Atmospheric Research 264 (2021) 105825

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

When and where horizontal advection is critical to alter atmospheric boundary layer dynamics over land: The need for a conceptual framework

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ARTICLE INFO

Keywords:
Atmospheric boundary layer
Horizontal advection
Temporal variability
Complex terrain
Frontal system

ABSTRACT

The thermodynamic properties of the atmospheric boundary layer (ABL) play an important role in several atmospheric processes such as convection initiation, turbulence mixing, the exchange of heat and momentum, and cloud-microphysics. Since the ABL depth (henceforth, BLD) defines the volume of the ABL, many studies consider BLD to be a key scaling parameter to understand and quantify ABL mixing processes. However, most of these studies attributed both BLD temporal and horizontal variability on various scales solely to the impact of underlying surface forcing via locally generated buoyancy fluxes and static stability. We argue that the impact of horizontal advection is often neglected yet important for a more thorough understanding of ABL thermodynamics and kinematics. Here we identified four potentially advection-dominated ABL regimes across (1) the urban-rural interface, (2) complex terrain and adjacent plains, (3) the land-sea interface where horizontal transport of marine boundary layer airmasses influences the regional ABL over coastal areas, and (4) frontal environments where mid-latitude cyclones affect ABL processes via passages of cold and warm frontal boundaries. We then introduced a conceptual framework based on observations so that ABL processes are explained not only by surface forcing but also by horizontal advection of mass, momentum, and energy. This work will help advance our understanding of ABL processes and single out potential sources that trigger drastic changes in ABL thermodynamic features including the BLDs under diverse horizontal advection environments.

1. Introduction

The atmospheric boundary layer (ABL) is a critical interface trading mass, energy, and momentum between the surface and free troposphere (FT) via turbulence (Stull, 1988). The ABL, being the link between the surface and the large-scale atmosphere, acts as the short-term "memory" of land-atmosphere interactions on a diurnal timescale and governs the distributions of aerosols, pollutants, greenhouse gases, and trace gases. Thus, the ABL plays an important role for (i) forming clouds and convection initiation (Pal et al., 2008), (ii) governing air quality and human health (Miao et al., 2019), (iii) improving forecasting of severe storms and climate projections (Cohen et al., 2015), (iv) guiding production of renewable energies (Stevens et al., 2015), and (v) other interwoven processes that influence climate, weather and air pollution (NASEM, 2018a).

The dynamical and physicochemical processes taking place in the ABL significantly impact all major atmospheric phenomenon and mechanisms taking place on timescales from short-term weather to longer-term climate. In addition to ground-based measurements, both aircraft and satellite missions for studying ABL processes are critical for the investigation of morphological differences in ABL kinematics and thermodynamics across different regions and seasons. Recently, NASA''s earth science decadal survey selected high-resolution observations and simulations of the ABL as a targeted observable for future airborne and spaceborne missions toward defining critical ABL science questions (NASEM, 2018b; Teixeira et al., 2021). Thus, an improved understanding of ABL thermodynamic features and their interactions with the underlying surface (e.g., land, ocean, ice surface) have potential implications for improving weather and air quality forecasts. Additionally, a better understanding of the ABL under diverse weather conditions over

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https://doi.org/10.1016/j.atmosres.2021.105825
Received 14 January 2021; Received in revised form 26 July 2021; Accepted 23 August 2021
Available online 26 August 2021

different land-surfaces is critical for advancing numerical models and improving parameterizations (e.g., Teixeira et al., 2008; Koffi et al., 2016). For instance, the combined effort using high-resolution observations and simulations help (1) improve the model physics; (2) perform data assimilation to improve model simulations (Tangborn et al., 2021); and (3) develop calibrated ensembles (Reen et al., 2014). Therefore, unprecedented observations of meteorological parameters within and above the ABL on diurnal, synoptic, subseasonal-to-seasonal, annual-to-interannual, and decadal timescales and a conceptual understanding of the ABL processes on micro, *meso*, synoptic, large, and global scales are important in the regime of a rapidly changing climate (Davy and Esau, 2016). Due to the rapid development of in-situ, and active and passive remote sensing instruments in the past few decades and their deployments from ground, aircraft, unmanned aerial vehicles, balloons, and spaceborne platforms, significant progress has been made in our understanding of the physical processes taking place in the ABL (Pal and Haeffelin, 2015).

Nevertheless, the impact of horizontal advection on ABL kinematics and thermodynamics has remained underexplored across complex interfaces originating in the (1) coastal regions linking marine and continental ABL airmass; (2) mountain-plain interfaces via advection of elevated mixed-layers (EMLs) far downstream from mountains to plains; (3) urban-suburban-rural interfaces via transporting urban boundary layer (UBL) airmasses over adjacent suburbs and rural regions, where advection of state variables via the mean wind can have as dominant an effect as turbulence in either a regular or quasi-regular manner; and (4) two different airmasses across frontal boundaries (e.g., warm and cold air streams) via mid-latitude cyclones affecting ABL features in both warm and cold sectors (Boutle et al., 2010).

In the past literature, it was clearly documented that most of the studies investigating ABL diurnal, seasonal, inter-annual variability ignore the contribution of advected airmasses while reporting their findings (Batchvarova and Gryning, 1991; Pal and Haeffelin, 2015). All four types of advections previously mentioned have important implications for meteorological processes from micro-through-meso-to-synoptic scales. The set of equations defining the kinematics, thermodynamics, and turbulent exchange in the ABL consider the existence of advective terms (Stull, 1988). However, there remains a question of surface homogeneity and flow stationarity when such a set of equations is considered.

To resolve the factors driving turbulent ABL regimes and ABL thermodynamic structures across aforementioned interfaces and during diverse weather conditions, large-eddy simulations (LES) were found to be an excellent tool (e.g., Lesieur and Métais, 1996; Nakayama et al., 2012; Stoll et al., 2020). Using a combination of the mixed-layer theory, LES, and observations, Pietersen et al. (2015) estimated the contributions of the advection of heat, moisture, and subsidence on the ABL development and found BLDs were overestimated by 70% when they only considered surface and entrainment fluxes, thereby underscoring the importance of considering advection and subsidence. Lastly, they found that the advection of airmasses, via both synoptic and mesoscale circulations, affected the BLD variability. Other researchers have used LES to investigate the impact of the dynamic processes of advection induced by different airmass circulations and exchanges. Cheng and Porté-Agel (2015) and Giometto et al. (2016) studied changes in the effective mixing length and roughness parameters for an idealized and realistic urban surface, respectively. Calmet and Mestayer (2016) used LES to investigate the development and evolution of the thermal internal boundary layer across land-sea interface in the complex coastal area of Marseille, France. Gopalakrishnan and Avissar (2000) found remarkable influences on particle dispersion, implying the heterogeneous ABL features in the ABL over mountain-plane interfaces. Thus, LES-based studies provided important guidance on the role of advection on BLD variability.

Additionally, past studies have explained the changes in ABL features under conditions of cold outbreaks and warm air mass advection (e.g., Klysik and Fortuniak, 1999). However, it is important to obtain the correct surface layer parameterization and further formulate the extension of the surface layer fluxes into the mixed layer since the fluxes above the atmospheric surface layer are modified by the presence of such advective flows. Additionally, advection is particularly important at times over specific areas, such as coastal environments or over horizontally flat terrain where one section is burnt or arid and a nearby area is vegetated. In these cases, advective terms may potentially violate the hypothesis of the separation of the microscale turbulence spectrum and synoptic mode of the time variation of mean horizontal wind speed.

Consequently, here, we focus on the concept that advection of contrasting airmass regimes is an important physical process in the ABL investigations. Thus, as was achieved using numerical simulations (e.g., the urban Weather Research and Forecasting (WRF) model or u-WRF, Chen et al., 2011a; Wong et al., 2019) to improve UBL simulations, there is also a great need for an observation-based approach for investigating ABL kinematics and thermodynamic features downwind of city centers that advect UBL airmasses via combinations of onshore or boundary layer flows and associated internal boundary layers over the adjacent suburban and rural areas (Angevine et al., 2006; Chen et al., 2011b).

The goal of this paper is to (1) illustrate the requirement to include airmass advection in our empirical findings to understand BLD variability on diverse temporal and spatial scales; (2) introduce a method to quantify the impact of horizontal advection on BLD variability; (3) present example results revealing advection-dominated features in BLDs; and (4) build a conceptual framework where ABL processes are explained not only by surface forcing but also by horizontal advection of mass, momentum, and energy. In addition to the surface-based measurements of meteorological parameters and upper air soundings, one also needs to utilize other ground-based remote sensing observations for studying ABL dynamics including both active remote sensing (e.g., lidars and radars; Bravo-Aranda et al., 2017; Rey-Sanchez et al., 2021) and passive remote sensing systems (e.g., microwave radiometers, Cimini et al., 2013). In summary, we seek to develop a conceptual framework to quantify the impact of horizontal advection on ABL turbulence features including BLDs and ABL kinematics under diverse meteorological conditions (Pal et al., 2020; Clark et al., 2020).

2. Four major complex interfaces modifying ABL dynamics

2.1. Urban-rural interface

Despite the continuously increasing urbanization around the world and the importance of cities in societies, our ability to design ecologically sustainable urban systems is limited particularly when it comes to reducing anthropogenic heat from cities. Meanwhile, the number of people living in urban areas around the world is projected to reach 68% by 2050 (United Nations, 2019). However, our inability to predict the future course of urban heat island (UHI) intensity (UHII) for diverse urbanized areas around the world remains one of the primary sources of uncertainty in our understanding of UBL processes (e.g., Szymanowski, 2005; Barlow, 2014).

For the urban-rural interface, several past studies have documented downwind enhancement of precipitation around the UBL (see Shepherd, 2005, for a brief review). Results from the Metropolitan Meteorological Experiment (METROMEX) indicated that summer precipitation was typically enhanced by 5%–25% over background values within 50–75 km downwind of the urban region and convective storms were found to occur 116% more frequently downwind of St. Louis than over the adjacent rural areas (Cadet, 1983). Rozoff et al. (2003) showed that UHI dynamically induces an organized downwind updraft cell, which can initiate moist convection under favorable thermodynamic conditions. Previous studies also confirmed that cities can initiate and disrupt convection, split convective storms, change precipitation features, and enhance downstream precipitation (e.g., Orville et al., 2001; Shepherd and Burian, 2003). On the other hand, Gardner (2004) and Duncan et al.

(2019) demonstrated that small changes in wind direction can drastically change the local-scale turbulence features over land.

A key uncertainty also exists in the definition of UHII itself. It is unclear how regional-scale horizontal wind patterns impact the spatial heterogeneities in near-surface temperature via the urban heat advection (UHA) processes. Klysik and Fortuniak (1999) investigated the impact of warm and cold advection in deforming the temperature field in Lodz, Poland and attributed the warm air mass advection to the formation of favorable thermal conditions in rural areas leading to an urban cool island in the night. Heaviside et al. (2015) presented a new approach to examine the extent of horizontal advection of warm air downwind of the conurbation area, while Bassett et al. (2016) found how horizontal winds modify the spatial pattern in heat and introduced the concept of UHA. However, the UHA concept has not been yet examined for smaller-sized cities. It is also unclear how numerical simulations assess the UHA and how UHA processes impact the UHII under different meteorological conditions (e.g., Scott et al., 2018).

Therefore, the typical weather conditions when UHA effects matter for UHII need to be resolved. These knowledge gaps exist likely due to the lack of spatially resolved information on the near-surface meteorological conditions inside and around the cities to infer two-dimensional advection-induced UHII. Nevertheless, without the consideration of UHA, quantification of UHII will remain challenging for adaptation, mitigation, and resiliency efforts. Past research has shown promising results on UHII variability during heat waves (Li and Bou-Zeid, 2013; Li et al., 2015) but no general conclusion was made for extreme temperature cases, particularly concerning the role of UHA. Additionally, during extremely warm conditions, it is unclear how the entire UBL and associated advection impact the ABL over adjacent rural areas.

2.2. ABL across coastlines

Moisture advected from the marine boundary layer (MBL) and the consequent development of an internal boundary layer significantly affects coastal meteorological processes, including convection initiation (e.g., Du et al., 2020). For ABL variability across coastal regions, some researchers reported the absence of a clear seasonal cycle in BLDs over several coastal sites, which they attributed to the influences of homogeneous MBL (e.g., Seidel et al., 2012; McGrath-Spangler and Molod, 2014). In contrast, Pal and Lee (2019a) found significant differences in BLDs under offshore versus onshore flow regimes during different seasons over the three coastal regions of the US (i.e., Pacific, Atlantic, and Gulf) and reported a clear seasonal cycle pattern in BLDs under offshore flow regimes. However, Pal and Lee (2019a) did not find any seasonal contrast in BLDs under onshore flow regimes; they further emphasized the need to consider advection while studying BLD features over coastal region as they also found no significant seasonal variability in BLDs under onshore flow regimes, which was also reported by Chan and Wood (2013). It has become evident that empirical analyses that neglect the role of advection of different air masses (here, onshore, and offshore flows) on ABL dynamics may obscure the airmass-dependent errors that will bias results. Additionally, using a 10-year BLD climatology obtained by general circulation models and relevant PBL mass budgets, Medeiros et al. (2005) also reported substantial land-sea contrasts in BLDs, which is consistent with Lee and Pal (2017) and Pal and Lee (2019a).

In addition to the UBL-induced warming downwind of cities and kinematics (e.g., Bassett et al., 2016), coastal cities add complexities in spatial variability in aerosols and cloud properties due to the combined impact of onshore flow, sea-breeze circulations, and UHI-induced circulations (e.g., Jauregui and Romales, 1996; Bornstein and Lin, 2000; Shepherd et al., 2002, 2010; Chen et al., 2011b). To investigate the horizontal extension of different types of ABL airmass advection, we performed a synthesis of horizontal scales and extensions involved in diverse atmospheric features and meteorological processes related to ABL advection around coastal urban "hotspot" (Table 1) including (1) onshore flow and sea-breeze convection, (2) influence of mesoscale land-sea breeze circulations that drive local convergence zones, (3) extension of UBL and associated impacts on CI, and (4) precipitation enhancement in the downwind of urban centers. The method for obtaining key features on the atmospheric features and processes as appeared in the Table 1 (column with header comment) is based on the reported: (1) maximum horizontal range of the sea-breeze front, (2) extension of the UBL affecting CI, (3) extension of the UBL warming and (4) size of the urbanized areas of the city.

2.3. Mountain-terrain interface

The EMLs often formed over complex terrains horizontally advect over plains and form a temperature inversion, commonly referred to as a "cap", or "lid", allowing for the buildup of potential instability, thus creating meteorological conditions conducive for severe thunderstorm formation, (Lanicci and Warner, 1991) including tornadogenesis "miles-away" from mountains (Stensrud, 1993; Demko et al., 2009; Gensini et al., 2019, Pal and Lee, 2019b).

2.4. ABL regimes across frontal boundaries

Whereas the BLD variability on diurnal, intra-diurnal, synoptic and seasonal time scales is well-documented, changes in ABL processes, before, during and after frontal passages or BLD variability as a function of weather patterns largely remain unexplored (Bond and Fleagle, 1988). Mid-latitude cyclones and associated passages of cold and warm fronts over the land surface lead to high impact weather events including deep moist convection and extreme precipitation. During quasi-periodic passages of cyclonic and anti-cyclonic flows, the ABL encounters vigorous changes (both vertically and horizontally) due to three competitive forcings: land-surface forcing via changes in soil moisture regimes due to precipitation, subsidence over the high-

Table 1
An overview of different horizontal scales involved in ABL advection around coastal urban regions reported in different studies.

Atmospheric feature and process	Horizonal extent or maximum range	Comment	Reference
Extension of sea-breeze front	100–300 km	Observed during the peak of its diurnal cycle	Simpson (1994)
Extension of internal boundary layer via onshore flow	100 km	Mid-Atlantic region and other coastal areas	Berman et al., 1999; Pal and Lee (2019a)
Extension of UBL impacting CI downwind	>30 km	Atlanta region	Shepherd et al., 2010; Aliaga et al., 2013
Extent of UHI circulation	90 km for Houston	2–3 times larger than the size of the city	Bornstein and Lin (2000)
Precipitation enhancement in the downwind of urban centers	50–75 km	5–25% over background values (METROMEX); rainfall increases of 9–17% downwind of major cities	Van den Heever and Cotton, 2007; Jin et al., 2005
Extension of UBL warming downwind	4–12 km (Birmingham, United Kingdom); 10–15 km (St. Louis, Missouri); 40 km (London, United Kingdom); 30 km (Paris, France);	A factor of the size of city and densely urbanized areas and land cover type	Schmid and Niyogi (2013); Pal et al. (2012)

pressure-dominated cold sector, cloud coverage, and frontal lifting. We aim to understand the frontal modification of ABL dynamics, and changes in BLDs during pre-to-post frontal conditions so that a comparison between BLDs in warm (pre-frontal) versus cold (post-frontal) sector airmasses can be revealed.

3. Methodology

The analytical models treating the morphology of ABL, and energy exchange assume horizontal-homogeneous conditions. Such numerical relationships are used in weather forecast and mesoscale simulations over locations where this assumption is not valid (e.g., plains adjacent to mountains, coastal regions). One way to reduce the uncertainty, due to parameterizations' restrictive assumptions, is to increase a model's resolution. Another way is to look into both the parameterizations and the ensemble-based methods. Nevertheless, neither approach considers the impact of the prevailing ABL flow-regimes and the relevant advection of ABL airmass reservoirs and their impact on regional-scale ABL features, particularly for locations affected by flows from mountains, seas, or urbanized areas.

In the past, some researchers provided important theoretical concepts of considering advection in studying ABL features. Using the concept of dimensionless convective distance (X^{ML}), they illustrated that even in presence of the large vertical turbulence regimes, horizontal advection of meteorological parameters via mean wind at different atmospheric layers can be the most dominant factor (Batchvarova and Gryning, 1991). In its simplest form, we postulate that a slowly growing ABL over a moist region can develop faster if a deeper ABL advects over the site. Thus, in addition to the advection of state variables, momentum and heat, we should also consider the advection of BLDs, as this is a measure of advection of airmass within the ABL (Pal and Haeffelin, 2015). Additionally, over complex interfaces like mountain-plain, urban-rural, coastal regions, and frontal boundaries, it is expected that the turbulence kinetic energy budget is also highly influenced by horizontal advection via changes in mean wind conditions.

Within this work, we have laid out the potential empirical approaches that will be explored to investigate the impact of advection on ABL kinematics and thermodynamics. Additionally, using this method, ABL dynamics could be studied most appropriately in three-dimensions (vertically via exchange of energy via turbulence mechanism (X-Z scale) and horizontally via advection of different ABL airmasses (X-Y scale) and their interactions in four dimensions (X-Y-*Z*-t scale). For instance, coastal cities with surrounding mountains would provide most appropriate testbed to understand the complexities involved due to the combined impact of (1) quasi-regular onshore-versus-offshore flows; (2) horizontal advection of EMLs from nearby mountain ridges under appropriate synoptic regimes; and (3) UBL "plume" on adjacent and downstream rural areas.

We introduced a methodology for the identification of advection dominated BLD regimes over land that would best constrain ABL parameterization of physical processes in numerical models. This empirical framework takes care of the integrated analyses of observations of BLD and dominant horizontal wind in the ABL. Such a framework is desirable for exploring the relative impact of surface forcing and advection governing BLD features on all timescales (e.g., diurnal, day-to-day, seasonal) which will facilitate a unified treatment and simplified ABL representation in both weather and climate models.

The method consists of four major steps: (i) identifying the sources that significantly impact observed BLD variability on regular basis (e.g., EML, MBL, UBL) or during synoptic-scale events (e.g., frontal passage), (ii) collecting BLD observations at hourly or sub-hourly or with high time-resolution, (iii) obtaining simultaneous observations of mean horizontal wind in the ABL, and (iv) investigating the BLD variability as a function of ABL wind on all timescales. For instance, for a coastal site, one would classify observed BLD variability into two categories: BLDs under offshore and onshore flows (Pal and Lee, 2019a). On the other hand, for a site located in a flat terrain in the proximity of mountains, one needs to classify the observed variability into two other categories: BLDs under mountain-downwind and flatland downwind (Pal and Lee, 2019b).

We hypothesize that frontal passages help modify BLDs drastically so that BLD differences between pre- and post-frontal days can help understand the role of mid-latitude cyclones on ABL dynamics during all four seasons over land. Finally, BLD contrasts obtained via analyzing the difference between BLDs during pre-frontal conditions (i.e., under warm sector flows) and post-frontal conditions (i.e., under cold sector flows) would illustrate the overall impact of frontal passages on ABL dynamics which would help advance our understanding of moist boundary-layer processes and single out potential sources that trigger drastic changes in ABL dynamics during, before, and after frontal passages over land.

4. Application of the conceptual framework: Selected example cases

In the following we emphasize the impact of advection on ABL features for two potential advection regimes: advection of urban heat across an urban-rural interface and frontal modification of ABL depth changes for a few cases. For brevity, to illustrate the impact of other two advection regimes on BLDs (i.e., coastal regions and mountain-flat terrain interface), we refer to selected previously obtained results.

4.1. Urban heat advection for a small city

Why small cities? We argue that "small cities matter" for all types of UHI-induced meteorological processes despite not having been addressed in the literature. Currently there are only 10 US major cities with populations of more than 1,000,000 (New York City, NY; Los Angeles, CA; Chicago, IL; Houston, TX; Phoenix, AZ; Philadelphia, PA; San Antonio, TX; San Diego, CA; Dallas, TX; and San Jose, CA). When looking at cities with populations between 100,000 and 1,000,000, there exist 252 (out of total 307) cities in the US (i.e., 82%) which have total population ranging between 100,000 and 300,000 (US Census 2010, Fig. 1). We note, though, that there exist different approaches to determine the population density within a city's metropolitan area, as the population density depends on how the metropolitan area is defined (e.g., city, town, borough, county, sub-urban region, etc.). There is a large amount of variability in city area size, and thus population density. For instance, Buffalo, NY and Chesapeake, VA both have populations of ~250,000, yet the population density of Buffalo is nearly 9 times that of Chesapeake, which is expected to influence UHII.

Through an ongoing collaborative research work focused on a minimum-temperature climatology for a small city in the southwest US (Lubbock, Texas), our analyses revealed high nighttime minimum temperatures on the northeast side of city in summer, yielding warmer temperature at the suburban site (i.e., Lubbock International Airport)

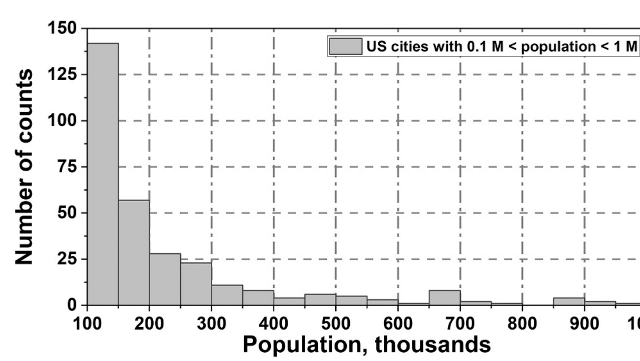

Fig. 1. Frequency distribution of the population of US cities with populations between 100,000 and 1,000,000.

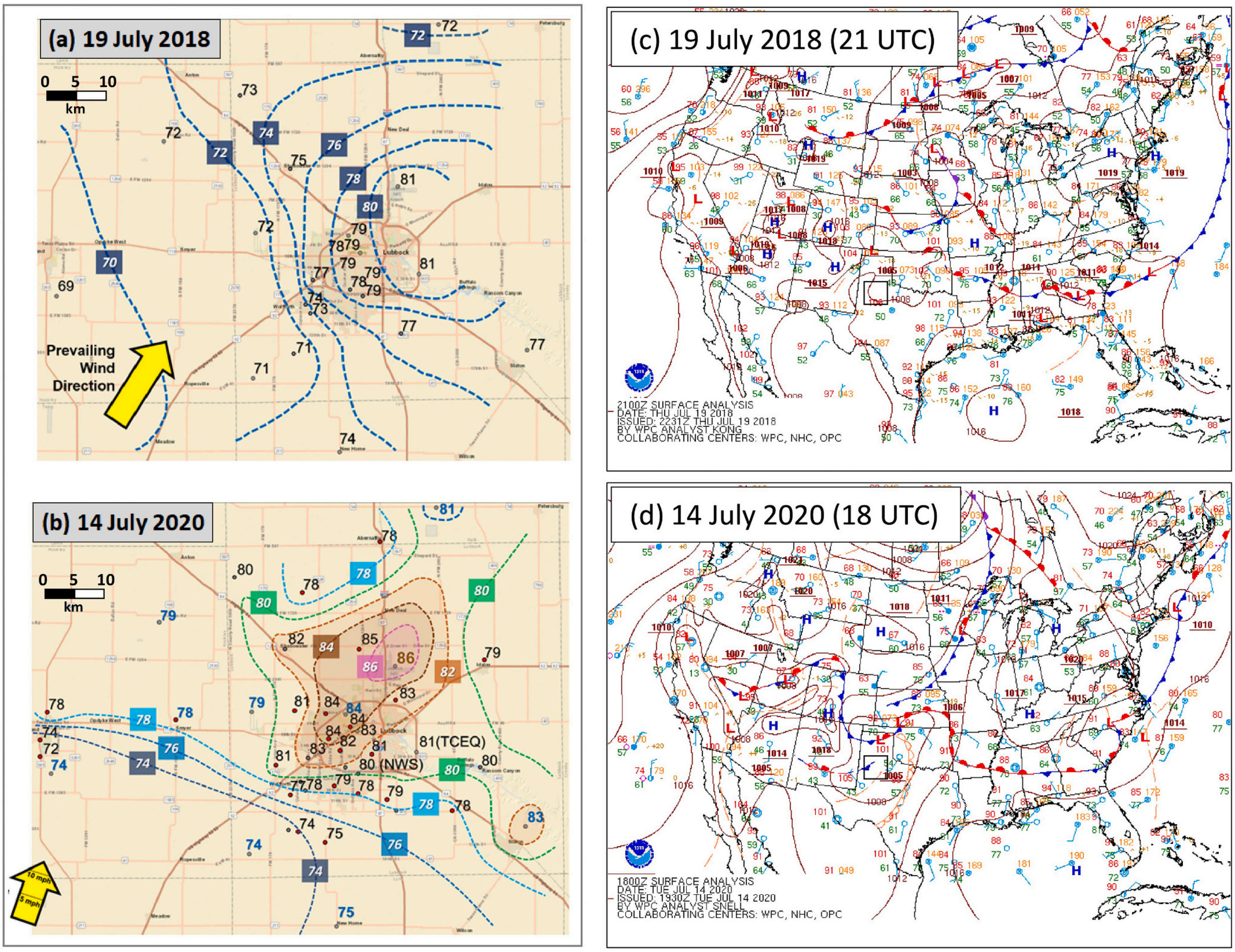

Fig. 2. Analyses of the near-surface temperature field (°F) observed at and around Lubbock indicating higher temperatures over the northeastern suburban site (Lubbock airport) than at the city regimes on (a) 19 July 2018 and (b) 14 July 2020 under prevailing south-southwesterly wind (yellow arrow). Source: NWS-WFO Lubbock; preliminary results of TTU-NWS collaborative research project. Data were obtained from ASOS, WTM, and private observations (Weather Underground). Synoptic set up via the WPC surface map analyses for 19 July 2018 (c) and 14 July 2020 (d). Source: WPC's Surface Analysis Archive; https://www.wpc.ncep.noaa.gov. The boxes in panels c and d mark the experimental region around Lubbock, Texas. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

compared to the temperature in the city (Fig. 2a). The results illustrate that in the early morning hours of 19 July 2018, the temperature at the airport only dropped to 81 °F, the warmest low temperature ever recorded at Lubbock airport. In contrast, on an average day, the temperature inside the city was found to be from a few degrees to about 6 °F warmer than the surrounding countryside. Additionally, very recently, NOAA reported that the month of July in 2020 "*tied for second-hottest July on record for the globe*".

Our findings also revealed that the Lubbock airport yielded its record warm minimum temperature on 14 July 2020 (Fig. 2b) that had been set two years ago in the absence of a heat wave (Fig. 2a). These analyses also showed very high minimum temperature for six consecutive nights during the same period (i.e., July 2020), which could be most likely attributed to the prevailing heatwave (Rastogi et al., 2020). We also found that both the prevailing horizontal wind and persistent cloud cover during the night were conducive for weak heat burst events in the area for the case shown in Fig. 2. For instance, for both cases, the spatial variability in the near-surface temperature was characterized by a sudden, localized increase in the temperature in the northeast sector of the urban region (Figs. 2a-b). The prevailing synoptic conditions over the regions for both days are shown via the NOAA Weather Prediction Center (WPC) surface map analyses (Figs. 2c-d). In particular, the 14 July 2020 case was characterized by the passage of a weak dryline during the afternoon which brought the experimental region under the impact of a dry airmass transported from the Mexican Plateau. Certainly, the analyses indicated the presence of a very moist airmass to the east of the dryline. To the west, the dewpoint temperature slowly decreased from 12.2 °C in southwest Oklahoma to 6.11 °C in southern New Mexico. Based on the METARs (METeorological Aerodrome Reports) obtained from the National Weather Service for the Lubbock international airport (KLBB), we found that the daily maximum and minimum temperature on 14 July 2020 was recorded to be 43.88 °C and 30 °C, respectively. The meteorological conditions were characteristic of a dry and deeply mixed ABL with peak heating between 2100 and 2200 UTC (i.e., 1500 and 1600 local time). With the corresponding warm temperatures, relative humidity values at the surface became extremely low. However, in this case, high-based showers developed and later produced several heat bursts in the area, providing evidence that there was still sufficient moisture present for moist convection. Nevertheless, a fundamental understanding on the UHA in both regimes (i.e., with and without heat waves, Fig. 2) warrants further detailed investigation.

4.2. Frontal modification of BLDs

Here we explored regular 00-UTC rawinsonde-retrieved afternoon-BLDs over 18 sites located in the eastern US during one-year period (Dec 2013- Nov 2014) as illustrated in Fig. 3. To this end, we determined BLDs from the rawinsonde profiles using the bulk Richardson number method outlined in e.g., Lee and De Wekker (2016) and Lee and Pal (2020). We determined frontal passages using 3-hourly surface synoptic charts for the entire year obtained from the WPC analyses.

We then analyzed frontal passages based on the radial distance of the front from the Integrated Global Radiosonde Archive (IGRA) sites (<200 km, 200 km ~ 400 km, and > 400 km; Near, Moderate, and Far, respectively) and the position of the front with respect to the IGRA site (pre-frontal, time of front, post-frontal) at the time of measurement (00 UTC). All frontal passages were considered to undergo both pre- and post-frontal positions within the time frame of 2 to 3 consecutive days. Here, we aim to understand the frontal modification of daytime BLDs during pre-to-post frontal conditions so that a comparison between BLDs in warm (pre-frontal) versus cold (post-frontal) sectors can be elucidated. Finally, we investigate the BLD-contrasts (i.e., BLD_{Warm} minus BLD_{Cold}) during the four seasons to understand how the frontal impact on BLDs vary seasonally.

Fig. 4 presents the results obtained for the BLD variability across frontal regimes over an example site Davenport (Iowa), during four seasons (winter: DJF; spring: MAM; summer: JJA; and fall: SON) between Dec 2013 and Nov 2014. These results clearly reveal case-to-case BLD variability on synoptic time scale during cold front passages. In general, BLDs in the warm sector (i.e., pre-frontal samples) during winter and spring were found to be deeper than the BLDs in the cold sector (i.e., post-frontal samples) highlighting the impact of frontal passages. Additionally, the BLD variability for the day of frontal passages (Green circles in Fig. 4) was low most likely due to precipitation during the frontal passages. For the other two seasons (summer and fall), no significant changes in BLDs were identified. These results reveal that the pattern and magnitude of ΔBLDs (i.e., warm versus cold sectors) vary substantially across the sites and seasons.

Within this empirical study, we investigated changes in ABL processes before and after frontal passages and explored BLD variability as a function of weather patterns. Previously, using numerical simulations (e.g., WRF), other researchers have provided important insights into the frontal differences in ABL thermodynamic features (e.g., Cohen et al., 2015; Booth et al., 2018). We found that due to the passages of cold fronts, BLDs become drastically modified so that there are significant differences between BLDs in the warm versus cold sectors. In particular, there exist significant contrasts in BLDs under the impact of frontal passages in winter and spring, unlike in summer and fall. Cumulatively, these results help diagnose impact of frontal-regimes and cyclone tracks when BLD-contrasts might be linked to the impact of contrasting meteorological processes taking place in the warm and cold sectors. Future research will help obtain a detailed understanding of the ABL

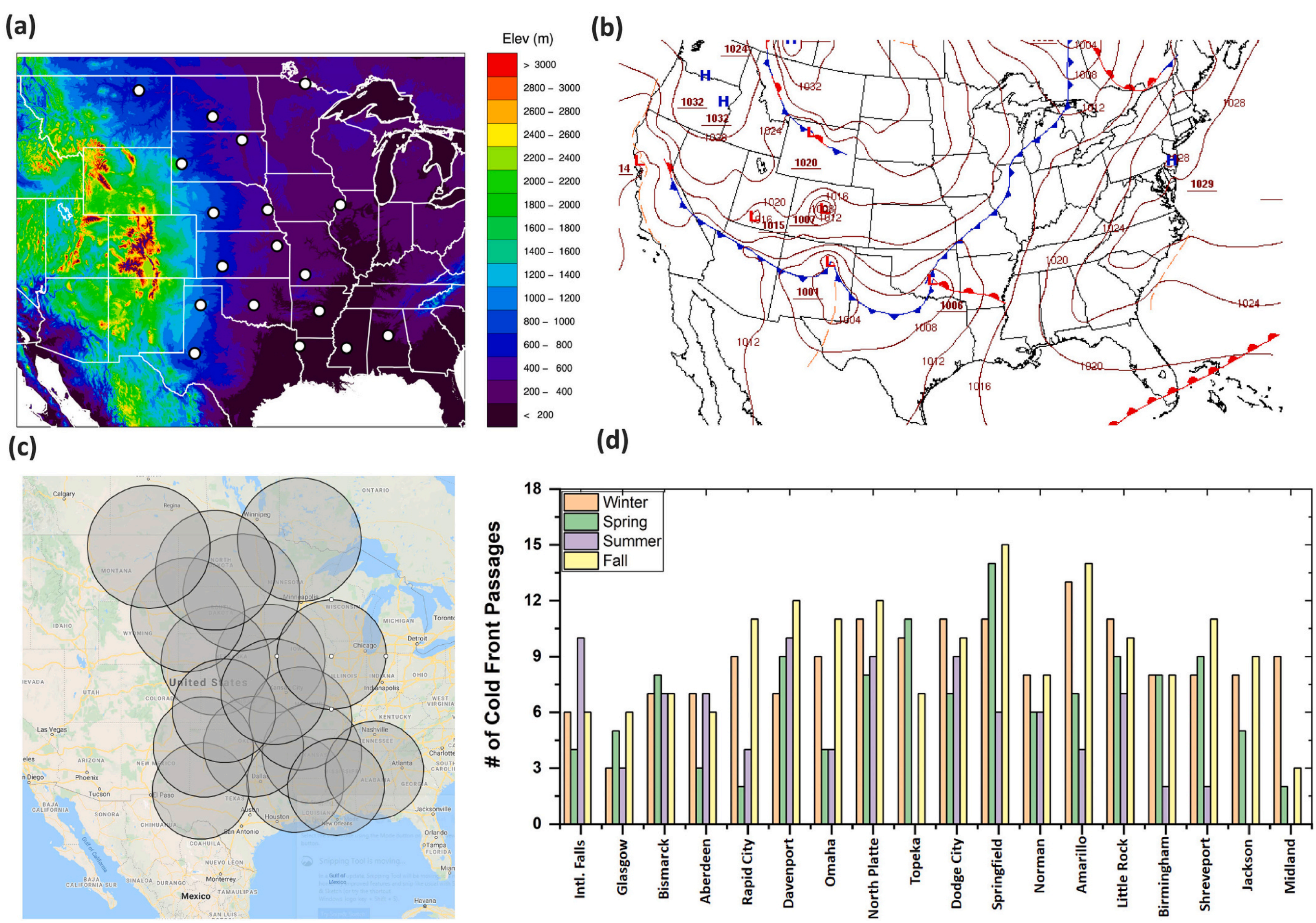

Fig. 3. (a) Locations of 18 IGRA sites (white-filled circles) overlaid on the topographical-maps (site-elevation in m MSL). (b) Sample surface synoptic charts used in the analyses for detecting frontal passages over the IGRA sites. Surface-charts (e.g., 13 June 2014 at 00 UTC) were obtained from NOAA's Weather Prediction Center. (c) IGRA sites with circles of 200-km radius to determine pre-and-post frontal samples of ABL depths measured. (d) Overview counts of cold front passages over the 18 IGRA sites in 2014. The cold front passages during which BLD measurements were available were only considered here.

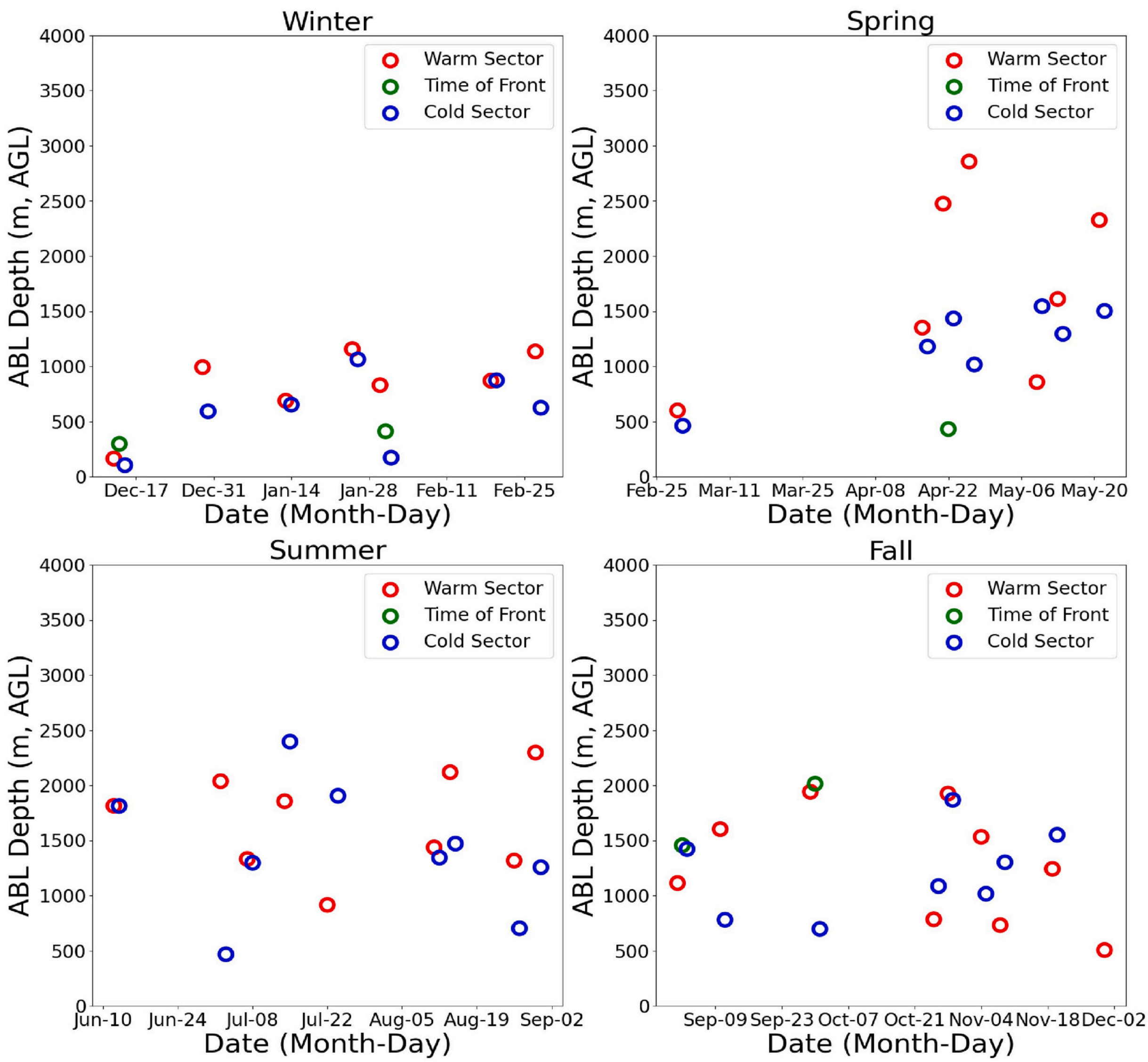

Fig. 4. BLD variability on synoptic time scale during cold front passages over an example site Davenport, IA during four seasons (DJF, MAM, JJA, and SON) between Dec 2013 and Nov 2014. Red and blue filled circles denote BLDs in warm and cold sectors, respectively. The BLDs measured on the day of frontal passages are also shown (green circles). We note that the samples for frontal days were found to be low for this site most likely due to unfavorable weather conditions and instrument malfunctions during high precipitation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

dynamics and thermodynamics which is essential to improve numerical weather forecasting in the frontal environment. Nevertheless, the first results obtained from this new conceptual framework are indeed encouraging, as they help to identify the changes in BLDs across mid-latitude cyclones during different seasons over land.

4.3. Coastal and mountain-induced modification of BLDs

As noted earlier, to illustrate the impact of the other two main advection regimes on BLDs (i.e., land-sea and mountain-flat terrain interfaces), we refer to previously published results and briefly summarize them here. Pal and Lee (2019a) found seasonally- and spatially varying differences in BLDs associated with offshore flows versus BLDs associated onshore flows. These differences were largest during the spring and summer than the fall and winter at sites along the Atlantic Ocean and Gulf Mexico. Sites along the Pacific Ocean also showed significant BLD differences that were likely enhanced by the mountains along the US west coast.

The impact of the advected mountain ABLs on the ABL over the downwind plains was further explored in Pal and Lee (2019b). They found that ABLs with their origin over the mountains were deeper than those with their origin over the plains. Furthermore, differences between the mountain-advected ABL and flatland-advected ABLs were deeper at sites downwind of the Rocky Mountains than at sites downwind of the Appalachian Mountains in all four seasons most likely due to higher elevations of Rockies than the Appalachians.

4.4. Future scope

Future research on this topic will use next-generation measurements and numerical simulations to address the role of advection on ABL thermodynamics. For instance, one will be able to find the most appropriate model physics in numerical models (e.g., the WRF, High Resolution Rapid Refresh (HRRR), etc.) for detailed process-based understanding of ABL kinematics under local-meso-synoptic scale advection via performing model-data-mismatch (MDM) experiments e.g., those recently performed using the HRRR model (e.g., Lee et al., 2019; Fovell and Gallagher, 2020). Further research work is underway which will enable a detailed understanding on the impact of horizontal advection on ABL at diverse spatial scales over land so that these may be implemented into the next generation of weather forecasting models e.g., the Unified Forecast System (UFS) (Tallapragada, 2018). Additionally, recent studies illustrated that in addition to thermal advection, the transport of aerosols associated with the prevailing horizontal advection also impact the BLD and ABL stability by perturbing the solar radiation (e.g., Zhong et al., 2017; Ma et al., 2020; Liu et al., 2021). Using high-resolution observations of aerosols and meteorological variables in Beijing, Zhao et al. (2019) identified a potential feedback mechanism among aerosol concentrations (mainly $PM_{2.5}$, particulate matter with diameters of 2.5 μm and smaller), aerosol radiative forcing, and BLD changes implying the impact of higher concentrations of transported aerosols on the reduction of local BLDs aggravating the aerosol pollution regimes. Thus, one should also consider this important feedback (aerosol-radiation-ABL) while considering impact of advection on BLD changes.

Our analyses will help build observational constraints for validating numerical models and improve boundary layer parameterizations so that the observed ΔBLDs during four seasons and can be replicated to obtain a better understanding of the impact of advection in modifying ABL dynamics. In future, we will compare these observational findings with the numerical simulations (e.g., WRF) to investigate the performance of state-of-the-art high-resolution numerical models and to determine whether these models can capture the impact of advection on the changes in BLDs in different seasons. For instance, the interdependence of the observed BLDs under two major horizontal advection regimes via the mean ABL wind will help resolve error characteristics in numerical simulations when MDMs either show very high or low values and finally better understand the BLD-contrasts (i.e., ΔBLD) under contrasting flow regimes of the ABL and associated physical processes. Additionally, combining numerical simulations and continuous measurements of ABL dynamics using active and passive remote sensing instruments during different weather conditions and across interfaces will be highly beneficial to investigate the changes in ABL features via horizontal advection (e.g., Koffi et al., 2016; Bravo-Aranda et al., 2017; Hegarty et al., 2018).

Results presented here will also guide an objective basis for defining requirements for future observing systems such as future satellite missions to observe aerosols, clouds, and the ABL. For instance, by evaluating the meteorology with airborne and satellite data, especially BLDs, ABL winds, thermodynamics and kinematics, transport fidelity, and the understanding of horizontal advection's role can be optimized. Although this framework sets up the work for BLD contrasts under diverse advection regimes, other atmospheric processes may also be considered under this framework. Finally, minimization of regional, diurnal, seasonal biases for BLD variability in the state-of-the-art numerical models will further aid numerical weather prediction.

5. Summary, and conclusions

In this article, we argue that advective processes are often neglected yet important for understanding ABL features, in particular, changes in BLDs. We showed compelling evidence illustrating that advection of ABL airmasses is important for ABL dynamics in coastal regions, areas of complex terrain, or any other region with significant horizontal gradients in land-surface forcing (i.e., urban-rural interface) and changing weather regimes (i.e., frontal passages). Using a novel methodology, this work brings an important perspective to ABL process studies. For instance, we showed how air mass exchange via advection is essential for better understanding of BLD changes across the different interfaces mentioned above. This work emphasized on the fact that it is important to understand baroclinic influences on BLD variability, especially as it relates to parameterizations of numerical simulations. The selected results on this topic indicated that the BLD differences due to passage of synoptic fronts provides novel insights. We presented a new methodology that allows detailed and systematic approach to analyze BLD differences across frontal system that has not yet received sufficient attention. Future observational and modelling approaches should consider an air-mass-following Lagrangian approach to obtain the next-generation of numerical systems to resolve the ABL dynamics pertaining to airmass exchange.

Knowledge gained from this work will help to improve representations of ABL processes and the numerical weather prediction of convection initiation processes over and near urban hotspots, coastal regions, mountainous regions, and along the storm tracks in weather forecasting models. Our results suggest that advection is one of the important dynamic processes affecting the thermodynamics of the ABL airmasses. Proper representation of the seasonal and diurnal features of BLDs is important since they inherently include BLDs affected by two entirely different airmasses advected over the region. Thus, this classification is important. For instance, the results reported have brought new empirical evidence on the BLD contrasts at land-sea and mountain-plain interfaces. Our results also suggest that even small cities matter with regards to advection of urban heat and affect resultant UHII scenarios. Further research on this topic is needed to determine UBL impact on the BLDs over adjacent rural and suburban areas. Nevertheless, our work showed how to characterize BLD contrasts and how to investigate, improve upon, and explain the relevant BLD changes toward building a comprehensive understanding on the impact of advection on ABL kinematics.

Data availability

The rawinsonde datasets used in this study were obtained from the IGRA data archive available at <ftp://ftp.ncdc.noaa.gov/pub/data/igra/data/>. The synoptic analyses and associated maps are available from Weather Prediction Center archive (https://www.wpc.ncep.noaa.gov/archives/web_pages/sfc/sfc_archive.php) and the METAR data are from the NWS archive https://www.aviationweather.gov/metar.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The lead author SP was supported by the Texas Tech University Faculty Start-up Funds and NASA Grant # 80NSSC19K0730 and the co-author NC was funded by the Program in Inquiry and Investigation: Pi2 program in Texas Tech University. We note that all results and conclusions of this study, as well as any views expressed herein, are those of the authors and do not necessarily reflect those of NOAA or the Department of Commerce. Finally, we thank two anonymous reviewers for their constructive criticisms and thoughtful suggestions which helped improve both the technical and scientific content of the manuscript.

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