a}(n, \lambda, r_i) \) are the aerosol-constituent specific extinction, scattering, and absorption efficiency obtained from the Mie calculation.

For moist-aerosol calculations one must consider that humidity causes aerosol particle growth, even at RH values far below saturation. This is handled by allowing the modal radius and the refractive index for each aerosol species to vary with RH. The standard deviation and the particle number density of the lognormal distribution for each species are not varied with RH. LEEDR calculates the humidity-altered radius value \( r(a_w) \) by obtaining the particle number density from (5) (using the dry \( r_M \) and \( \sigma \)) and then solving (4) for \( r(a_w) \) using the humidity-specific \( r_M \) and holding the particle number density \( dN/d(\log r) \) constant. This is described by

\[
\log(a_w) = \pm \left[ -\ln(ND \sqrt{2\pi} \log(\sigma))(2(\log r)^2) \right]^{1/2} + \log r_M, \tag{6}
\]

where \( ND = dN/d(\log r) \), \( \sigma \) is the standard deviation from d’Almeida et al. (1991) or Hess et al. (1998), and \( r_M \) is the modal radius for the given RH. Note that the first term on the right side of (6) is negative when ND is calculated using a dry particle radius \( r_0 < 1 \mu m \) and is positive when \( r_0 \approx 1 \mu m \). LEEDR considers aerosols to be “dry” if RH < 50%. For RH ≥ 50%, modal radii are
interpolated from the values given in Table 6.2 of d’Almeida et al. (1991).

Moist growth of aerosol particles changes not only their size but also their index of refraction. LEEDR again follows d’Almeida et al. (1991) and derives the humidity-altered index of refraction from

\[ n = n_w + (n_0 - n_w) \left( \frac{r_0}{r(a_w)} \right)^3, \]

(7)

where \( n = n_r + in_i \), \( n_w \) is the refractive index for liquid water, \( n_0 \) is the refractive index for the dry particles, \( r_0 \) is the radius of the dry particles, and \( r(a_w) \) is the radius of the particle at the given RH obtained with (6). With the humidity-altered radius value and index of refraction, LEEDR reinvokes the Wiscombe module to get RH-altered radius value and index of refraction, the particle at the given RH obtained with (6). With the humidity-altered radius and index of refraction, LEEDR again interpolated from the values given in Table 6.2 of d’Almeida et al. (1991).

d. Molecular absorption

Molecular absorption calculations are made by combining line strength data as defined in Rothman et al. (2009) from the High Resolution Transmission (HITRAN) 2008 molecular absorption database with temperature, dewpoint, and pressure vertical profiles derived from ExPERT as outlined above using the method developed in Walter and Mani (2002). The top 13 absorbing species, summarized in Table 2 with their corresponding concentrations, from HITRAN 2008 are considered in LEEDR.

For wavelengths shorter than 1 mm (frequencies higher than 300 GHz), pressure broadening of the absorption lines is done in LEEDR by assuming the Lorentz line shape. For wavelengths of 1 mm and longer, the van Vleck–Weisskopf asymmetrical line shape is used (Petty 2006).

e. Inputs: Ground Level tab

LEEDR additionally has the capability to allow user-defined surface data as input to create an atmospheric profile. LEEDR’s default is to use the climatological probabilistic data that correlate with the users’ input scenario (i.e., location, season, and time of day); having current surface observations creates a more realistic profile in the BL, however. The Ground Level tab provides options for identifying observed meteorological values for pressure \( P \), temperature \( T \), dewpoint \( T_d \), and relative humidity (RH, in percent) at ExPERT sites (Randall et al. 2011).

### Table 2. Molecular absorbers considered in LEEDR.

<table>
<thead>
<tr>
<th>Absorber</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2O (water vapor)</td>
<td>Variable</td>
</tr>
<tr>
<td>CO2 (carbon dioxide)</td>
<td>3.80 × 10^-4</td>
</tr>
<tr>
<td>O3 (tropospheric ozone)</td>
<td>Variable</td>
</tr>
<tr>
<td>N2O (nitrous oxide)</td>
<td>3.20 × 10^-7</td>
</tr>
<tr>
<td>CO (carbon monoxide)</td>
<td>1.50 × 10^-7</td>
</tr>
<tr>
<td>CH4 (methane)</td>
<td>1.794 × 10^-6</td>
</tr>
<tr>
<td>O2 (oxygen)</td>
<td>0.209</td>
</tr>
<tr>
<td>NO (nitrogen oxide)</td>
<td>2.99 × 10^-10</td>
</tr>
<tr>
<td>SO2 (sulfur dioxide)</td>
<td>2.93 × 10^-10</td>
</tr>
<tr>
<td>NO2 (nitrogen dioxide)</td>
<td>2.99 × 10^-11</td>
</tr>
<tr>
<td>NH3 (nitrogen hydride)</td>
<td>5.03 × 10^-11</td>
</tr>
<tr>
<td>HNO3 (nitric acid)</td>
<td>5.30 × 10^-11</td>
</tr>
</tbody>
</table>

3. Method

The purpose of this study is to validate LEEDR’s climatological extinction profile results to those observed with lidar and to validate the Ground Level tab’s capability to improve the lower-atmospheric definition by using surface observations or other user input in the BL definition rather than surface climatology. Thus, it must be shown that inputting surface measurements of temperature, pressure, and moisture content instead of climatological surface values leads to better comparisons of radiosonde BL profiles to LEEDR-modeled BL profiles. Since the radiosonde profile for a given day, time frame, and location contains actual measured data, it is referred to as the “control” dataset for clarity purposes throughout this paper. Profiles output from LEEDR used in this study are created by considering the typical atmospheric parameters that are present at the WPAFB location. Because WPAFB does not perform routine
balloon launches, all radiosonde data used in this study are taken from the nearest National Weather Service (NWS) site: Wilmington, Ohio (ILN; World Meteorological Organization identifier 72426), which is approximately 50 km southeast of WPAFB. One example of the kind of improvement one can get when using observed surface data to create a BL profile rather than surface climatology can be seen in Fig. 4. This figure demonstrates that when surface observations (e.g., temperature, pressure, and RH) are available and indicate that climatology is not representative of the actual conditions then the LEEDR Ground Level tab function can offer a dramatically improved characterization of the lower atmosphere and BL.

To establish the validity of the distinctly shaped extinction curves of the ExPERT profiles seen in Fig. 3, comparisons with lidar profile measurements that are available in the open literature are made. Care had to be taken when making the comparisons with published profiles that the meteorological conditions—especially the surface visibility—were matched as closely as possible.

For the validation analysis, two types of LEEDR atmospheric profiles (each modeling accompanying temperature and dewpoint temperature profiles) were created and compared with a radiosonde’s temperature and dewpoint temperature profiles for WPAFB for the same time frame, season, and throughout the same BL as identified from the radiosonde. The first type of atmospheric profile created in LEEDR considered a comparative control radiosonde’s surface temperature, dewpoint temperature, and pressure measurements. This input was applied on the Ground Level tab for consideration during LEEDR-performed profile (temperature and dewpoint) calculations. The second type of LEEDR atmospheric profiles (for temperature and dewpoint) that were developed considered only the WPAFB ExPERT database surface climatology (Randall et al. 2011).
Both winter and summer seasons were considered in this validation research. For the winter portion of the comparison, ILN radiosonde launch data covering the period from December 2010 to the first week in March 2011 were collected. The NWS generally conducts two radiosonde launches per day at 1200 UTC (0700 LT) and 0000 UTC (1900 LT). From each time group, 25 radiosonde launches were chosen on the basis of accompanying observations indicating clear conditions. Therefore, a total of 50 winter launches from one site were used in this portion of the validation (Randall et al. 2011).

The validation study is concerned only with the BL since it is usually well mixed and, once beyond the BL, LEEDR reverts back to the ExPERT-database regional climatology for upper-air (free atmosphere) characterizations. Although LEEDR has default BL heights that are based on time of day and season (winter or summer) as shown in Table 1, the user has the option of indicating an observed BL height to support further accuracy of the output. A BL was identified for each of the 50 control radiosondes by locating the pressure level at which the dewpoint depression first became significant, as evidenced by where the temperature started to increase with height and the dewpoint temperature decreased with height (Stull 1988; Wallace and Hobbs 2006). Determining the top of the BL location was accomplished to ensure proper interpolation and error calculations. The same layer was considered within each LEEDR profile set to allow for a more direct comparison with the accompanying control radiosonde. From this estimation, the nearest equivalent pressure level from the control radiosonde’s data was located and its given height in meters was used in LEEDR (Randall et al. 2011).

The next step in the study was to create these two types of LEEDR profiles (again, each modeling BL temperatures and dewpoints) by either including or disregarding input of the surface data from the control radiosonde on the Ground Level tab. When not using the surface data from the control radiosonde, the surface data in the ExPERT climatology are used instead. When creating either type of LEEDR profile, the time frames selected from the available 3-h time groups were 0600–0900 WPAFB local time for comparison with a 1200 UTC radiosonde launch and 1800–2100 LT for 0000 UTC launches.

The root-mean-square error (RMSE) method was used to quantify the differences between both types of LEEDR profiles and the control radiosonde BL profiles. Prior to performing the RMSE calculations, minor interpolations were required to produce temperatures and dewpoint temperatures at pressure levels in the LEEDR BL profiles that were consistent with the radiosonde
control BL data for comparison purposes. Therefore, these interpolations were performed on both the LEEDR-created Ground Level tab and climatology BL profiles. RMSE calculations were performed on profile data separated into two time-frame groups: 1200 and 0000 UTC.

4. Results

a. Extinction-profile comparisons

One of the primary results of creating lapsing profiles of temperature and dewpoint from surface data and coupling them with aerosol characterizations that allow those aerosol size distributions to vary in response to varying RH is that aerosol extinction effects are no longer directly tied to aerosol concentration or number density. In other words, although aerosol concentration or number density may be constant with height through the BL and then decrease dramatically above the BL, the extinction loss on visible and infrared energy caused by the aerosols may increase with height above the surface and reach a maximum at the top of the BL.

The differences between ExPERT site profiles, which include realistically lapsing temperature and dewpoint with height, and standard-atmosphere vertical profiles of extinction through the BL are clearly illustrated in Fig. 3. Differences among individual ExPERT site profiles are almost as dramatic when comparing sites that typically have soluble aerosols with sites characterized by insoluble aerosols. Midlatitude sites typically have aerosol mixtures that are predominantly water soluble, whereas desert aerosols are typically more mineral based and are much less water soluble (Hess et al. 1998; Fiorino et al. 2007). In an effort to demonstrate that such an elevated “spike” in aerosol scattering does occur in BLs that are characterized by soluble aerosols and that the spike is not as evident in BLs that are characterized by insoluble aerosols or very dry conditions, three sites from lidar experiment studies were selected and the data were compared with LEEDR-modeled data. In addition, each of the three experiment studies selected for comparison used lidars of a different wavelength—further demonstrating LEEDR’s capability to model virtually any laser wavelength.

Figure 5 compares lidar data from the Spinhirne et al. (1980) study conducted near Tucson, Arizona (a desert site; approximately 32°N, 111°W), with a 690-nm lidar in November 1975 with LEEDR-modeled data. The Spinhirne et al. plots in Fig. 5 show relatively constant particulate (aerosol) scattering extinction with height in the BL—with some minor zigzagging around ~0.018 km⁻¹ scattering loss. The Spinhirne et al. particulate plot suggests with the marked dropoff in aerosol...
backscatter near 2500 m that this was the top of the well-mixed BL on that particular day. Therefore, the simulation in LEEDR used a BL height of 2500 m at the ExPERT site near Tucson (Davis-Monthan Air Force Base); GADS winter aerosols for a latitude and longitude of 32°N, 111°W; visibility of 90 km; and Ground Level tab surface conditions appropriate for the location for a November afternoon (T = 22°C and Td = −2°C). The visibility of 90 km is reasonable given the observations for the date, time, and location but was set somewhat arbitrarily to make the LEEDR aerosol scattering approximately the same value as the Spinhirne et al. particulate values. The point here is not that the magnitudes of the Spinhirne et al. and LEEDR aerosols scattering data are nearly the same, it is that the aerosol scattering profiles are similar with no very marked elevated spike in extinction. It is worth mentioning that both scattering plots do show a small spike at the top of the BL but not at all like that seen in the right panel of Fig. 3 and in Figs. 6 and 7. This relatively constant aerosol scattering extinction with height is expected given the predominant insoluble-aerosol type for the site and the low RH of the desert BL. Note that the plots in Fig. 5 match more closely with the standard-atmosphere plots in the left panel of Fig. 3.

Figure 6 compares lidar data from the Matthias and Bosenberg (2002) study conducted near Hamburg, Germany (a midlatitude site; approximately 54°N, 10°E), with a lidar operating at both 355 and 351 nm in August 1998 with LEEDR-modeled data. The Matthias and Bosenberg plots (all derived from aerosol backscatter only) in Fig. 6 are considerably different from the Spinhirne et al. LEEDR plots in Fig. 5 in that the Hamburg data display a very marked elevated spike in aerosol scattering extinction. The Matthias and Bosenberg data suggest that the depth of the well-mixed layer was about 1900 m. The comparison simulation in LEEDR for Fig. 6 used a BL height of 1900 m at the Hamburg ExPERT site; GADS summer aerosols for a latitude and longitude of 54°N, 10°E; visibility of 40 km; and climatological evening surface conditions for Hamburg for August (T = 20°C and Td = 12°C). Again, the visibility setting of 40 km is reasonable given the observations for the date, time, and location but was primarily set to make the LEEDR aerosol scattering approximately the same value as the Matthias and Bosenberg values. An important finding is that both the LEEDR plots and the Matthias and Bosenberg plots clearly indicate an elevated aerosol extinction layer that is due to aerosol scattering effects. In addition, the Matthias and Bosenberg dual-angle measurement obtained a surface value; this result shows that the ~0.4 km⁻¹ difference from the surface to the upper BL maximum in extinction predicted by LEEDR is supported by observations. In the LEEDR aerosol scattering profile, the reason for the increase in scattering extinction with height is the increase in the sizes of the soluble aerosol distributions in response to the increase of RH from a surface value of 59% to ~100% from 1000 to 1900 m. It is assumed that the increase in scattering
extinction seen in the Matthias and Bosenberg plots is due to the same reasons.

Maritime aerosols tend to be salt based and are highly soluble. Thus, it could be expected on the basis of the comparisons seen in Fig. 6 that maritime BLs could also show an elevated spike in extinction, but in a BL with less depth than is typically found over land. Figure 7 compares spaceborne lidar data from the Hart et al. (2005) study of the measurements collected from the 532-nm Geoscience Laser Altimeter System (GLAS) on the Ice, Cloud, and Land Elevation Satellite (ICESat) in October 2003 with LEEDR-modeled data. Of interest is that the data from the GLAS ocean path selected for illustration by Hart et al. show an extinction peak at just over 500 m above the surface—this peak corresponds fairly well to LEEDR’s assumed BL height of 500 m for all oceanic sites. For comparison with LEEDR, an Indian Ocean point at 5.3°N, 54.4°E; both ANAM and GADS aerosols; 50-km visibility; and default summer climatological conditions (\(T = 26^\circ\text{C}, T_d = 24^\circ\text{C},\) and sea surface temperature = 25.7°C) were considered. The LEEDR plots for 532 nm in Fig. 7 show scattering extinction peaks that are just below the GLAS peaks, but with the extinction values for the ANAM plots peaking at much higher values than both the observed GLAS data and the modeled GADS aerosol plot. Note that the ANAM aerosols were specifically developed to match wind-driven ocean aerosols whereas the GADS aerosols were developed with an emphasis on overland characterization but that it is the GADS aerosol characterization that matches the observed GLAS data more closely in Fig. 7.

In summary, the LEEDR extinction profiles correctly simulate measured aerosol extinction profiles in terms of profile shape with height and, in the overland cases, closely match actual extinction values.

b. RMSE results

Figure 8 details the WPAFB temperature and dewpoint temperature RMSEs (°C) within the BL of the Ground Level tab and climatology profiles as compared with the radiosonde. The dotted, dashed, and dot–dashed lines are averages as defined in the legend (Randall et al. 2011).
different marker styles represent the Ground Level tab and climatology RMSEs for temperature and dewpoint temperature plotted against the launch date of the comparative control radiosonde at 1200 UTC (0600–0900 LT). The different line styles represent the average temperature or dewpoint temperature RMSEs considering all 25 winter 1200 UTC cases for either the Ground Level tab or climatology. It is important to note that both the temperature and dewpoint temperature mean errors for the BL profiles created using the Ground Level tab (labels Mean RMSE Temp Grnd Tab and Mean RMSE Dwpt Grnd Tab) are below the error values produced from the climatology profile (Mean RMSE Temp Climo and Mean RMSE Dwpt Climo). This result indicates that the Ground Level tab profiles created in LEEDR for the site studied for 1200 UTC are on average closer to the measured radiosonde temperature and dewpoint temperature profiles. (Randall et al. 2011)

Figure 9 details the temperature and dewpoint temperature RMSEs for the BL of the Ground Level tab and climatology profiles as compared with the control radiosonde. These RMSEs are calculated from the 25 winter 0000 UTC (1800–2100 LT) cases, however. The coded line and marker styles represent the same variables as in Fig. 8. Both the temperature and dewpoint temperature mean errors for the BL profiles created using the Ground Level tab (Mean RMSE Temp Grnd Tab and Mean RMSE Dwpt Grnd Tab) are less than the error values produced from the climatology profile (Mean RMSE Temp Climo and Mean RMSE Dwpt Climo). This result indicates that the Ground Level tab profiles created in LEEDR for 0000 UTC are also on average closer to the measured radiosonde temperature and dewpoint temperature profiles. (Randall et al. 2011)

The 1200 UTC plots represent a morning scenario during the winter at WPAFB, and the 0000 UTC plots represent an evening scenario. Figures 8 and 9 indicate that the temperature RMSE value is approximately 2.3°C greater in the morning. This increased error is due to surface temperature inversions in the radiosonde data that are not captured by LEEDR. LEEDR characterizes the temperature and humidity within the BL from surface data according to (1)–(3) without regard to the possibility of a nonadiabatic or stable BL. Therefore, if a temperature inversion is present, the modeled Ground Level tab profile will be more dissimilar than usual beginning just
above the surface, as displayed in Fig. 10. It is evident from Figs. 8–10, however, that (on average) using the Ground Level tab is more beneficial than disregarding available observed surface parameter measurements even if an inversion (that is not captured by LEEDR) is present (Randall et al. 2011).

Figure 11 shows composite winter 0000 and 1200 UTC average RMSE values for both the temperature and dewpoint temperature from profiles created with the Ground Level tab and profiles created with climatology for all 50 winter radiosonde cases. From Fig. 11 one can quickly surmise that, when considering all 50 winter radiosonde comparisons, the difference between the RMSE calculated from using the Ground Level tab and that using the climatology is approximately 6°C for dewpoint temperature and 3°C for temperature.

For the summer comparison portion of this study, ILN radiosonde data covering the period from June through August 2010 were collected. As was done for the winter comparisons, 25 radiosonde profiles were chosen from each time group (1200 and 0000 UTC) on the basis of accompanying observations indicating clear or scattered cloud conditions. Therefore, a total of 50 launches from the ILN site were used as the control for the summer comparisons. Because at a midlatitude site like WPAFB summer temperatures and dewpoints exhibit smaller deviations from climatology than is observed in the winter, it was anticipated that the differences between the Ground Level tab BL characterizations and the climatology BL characterizations, along with the overall RMSEs, would all be smaller for the summer comparisons.

Figures 12 and 13 summarize the summer comparison results; these figures are analogous to the winter comparisons in Figs. 8 and 9, respectively. The results captured in these figures confirm the anticipated smaller climatology versus observed differences and RMSEs from the control radiosonde values. These smaller summer differences and RMSEs are likely due to the midlatitude summer season having smaller temperature gradients, temperature and moisture fluctuations, and deviations from climatology (Wallace and Hobbs 2006). In addition, summer is characterized by more daylight and no snow cover—both of which reduce the occurrence of temperature inversions (Wallace and Hobbs 2006) that

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**Fig. 10.** Realization of the atmospheric temperature and dewpoint profiles determined from radiosonde observations, ExPERT climatological data, and Ground Level tab user input data (labeled as LEEDR BL). Note that the inversion evident in the radiosonde data can cause differences in the Ground Level tab profile vs the radiosonde profile that would not be present without the inversion. Note also that the BL height is set at 800 hPa for the LEEDR climatology and Ground Level tab profiles because it corresponds to the approximate RL (Randall et al. 2011).
can degrade the Ground Level tab performance. Temperature inversions, like the one seen in the winter radiosonde plot in Fig. 10, are still evident in many of the twenty-five 1200 UTC (morning) summer soundings but are not evident at all in the summer 0000 UTC profiles; the lowest RMSE values are consequently found for the 0000 UTC BL temperature profiles created with the Ground Level tab, as seen in Fig. 13. Of interest is that the summer morning inversions appear to have allowed the climatology BL temperature profiles to have slightly smaller RMSEs than the Ground Level tab profiles at 1200 UTC; this is shown in Fig. 12.

Figure 14 plots the mean composite RMSEs for the summer season. Considering all 50 summer radiosonde comparisons, the difference between the RMSE calculated from using the Ground Level tab and that using the climatology is approximately 1.2°C for dewpoint temperature and for temperature.

It is important to also understand the tolerances of the radiosonde sensors used for this study. The specific instrument tolerances are listed in Table 3. The RH tolerance represented as a percentage indicates that its actual value will be variable depending on the observed temperature. This variance also affects the known dewpoint temperature tolerance value. Thus, an approximated tolerance value for the dewpoint is ±1.5°C. It can be concluded then that the temperature and dewpoint temperature overall mean RMSE values from both the winter and summer LEEDR-modeled profiles are significant in that they exceed the sensitivity tolerances of the radiosonde sensors (Randall et al. 2011).

Figure 15 shows the vertical temperature, dewpoint, and RH profile mean RMSE for WPAFB through the BL (from the surface to the BL height as defined in Table 1) for each time and season (Burley 2012). Temperature, dewpoint, and RH profiles are all better predicted by the GFS numerical forecasts than by the 50th-percentile ExPERT data and the Ground Level tab for all seasons and times of day. The 12-h forecast performs the best of the three forecasts; the improvement from the 48- to the 24-h forecast is relatively small as shown by the fact that for almost all cases the difference in values is less than the uncertainty associated with the measurement instruments as listed in Table 3. The Ground Level tab outperforms the climatology data in terms of RH and temperature profiles for all but the summer 1200 UTC times. This result is due to the presence of small temperature inversions in many of the 1200 UTC summer soundings that introduced slightly larger errors in the Ground Level tab temperatures than in the climatology temperatures. The U.S. Standard Atmosphere, 1976 also has smaller RMSE differences than the ExPERT climatology and
the Ground Level tab in RH for the same time and season yet has larger RMSE differences both in terms of temperature and dewpoint for all cases. Surprising is that the U.S. Standard Atmosphere, 1976 has smaller RMSE differences than all other atmospheres, including forecasts, in terms of RH prediction for the winter 0000 UTC case. While the seasonally unvarying U.S. Standard Atmosphere, 1976 temperature and dewpoint values are rarely representative of actual conditions or climatology, the dewpoint depression difference results by coincidence in RH values that are apparently representative of the winter 0000 UTC conditions in this study. In general, errors for all summer 1200 and 0000 UTC atmospheres are lower than those for corresponding winter times. For all but the 1200 UTC time Ground Level tab and winter standard-atmosphere profiles, the dewpoint mean RMSE is larger than the temperature mean RMSE (Burley 2012). Typically, temperature is more accurately measured than moisture (dewpoint) and exhibits less climatic variability than is the case for dewpoint measurements, and therefore it is somewhat expected that temperature RMSE would be smaller than dewpoint RMSE. The U.S. Standard Atmosphere, 1976 provides dewpoint values that are more closely aligned with winter values for WPAFB than with summer values; this situation leads to lower winter dewpoint RSME values for the standard-atmosphere dewpoint. Temperature RSME slightly exceeds dewpoint RSME in the 1200 UTC Ground Level tab results because morning temperature inversions that are not accounted for in the Ground Level tab calculation method introduce errors in the mean BL temperature comparisons.

While these meteorological results support our conclusion that using the LEEDR Ground Level tab will more closely model a realistic atmospheric profile, impacts of these results on potential HEL military operations were simulated using a newly developed prototype, HELTDA, to highlight possible effects on HEL mission planning.

c. HELTDA results

Dwell-time RMSE in seconds for engagement scenarios involving HEL systems operating at 1.045 and 1.31525 μm in the BL at WPAFB are depicted in Fig. 16 (Burley 2012). These two wavelengths were chosen for simulation because they represent potential HEL operating wavelengths and are affected in significantly different ways by the atmosphere. It was hypothesized
that atmospheric characterization methods corresponding to improved prediction of vertical profile meteorological parameters (temperature, dewpoint, RH, wind speed, and wind direction) would yield improved dwell-time predictions. The left column of Fig. 16 shows that in some cases the exact opposite is true at the 1.045-μm wavelength. The U.S. Standard Atmosphere, 1976 yields a wide range of dwell-time errors depending on season and time of day. This is expected, as the same trend was visible in the vertical profile simulations because of the rigid characterization methods of the standard atmosphere that only vary with altitude and not with location, time, or season. Despite a better average characterization of all atmospheric parameters in the vertical profile, the Ground Level tab profile fails to outperform the climatology profile for all but the winter 0000 UTC case. Note the large increase in errors between the summer 0000 UTC and summer 1200 UTC results for 1.045-μm cases. This is most likely due to the relatively large RH errors for summer mornings (see Fig. 15) when the RH value is often near 100%; small changes in RH at values near 100% can have a significant effect on aerosol size distributions that are the primary attenuators of 1.045-μm laser-beam energy.

Despite providing a vertical resolution of only three layers (surface, 925 hPa, and 850 hPa), the GFS forecasts compare favorably to or outperform in terms of RMSE differences the U.S. Standard Atmosphere, 1976 as well as the climatology and the Ground Level tab for all seasons and times of day. The improvement gained by using a shorter forecast lead time (e.g., using 24 vs 48 h) is minimal for all cases except the summer 0000 UTC 1.315 25-μm case. The best forecast is actually provided at 48 h for the 1.045-μm winter 1200 UTC case. The forecast advantage over climatology ranges from 0.6 to 8.2 s. This result suggests that atmospheric characterization through the use of forecast data can on average provide a better prediction of dwell-time requirements. Without going into the specifics of weapon-system engagement scenarios, the general idea of a HEL weapon system is that it will have a firing capacity of 30–40 s before recharge and temperature stabilization are needed. The intent is not to use the entire capacity of the laser on one target. It would be optimal to successfully engage as many targets as possible before a potentially time-consuming recharge is necessary. It is militarily more advantageous to engage six targets with 5-s dwell times than five targets with 6-s dwell times (Perram et al. 2010). Thus, the results shown in Fig. 16 strongly
suggest that GFS data can optimize HEL weapon system performance by allowing a greater number of targets to be engaged with each laser-firing cycle of the HEL system.

Molecular absorption in the atmosphere is primarily attributed to water vapor, and the 1.045-μm line is considered to be a “clean” line with minimal molecular effects (Perram et al. 2010). Aerosol scattering is modeled as a function of aerosol size. As noted in section 2, LEEDR assumes Mie scattering for aerosols, and the extinction coefficient is a function of wavelength and aerosol size. Aerosol size distributions in this simulation are taken from the GADS database and are modified for varying RHs with height according to (6). Whereas dewpoint is a direct measure of the amount of water vapor in the atmosphere, RH is dependent on temperature and dewpoint variations.

The unexpected results for the climatology and Ground Level tab profiles at the 1.045-μm wavelength can be explained by the combination of these nonlinear processes in a multivariable problem. While each atmospheric parameter examined in the vertical profile was shown to have less error for the Ground Level tab profiles, the nonlinear combination results in a larger dwell-time error. For lasers that operate at high water absorption lines, such as 1.31525 μm, these factors do not have nearly as significant an influence.

It is important to note that the control data for this simulation do not include any aerosol size data. All atmospheres are simulated by assuming the GADS database for aerosol distributions. Although this approach provides a realistic estimate of aerosol number densities and size distributions, it does not represent actual conditions. The inclusion of these data acquired in situ would most likely change the control results to some degree. These data were not available for analysis; their inclusion could prove significant in performance assessments.

For the engagements seen on the right side of Fig. 16, the nonlinear effects do not affect the dwell-time errors in the same manner. This result is due to the molecular absorption at 1.31525 μm. Aerosol extinction continues to be larger in magnitude in comparison with molecular absorption; molecular absorption induces thermal blooming, however, which produces a larger effect in dwell time.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Instrument tolerance</th>
<th>Instrument response time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RH</td>
<td>±5%</td>
<td>In seconds</td>
</tr>
<tr>
<td>Temperature</td>
<td>±0.3°C</td>
<td>&lt;4</td>
</tr>
<tr>
<td>Pressure</td>
<td>±0.5 hPa</td>
<td>&lt;1</td>
</tr>
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</table>
In terms of mathematics, the effects of thermal blooming can be quantified through the use of a strength index called the thermal blooming distortion number $N_d$ (Perram et al. 2010):

$$N_d = \frac{4\sqrt{2}kP}{\rho_0 C_p} \int_{\text{path}} \frac{a(z)\tau(z)n_T(z)}{V_{\text{wind}}(z)D(z)} dz,$$

where $z$ in this case is distance along the total slant path of the beam, $a(z)$ is the absorption coefficient, $V_{\text{wind}}$ is the effective wind speed, $k$ is wavenumber, $D(z)$ is the beamwidth, $\tau(z)$ is the transmission at range $z$, $n_T(z)$ is the thermal refractive gradient, $\rho_0$ is the surface atmospheric density, and $C_p$ is the specific heat at constant pressure for dry air. Equation (8) demonstrates that an increase in absorption will cause an increase in thermal blooming distortion of the beam and that an increase in the wind blowing across the beam will reduce the effects of thermal blooming. Thermal blooming is also modulated by the amount of scattering that is present in relation to the absorption; this effect is captured with the transmission parameter in the numerator of (8).

Thermal blooming is directly affected by the amount of water vapor in the atmosphere, which is directly measured by dewpoint; therefore, a better prediction of water vapor leads to a better prediction in dwell time when thermal blooming is the dominant attenuation mechanism. For WPAFB, the Ground Level tab outperforms the climatology for all times and seasons in dewpoint prediction and dwell-time prediction for the 1.315 $\mu$m scenario. Note that at this wavelength during the summer the standard atmosphere is the worst characterization but that in the winter it is nearly equivalent to the climatology. This result is because the nonseasonally varying standard-atmosphere dewpoint characterization is close to climatological dewpoint values for winter at WPAFB.
5. Conclusions

This research compares the LEEDR vertical profiles created from input surface observations with actual observations from radiosonde balloon launches. Results are then compared with the modeled LEEDR climatological sounding for the same time of day and season. Differences from the truth radiosonde data are calculated and quantified as RMSEs. These RMSEs are found to be smaller for profiles created from surface observations than for those made from climatological data for the same season and time. Furthermore, impacts of these differences are demonstrated with a relevant tactical HEL simulation, the HELTDA. By using the RMSE calculations as described herein—based on the 50 winter, clear-day radiosonde scenarios and 50 summer, nearly clear-day radiosonde launches—the average error produced when creating a winter atmospheric profile by using the Ground Level tab is smaller by a factor of roughly 1.8–2.5 than that for a purely LEEDR climatologically based profile and by approximately 20%–25% when creating a summer profile. These errors not only affect the ability to accurately characterize the atmosphere, they could have a significant impact on operational missions involving directed-energy platforms.

Advantages in atmospheric characterization must translate to expected high-energy-laser performance advantages to have a significant impact on operations. For relevant engagement scenarios, dwell-time errors differed significantly from the hypothesized results. Variability in the standard atmosphere’s meteorological performance translated to variability in dwell-time error. In some cases, standard atmospheres continued to provide accurate results, yet the confidence in reported dwell times would be extremely limited in a real-world engagement scenario. On the basis of vertical profile validation results, however, it was hypothesized that HEL engagement dwell times would be better predicted by Ground Level tab atmospheres than by climatology for most locations, seasons, and times. This conclusion was not true for the 1.045-μm wavelength, indicating a wavelength dependence for the performance prediction results.

Despite the fact that most meteorological parameters were better characterized by the Ground Level tab than by climatology, the overall dwell-time results were worse. For the 1.31525-μm wavelength, the Ground Level tab
consistently outperformed climatology as hypothesized. This discrepancy is credited to the increased effects of water vapor–induced thermal blooming at the 1.315-μm wavelength as a result of molecular absorption (which is not nearly as significant at 1.045 μm) and to the multivariate nature of the total dwell-time calculation.

The Ground Level tab input into LEEDR allows a more accurate atmospheric characterization for any radiative transfer scenario at any wavelength from 350 nm to 8.6 m, which in turn permits better high-spectral-resolution atmospheric compensation or correction for a wide variety of remote sensing applications. This research additionally shows that utilization of numerical weather prediction data, such as widely available GFS data, improves even further the atmospheric characterization in terms of simulating expected high-energy-laser performance.

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