



Investigation of the Spatial Variability of the Convective Boundary Layer Heights over an Isolated Mountain: Cases from the MATERHORN-2012 Experiment

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ABSTRACT

Spatiotemporal variability in the convective boundary layer height z_i over complex terrain is governed by numerous factors such as land surface processes, topography, and synoptic conditions. Observational datasets to evaluate weather forecast models that simulate this variability are sparse. This study aims to investigate the z_i spatial variability (along a total leg length of 1800 km) around and over a steep isolated mountain (Granite Mountain) of horizontal and vertical dimensions of 8 and 0.9 km, respectively. An airborne Doppler lidar was deployed on seven flights during the Mountain Terrain Atmospheric Modeling and Observations (MATERHORN) campaign conducted at Dugway Proving Ground (Utah) from 25 September to 24 October 2012. During the afternoon, an east–west z_i gradient over the region with z_i that was approximately 200 m higher on the eastern side than on the western side of Granite Mountain was observed. This gradient illustrates the impact of two different land surface properties on z_i spatial variability, with a sparsely vegetated desert steppe region on the east and a dry, bare lake-bed desert with high subsurface soil moisture to the west of Granite Mountain. Additionally, the z_i spatial variability was partly attributed to the impact of Granite Mountain on the downwind z_i . Differences in z_i were also observed by the radiosonde measurements in the afternoon but not in the morning as the z_i variability in morning were modulated by the topography. The high-resolution lidar-derived z_i measurements were used to estimate the entrainment zone thickness in the afternoon, with estimates ranging from 100 to 250 m.

1. Introduction

Weather forecasting in mountainous regions is a challenging research task (e.g., Wulfmeyer et al. 2011; Chow et al. 2013; Fernando et al. 2015). The poor simulation of the boundary, entrainment, and residual layers, including the diurnal development of the convective boundary layer (CBL) height z_i , is partially responsible for the deficiencies in forecasting mountain weather (e.g., Brown et al. 2006; Demko et al. 2009; Conrick et al. 2015). An improved representation of CBL variability in complex terrain is important because it affects many atmospheric processes including

the triggering of convection owing to 3D circulations due to heterogeneous land surfaces (e.g., Kalthoff et al. 2009; Garcia-Carreras et al. 2010, 2011; Taylor et al. 2011; Behrendt et al. 2011a; Rieck et al. 2014), the overshooting of thermals, entrainment, and the dispersion of pollutants (e.g., Kossmann et al. 1998; Steyn et al. 2013; Garcia-Carreras et al. 2015).

A detailed understanding on the dynamics of the CBL and relevant z_i spatial variability is necessary to improve our understanding of entrainment that needs to be parameterized within mesoscale models (e.g., Ayotte et al. 1996). Additionally, some past studies have illustrated how thermal ridges over the mountains become convergent lines for the horizontal flow (e.g., Lieman and Alpert 1993). Also, elevated mixed layers over ridges help trigger sharp increases in the z_i values over lower terrain downwind (e.g., Rotach and Zardi 2007; De Wekker and Kossmann 2015; Fernando et al. 2015).

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For a better understanding of the factors driving the land–atmosphere interactions and the mesoscale (from tens to hundreds of kilometers) z_i variability over complex terrain and entrainment processes, it is important to collect datasets such as highly spatially resolved z_i , its growth rate, and the entrainment zone thickness (EZT). These parameters can then be used for the evaluation of boundary layer parameterizations in meteorological models (e.g., [Chow et al. 2013](#); [Banks et al. 2015](#)) and the investigation of CBL scaling and entrainment processes (e.g., [Stull 1988](#); [Behrendt et al. 2015](#)).

The spatiotemporal variability in z_i over complex terrain is strongly influenced by terrain-forced and thermally driven flows over a large range of spatial and temporal scales ([Whiteman 2000](#)). Other causes of spatial variability in z_i over mountainous regions may include flow oscillations, upslope flow convergence at ridgetop, flow separation, and hydraulic jumps (e.g., [Chow et al. 2013](#); [De Wekker and Kossmann 2015](#); [Fernando et al. 2015](#)). Additionally, CBL development in mountainous areas responds to variations in land cover, soil moisture, terrain height, and other surface characteristics (e.g., [Banta 1985](#); [De Wekker et al. 2004](#); [Behrendt et al. 2011a](#); [De Wekker and Kossmann 2015](#)).

Previous observations in mountainous terrain show that the CBL structures tend to be more horizontally homogeneous in the afternoon than in the morning (e.g., [Kalthoff et al. 1998](#); [Kossmann et al. 1998](#); [De Wekker et al. 2004](#)). The role of soil moisture and land cover type as important surface forcing in determining the mesoscale CBL structure over flat terrain has been shown in many studies (e.g., [Reen et al. 2006](#); [Desai et al. 2006](#)). However, similar studies examining the CBL structure over complex terrain are sparse. Additionally, surface–atmosphere interactions modulate the z_i spatial variability. For instance, [King et al. \(2006\)](#), while comparing diurnal variability of z_i at two similar sites, attributed the lower z_i at one of the sites to the partitioning of available energy into latent heat fluxes. Similar results were also reported in [Endo et al. \(2008\)](#) for z_i variability over a humid terrestrial area. Based on the studies focusing on the soil moisture control on the exchange of energy in dryland ecosystems (e.g., [Williams and Albertson 2004](#)), it could be stated that the role of soil moisture in modulating z_i spatial variability is more dominant for arid and semiarid regions than over moist and vegetated surface (e.g., [Sanchez-Mejia and Papuga 2014](#)). However, investigations of the effect of soil moisture and land–atmosphere interactions on z_i spatial variability over arid mountainous regions remain limited in the literature.

Spatial variability of z_i occurs at various scales. At scales of the CBL height or smaller, the z_i variability has been shown to be proportional to the EZT (e.g.,

[Flamant et al. 1997](#); [Pal et al. 2012](#)). Entrainment processes taking place near the z_i are of particular interest for investigating turbulence features within and above the CBL. Numerous efforts have been made to estimate the EZT in terms of measurable boundary layer parameters (e.g., [Gryning and Batchvarova 1994](#)). Both quantitative and qualitative sources of information on the EZT are important for obtaining a better understanding of the entrainment velocity and entrainment heat flux since the entrainment zone bottom and top heights correspond to altitudes where the buoyancy flux vanishes (e.g., [Stull 1988](#); [Davis et al. 1997](#); [Pal 2016](#)). A detailed understanding of EZT variability is also important for estimating local length scales in the parameterizations of shear production at the CBL top ([Boers and Eloranta 1986](#)).

Many previous studies made efforts to define the EZT over flat terrain using z_i spatial variability obtained from airborne lidar measurements (e.g., [Flamant et al. 1997](#); [Davis et al. 1997](#); [Kiemle et al. 1997](#)), as well as temporal z_i variability using ground-based scanning (e.g., [Boers and Eloranta 1986](#)) and vertically pointing lidars (e.g., [Cohn and Angevine 2000](#)). However, such measurements of EZT over complex terrain remain limited. It is also unclear whether or not z_i spatial variability over complex terrain can be used to estimate EZT since CBL regimes over mountainous areas are more complex than over flat homogeneous terrain (e.g., [Reen et al. 2006](#); [Pal et al. 2010](#)).

Here, we present a unique airborne lidar-based investigation of z_i spatial variability over an arid mountainous region under variable meteorological and surface conditions (different surface forcing regimes and synoptic settings), in a growing morning CBL and quasi-stationary afternoon CBL, over two contrasting land cover types (sparsely vegetated and bare soil), and for two different soil moisture regimes over the plains east and west of an isolated mountain. Additionally, small-scale z_i fluctuations were utilized to estimate EZT in the afternoon CBL over the experimental region following the method discussed in past literature (e.g., [Melfi et al. 1985](#); [Flamant et al. 1997](#); [Pal et al. 2010](#)).

Based on the previous studies, we hypothesize that under quiescent atmospheric conditions with weak wind (typically $<5 \text{ m s}^{-1}$ at the 700-hPa pressure level) z_i spatial variability is larger than during conditions with stronger synoptic forcing and that this variability is not only driven by the buoyant heat transfer from the underlying surface but also by the underlying topography and lower-tropospheric stability. In addition to the underlying orographically structured terrain, the observed mesoscale z_i variability is also expected to result from the heterogeneity in the land surface properties that exist in the experimental area.

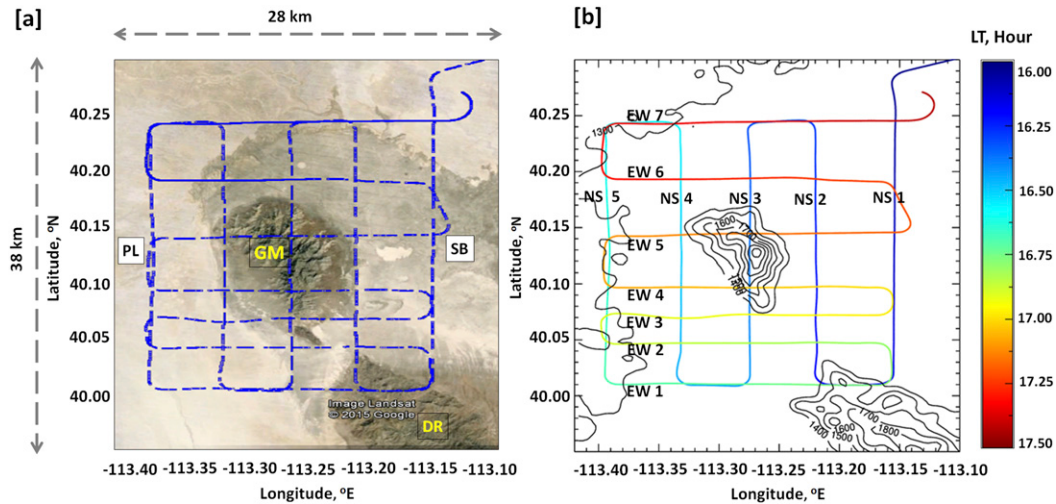


FIG. 1. (a) Satellite image showing the locations of Granite Mountain (GM), Dugway Range (DR), surface stations with vertical sounding systems [Sagebrush site (SB) and Playa site (PL)], and a typical flight pattern of the TODWL with the EW and NS legs. Vertically and horizontally aligned gray dashed lines indicate the NS (38 km) and EW (28 km) extents of the domain considered. (b) Orography of the MATERHORN-X experimental region showing the TODWL flight tracks in the afternoon (between 1555 and 1730 LT) on 6 Oct 2012 covering an area of around 500 km² during the MATERHORN-X field phase. The colors along the tracks indicate the local time (MDT) at which the TODWL was at a certain location. The surface elevation in the contour plot ranges from below 1290 to above 2000 m MSL. (Source of the satellite image is Google, Inc.)

We used airborne Doppler wind lidar data to estimate z_i during the Mountain Terrain Atmospheric Modeling and Observations (MATERHORN) campaign in 2012 that took place between 23 September and 24 October 2012 at the U.S. Army's Dugway Proving Ground area in Utah. The campaign was conducted within the experimental component of the MATERHORN project (henceforth, MATERHORN-X). In this study, the z_i variability around an isolated mountain peak located near the Great Salt Lake Desert is investigated for three morning and four afternoon cases using observations from MATERHORN-X. To this end, we 1) characterize the z_i spatial variability over and around Granite Mountain during both morning and afternoon CBL regimes and 2) determine the roles of both the complex topography and the changes in the surface forcing owing to the land surface heterogeneity on the z_i spatial variability.

Most of the flight days were chosen for quiescent conditions during the month-long campaign. In this paper, we selected the intensive observation periods (IOPs) when the Twin Otter Doppler Wind Lidar (TODWL) flights were available to address the z_i spatial variability during both morning and afternoon. To the best of our knowledge, these measurements are the first of their kind of z_i spatial variability over a mountainous area using a state-of-the-art airborne Doppler lidar technology.

2. Experimental area and MATERHORN-X perspective

MATERHORN-X took place at the Granite Mountain Atmospheric Sciences Test Bed (GMAST) approximately 137 km southwest of Salt Lake City, Utah, in the Great Salt Lake Desert (Fig. 1). A comprehensive overview of MATERHORN-X is provided in [Fernando et al. \(2015\)](#). Numerous in situ and remote sensing observations were made including tower-based micrometeorological measurements, ground-based remote sensing measurements, and airborne measurements with in situ and remote sensing instruments.

The entire field experiment consisted of ten 24-h IOPs; among them, five were characterized by quiescent atmospheric conditions (700-hPa winds $< 5 \text{ m s}^{-1}$). The experimental region is an isolated, arid area with terrain varying from salt flats to sand dunes and from isolated hills to rugged interconnected mountains. Considerable terrain heterogeneity exists in the area with ground elevation varying from 1100m above mean sea level (MSL) to 2000m MSL. The experimental region is also characterized by sparse vegetation and little human influence.

There were two major experimental sites west and east of Granite Mountain. An experimental site was located about 15 km west of Granite Mountain on the salty-clay playa (henceforth, Playa site: 40.134909°N,

113.45097°E, 1296 m MSL). This site is extremely flat, with the elevation varying by less than a few meters over an extended area. Silt loam and playa are dominant soil types at Dugway range (Fig. 1). A second experimental site was located about 13 km east of Granite Mountain in an area that is mainly covered by sparse desert shrub vegetation (e.g., greasewood, grasses) that is mostly less than 50 cm tall and highly representative of the land cover of the area. This site is referred to as the Sagebrush site (40.12136°N, 113.12907°E, 1316 m MSL). The ground distance between the Playa and the Sagebrush sites is ~ 28 km.

3. Instruments and datasets

A downward-pointing scanning Doppler wind lidar aboard a Twin Otter aircraft [operated by the Center for Interdisciplinary Remotely Piloted Aircraft Studies (CIRPAS)] performed measurements of both vertical and horizontal wind speeds in addition to the aerosol backscatter profiles (e.g., Godwin et al. 2012; De Wekker et al. 2012). The key aim behind the deployment of the TODWL was to measure winds and z_i at high spatial resolution over horizontal distances of a few tens of kilometers and to capture the interaction between mesoscale and synoptic-scale flows over the experimental area. The TODWL provides vertical cross sections of aerosol backscatter measured along the flight tracks (Fig. 1), which we used to estimate spatially resolved fields of z_i along a total flight leg length of ~ 1800 km during the selected IOPs of the campaign.

During MATERHORN-X, Twin Otter flights were conducted during four IOPs between 5 and 18 October 2012; each research flight lasted ~ 4 h. A total of seven research flights yielded ~ 3000 quality-controlled wind profiles between the surface and 3250 m MSL. The full overlap of the TODWL transceiver is attained at a range of ~ 200 m from the lidar platform, typically flying at an altitude of 3500 m MSL. The typical north-south-oriented (NS) flight legs were around 26 km long while east-west-oriented (EW) legs covered a ground distance of around 21 km, keeping Granite Mountain in the middle (Fig. 1). All IOPs had similar flight patterns that consisted of EW and NS transects. Plan-view plots of z_i obtained for four IOPs were analyzed to investigate the z_i spatial variability over the experimental region. For presentation and discussion of the results, we used local time [LT = UTC - 6 h, often called mountain daylight time (MDT)].

TODWL provides two-dimensional cross sections of the absolute wind vector with high accuracy ($< 0.1 \text{ m s}^{-1}$ in three components of wind). For the MATERHORN-X flights, wind profiles were processed at a vertical resolution

of 50 m and a horizontal resolution of ~ 1.5 km. The TODWL is equipped with a 2- μm Doppler wind lidar using the coherent detection technique (e.g., Godwin et al. 2012). The laser beam is directed by a two-axis cylindrical scanner mounted on the aircraft side door. A frequently used scanner configuration directs the lidar beam off nadir (angle of 20°) to perform step-stare conical scans below the aircraft with azimuth steps of 30° . A total of 12 such stares (steps) with 1-s dwells were performed in about 20–25 s, tracing out a cycloidal pattern over an aircraft flight distance of ~ 1 –1.2 km. Range resolution of TODWL was set to 45 m during postprocessing. Additionally, TODWL performs nadir-pointing measurements for 5 s between two consecutive conical scans.

The major data products of TODWL are three components of wind and profiles of signal-to-noise ratio (SNR) along the line of sight. The SNR serves as a reasonable representation of aerosol loading, more specifically, the gradients of aerosol backscatter. In this paper, we mainly used TODWL-derived profiles of aerosol backscatter to determine z_i . Previously, De Wekker et al. (2012) addressed the potential of the TODWL for investigating the spatial structure of topographically driven flows in complex coastal terrain in southern California.

The flight patterns during the experiment were designed to study the impact of topography on the mean and turbulence structure of the CBL and to provide estimations of the z_i spatial variability. The areal coverage ($\sim 550 \text{ km}^2$) provided by the TODWL measurements allowed us to investigate z_i spatial variability with a horizontal resolution of 100 m along the flight legs since the z_i retrieval was based on 2-s-averaged SNR profiles with an aircraft speed of 50 m s^{-1} .

During a typical flight pattern, NS transects were flown first followed by EW transects. The NS1 (i.e., leg 1 along NS transect) and NS2 are east of Granite Mountain, NS4 and NS5 are west of Granite Mountain, and NS3 is directly over Granite Mountain. The EW1 (i.e., leg 1 along EW transect), EW2, and EW3 legs are south of Granite Mountain, and EW5 and EW6 are north of Granite Mountain, while EW4 was mostly over Granite Mountain. An infrared temperature sensor (pyrometer, provided by Heitronics KT 19.85) was also mounted on the aircraft to measure surface temperature along the track of each flight leg. The interpretation of infrared temperature measurements is dependent on various factors that are difficult to characterize, including the surface material, surface roughness, view angle, and changes in the surface emissivity. Thus, infrared temperature measurements were only used qualitatively to obtain a picture of the surface temperature variability, which helped explain the observed spatial z_i variability.

TABLE 1. Overview of near-surface daytime mean horizontal wind speed and direction (10 m AGL), incoming solar radiation, and daytime maximum temperature (5 m AGL) difference between the two sites (SB minus PL) for each of the six flight days. Note that, for the 14 October case, meteorological characteristics only during afternoon research flights are provided.

Date (2012)	IOP No.	Wind speed (m s^{-1})	Wind direction	Incoming solar radiation (W m^{-2})	Temperature difference between the two sites ($^{\circ}\text{C}$)	Surface moisture (g kg^{-1})
6 Oct	4	3–4	NNW	705	1.95	2.02
7 Oct	4	3–5	NNW	700	1.50	1.28
9 Oct	5	2–3	N	620	1.05	2.04
10 Oct	5	1–2	SSW	600	1.90	2.16
14 Oct	6	2–4	SSW	590	0.25	5.57
17 Oct	7	8–12	N	620	0.15	2.57

We also used measurements [5 m above ground level (AGL)] from two tower-based eddy covariance systems deployed at both the Sagebrush and the Playa sites. Air temperature, humidity, and their associated fluxes were available at four different levels on a 20-m-tall tower. At both the Playa and Sagebrush sites, other ground-based instruments (e.g., Campbell Scientific HMP45 temperature–relative humidity probe in radiation shield, sonic anemometer, and Onset Computer Corporation HOBO data logger) and radiation sensors (Kipp and Zonen CMP21 pyranometer and CGR4 pyrgeometer) were also deployed to obtain near-surface meteorological observations (5 m AGL), incoming and outgoing solar radiation, and albedo. Further details on the experimental sites, instrumentations, and overview on the different IOPs are reported in [Fernando et al. \(2015\)](#).

4. Meteorological conditions during the selected IOPs

In the present paper, special emphasis is given to the z_i spatial variability in a mesoscale domain during four IOPs with TODWL deployment (viz., IOP 4, 6–7 October; IOP 5, 9–10 October; IOP 6, 14–15 October; and IOP 7, 17 October 2012). Most of the IOPs lasted 24 h, which helped capture CBL processes taking place during both morning and evening transitions in the area. IOPs 4–6 took place during quiescent conditions. IOP 7 took place in more synoptically forced conditions than the other IOPs. IOPs 6 and 7 took place after a rainfall event on 12 October 2012.

Using synoptic maps, radiosonde observations, near-surface meteorological measurements, and TODWL-derived horizontal wind fields at different heights, we investigated the prevailing meteorological conditions during the selected IOPs. An overview of the near-surface meteorological conditions during the flight days are shown in [Table 1](#) while surface analysis charts for the IOPs are shown in [Fig. 2](#). Radiosonde measurements over both the Sagebrush and Playa sites illustrate the thermodynamic structure of the boundary layer and the lower free atmosphere during the selected IOPs ([Fig. 3](#)).

During IOP 4, a surface high pressure system was located in the northeast of Wyoming and a shallow layer of cold north-northwesterly synoptic flow was present as was evident with the surface analysis chart ([Fig. 2](#)). The CBL over the Playa site was cooler than that over the Sagebrush site by 2° – 5°C , as was confirmed by the near-surface meteorological measurements at both sites. This temperature difference between the two sites existed during IOPs 4 and 5. However, after the rain event on 12 October, no such significant temperature difference was observed during IOPs 6 and 7. During IOP 5, a high pressure system was located south of the study area with a transition from weak west-northwesterly flow on 9 October to a more moist southwesterly flow at 700 hPa on 10 October. During the afternoon TODWL flights on 9 October, northerly mesoscale upvalley flow prevailed in the CBL while in the upper levels (around 4000 m MSL) southerly flow dominated (not shown here).

IOP 6 was similarly characterized by high pressure located in southern Utah with weak synoptic flows from the south ([Fig. 2](#)). However, just 2 days prior to IOP 6, a precipitation event took place in the experimental area with total precipitation amounts ranging between 3 and 10 mm around the Sagebrush site area and at the Playa site, respectively. The CBL moisture content changed from a mean water vapor mixing ratio of $2\text{--}3\text{ g kg}^{-1}$ before the rain event to $4\text{--}5\text{ g kg}^{-1}$ or even more after the rain event ([Fig. 3](#)). In the photographs taken during the experiment, changes in the soil and surface properties were evident in the Playa site near the North Playa site between IOPs 5 and 6, which we attribute primarily to the rain event.

IOP 7 was characterized by stronger synoptic flows than the other IOPs. The synoptic winds were northwesterly and peaked at more than 12 m s^{-1} at 700-hPa level at the beginning of IOP 7, decreasing throughout the remainder of the IOP. The TODWL measurements above 2000 m MSL reported mainly northerly winds.

5. Methods for determining CBL height z_i

The Haar wavelet technique has been utilized for determining z_i from many previous airborne lidar

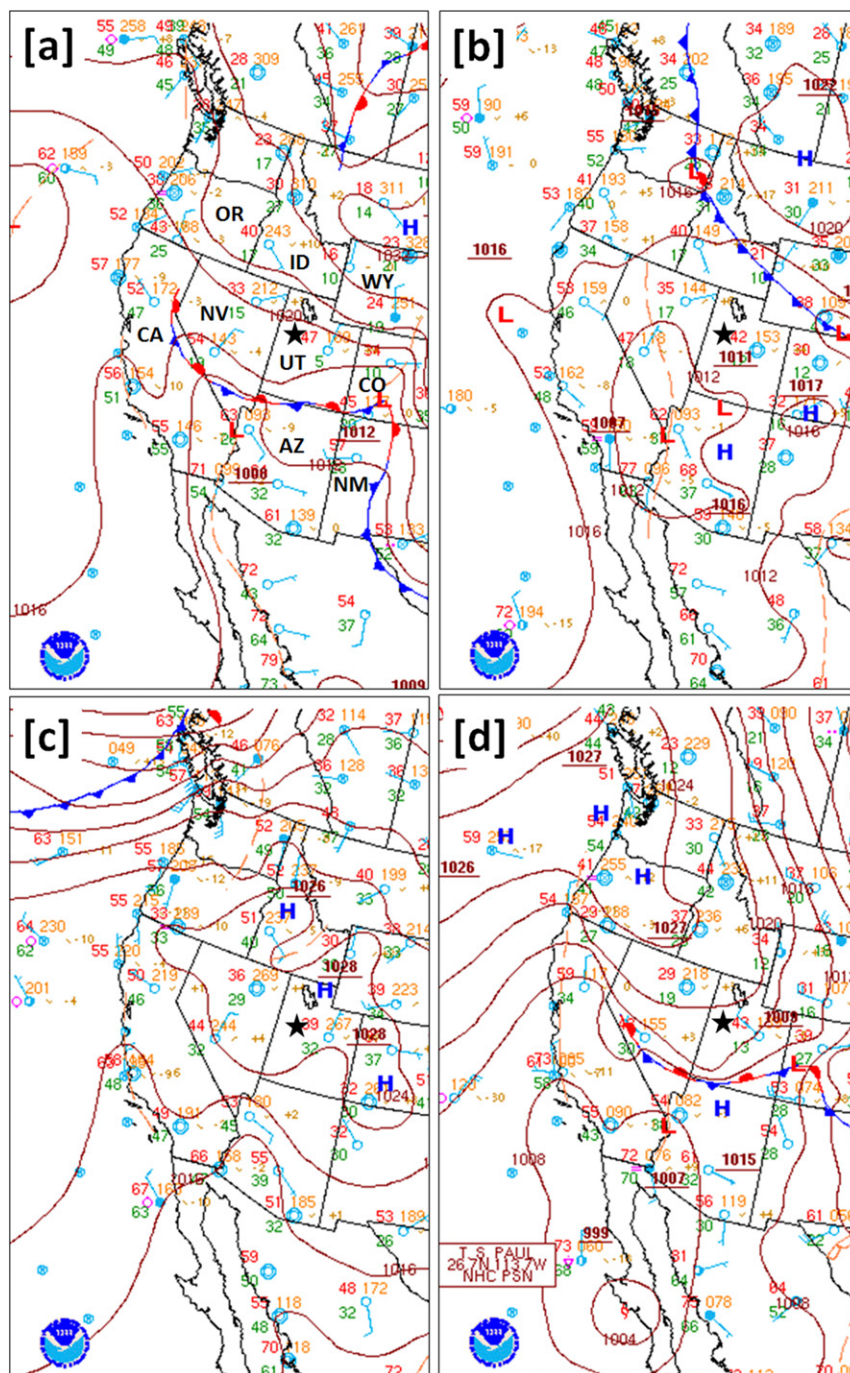


FIG. 2. Surface synoptic charts at 1200 UTC (a) 6, (b) 9, (c) 14, and (d) 17 Oct 2012 for the western United States. The location of the experimental area is marked by a black star, and the states are labeled in (a). (Figures courtesy of the NOAA Weather Prediction Center; <http://www.wpc.ncep.noaa.gov>.)

measurements (e.g., Davis et al. 1997; Kiemle et al. 1997). This method is advantageous over other gradient-based approaches for being less prone to noise in the signals and suitable under many meteorological situations. Additionally, the method is able to deal with

complex situations including multiple aerosol stratifications and can be applied to high-range-resolved profiles of aerosol backscatter (e.g., Davis et al. 1997; Cohn and Angevine 2000; Wulfmeyer et al. 2010; Pal et al. 2010, 2015; Behrendt et al. 2011a,b). Sensitivity tests

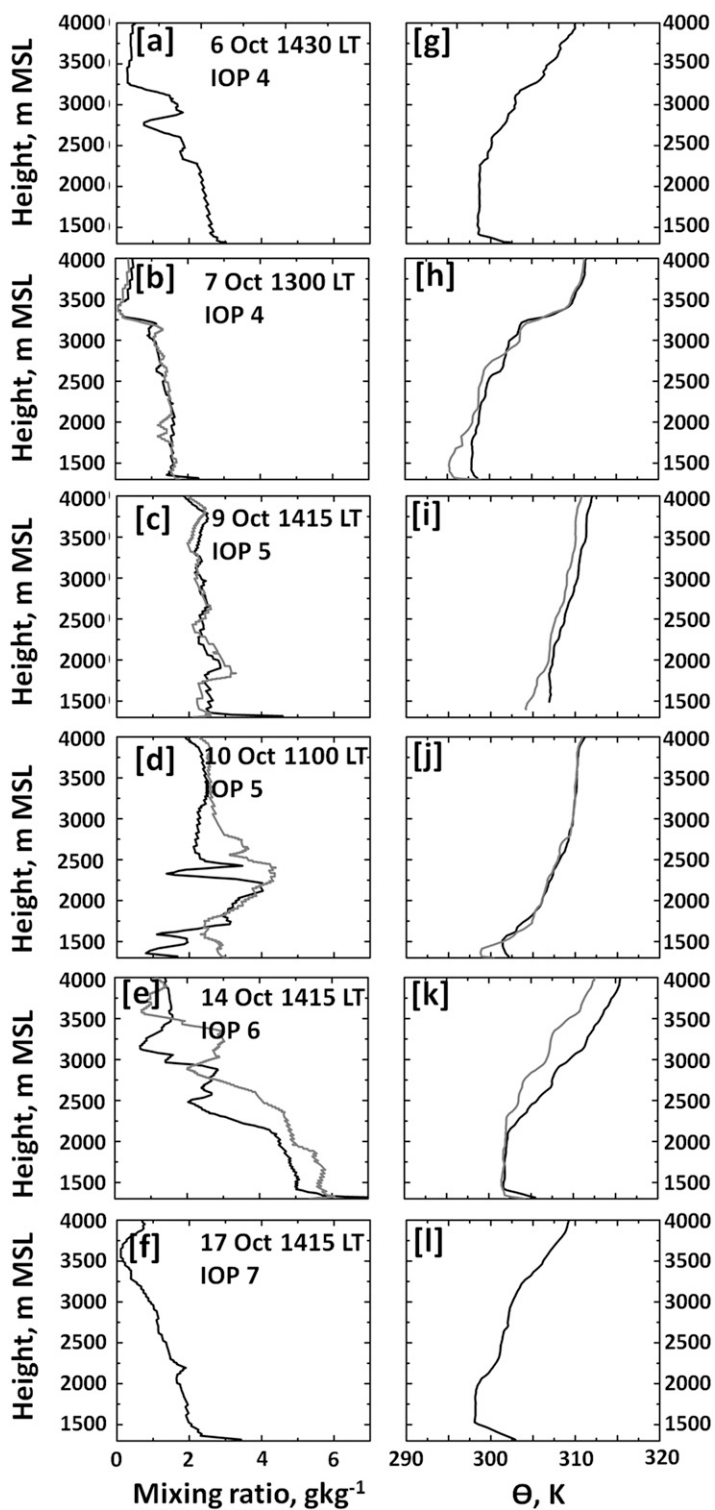


FIG. 3. Daytime radiosonde-derived profiles of (a)–(f) water vapor mixing ratio and (g)–(l) potential temperature θ over Sagebrush (black solid line) and Playa (gray solid line) sites during IOPs 4–7.

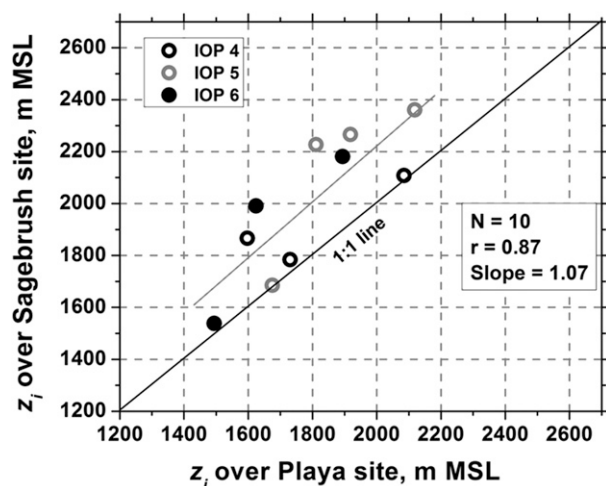


FIG. 4. Intercomparison between z_i over the PL and SB sites retrieved from simultaneous radiosondes launched during IOPs 4 (black circles), 5 (gray circles), and 6 (black solid circles). Indicated are N for the number of radiosonde pairs and r for the linear regression coefficient. The black solid line (1:1 line) indicates a perfect agreement between z_i over two sites, and the gray solid line marks the regression line.

were performed to select an appropriate dilation value (200 m here) following Cohn and Angevine (2000) and Pal et al. (2010). In this study, we refer to z_i relative to MSL and not relative to ground level.

Additionally, we determined daytime z_i using the radiosonde profiles of thermodynamic variables at the Playa and Sagebrush sites to compare with the lidar-derived z_i and to provide a general overview of the daytime z_i on different IOPs. We also performed a detailed intercomparison between lidar and radiosonde estimations of z_i during both morning and afternoon flight hours to evaluate the wavelet-based results.

6. Results and discussion

a. Radiosonde-derived z_i over the eastern and the western sites

First, a total of 37 radiosonde profiles [23 over the western site (Playa) and 14 over the eastern site (Sagebrush)] obtained on the four IOPs were analyzed to investigate the differences in daytime z_i between the Playa and the Sagebrush sites. There were 10 occasions where radiosondes were launched simultaneously from the Playa and Sagebrush sites. A bulk Richardson number method was applied to determine z_i using the radiosonde profiles of temperature, humidity, and horizontal wind speed (e.g., Seibert et al. 2000). The z_i over the Sagebrush site was higher than z_i over the Playa site by up to 25% (185 m while averaged over the four IOPs)

with larger absolute differences in z_i between the two sites occurring during the afternoon than during the morning (Fig. 4). Note that the ground level at the Sagebrush site is ~ 20 m higher than at the Playa site, which slightly influences the observed differences.

IOPs 4 and 5 were characterized by the presence of a deep CBL (with z_i between 2200 and 2600 m MSL) transitioning into a deep residual layer during the night. This deep residual layer facilitated rapid CBL growth the next morning. This positive feedback cycle was disrupted by the precipitation event on 12 October 2012, which consequently triggered a significant increase in the soil moisture content and in the CBL moisture regime (increase of $2\text{--}3 \text{ g kg}^{-1}$ in the CBL). The amount of incoming solar radiation was similar at both the Playa and Sagebrush sites with a larger average daytime albedo measured at the Playa site (0.31 with a range between 0.24 and 0.35) than at the Sagebrush site (0.27 with a range between 0.18 and 0.29) (Massey et al. 2014). Furthermore, sensible heat fluxes and z_i were lower over both sites during IOP 6 than during IOPs 4 and 5 (see section 6e).

b. Comparison between radiosonde- and TODWL-derived z_i

Previous z_i intercomparison studies (lidar versus radiosonde) explain inconsistencies as a result of radiosonde drift and application of two different methods to estimate z_i : 1) an aerosol-gradient-based method for the lidar measurements and 2) a thermodynamic profile-based approach for radiosonde measurements (e.g., Seibert et al. 2000). These inconsistencies were found both for temporal z_i variability using ground-based lidars (e.g., Davis et al. 1997; Cohn and Angevine 2000; Pal et al. 2013) and for z_i spatial variability using airborne lidars (e.g., Behrendt et al. 2011a; Scarino et al. 2014). Additionally, we recognize that CBL heights derived from thermodynamic profiles and from aerosol backscatter profiles may be different over mountainous areas because of terrain-induced exchange processes (e.g., De Wekker et al. 2004).

Before discussing the intercomparison between TODWL- and radiosonde-derived z_i results, it should be noted that the closest NS flight legs available for comparison on the eastern (western) side of Granite Mountain were at a horizontal distance of 5.5 km (2.5 km) from the Playa (Sagebrush) radiosonde site. An intercomparison between TODWL and radiosonde measurements of z_i for both the Playa and Sagebrush sites during morning and afternoon missions shows that CBL heights from thermodynamic and from aerosol backscatter profiles are comparable for the current dataset (Fig. 5). For the box-and-whisker analyses, we

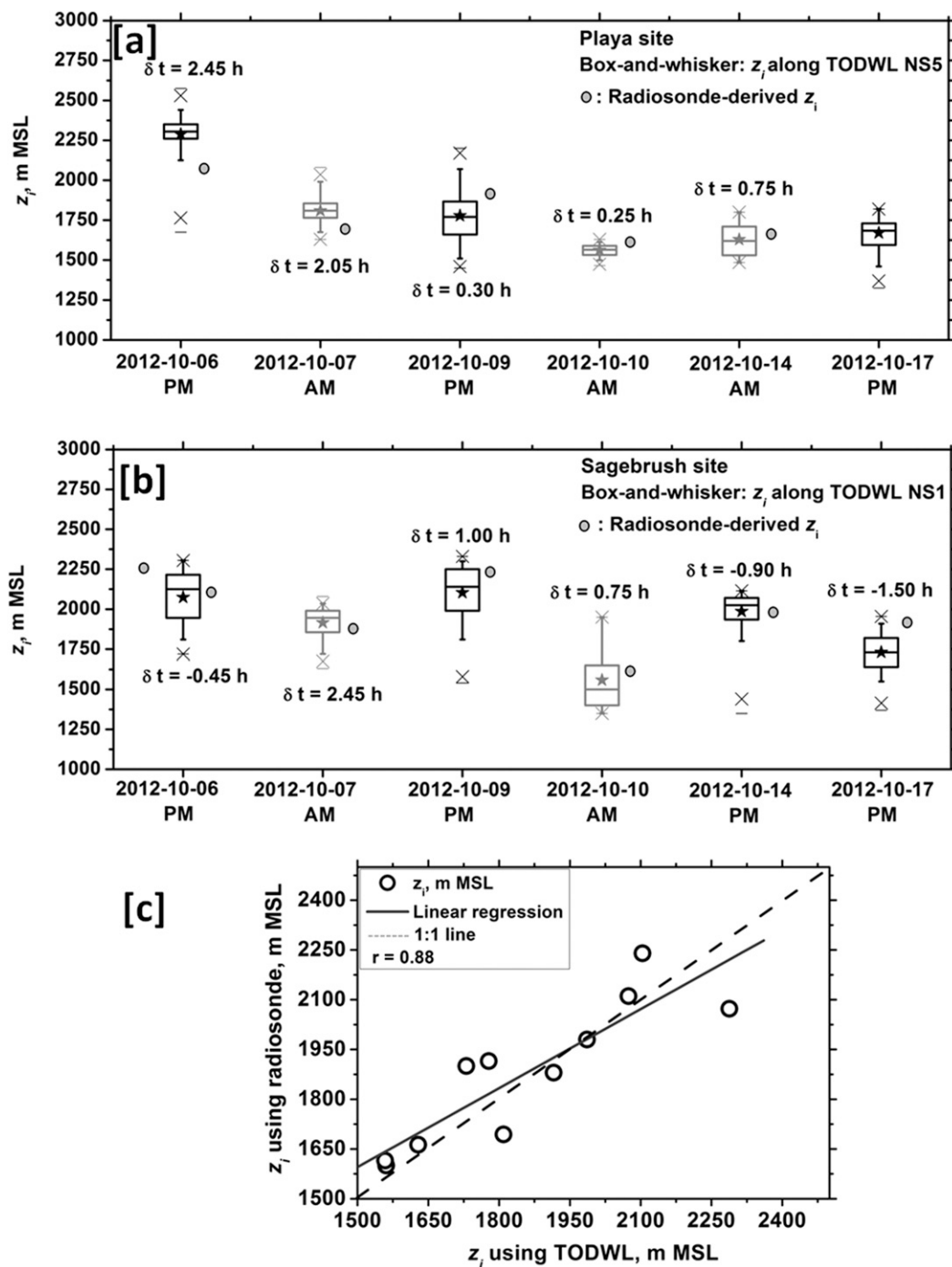


FIG. 5. TODWL- and radiosonde-derived z_i observed over the (a) PL and (b) SB sites along with (c) linear regression analysis between mean values of TODWL- and radiosonde-derived instantaneous z_i . Box-and-whisker analyses of z_i along NS flight legs around both sites during morning (gray boxes) and afternoon (black boxes) CBL regimes are shown along with the radiosonde-derived z_i (gray circles) obtained over both sites. Here, δt indicates the time difference between the radiosonde launches and the TODWL overpass along the NS1 (for SB) and NS5 (for PL) legs. Also shown is z_i from radiosonde measurements at 1430 LT over the SB site for 6 Oct [marked by the gray circle located to the left of the box in (b)].

considered the TODWL-derived z_i values along NS5 (NS1) located over the flat terrain areas close to Playa (Sagebrush). The z_i values obtained with the radiosonde profiles for the launches from both the Playa and the Sagebrush sites around the overpass times of TODWL are also indicated for comparison.

On 6 October, the afternoon TODWL flights took place around 1500 LT, while radiosonde measurements at the Playa site were around 1810 LT. There were two radiosonde launches at 1430 and 1810 LT over the Sagebrush site, but only the former radiosonde launch was considered for the TODWL versus radiosonde intercomparison. To take into account the possible effect of z_i evolution over time during the time between the TODWL overpass and the radiosonde launches, this time difference δt is also indicated in Fig. 5.

We found that δt (radiosonde launch time minus TODWL overpass time) varies between -1.5 and $+2.5$ h. Results indicate that for a δt of less than an hour, the observed z_i differences (radiosonde-derived z_i minus TODWL-derived z_i) lie around ± 50 m. Also, for cases with larger δt , in particular, for the morning flight hours, a large difference between TODWL- and radiosonde-derived z_i was found that suggests a larger impact of morning z_i growth on the intercomparison results. The relationship between δt and the observed z_i difference is definitely not straightforward given the observed heterogeneity in the spatial z_i field over the area, and the relatively small number of samples ($n = 11$ here) available for intercomparison.

A linear regression analysis resulted in a correlation coefficient of 0.88 and a mean absolute difference of 21 m based on 11 samples (Fig. 5). For growing CBL regimes in the morning, local surface heterogeneity plays a major role in modulating z_i spatial variability over complex terrain (e.g., Steyn et al. 2013). In the case of a rapidly growing CBL in the morning, the intercomparison becomes challenging from both experimental and statistical points of view largely because of nonstationarity present in the growing z_i over land surfaces (e.g., Fedorovich et al. 2004).

The intercomparison results presented here are similar to previous findings over complex terrain reported by Behrendt et al. (2011a) and Scarino et al. (2014). For instance, Scarino et al. (2014) illustrated that the mean absolute differences between ground-based radiosonde and ceilometer observations and airborne measurements are only well correlated for relatively short distances (<30 km) in their experimental setup with underlying topography and land cover, indicating the challenges involved with capturing the z_i spatial variability by limited ground-based measurements.

Within numerous studies in the past, differences found between lidar and radiosonde-based z_i variabilities were

used as a measure of uncertainties in the lidar-based z_i estimates (e.g., Seibert et al. 2000; Lammert and Bösenberg 2006; Haeffelin et al. 2012; Pal et al. 2013). Thus, results presented in Fig. 5 suggest that an uncertainty of about 21 m needs to be considered for the TODWL-derived z_i estimates. However, caution needs to be taken into account for such z_i uncertainty estimations using lidar measurements over mountainous areas like the MATERHORN experimental region, since it has been clearly shown that the intercomparison results (Figs. 4 and 5) and z_i variability over the experimental area are largely influenced by topographical features and local heterogeneity in the surface fluxes. Additionally, the number of samples ($n = 11$) considered here is relatively low when compared with the long-term z_i variability studies (e.g., Pal and Haeffelin 2015). Independent error estimation in z_i based on only lidar-derived profiles of aerosol backscatter is considered to be an important future research task.

Despite the challenges involved in comparing observations from a sensor launched from a particular place (radiosonde) with a moving platform (TODWL), we can conclude that TODWL- and radiosonde-derived z_i are in reasonably good agreement, which confirms that high-resolution z_i estimates using TODWL-derived backscatter profiles are appropriate for investigating z_i spatial variability in the experimental region.

c. Spatial variability in z_i using TODWL measurements

In the following, we discuss five different types of z_i variability: 1) z_i variability along a leg (e.g., NS3), 2) z_i variability among different legs (e.g., NS1, NS2, NS3, EW1, EW2, etc.), 3) the z_i gradient in the experimental domain using z_i along NS1 and NS5, 4) z_i spatial variability during morning and afternoon periods, and 5) differences in the z_i spatial variability among four IOPs. Thus, for brevity and for harmonization among different situations of z_i spatial variability (Figs. 6–8), we used different color-bar scale limits for the morning (i.e., 1300–2300 m MSL) and for the afternoon z_i estimates (i.e., 1400–2600 m MSL). Additionally, for investigating z_i spatial variability during all of the IOPs, we did not use the TODWL measurements taken during the times when the aircraft turned and tilted while moving from one straight leg to another (e.g., NS1 to NS2; EW1 to EW2). During these times, most of the lidar backscatter profiles were erroneous and z_i could not be determined.

1) IOP 4 (6–7 OCTOBER 2012)

During IOP 4 on 6 October 2012, the TODWL collected data during five NS flight legs in the afternoon between 1455 and 1530 LT. The plan-view plot of z_i

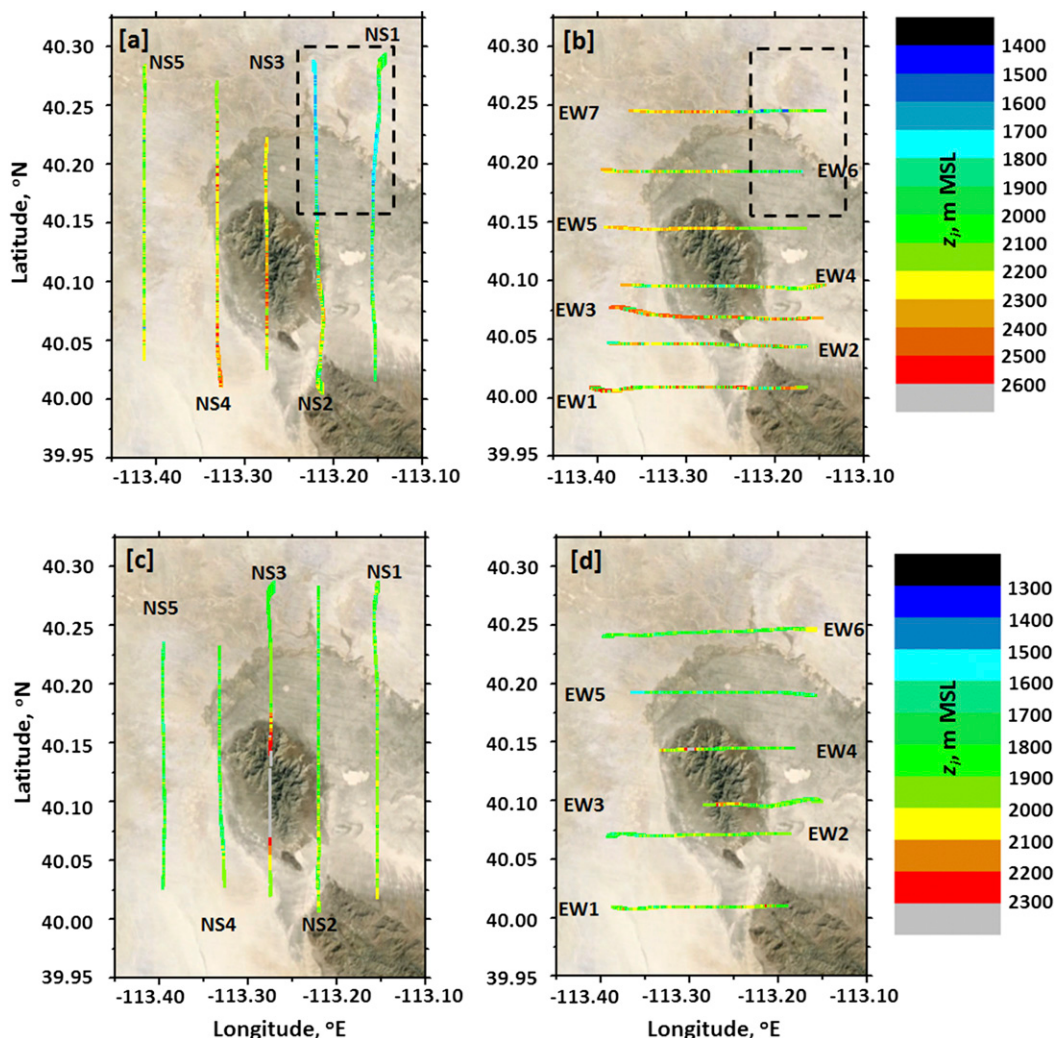


FIG. 6. TODWL-derived z_i estimates with a spatial resolution of about 100 m along the flight tracks during the afternoon of 6 Oct 2012 for (a) NS transects between 1459 and 1539 LT and (b) EW transects between 1540 and 1620 LT and during the morning of 7 Oct 2012 for (c) NS transects between 1018 and 1101 LT and (d) EW transects between 1102 and 1145 LT. The names of both the EW and NS transects are indicated (e.g., NS1, EW1) at the starting points of the legs. Regions of elevated aerosol layers observed by TODWL are marked with dashed rectangles in (a) and (b). Note that two different color bars are used to discriminate z_i spatial variability over different regions during the afternoon [(a) and (b)] and morning periods [(c) and (d)]. The average speed of the aircraft was around 50 m s^{-1} so that it flew a total distance of around 26 km along each flight leg. Measurements during the turns were not used for the analyses. (Source of the satellite images is Google, Inc.)

indicates higher z_i west than east of Granite Mountain (Fig. 6). Additionally, data from a radiosonde launched at 1430 LT at the Sagebrush site confirmed $z_i \approx 2250 \text{ m MSL}$, which agrees well with the TODWL-derived z_i along NS1 around 1500 LT, which was 2175 m with a standard deviation of 158 m. The standard deviation was estimated using the z_i values along the entire flight leg NS1. There was no radiosonde launched from the Playa site around the TODWL flight hours to compare with the lidar-observed z_i variability.

In general, lower z_i values were observed for the first two legs (NS1 and NS2), which occurred east of Granite Mountain, than for the other two legs (NS4 and NS5), which occurred west of Granite Mountain. This indicates the presence of processes that act to inhibit CBL growth east of Granite Mountain in this particular case. The time–height cross sections of aerosol backscatter signal intensity along NS1 and NS2 show the presence of an elevated aerosol layer around the altitudes of 2800–3000 m MSL in the northern parts of legs NS1 and NS2.

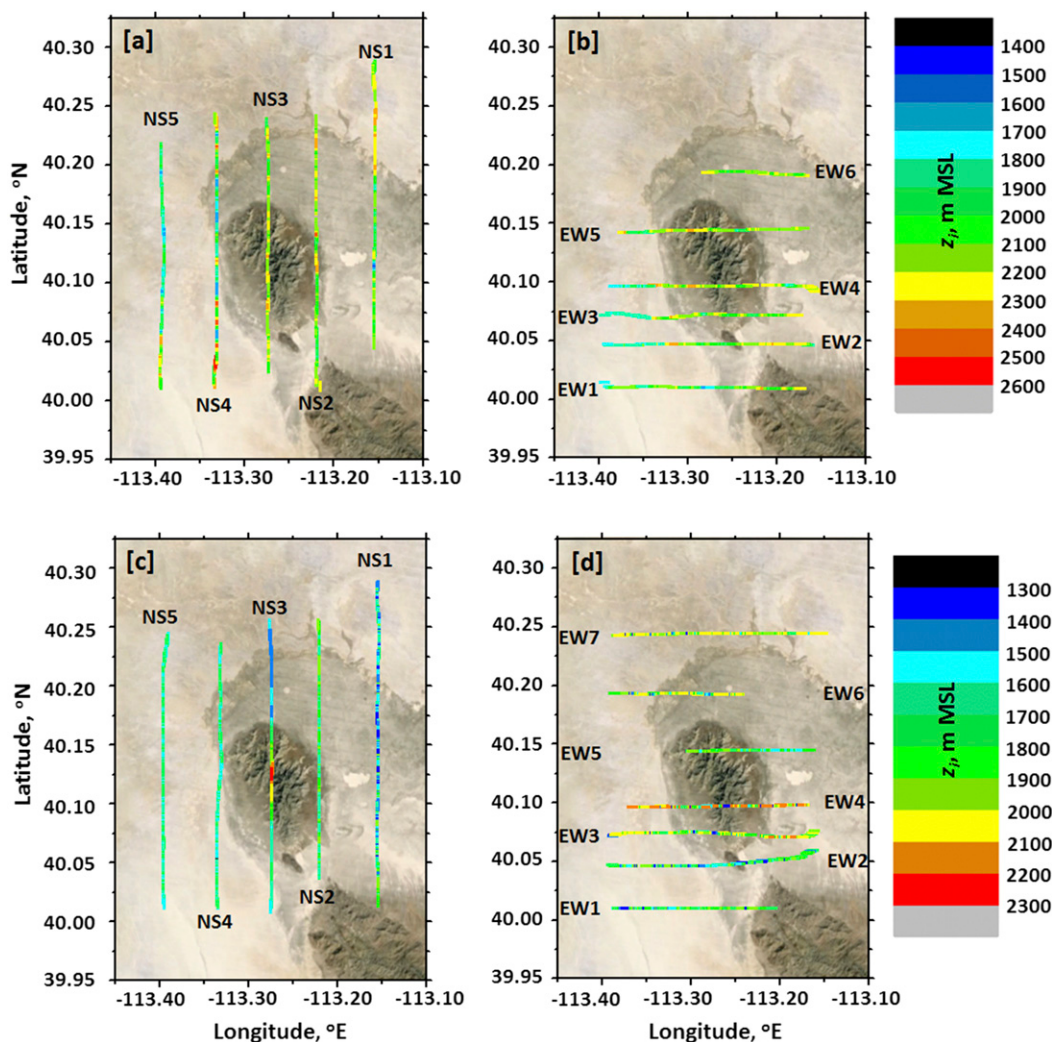


FIG. 7. As in Fig. 6, but during the afternoon of 9 Oct 2012 for (a) NS legs between 1600 and 1643 LT and (b) EW legs between 1644 and 1715 LT and during the morning of 10 Oct 2012 for (c) NS legs between 1012 and 1053 LT and (d) EW legs between 1054 and 1137 LT.

The radiosonde profile at the Sagebrush site also showed layers of enhanced stability and moisture content above the CBL (see Fig. 3a) that most probably weakened the upward mixing and reduced the further growth of z_i . The TODWL-observed aerosol layer is presumably advected from north of Granite Mountain with potential temperature inversions that acted like a lid. The TODWL measurements of horizontal wind field confirmed the prevailing northwesterly winds at 3000 m MSL. In past studies, it has been suggested that the presence of such a stable layer with enhanced stability inhibits boundary layer growth (e.g., Pal et al. 2010; Barlow et al. 2011; Luo et al. 2014).

Occurrences of such elevated layers are particularly common in the atmosphere over mountainous terrain

governed by multiple temperature inversions. The pollutants above the CBL are trapped between two stable layers and become decoupled from the surface as they are not affected by turbulent transport processes as opposed to the CBL, where this transport is mainly ensured by CBL thermals (Stull 1988). In some other studies discussing aircraft-based measurements, these layers were associated with venting processes (e.g., Blumenthal et al. 1978; Wakimoto and McElroy 1986; De Wekker et al. 2004). These stratified layers are in general associated with stronger backscatter than the well-mixed CBL aerosol structures, and remain separated from the boundary layer inversion, in particular, over mountainous areas (e.g., Blumenthal et al. 1978; Bradley et al. 2015). The high SNR in the

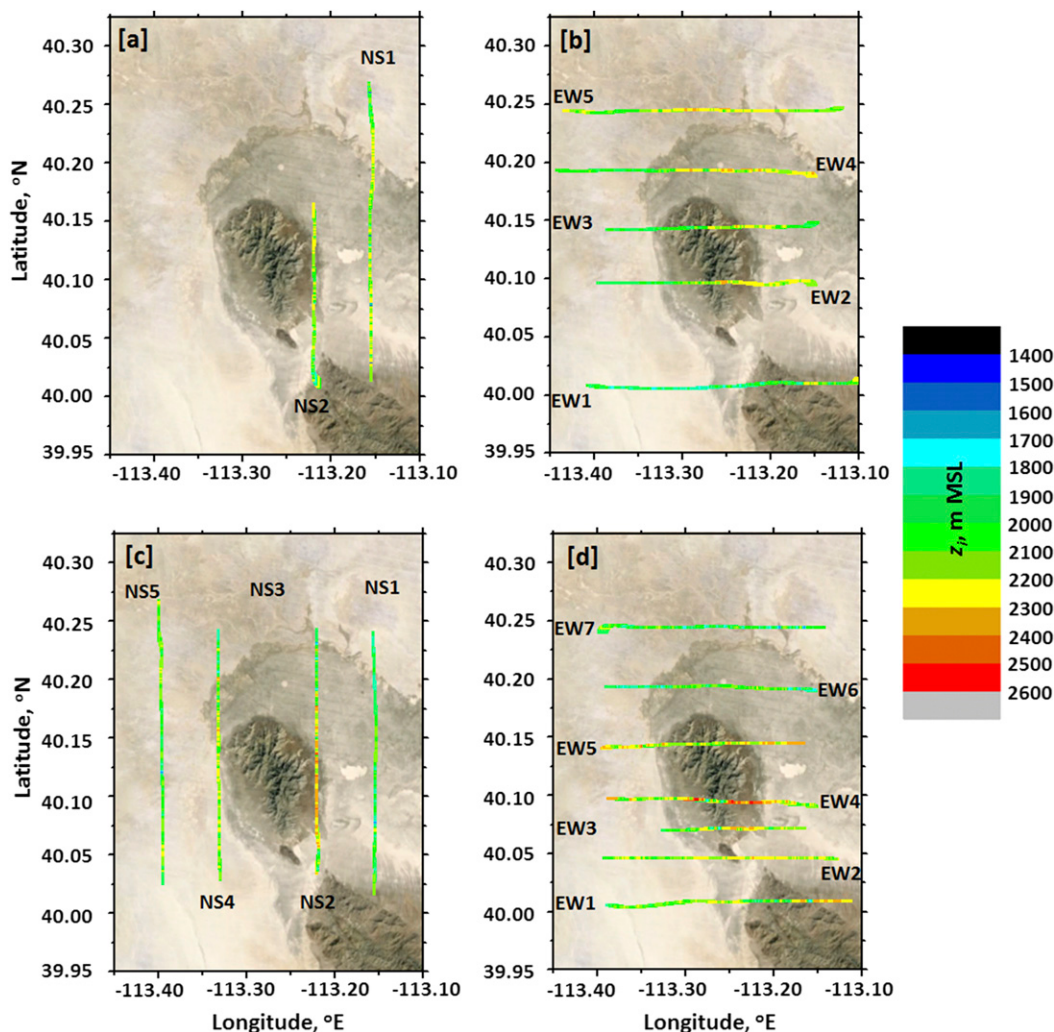


FIG. 8. The z_i spatial variability obtained from TODWL legs during the afternoon of 14 Oct 2012 for (a) NS legs between 1509 and 1522 LT and (b) EW legs between 1605 and 1646 LT and 17 Oct 2012 for (c) NS legs between 1535 and 1605 LT and (d) EW legs between 1610 and 1655 LT. The color bar on the right applies to the z_i variability on both days, unlike in the previous figures.

TODWL-derived backscatter profiles on the eastern side of Granite Mountain allowed for the detection of the sharp gradient of aerosol backscattering near the CBL top below the elevated aerosol layer. In contrast, no such elevated aerosol layer was observed along the legs on the western side of Granite Mountain.

Additionally, along NS3, NS4, and NS5, z_i estimates are considerably larger to the south than to the north of Granite Mountain (see Fig. 6a). On this day, the TODWL measurements of horizontal wind profiles and the surface meteorological observations confirmed the presence of a weak northerly upper-level flow ($<5 \text{ m s}^{-1}$) and weak north-northwesterly surface winds ($<5 \text{ m s}^{-1}$). It is possible that these prevailing northerly winds advected higher z_i downwind of the mountain when

compared with the northern sector. Previously, McElroy and Smith (1991) and Arritt et al. (1992) also found that deep CBLs that formed over mountainous terrain can be advected downwind over low terrain and consequently affect the dispersion of air pollutants.

The EW legs confirmed a similar quasi-stationary and spatially variable z_i (i.e., west–east z_i gradient), as was found from the NS legs. However, some growth in z_i was observed during more than 1 h of TODWL observations based on the higher z_i in the EW transects than in the NS transects. In particular, over the southeast side of Granite Mountain a considerable region of z_i growth was observed ($\sim 200\text{--}300 \text{ m}$). The EW legs also show lower z_i to the northeast sector of Granite Mountain than to the northwest sector.

TODWL performed five NS flight legs and six EW flight legs during the morning transition period on 7 October 2012 (Figs. 6c and 6d). Especially along NS3 and EW4, which cross directly over Granite Mountain, z_i follows the terrain closely at a height of ~ 400 m AGL. Previous studies also illustrated the fact that when the heating starts during the morning transition period, z_i nearly follows the underlying topography (e.g., Lieman and Alpert 1993; Kalthoff et al. 1998; De Wekker and Kossmann 2015). Over the flat area east of Granite Mountain, z_i is ~ 110 m higher than west of the mountain. There was considerable z_i spatial variability during the morning transition period on this day along the NS and the EW legs. The observed z_i spatial variability is attributed to the rapidly growing CBL during the morning transition period. In such situations, local differences in surface characteristics can result in z_i spatial variability over relatively small spatial scales (e.g., Lenschow and Stankov 1986; Steyn et al. 2013).

2) IOP 5 (9–10 OCTOBER 2012)

During the afternoon TODWL flights on 9 October 2012, the CBL was well developed over the experimental region. The value of z_i was up to 300 m higher along the eastern side and over Granite Mountain (NS1 and NS2) than over the western side of Granite Mountain (NS4 and NS5) (Fig. 7a). No terrain-following z_i was detected over Granite Mountain along NS3. Radiosonde-derived thermodynamic profiles over the Playa and the Sagebrush sites also confirmed the presence of well-mixed CBL features during this time. These measurements confirm that z_i does not follow the height of the underlying topography in the presence of a deep well-mixed CBL, which is similar to the findings reported in some previous studies (e.g., Kalthoff et al. 1998; Kossmann et al. 1998; De Wekker et al. 2004; Behrendt et al. 2011a). Under these conditions when the largest turbulent eddy size, scaled to z_i , exceeds the vertical scale of the topography (here, ~ 1 km), z_i is not influenced by underlying topography (e.g., Panofsky et al. 1977; Banta 1985; Choi et al. 2011). However, there exists a clear east–west difference (i.e., higher z_i over the eastern site than over the western site) of up to 300 m, which was caused by differences in land surface type and soil moisture between these two regions of the experimental area (see sections 6d and 6e for further discussion).

Additionally, TODWL-derived horizontal wind profiles (not shown here) confirmed the presence of west-southwesterly flow with wind speeds of around $5\text{--}7\text{ m s}^{-1}$, while tower measurements indicated the near-surface winds to be light ($2\text{--}3\text{ m s}^{-1}$) south-southwesterly. Thus, during such prevailing synoptic settings, a deeper CBL

could be expected over the Sagebrush site downwind of Granite Mountain. In general, if a deeper CBL forming over the mountain is advected downstream, it enhances the z_i on the downwind side of the mountain (e.g., Lieman and Alpert 1993; Demko et al. 2009; Demko and Geerts 2010).

Values of z_i obtained from the EW flight legs between 1645 and 1715 LT on 9 October 2012 also confirm the higher z_i over the eastern side than over the western side of Granite Mountain (Fig. 7b). Additionally, no significant increase was observed in z_i between flight legs that sampled the same location 30 min apart, confirming that there was no further CBL growth during this time. For instance, z_i was around 2300 m MSL over the Sagebrush area and around 2000 m MSL over the Playa site area for both the NS and EW transects.

On the morning of 10 October 2012, five NS and seven EW legs were flown (Figs. 7c and 7d). The lidar system encountered some instrumental malfunctions while flying west of Granite Mountain. Thus, z_i measurements were missing on the western part of leg EW5. Additionally, a few white dots along the tracks mark the locations where z_i retrieval was not possible because of erroneous lidar profiles. A shallow CBL (approximately 300 m deep) was present over the area except along flight leg NS3 over Granite Mountain, where orographic enhancement of the CBL is clearly present near the ridgetop. Ground-based ceilometer measurements near the western slope of Granite Mountain indicated a rapidly growing CBL during this period (growth rate of 120 m h^{-1}). Consequently, z_i increases during the time that the NS flight legs and the EW flight legs were flown. For instance, z_i increased by about 100 m in half an hour (i.e., growth rate of 200 m h^{-1}) over the Sagebrush area and over the Playa area, which is different than over the western slope of Granite Mountain. The aircraft-derived z_i growth rate involves more areal coverage, unlike the ground-based ceilometer observations over a particular place, which are just like “needle” measurements over a particular location. Additionally, as mentioned earlier, land surface heterogeneity in the experimental domain is a crucial factor in determining z_i variability and growth rates.

3) IOP 6 (14 OCTOBER 2012)

IOP 6 on 14 October 2012 took place after the rainfall event on 12 October 2012 so that a decrease in both near-surface temperature (by 5°C) and diurnal temperature range ($\sim$ by 5°C) was observed when compared with the IOPs before the rainfall event. On this IOP, the TODWL performed both morning and afternoon measurements. Unlike other IOPs, it was not possible to obtain a symmetric grid for the flight tracks covering the

entire experimental domain because of some unavailable TODWL measurements on this day. Consequently, flight legs were truncated at various places. A terrain-following z_i over Granite Mountain was observed for the NS3 flight leg and for the EW4 flight leg during the morning mission (not shown here).

In the afternoon a well-developed CBL regime with z_i of around 2230 m MSL was observed along flight legs NS1 and NS2 (Fig. 8a). Along flight legs EW2, EW3, and EW4, z_i in the eastern part was about 200 m larger than in the western part while differences along southernmost leg EW1 were small (Fig. 8b). Because of unavailable NS flight legs over the western side of Granite Mountain (i.e., NS4 and NS5) during the afternoon, it was not possible to investigate further the east–west z_i gradient.

In the afternoon, a heterogeneous z_i is observed along leg EW5 with a mean z_i of 2175 m MSL with a standard deviation of about 82 m. For brevity, we computed the mean z_i for two different sectors along EW5, which yielded a mean z_i of 2207 m with a standard deviation of 70 m (along the EW5 sector between 113.12° and 113.30°W) and 2102 ± 76 m MSL (along the EW5 sector between 113.31° and 113.44°W) east and west of the Playa border, respectively, confirming an east–west gradient in the z_i field on the northern side of the experimental area. Such z_i variability was consistent with heterogeneous land surface characteristics (e.g., the border between the northern Sagebrush area and northern Playa area) along the flight track.

4) IOP 7 (17 OCTOBER 2012)

Data collected during IOP 7 provide us with an opportunity to investigate the afternoon CBL during synoptically forced situations. IOP 7 was characterized by postfrontal strong north-northwesterly winds in the upper level ($>10 \text{ m s}^{-1}$) and in the CBL ($\sim 5 \text{ m s}^{-1}$), as was confirmed by the radiosonde and TODWL observations at 1400 LT. Thus, the prevailing synoptic flow patterns dominated the boundary layer evolution on this day. Near-surface meteorological measurements also indicated northerly winds of 5 m s^{-1} at both the Playa and the Sagebrush sites. Also, the daytime maximum sensible heat flux at the Playa site was lower ($\sim 80 \text{ W m}^{-2}$) than during other IOPs ($\sim 120 \text{ W m}^{-2}$). The estimated z_i results were lower (around 2200–2400 m MSL) than those for the other afternoons, with notable z_i spatial variability near Granite Mountain (Figs. 8c and 8d).

Unlike on other IOPs, there was no clearly visible east-to-west gradient in the z_i along NS transects for the well-mixed CBL regime in the afternoon. However, z_i in the southern and southeastern regions of Granite Mountain was highly variable and was higher (by more

than 200 m) than in the northern and northwestern regions. As mentioned, the TODWL-derived horizontal wind field showed the presence of north-northeasterly winds in the CBL so that higher z_i might have advected downwind of Granite Mountain (i.e., in the southeastern region of Granite Mountain).

It should be mentioned that the absence of an east–west z_i gradient could be most probably attributed to the prevailing synoptic conditions so that the CBL during the afternoon on 17 October 2012 was affected by CBL wind speed. Banta and White (2003), using a sample of 15 dry days from the Southern Oxidants Study, clearly illustrated that the presence of strong wind can even cancel the impact of surface forcing on z_i spatial variability. Following Taylor’s frozen turbulence hypothesis, one can consider that the turbulent length scale of the CBL eddies is closely related to the wind speed (Taylor 1938) so that the impact of increasing boundary layer wind speed is to enlarge the length (distance) scale required for the CBL to respond to the surface forcing (Lenschow and Stankov 1986). Thus, one can expect that with increasing wind speeds, the CBL is less heterogeneous.

Other researchers have also shown that even for a situation with more than light synoptic winds, advection rather than surface forcing can play an important role in modulating the z_i spatial variability in mountainous areas (e.g., Kiemle et al. 1997; Behrendt et al. 2011a, Steyn et al. 2013). Our findings on the z_i spatial variability on 17 October qualitatively agree with the results reported in the aforementioned studies. Nevertheless, further observational and modeling efforts would be required to draw a robust conclusion on the relative importance of advection and surface buoyancy flux on the observed z_i spatial variability over inhomogeneous terrain like the MATERHORN experimental area, and this work is the first step in that direction.

d. Statistical overview on the z_i spatial variability

The z_i variability observed during different IOPs is described using box-and-whisker analyses of z_i along the NS flight legs (Fig. 9) and the EW flight legs (Fig. 10). The analysis for the NS and EW flight legs provides an indication of the z_i variability across Granite Mountain in a direction from west to east in Fig. 9 and from south to north in Fig. 10, respectively. Lower values of z_i are generally encountered on the western side of Granite Mountain. However, on 6 October, z_i was lower on the eastern side, which coincided with the presence of a stable layer and relevant thick aerosol layer above the CBL on the eastern side of Granite Mountain along NS1 and NS2, as discussed before.

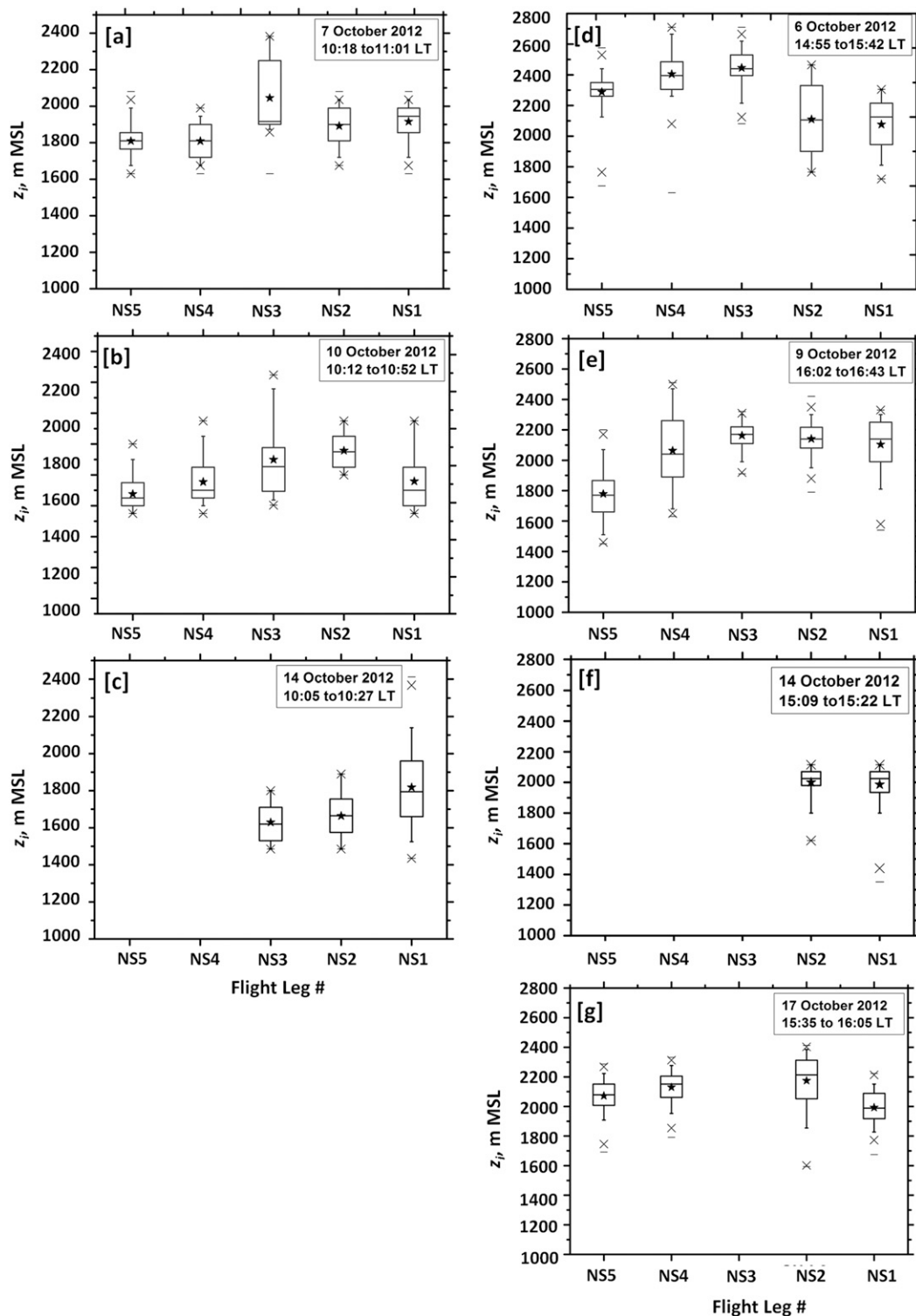


FIG. 9. Box-and-whisker plots of z_i (m MSL) along the NS flight legs performed for all four IOPs during (a)–(c) morning and (d)–(g) afternoon TODWL missions. Moving from left to right along the horizontal axis is equivalent to going from west to east. In each box, the solid lines indicate the median and the extent of the boxes (25th and 75th percentiles); whiskers represent the 5% and 95% values of z_i along each track. The solid star is the mean value, and the asterisks are the maximum and minimum. Note two different y-axis scale limits for morning and afternoon flight legs are used, which helps to illustrate the spatial variability during both morning and afternoon CBL regimes.

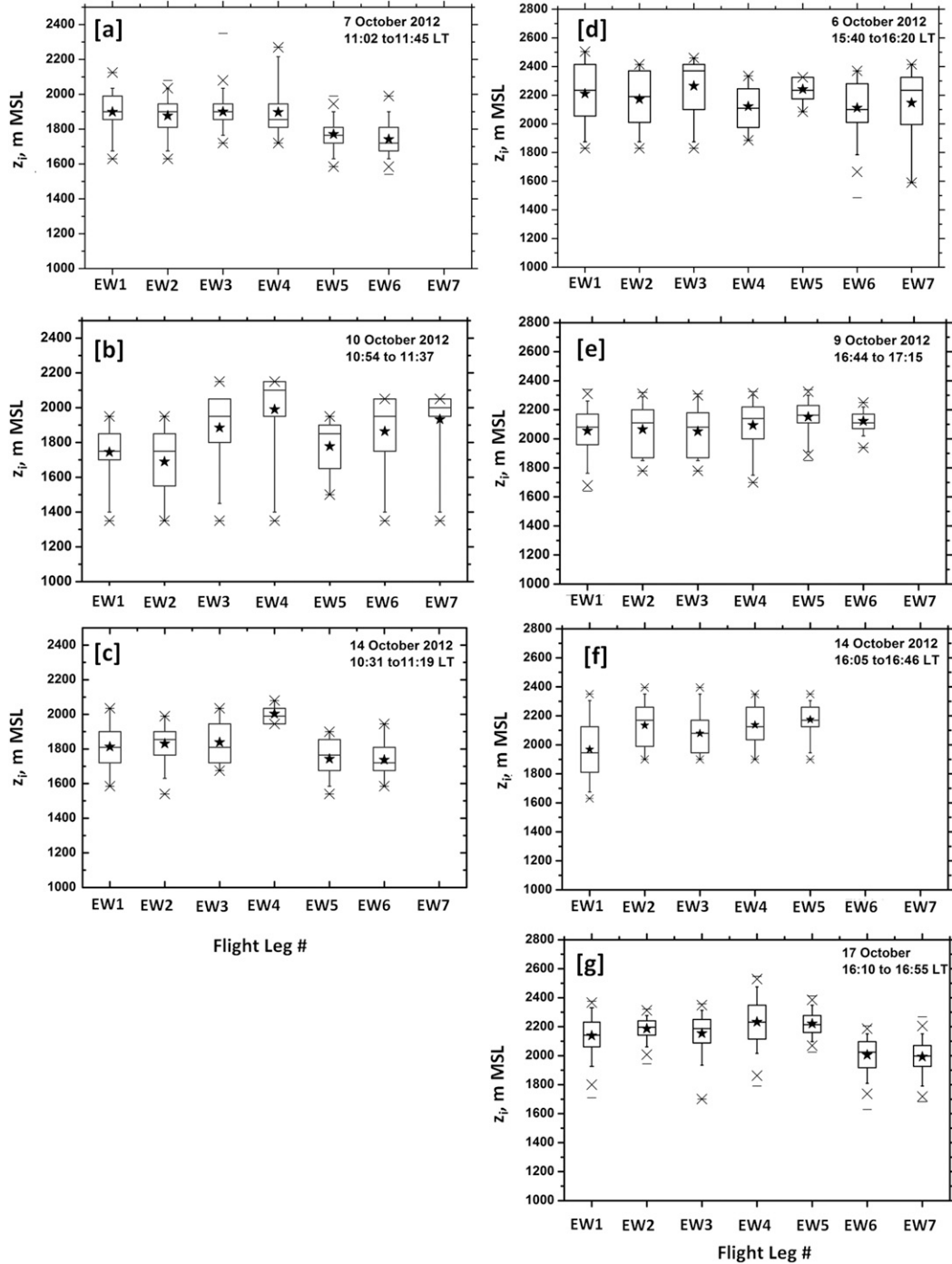


FIG. 10. As in Fig. 9, but for EW flight legs during three IOPs: (a)–(c) morning and (d)–(g) afternoon missions. Moving from left to right along the horizontal axis is equivalent to going from north to south. Two different y-axis scales are kept for morning and afternoon measurements to compare different morning and afternoon CBL regimes during different IOPs.

In general, z_i spatial variability was larger during the morning flights than during the afternoon flights. In particular, during the morning transition periods of IOP 4 (7 October) and IOP 6 (14 October), a moderate

south–north z_i gradient (with ~ 150 m higher z_i in the south than in the north) was observed (Fig. 10), while on other mornings such a gradient was not observed. The TODWL-derived horizontal wind field suggested

prevailing north-northwesterly flow at 3000 m MSL during morning hours on 7 October so that enhanced z_i to the southeast of Granite Mountain illustrated the possible role of advection from higher z_i over the mountain to downwind areas. A similar conclusion cannot be made for the 14 October morning TODWL flights as the data coverage was not sufficient (e.g., unavailable NS1 and NS2 legs) and the observed horizontal wind speed and direction were highly variable with altitude.

We performed statistical analyses on all of the measurements of z_i obtained along NS legs during different IOPs (Table 2). We did not perform similar analyses for investigating z_i variability along the EW flight legs since a major portion of those flight legs were over the two mountain ranges (Dugway range and Granite Peak), making it difficult to sample statistically significant z_i datasets for comparing east–west gradient in the z_i .

To quantify further the observed z_i spatial variability, we mainly focus here on the histogram of z_i along different NS legs and discuss the results using the standard deviation of z_i (σ_{z_i}), illustrating small-scale z_i fluctuations (see Table 2). The σ_{z_i} results along different legs most probably indicate the presence of vigorous thermals and terrain-following CBLs during the mornings of 7, 10, and 14 October (see NS3 in Figs. 6 and 7).

In general, the CBL consists of highly fluctuating and irregular structures and eddies; consequently, z_i variability necessarily carries this information by its irregularity in space and time (e.g., Beyrich and Gryning 1998; Flamant et al. 1997). Thus, the daytime thermal updrafts and downdraft signatures embedded in z_i fluctuations are found in σ_{z_i} . However, σ_{z_i} results along NS3 during the afternoons of 6 October (88 m) and 9 October (117 m) are smaller when compared with σ_{z_i} along the other legs confirming no significant impact of Granite Mountain (i.e., underlying orography-induced enhancement) on z_i . While comparing σ_{z_i} along different NS flight legs (NS1–NS5), larger σ_{z_i} was mostly observed along NS3 (i.e., NS flight leg over Granite Mountain) than over the other legs in the morning. This contrast could mainly be attributed to the effects of the underlying topography during the morning transition period.

In previous studies over flat and homogeneous terrain, the standard deviation of the quasi-stationary z_i over both temporal and spatial domains was defined as the EZT (e.g., Melfi et al. 1985; Flamant et al. 1997; Pal et al. 2010). However, such estimations were not performed in the past for z_i spatial variability over mountainous areas, in particular, using airborne lidar observations. Entrainment processes near z_i involve interactions between CBL plumes and free-atmospheric air, which

TABLE 2. Overview of the observed z_i spatial variability along TODWL NS legs during afternoon and morning flight missions of four IOPs over the experimental area.

Date (2012)	IOP No.	Time (LT)	Leg No. and orientation	Mean z_i (m MSL)	σ_{z_i} (m)
6 Oct	4	1455–1542	NS1	2175	158
			NS2	2109	237
			NS3	2445	117
			NS4	2404	131
			NS5	2287	112
7 Oct	4	1018–1101	NS1	1915	85
			NS2	1892	96
			NS3	2045	193
			NS4	1809	89
			NS5	1809	93
9 Oct	5	1602–1643	NS1	2104	168
			NS2	2141	110
			NS3	2163	88
			NS4	2063	240
			NS5	1778	167
10 Oct	5	1012–1052	NS1	1558	180
			NS2	1757	123
			NS3	1701	223
			NS4	1455	135
			NS5	1375	100
14 Oct	6	1005–1027	NS1	1970	211
			NS2	1763	123
			NS3	1728	104
		1509–1522	NS1	2136	109
			NS2	2150	98
17 Oct	7	1530–1605	NS1	1730	111
			NS2	1682	163
			NS4	1597	120
			NS5	1670	101

leads to high-amplitude z_i fluctuations. Thus, we consider that z_i spatial variability along different legs (i.e., σ_{z_i}) during afternoon flight missions over the experimental area could be used to help estimate EZT. The z_i spatial variability observed with TODWL measurements is most likely indicative of alternating regions of rising thermals and downdrafts superimposed on smaller-scale turbulence, as was found in previous airborne lidar-based studies of z_i variability.

However, for terrain-following z_i , as was observed in the morning period on different IOPs, σ_{z_i} was due to the combined effects of terrain-induced and surface heterogeneity forced fluctuations in z_i and, thus, was not necessarily a measure of EZT. Additionally, the method based on a standard deviation approach strictly considers quasi-stationary time series of well-mixed CBL height and, thus, is inappropriate for morning time z_i , as growth rate is an issue during this time of the day. Thus, we suggest that temporal/spatial fluctuations in z_i during the morning over mountainous areas do not carry information about the EZT. Nevertheless, σ_{z_i} measurements reported here could serve as a good basis for

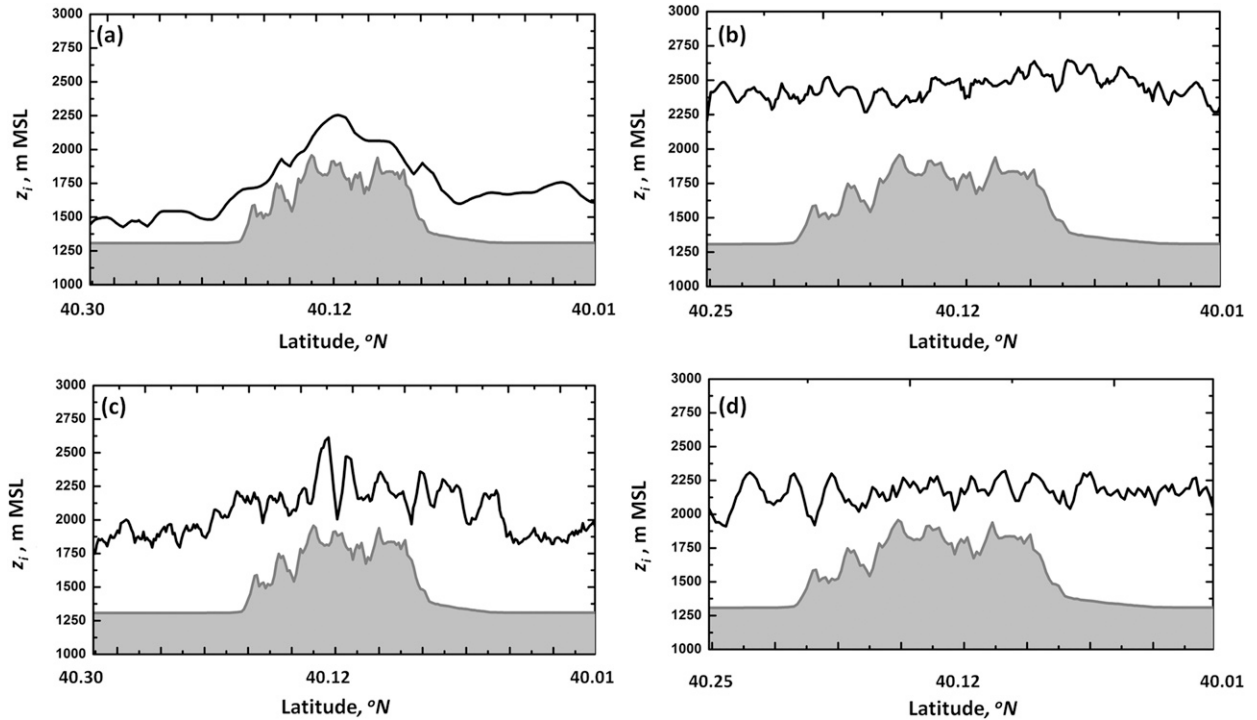


FIG. 11. The z_i spatial variability along NS legs passing over Granite Mountain during morning flights on (a) 10 and (c) 14 Oct and during afternoon flights on (b) 6 and (d) 9 Oct 2012. The underlying orography (m MSL) along the flight tracks is shown in grayscale.

comparison with z_i spatial variability in high-resolution numerical models.

e. Further discussion on the z_i spatial variability

During MATERHORN-X in 2012, key features that were observed in the z_i spatial variability are 1) an east–west gradient in z_i during the afternoon with higher z_i over the eastern side than over the western side of Granite Mountain on 9 and 14 October and with lower z_i over the eastern side than over the western side of Granite Mountain on 6 and 17 October, 2) terrain-following z_i features during the morning transition period with higher z_i above ridgetop than over the surrounding valley, and 3) relatively less terrain-following z_i spatial variability during the well-mixed CBL regime in the late afternoon than in the morning. For instance, z_i variability along the NS legs passing over Granite Mountain (i.e., NS3) during morning flights on 10 and 14 October and during afternoon flights on 6 and 9 October indicates the relatively larger impacts of the underlying topography on the z_i variability during the morning than during the afternoon on all days (Fig. 11). Additionally, the overview of the z_i spatial variability along NS3 (Table 2) also shows that σ_{z_i} along NS3 is always smaller in the afternoon than in the morning.

Previously, Kalthoff et al. (1998) found that the impact of orography on z_i is more pronounced for morning

CBL regimes than for afternoon quasi-stationary CBLs. However, the measurements selected in their case studies were also affected by fog in the valleys so that the spatial differences were also attributed to the fog in various areas in their experimental domain. In our study, the key findings on the investigation of the z_i spatial variability and the impact of orography on z_i are based on 1) multiple morning and afternoon CBL regimes along similar north–south- and east–west-oriented flight tracks, 2) mostly clear-sky conditions without any occurrence of fog, and 3) an experiment over and around an isolated mountain with well-defined land surface characteristics in the adjacent areas.

In this section, we also discuss differences between z_i over the plains east and west of Granite Mountain (i.e., the Sagebrush and Playa sites) and the characteristics of both the growing CBL in the morning and the quasi-stationary CBL in the afternoon on different TODWL flight days. Another factor for inducing z_i spatial variability into the experimental area is the land surface heterogeneity resulting in the spatial variability of the near-surface sensible heat flux. Differences in the sensible heat flux could also be attributed to the different soil thermal properties at the Playa and Sagebrush sites. Dry soil conditions help maintain high sensible heat fluxes, which can explain the larger boundary layer development east rather than west of Granite Mountain.

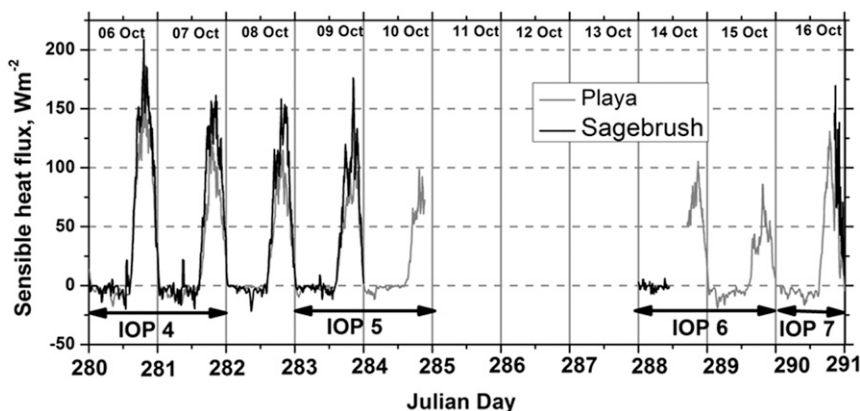


FIG. 12. The diurnal course of near-surface (5 m AGL) sensible heat flux (W m^{-2}) at both the PL (gray solid line) and SB (black solid line) sites from days 280 to 291. The horizontally aligned arrows indicate the time periods of the four IOPs discussed in the text.

We therefore analyzed tower-based sensible heat flux measurements at both the Sagebrush and the Playa sites (Fig. 12). Daytime sensible heat flux is larger (25%–30%) at the eastern site than at the western site, which also triggered the higher daytime temperature at the Sagebrush site than at the Playa site. Previously, Rife et al. (2002) found similar differences between the Playa site and the surrounding desert and reported that the Playa site has a higher albedo, less vegetation, and a higher soil thermal conductivity than the surrounding desert. A significant increase in the surface moisture occurred as a result of the precipitation event on 12 October that had a large impact on the z_i spatial variability. The precipitation event triggered an increase in the near-surface humidity and CBL moisture content. Consequently, this event played an important role in determining the partitioning between sensible and latent heat fluxes and resulted in a reduced sensible heat flux and lower z_i .

In lieu of micrometeorological measurements at high spatial and temporal resolutions, numerous past studies elucidated the relationship between near-surface temperature and z_i variability to understand the features in the surface forcing on z_i evolution during different times of the day and found that near-surface meteorological variables could serve as potential indicators for z_i driving factors (e.g., Seidel et al. 2012; Zhang et al. 2013; Pal et al. 2014, 2015). Therefore, we performed two different analyses: 1) determination of the differences in the near-surface (5 m AGL) air temperature and relative humidity at both the eastern and the western sites (Fig. 13) to illustrate the east–west gradient in the z_i spatial variability and 2) analyzing the IR-sensor measured temperature field along the flight legs to understand the impact of surface forcing on z_i variability along different legs.

In general, a higher daytime temperature was observed at the eastern site than at the western site. Also visible is an increasing trend in the near-surface temperature from 6 to 11 October, which was disrupted because of the precipitation event on 12 October (Fig. 13). This pattern is consistent with the radiosonde-derived thermodynamic profiles and TODWL z_i measurements. Additionally, two different trends were observed for relative humidity: a decreasing trend from 6 to 9 October and then an increasing trend from 9 to 12 October at both sites. While considering the daytime mean afternoon temperature, we also found that the eastern site was warmer than the western site by more than 5°C ; while for nocturnal mean temperature, the eastern site was cooler by around 4°C . Consequently, the diurnal temperature range at the Sagebrush site was larger than the diurnal temperature range at the Playa site by more than 10°C .

For most of the day on 6 October, the sensible heat flux at the Playa site was lower than at the Sagebrush site. For instance, the daytime maximum sensible heat fluxes at the Playa and Sagebrush sites were 175 and 208 W m^{-2} , respectively. This difference once again confirms that the difference in the surface forcing between the Playa and Sagebrush sites was similar during the IOPs that took place before the rain event on 12 October. After the rainfall event, the daytime near-surface temperatures at those two sites were not significantly different from those during the IOPs before the rainfall event (Fig. 13). Additionally, IOP 7 (a postfrontal case) was characterized by high northwesterly synoptic winds (10 – 15 m s^{-1}) with low CBL moisture ($<2.5 \text{ g kg}^{-1}$) with moderate CBL wind ($\sim 5 \text{ m s}^{-1}$) with less dependence of z_i spatial variability on the surface temperature than on the quiescent IOPs (4 and 5).

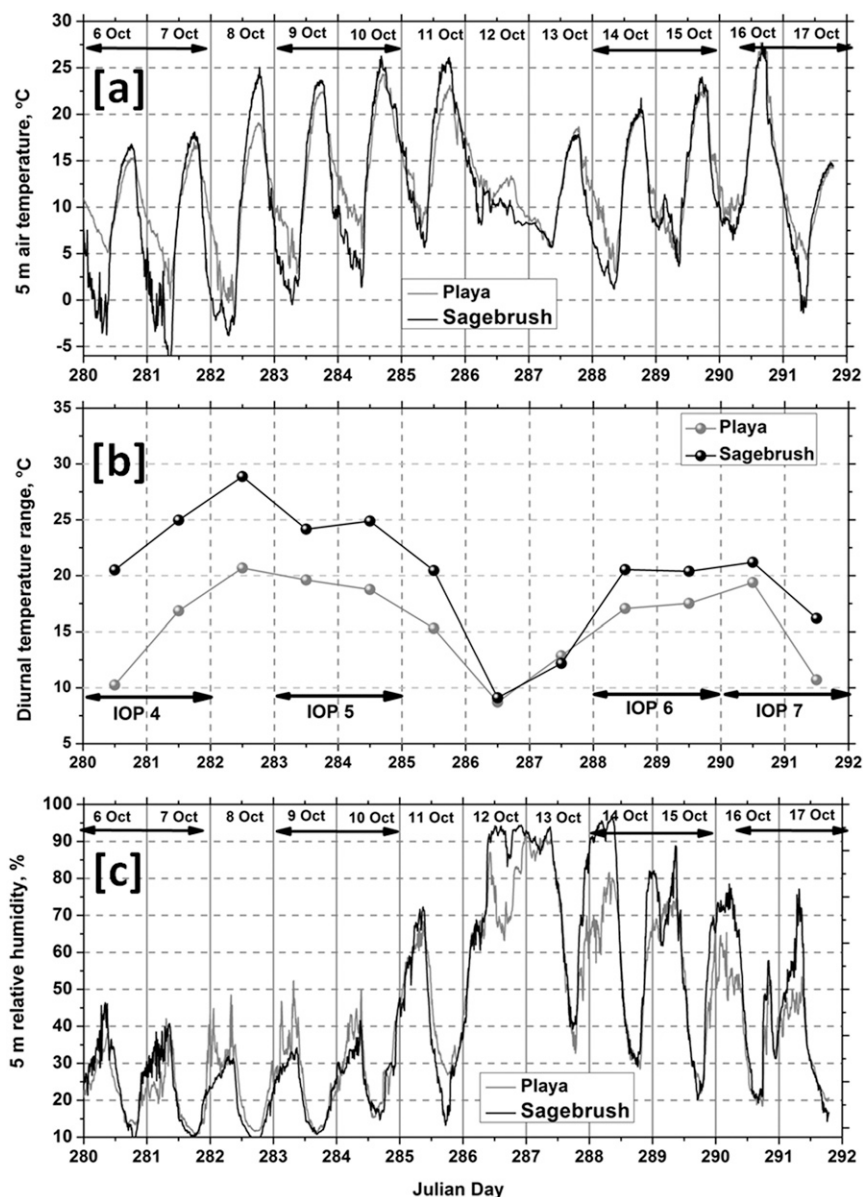


FIG. 13. Day-to-day variability in the near-surface (5 m AGL) (a) temperature and the corresponding (b) diurnal temperature range and (c) relative humidity at both the SB (black solid line) and PL (gray solid line) sites from 6 to 17 Oct 2012. The temporal resolution for both temperature and humidity time series is 1 min. Horizontally aligned arrows indicate the spans of the four selected IOPs.

Using the simultaneous near-surface meteorological measurements at the Sagebrush and Playa sites, we could explain the east–west gradient observed in z_i over the experimental area. However, it is not feasible to attribute the observed z_i along the different TODWL legs to the meteorological measurements at two fixed locations. Previous studies on the combined meteorological and z_i measurements (e.g., Reen et al. 2006; Seidel et al. 2012; Pal et al. 2013) motivated us to investigate further the

spatial variability in surface temperature along the flight track obtained by the infrared temperature sensor on board the Twin Otter aircraft.

Therefore, we performed similar box-and-whisker analyses of surface temperature as was done for z_i (Fig. 14). Measurements during morning periods show a heterogeneous temperature distribution, as was found for z_i over the area (see Figs. 14a,c,e for 7, 10, and 14 October, respectively), which could be attributed

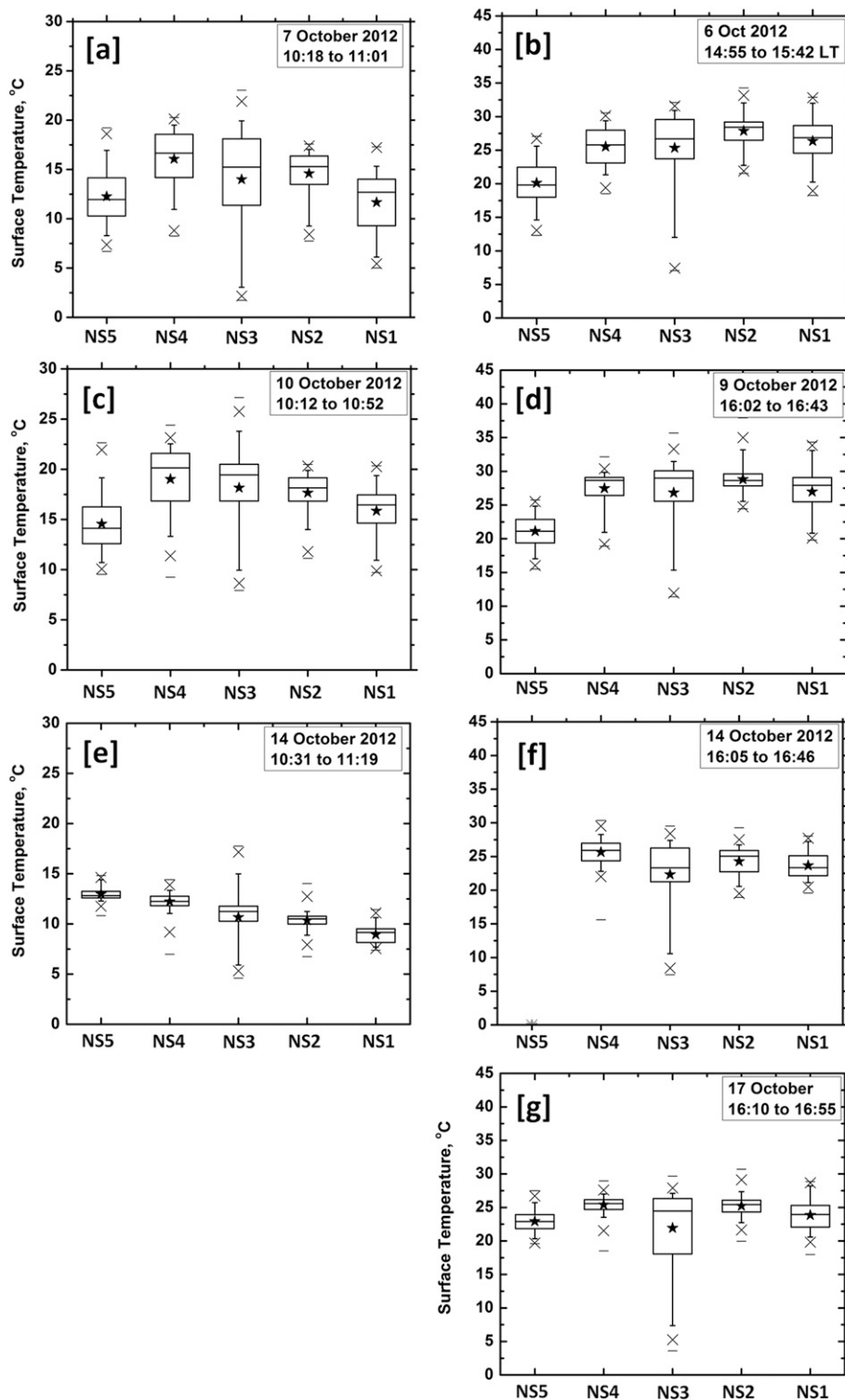


FIG. 14. Box-and-whisker plots of surface temperature variability (measured by an infrared temperature sensor on board the Twin Otter aircraft) along NS flight legs during the mornings of (a) 7, (c) 10, and (e) 14 Oct and the afternoons of (b) 6, (d) 9, (f) 14, and (g) 17 Oct 2012. The y-axis scales differ for the morning and afternoon measurements.

partly to the shadows cast by Granite Mountain. However, both z_i and surface temperature variability along the NS legs along the eastern and western sides of Granite Mountain show similar tendencies (higher z_i and higher temperature on the eastern side than on the western side of Granite Mountain) for the afternoon measurements (see Figs. 14d,f for 9 and 14 October, respectively). Although a similar east–west gradient was observed for the surface temperature on 6 and 17 October (Figs. 14b,g, respectively), the z_i gradient was different on these days as a result of the presence of an aerosol layer above the CBL top on 6 October and because of strong advection on 17 October, as explained before. In general, the results suggest that the geographical distribution of surface temperature corresponds well with the expected distribution based on patterns of z_i spatial variability.

7. Summary and conclusions

In this paper, we analyzed CBL heights during seven research flights conducted during four IOPs as part of the MATERHORN-X Fall experiment in 2012. High-resolution measurements obtained with an airborne Doppler lidar were used to characterize the z_i spatial variability over and around an isolated mountain located in an arid environment. The spatial resolution observed here has rarely been possible previously and has been limited only to occasional field programs such as this one. Furthermore, while the present study strictly provides key observational aspects of z_i spatial variability and some key factors governing them, the dataset is highly valuable for future research involving numerical simulations on boundary layer process studies in mountainous areas. Additionally, radiosonde observations were also used to study z_i over the western and eastern sides of Utah's Granite Mountain with significantly different surface characteristics (e.g., land cover, surface type).

A detailed intercomparison between lidar and radiosonde observations was performed with an emphasis on the impact of δt (radiosonde launch time minus TODWL overpass time) to discriminate possible differences in z_i that may be due to z_i evolution over time. We found larger impacts of δt on the observed differences in z_i during the morning than during the afternoon periods as a result of morning CBL growth. For instance, for δt of less than an hour, the observed z_i differences (radiosonde-derived z_i minus TODWL-derived z_i) were reported to be ± 50 m. Overall, z_i estimates using TODWL and radiosonde data agree well given the difficulty and uncertainty associated with comparing data from an airborne sensor with data from radiosondes

launched from the ground. Radiosonde-based observations also confirm the z_i spatial variability (east–west gradient).

A unique aspect of this study is the investigation of the daytime z_i spatial variability over a mountainous area using airborne Doppler lidar measurements. We found that while the CBL structure in the morning is highly inhomogeneous and terrain following, the afternoon CBL structure tends to be less dependent on the underlying terrain inhomogeneity than in the morning, as was found in previous studies (e.g., Kalthoff et al. 1998). In particular, using the TODWL-derived spatial z_i maps, it was possible to illustrate the distinct roles of 1) an isolated mountain peak in modulating the z_i spatial variability, in particular during the morning transition period; 2) an isolated mountain in enhancing z_i on the downwind side, in particular during the afternoon; 3) a stable layer above the CBL and the related presence of an aerosol layer in altering the z_i spatial variability pattern (here along the east–west gradient) existing in the experimental region; 4) different surface types east and west of the isolated mountain; and 5) a precipitation event in between two IOPs in changing near-surface and CBL humidity regimes and, consequently, z_i variability. All of these factors acted together to shape the overall z_i spatial variability during the campaign.

Among all of the case studies presented for a quasi-stationary CBL regime during the afternoon period when winds were light (i.e., wind speed $\sim 5 \text{ m s}^{-1}$), the z_i gradient (east–west or north–south) was further enhanced because of a deeper CBL on the downwind side of the mountain than on the upwind side (e.g., 6 October with prevailing west-northwesterly flow, 9 October with southerly flow, and 14 October with westerly flow). Downwind advection of a deep CBL over the mountain likely plays a role in these cases. Similar z_i enhancement southeast of Granite Mountain was observed during the morning on 7 October. However, the roles of both surface heterogeneity and the variable z_i growth rates during morning transition period cannot be ignored.

Two different near-surface meteorological conditions prevailed east and west of Granite Mountain with higher temperatures, a larger diurnal temperature range, and larger sensible heat fluxes east than west of the mountain. This difference played an important role in governing the observed east–west gradient in the z_i spatial variability, though qualitative, infrared temperature sensor (aboard Twin Otter flights) measurements of surface temperature fields helped explain similar tendencies to results observed for z_i over the experimental area. However, the east–west gradient was not found on 6 and 17 October because of the presence of 1) an

elevated aerosol layer associated with a stable layer and 2) an advection-dominated CBL, respectively.

The EZT estimation method assumes quasi-stationary and quasi-homogeneous CBL regimes, which were not observed during the morning over the experimental area. Rather, the z_i spatial variability during the morning was modulated by the combined impacts of the underlying orography and the entrainment processes near the z_i . Consequently, estimation of EZT remains challenging. Additionally, detailed analyses of the spectral spread of the TODWL returns in future research efforts could offer another estimate of turbulence within each illuminated volume. This approach can potentially provide more direct estimates of turbulence and EZT than the statistical analyses considered here (e.g., Frehlich and Cornman 1999).

The z_i estimates and observed variability discussed in this work can be used for many future research activities including the investigation of CBL turbulence and the evaluation of numerical models. Results presented clearly suggest that z_i spatial variability over mountainous terrain both during morning and afternoon hours reveals complexities mainly due to the combined effects of heterogeneous land surface forcing and the underlying orography that may require improved parameterizations in present-day numerical models.

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