Abstract

The California Research at the Nexus of Air Quality and Climate Change (CalNex) and Carbonaceous Aerosol and Radiative Effects Study (CARES) field campaigns during May and June 2010 provided a data set appropriate for studying the structure of the atmospheric boundary layer (BL). The NASA Langley Research Center (LaRC) airborne High Spectral Resolution Lidar (HSRL) was deployed to California onboard the NASA LaRC B-200 aircraft to aid in characterizing aerosol properties during these two field campaigns. Measurements of aerosol extinction (532 nm), backscatter (532 and 1064 nm), and depolarization (532 and 1064 nm) profiles during 31 flights, many in coordination with other research aircraft and ground sites, constitute a diverse data set for use in characterizing the spatial and temporal distribution of aerosols, as well as the depth and variability of the daytime mixed layer (ML) height. This work illustrates the temporal and spatial variability of the ML height in the vicinity of Los Angeles and Sacramento, CA to evaluate how a stationary measurement is representative of a larger region. In the LA Basin, ML heights derived from HSRL measurements and compared to ML height derived from a ceilometer result in a mean bias difference of 10 m for regions up to 30 km away from the ceilometer site, but increase to over 200 m for larger distances. In Sacramento, ML heights from two radiosonde profile sites at different elevations (30 m and 454 m MSL, respectively) are within 150 m of the ML heights derived from HSRL at a distance of 15 km from the sites. Simulated ML heights from the Weather Research and Forecasting Chemistry (WRF-Chem) community model are compared with HSRL ML heights to evaluate the models performance. When compared to aerosol ML heights from HSRL, thermodynamic ML heights from WRF-Chem were under predicted, shown by a bias difference value of -157 m in the CalNex region, but over predicted with a bias difference of 220 m in the CARES region. WRF-Chem simulations of aerosol backscatter profiles are used to derive ML heights in the same manner as HSRL aerosol backscatter profiles. ML heights derived from these WRF-Chem aerosol backscatter profiles as well as the standard ML heights derived from WRF-Chem simulations of potential temperature show similar agreement to the ML heights derived from the HSRL aerosol backscatter profiles.

Introduction – Revision Version

Since the mid 1960s, scientists have been researching different methods in order to determine the height of the atmospheric boundary layer (BL) within the troposphere (Hosler and Lemmons, 1972; Stull, 1988; Heffter, 1980). The BL, also known as the convective boundary layer (CBL), results in roughly uniform vertical profiles of moisture and potential temperature within that layer (Stull, 1988). A study in San Diego conducted in late 1971 and early 1972 (Noonkester et al., 1974) assessed the similarities and differences in lidar and high-resolution microwave radar echoes in measuring parameters within the BL. In the 1981 NASA Goddard Space Flight Center report, Atlas and Korb (1981) examined the potential for using lidar observations for researching weather and climate. A portion of the report presents the use of aerosol profile measurements for determining BL heights and utilizing this data in regional and global forecasting models through incorporation of the BL height as a prognostic variable.

The National Research Council (2009) points to inadequacies in current national mesospheric observational capabilities necessary for addressing priorities like forest wildfire smoke dispersion, more extensive air quality forecasting, short-range forecasting of high-impact weather, and support to regional climate modeling. In particular, vertically resolved mesoscale observations are lacking and the report specifically recommends that determining the height of the atmospheric BL should be one of the highest priorities for addressing these inadequacies. There is also interest in BL height research for incorporation into weather and air quality forecasting models and for climate studies. The Department of Energy's Atmospheric System Research program includes in its science plan (Department of Energy, 2010) the importance of measuring and studying PBL heights by analyzing aerosol and cloud interactions, topographic features and tropospheric dynamics, which would be included in the development and evaluation of forecasting models.

Several studies have examined how well various models perform when compared with BL heights derived from a radiosonde or a lidar. Angevine and Mitchell (2001) evaluated the National Centers for Environmental Prediction

(NCEP) Mesocale Eta model using select radiosonde profiles during the summer months of 1997 and 1998 at the University of Illinois Bondville Road field site near Champaign-Urbana and again during the summer months of 1999 at the Cornelia Fort site in Nashville, Tennessee. The authors concluded that during the hours between 1400 and 2300 UTC (0800 and 1700 Central Standard Time), the Eta model is reasonably accurate (correlation coefficients (R) ranged from 0.75 to 0.82) compared to those heights derived from the radiosonde. During two of the three years, the comparisons were worse in the afternoon hours due to the prevalent cumulus cloud cover. Morning correlation coefficients (R) were ~ 0.75 and were as low as 0.26 and 0.5 during the afternoon. A ground-based lidar was used to measure aerosol backscatter and estimate BL heights in the urban city of Zanjan, Iran. The lidar-estimated BL heights were compared to simulated BL heights from the Fifth-Generation Mesoscale Model (MM5) (Bidokhti et al., 2008). Additionally, lidars on satellites have been utilized to evaluate models on a global scale. Measurements from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) on the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite are used to validate the Goddard Earth Observing System-version 5 (GEOS-5) Modern-Era Retrospective analysis for Research and Applications (MERRA) PBL heights (Jordan et al., 2010). Extensive comparisons between the model output and the satellite observations in the Western Hemisphere and over Africa resulted in correlation coefficients (R) ranging from 0.47 to 0.73. Furthermore, this study provided insight to regional PBL height variances that might not be detected by a global circulation model. PBL heights from the global European Centre for Medium-Range Weather Forecasts (ECMWF) model were evaluated using PBL heights derived from the Geoscience Laser Altimeter System (GLAS) (Palm et al., 2005). The ECMWF BL heights were generally lower than the GLAS-derived ML heights over the ocean, but small-scale and global patterns of BL heights revealed similar features.

Several field campaigns have included comparisons of BL heights. The Atmospheric Mass Balance of Industrially Emitted and Natural Sulfur (AMBIENS) experiment in October 1977 estimated PBL heights with sodar, lidar, and temperature profiles from a double theodolite balloon-tracking system (Coulter, 1979). During the 1992 Atlanta field intensive (Marsik et al., 1995), a combination of lidar, radiosonde, and wind profiler measurements were used to derive the BL heights, and a comparison was made between all three methods and results. The Pacific 1993 field campaign (Hayden et al., 1997) analyzed the vertical, chemical, and meteorological structure of the BL heights in the lower Fraser Valley near Vancouver, Canada. This study utilized aircraft lidar, in situ instruments, and radiosondes to derive the BL heights. In early 2000, ground-based European Aerosol Research LIdar NETwork (EARLINET) and radiosondes were used to detect the seasonal evolution of BL heights (De Tomasi and Perrone, 2006) near Lecce, Italy for a period of two years. Since Lecce is located on a peninsula, the study also analyzed the effects of the sea breeze on the BL heights. In general, these previous studies have demonstrated the ability to compute BL heights from a variety of instruments and methods. However, the majority of these studies rely on measurements obtained at limited number of sites so that the spatial variability of the boundary produced by models cannot be fully evaluated. In the current study, measurements acquired by the , the NASA Langley Research Center (LaRC) airborne High Spectral Resolution Lidar (HSRL) during recent science campaigns are used to evaluate the spatial and temporal variabilities of the BL Height.

In this paper, the BL heights will be referred to in this article as the mixed layer (ML) height (Hayden et al., 1997; Seibert et al., 2000; Stull, 1988; Tucker et al., 2009). Tucker et al. (2009), defines the ML height as the volume of atmosphere in which aerosol chemical species emitted within the BL are mixed and dispersed and is applicable to what we are deriving from the airborne HSRL. This term will be used for both lidar/ceilometer and radiosonde measurements. In areas where it might be necessary to denote which ML height we refer to, we will add “aerosol” when discussing the lidar/ceilometer-derived heights and “thermodynamic” when referring to heights derived from potential temperature. These terms will also apply for the WRF-Chem model as well when we discuss modeled thermodynamic profiles and modeled backscatter.

This paper presents the methodology used to derive ML heights from airborne HSRL measurements of aerosol backscatter and describes how these ML heights are used to evaluate modeled ML heights from the 2010 CalNex and CARES field campaigns. Portions of the flights during these field campaigns occurred over complex terrain in California. Multiple methods are used to derive ML heights and compare measured and simulated ML heights. Section 2 summarizes the locations, instruments involved, and science questions that are addressed for the CalNex and CARES. Section 3 describes the data products from the airborne HSRL instrument and the WRF-Chem model, and provides an overview of the methods used to calculate the ML heights. Section 4 is discusses these analyses in the context of the CalNex and CARES campaigns and summarizes the HSRL ML height values in comparison with the ML heights from radiosondes, a ceilometer, and the WRF-Chem model. Lastly, in Section 5, the a comparison between the measured and modeled ML heights is presented along with a discussion of how these results may guide future model developments.