Influence of Mesoscale Dynamics and Turbulence on Fine Dust Transport in Owens Valley

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ABSTRACT

Fine dust particles emitted from Owens (dry) Lake in California documented during the Terrain-Induced Rotor Experiment (T-REX) of 2006 have been examined using surface observations and a mesoscale aerosol model. Air quality stations around Owens (dry) Lake observed dramatic temporal and spatial variations of surface winds and dust particulate concentration. The hourly particulate concentration averaged over a 2-month period exhibits a strong diurnal variation with a primary maximum in the afternoon, coincident with a wind speed maximum. The strongest dust event documented during the 2-month-long period, with maximum hourly and daily average particulate concentrations of 7000 and 1000 μg m⁻³, respectively, is further examined using output from a high-resolution mesoscale aerosol model simulation. In the morning, with the valley air decoupled from the prevailing westerlies (i.e., cross valley) above the mountaintop, fine particulates are blown off the dry lake bed by moderate up-valley winds and transported along the valley toward northwest. The simulated strong westerlies reach the western part of the valley in the afternoon and more fine dust is scoured off Owens (dry) Lake than in the morning. Assisted by strong turbulence and wave-induced vertical motion in the valley, the westerlies can transport a substantial fraction of the particulate mass across the Inyo Mountains into Death Valley National Park.

1. Introduction

Owens (dry) Lake is located in Owens Valley, which is a northwest–southeast-oriented quasi-two-dimensional valley between the Sierra Nevada ridge and the Inyo Mountains (Fig. 1a) in eastern California. While Owens Valley is nearly two-dimensional, the topography around Owens (dry) Lake is complex and highly three-dimensional with rich multiscale features (Fig. 1b). Historically, fed by streams such as the Owens River, Owens (dry) Lake was a perennial salt lake and an important stopover site for migrating birds in the western United States. The lake level dropped quickly after the Los Angeles Department of Water and Power (LADWP) started diverting the Owens River to feed the Los Angeles Aqueduct in 1913, and eventually became a dry lake by 1926. The windblown dust from the approximately 280-km² dry lakebed of Owens (dry) Lake, a toxic mixture of arsenic, cadmium, nickel, and sulfates, has been found across the western United States (Gill and Gillette, 1991; Reid et al. 1994). It is believed that Owens (dry) Lake is the single largest source of aerosol particles with aerodynamic diameters smaller than 10 μm (PM-10) in the United States (Reheis 1997). The fine salt-rich particles scoured off the dry lake bed by strong winds can cause a variety of health problems to human beings (Abbey et al. 1995), reduce visibility, and harm vegetation (Marchand 1970; Reheis 1997) as far as 100 mi away.

For given soil textures and wetness, the dust lofting is largely controlled by near-surface meteorological conditions, namely wind speed and stability (therefore, surface friction velocity). In a recent study of the high wind climatology in Owens Valley, Zhong et al. (2008) found that strong winds (defined as hourly mean wind speed above 7 m s⁻¹) observed by stations on the valley floor are primarily bidirectional, either up-valley...
FIG. 1. (a) Google terrain map of Owens Valley and surrounding topography. The approximate locations of the six DRI surface AWSs used to construct Fig. 8 are shown as small white dots. (b) Google terrain map of Owens (dry) Lake and the surrounding topography. The Owens (dry) Lake area is gray shaded and locations of seven GBUAPCD air quality stations are labeled in (b).
Observations

Sections 2. Observations period (IOPs) are presented in section 4. The results are transport during one of the T-REX intensive observation and some model validation results. The dust lofting and section 2. Section 3 describes the numerical configuration for the 2-month-long T-REX period are reported in simulation to provide some new insights into the role of mesoscale dynamics and turbulence in lofting and trans-

This study is partially motivated by observations obtained from the Terrain-induced Rotor Experiment (T-REX; Grubišić et al. 2008), which took place over the Sierra Nevada and Owens Valley during March–April 2006. The primary focus of T-REX is on mountain waves and wave-induced rotor circulations associated with the cross-barrier flow impinging on the sierra ridge. As will be shown below, the observed PM-10 concentration around Owens (dry) Lake exhibits strong temporal and spatial variations. The dust lofting and transport processes are complicated by small-scale circulations, down-slope winds, mountain waves, and turbulence induced by the surrounding high mountains. The objective of this study is to use the PM-10 and meteorological observations obtained during T-REX and a high-resolution numerical simulation to provide some new insights into the role of mesoscale dynamics and turbulence in lofting and transporting fine particles in mountainous areas.

The remainder of this paper is organized as follows. The surface observations around Owens (dry) Lake for the 2-month-long T-REX period are reported in section 2. Section 3 describes the numerical configuration and some model validation results. The dust lofting and transport during one of the T-REX intensive observation periods (IOPs) are presented in section 4. The results are summarized in section 5.

2. Observations

The Great Basin Unified Air Pollution Control District (GBUAPCD) operates seven air quality monitoring stations located around Owens (dry) Lake, namely Bill Stanley (BS), Oalanca (OL), Shell Cut (SC), Keeler (KL), Flat Rock (FR), Dirty Socks (DS), and Lone Pine (LP) (see Fig. 1b for locations), which measure the surface PM-10 concentration, wind speed, and wind direction. Technical details about these stations can be found at the GBUAPCD Web site (http://www.gbuapcd.org/). In this section, we first examine some climatologic aspects of the PM-10 concentration and winds around Owens (dry) Lake for March–April 2006 and then focus on 25 March 2006, on which date the maximum PM-10 concentration was observed near Owens (dry) Lake.

a. Surface wind and PM-10 concentration climatology

The daily PM-10 concentration observed by the seven stations around Owens (dry) Lake exhibits both strong temporal and spatial variations (Fig. 2a). For some dusty days, the surface PM-10 concentration varies from station to station by one order of magnitude or more, even though these stations are only a few kilometers apart. The U.S. Environmental Protection Agency (U.S. EPA) ambient air quality standard for the 24-h average PM-10 concentration is 150 μg m$^{-3}$, and the corresponding California Environmental Protection Agency/Air Resources Board (CA EPA/ARB) standard is 50 μg m$^{-3}$, which is stricter. According to Fig. 2a, during the 60-day T-REX observational period, there were 10 dusty days with the PM-10 daily average concentration exceeding the California standard at one or more stations. Among these 10 days, there are 3 very dusty days, with the observed maximum PM-10 daily concentration exceeding the U.S. EPA standard, namely 14 March, 25 March, and 16 April 2006, corresponding to T-REX IOPs 4, 6, and 13, respectively (Grubišić et al. 2008). It is worth noting that IOPs 4, 6, and 13 are also the three strongest mountain wave events observed during T-REX associated with persistent westerlies above the mountaintop level (Smith et al. 2008; Doyle et al. 2011). Particularly, on 25 March 2006, the daily average PM-10 concentration exceeds the U.S. EPA PM-10 standard at five stations—DS, BS, SC, LP, and FR—with a maximum of approximately 1000 μg m$^{-3}$ documented at DS. The surface wind speeds are generally stronger during the 10 dusty days than the rest of the days, with the exceptions of 1 and 4 April. During the first 3 days of April, although the surface winds are strong, the observed PM-10 concentration is relatively low, due to light snowfall inside Owens Valley. In general, stronger winds (i.e., 10 m s$^{-1}$ or more) are more often observed at the three stations located near the western valley slope, namely, DS, BS, and OL. Winds at the three eastern stations (i.e., KL, FR, and SC) are noticeably weaker (i.e., less than 10 m s$^{-1}$). It is interesting that, for IOPs 6 and 13, the largest PM-10 concentration is observed at DS while the strongest surface winds are actually documented at BS, implying the importance of dust transport and dispersion processes. During the 2-month-long period, the predominant wind direction in Owens Valley is approximately southerly or south-southeasterly (i.e., up-valley winds), and the second-most-frequent wind direction is north-northwesterly (i.e., down-valley winds). This is consistent
with the wind climatology inside Owens Valley found by previous studies (Zhong et al. 2008).

The 2-month-average surface PM-10 concentration also exhibits a clear diurnal variation with a primary maximum between 1300 and 1700 Pacific standard time (PST) in the afternoon, approximately coincident with the surface wind speed maximum (Fig. 3). Large PM-10 concentrations tend to be observed more often in the afternoon as well (Fig. 3b). The afternoon wind maximum in Owens Valley is consistent with the findings by Zhong et al. (2008) and Jiang and Doyle (2008). Both the mean concentration and the occurrence frequency of high PM-10 concentration are much lower in the morning and early afternoon hours. The vector average wind direction in the valley ranges from south-southwesterly to southerly (i.e., primarily up-valley winds) and exhibits little diurnal variation (Fig. 3d). However, the PM-10 mass-weighted average wind direction, derived from the mass-weighted mean u and v components (i.e., $\bar{u}_m, \bar{v}_m = \sum(c_i u_i, c_i v_i) / \sum c_i$) reveals some interesting diurnal variations. Particularly, the average winds are southwesterly in the afternoon, suggesting that, while the mean winds inside Owens Valley are predominately oriented along the valley, the occurrence of high PM-10 concentration events is likely associated with the presence of cross-valley winds (i.e., WSW and, hereinafter, are also referred to as westerly for the convenience of description).

b. 25 March 2006

As shown in Fig. 2, the largest PM-10 concentration is documented on 25 March, which is the first day of IOP 6, a 2-day T-REX IOP characterized by strong persistent southwesterly winds at the sierra mountaintop level and large-amplitude mountain waves over Owens Valley (Grubišić et al. 2008; Smith et al. 2008; Jiang and Doyle 2009). The daily PM-10 concentrations observed at most stations are above the U.S. EPA standard and the maximum is approximately 1000 $\mu$g m$^{-3}$ at Dirty Socks (Fig. 2), exceeding the California standard by nearly 20 times. The PM-10’s emission, transport, and dispersion are further examined in the following sections based on observational data and a high-resolution numerical simulation.

For IOP 6, the large-scale flow condition is characterized by a pressure trough at 500 hPa, which is located offshore of the Pacific Northwest in the early morning of 25 March and propagates across the Sierra Nevada in

FIG. 2. Daily average of the (a) PM-10 concentration, (b) wind speed, and (c) wind direction derived from observations at the seven GBUAPCD stations for March–April 2006. In (a), only daily concentrations above the California 24-h average PM-10 concentration standard (i.e., 50 $\mu$g m$^{-3}$) are shown and in (b) only wind speeds above 7 m s$^{-1}$ are shown. The dashed line in (a) corresponds to 150 $\mu$g m$^{-3}$ and the three most dusty IOPs are labeled.

FIG. 3. Diurnal variation of (a) PM-10 concentration ($\mu$g m$^{-3}$), (b) high PM-10 frequency (solid, 50 $\mu$g m$^{-3}$; dashed, 150 $\mu$g m$^{-3}$, respectively), (c) wind speed (m s$^{-1}$), and (d) wind direction (°) vector averaged over the seven surface stations and March–April 2006. The PM-10 concentration weighted–average wind direction is shown in (d) by the times signs.
the afternoon (Fig. 4). This short-wave trough directs progressively stronger southwesterly winds toward the Sierra Nevada on 25 March 2006. Associated with strong cross-barrier winds at the mountaintop level (i.e., around 4 km), moderate- to large-amplitude waves were documented by both the National Science Foundation (NSF) Wyoming King Air flying in the lower to middle troposphere (Jiang and Doyle 2009) and the NSF–National Center for Atmospheric Research (NCAR) High-Performance Instrumented Airborne Platforms for Environmental Research (HIAPER) flying between 9 and 13 km (Smith et al. 2008; Doyle et al. 2011). Figure 5a shows wind and potential temperature profiles derived from a radiosonde launched from the NCAR Mobile GPS Advanced Upper Air System (MGAUS) near Fresno, California, located approximately 100 km to the west of Independence. It is evident that the zonal wind component \( u \) is less than 5 m s\(^{-1}\) below 2.5 km MSL, likely due to the blocking effect of the sierras. The wind speed reaches 15 m s\(^{-1}\) between 3 and 5 km MSL and the wind direction is approximately perpendicular to the main sierra ridge, a condition that favors strong mountain wave generation. The mountaintop-level wind speed increases progressively throughout most of the day, associated with the passage of the short-wave trough in Fig. 4. According to the radiosonde launched from the NCAR Integrated Sounding System (ISS) site, located at the Independence airport in Owens Valley [Fig. 1a, approximately 34 km to the north of the northern tip of Owens (dry) Lake], the horizontal winds inside Owens Valley (i.e., below the mountaintop level) are significantly different from their upstream counterparts, likely

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**FIG. 4.** The geopotential height contours (interval of 30 gpm) at the 500-hPa level derived from the NCEP–NCAR reanalysis for (a) 1200 UTC 25 Mar and (b) 0000 UTC 26 Mar. The corresponding fields derived from the COAMPS 40.5-km grid are shown in (c) and (d), respectively, with the wind speed (grayscale, interval of 3 m s\(^{-1}\)) and wind vectors included.
FIG. 5. The horizontal wind components and potential temperature profiles from GPS radiosondes launched at 1200 UTC 25 Mar from (a) Fresno and (b) Independence (i.e., within Owens Valley), respectively. The corresponding profiles interpolated from the COAMPS simulation are included for comparison.
modified by mountain waves and in-valley circulations below the mountaintop level (Fig. 5b). Upstream of the sierras, the lower to midtroposphere is relatively stable during IOP 6. Inside the valley, the early morning sounding reveals a shallow stable layer above the valley floor, and in the afternoon, a deep well-mixed layer develops in association with strong surface heat fluxes within Owens Valley (not shown).

During the afternoon of 25 March, associated with strong winds in Owens Valley, dust swirls were seen near Independence, likely induced by intense horizontal wind shear associated with flow through relatively narrow gaps along the sierra ridge (e.g., Grubišić and Billings 2007). A GBUAPCD Web camera located at Owens (dry) Lake shows dust plumes and decreased visibility. A photograph taken from the U.K. Facility for Airborne Atmospheric Measurements (FAAM) BAe-146 aircraft flying across Owens Valley from the middle to the upper troposphere is shown in Fig. 6. Dust plumes are evident, originating from both the southwestern and northwestern portions of Owens (dry) Lake and oriented approximately along the cross-valley direction (i.e., eastward; see Fig. 6). A “foehn wall” is evident over the lee slope of the sierra ridge, followed by a cloud clearance zone downstream (i.e., foehn gap), implying strong descent of the low-level flow over the lee slope, as indicated by the schematic streamline (Fig. 6), which is inferred from this picture and other observations. The dust plumes are relatively thin for the first few kilometers and then thicken quickly with the downstream distance, likely due to either hydraulic jump-induced boundary layer (BL) expansion or wave-induced BL separation.

A large PM-10 concentration was observed around Owens (dry) Lake at all stations on 25 March (Fig. 7). The observed PM-10 concentration exhibits strong temporal and spatial variations. In general, the PM-10 concentration shows a primary maximum in the afternoon and a secondary maximum before local noon. Between the two maxima, a PM-10 concentration minimum appears at most stations between 1200 and 1500 PST. The maximum hourly PM-10 concentration, approximately 7000 μg m⁻³, was documented at DS, around 1900 PST. During the night, the surface winds over Owens (dry) Lake are characterized by the presence of both weak up- and down-valley winds. Around 1000 PST, the surface winds reach a maximum at all stations and the wind directions range from south-southeasterly (i.e., up-valley winds) at stations DS and LP to south-southwesterly (i.e., nearly cross-valley direction) at stations BS and OL. In the afternoon, the wind speed in most stations weakens with time with the exception of the two stations located closest to the western valley slope (OL and BS), where the winds become significantly stronger than the wind speed maximum in the morning and the wind direction becomes southwesterly (i.e., cross valley). The strong cross-valley winds recorded at OL and BS persist through the afternoon and weaken quickly after sunset. The winds at the three stations located along the eastern edge of the lake (i.e., SC, FR, and KL) remain approximately southerly in the afternoon and the wind speed is significantly weaker than at OL and BS. After sunset, the winds...
are weak at all stations with the wind direction varying from northwesterly to northeasterly. A surface automatic weather station (AWS) network, located at Independence (Fig. 1 for locations) and operated by the Desert Research Institute (DRI), documented a qualitatively similar diurnal variation of the surface winds (Fig. 8), including an increase in the westerly component from the early afternoon to sunset. After sunset, the westerlies cease over most of the valley floor and the up-valley winds prevailing during daytime switch to down-valley winds.

The temporal and spatial variations of the wind speed, wind direction, and PM-10 concentration indicate two different wind conditions for the PM-10 generation over Owens (dry) Lake on 25 March 2006. In the morning, despite the persistent westerlies above the mountain-top, relatively strong up-valley winds are present within Owens Valley, and apparently account for the observed morning PM-10 maximum. A transition occurs around local noontime. The strong downslope winds over the western valley slope finally reach the western part of the valley floor. The severe downslope winds recorded by stations OL and BS blow fine particles off the western portion of the dry lake bed and create the afternoon PM-10 maximum. The downslope flow likely experiences a hydraulic jump or rotor [i.e., vertical circulations with flow reversal above the ground usually associated with boundary layer separation forced by gravity waves in the lee of barriers; Doyle and Durran (2002); Jiang et al. (2007)] somewhere over Owens (dry) Lake between the

![Figure 8](https://example.com/fig8.png)

**Fig. 8.** The distance–time diagram of the (a) $u$ (grayscale, increment = 2 m s$^{-1}$) and (c) $v$ (grayscale, increment = 1 m s$^{-1}$) wind components derived from the DRI AWS surface observations on 25 Mar 2006. The 6 AWSs used for this analysis are oriented across the valley floor (see Fig. 1 for locations). The cross-valley distance from the westernmost station, station 1, is labeled along the abscissa. (b),(d) As in (a),(c), but for the corresponding diagrams derived from the COAMPS simulation.
two stations in the west (i.e., OL and BS) and the three stations to the east (i.e., SC, FR and KL). The hydraulic jump (or rotor) slows down the surface winds and causes the sudden thickening of the dust plume by vertically stretching the BL (or causing BL separation from the ground) as suggested by Fig. 6.

3. Numerical model description

a. COAMPS and model setup

The atmospheric component of the Coupled Ocean–Atmospheric Mesoscale Prediction System (COAMPS; Hodur 1997) is used for this study. COAMPS is a fully compressible, nonhydrostatic, and terrain-following mesoscale model featuring a suite of physical parameterizations. The turbulence kinetic energy (TKE), $e = (u'^2 + v'^2 + w'^2)/2$, is a prognostic variable governed by the equation (Mellor and Yamada 1974; Thompson and Burk 1991)

$$\frac{De}{Dt} = K_M \left( \frac{\partial U}{\partial z} \right)^2 - K_H \frac{\partial \theta}{\partial z} + \Gamma \frac{c^2}{2} + D_e,$$  \hspace{1cm} (1)

where $K_M$ and $K_H$ are the eddy mixing coefficients of the momentum and heat given by $K_{M,H} = S_{M,H}^+ (2e)^{1/2} \Gamma$, $\Gamma$ is a constant, $S_{M,H}$ are functions of the local Richardson number, $l_m$ is the mixing length, and $D_e$ represents the subgrid-scale TKE mixing. The subgrid-scale mixing of momentum and heat fluxes is parameterized as

$$\overline{w'u'} = -K_M \frac{\partial U}{\partial z}$$

$$\overline{w'v'} = -K_H \frac{\partial \theta}{\partial z}.$$  

The surface fluxes are calculated from a surface energy budget based on the force–restore method (Louis 1979; Wang et al. 2002).

The computational domain contains five horizontally nested grid meshes of $91 \times 91, 133 \times 133, 133 \times 133, 157 \times 157$, and $157 \times 157$ grid points, and the corresponding horizontal grid spacings are 40.5, 13.5, 4.5, 1.5, and 0.5 km, respectively (Fig. 9a). The aerosol model is activated only in the innermost domain (i.e., 0.5-km grid). The terrain data are based on the Global Land One-km Base Elevation (GLOBE) dataset and the terrain in the 0.5-km mesh is shown Fig. 9b. There are 62 vertical levels with 20 levels in the lowest 3 km and coarser spacings aloft. The model top is located at approximately 30 km MSL and a sponge boundary condition is applied to the top 10 levels (i.e., ~10 km) to minimize downward wave reflection. The initial fields for the model are created from a multivariate optimum interpolation analysis of upper-air sounding, surface, commercial aircraft, and satellite data sources that are quality controlled and blended with the 12-h COAMPS forecast fields. Lateral boundary conditions for the outermost grid mesh are derived from Navy Operational Global Atmospheric Prediction System (NOGAPS) forecast fields. The 36-h forecast period runs from 0000 UTC 25 March to 1200 UTC 26 March with a data output frequency of 5 min.

b. Aerosol model

A dust microphysical aerosol model is fully embedded in COAMPS (Liu and Westphal 2001; Liu et al. 2003, 2007). The dust module uses the same grid structure as the dynamics model. The aerosol concentration for each bin is governed by the following prognostic equation:

$$\frac{\partial C}{\partial t} = \frac{\partial (uC)}{\partial x} - \frac{\partial (vC)}{\partial y} - \frac{\partial (w + v_f)C}{\partial z} + D_x + D_y$$

$$+ D_z + C_{src} - C_{sink},$$  \hspace{1cm} (2)

where $(u, v, w)$ are the velocity components in the $x, y,$ and $z$ directions; $v_f$ is the particle settling velocity; $D_x, D_y,$ and $D_z$ are the turbulent mixing terms; and $C_{src}$ and $C_{sink}$ denote the source and sink terms, respectively. For this study, the PM-10 particles are represented as four discrete size bins with particle diameters of 1, 2.5, 5, and 10 $\mu m$, respectively (referred to as bins 1–4 hereinafter).

Following Stokes’s law, for a given bin with a mean radius (m) $R_p$, the particle terminal velocity $v_f$ is given by

$$V_f = \frac{2gR_p^2\rho_p C_c}{9\rho_a} \times 10^{-4},$$  \hspace{1cm} (3)

where $\rho_p$ is dust density (=2650 kg m$^{-3}$ throughout this study), $g$ is the gravitational acceleration (m s$^{-2}$), and $C_c$ is the Cunningham correction factor, given by

$$C_c = 1 + \frac{\alpha}{R_p \left[ 1.257 + 0.4 \exp ( -1.1 \frac{\rho_a}{\rho_p} ) \right]}. \hspace{1cm} (4)$$

The values for the viscosity and mean free path of air molecules, $\nu$ and $\lambda$, are obtained from Seinfeld (1986). In the lower troposphere ($\rho_a \approx 1.2$ kg m$^{-3}$), the terminal velocities for the four bins are approximately 0.008, 0.05, 0.2, and 0.8 cm s$^{-1}$, respectively.

The total aerosol emission flux, $F$ (kg m$^{-2}$ s$^{-1}$), is given by (Gillette and Passi 1988; Westphal et al. 1988; Nickling and Gillies 1993; Alfaro et al. 1997; Liu et al. 2007)

$$F = \alpha A u_{*}^4 \quad \text{for} \quad u_{*} > u_{*t} \quad \text{and} \quad w_s < w_{st} = 0,$$  \hspace{1cm} (5)

where $u_{*}$ is the friction velocity, $u_{*t} = 0.6$ m s$^{-1}$ is the threshold friction velocity for dust lofting, $w_{s}$ is the ground wetness, and $\alpha = 1.42 \times 10^{-5}$ (kg m$^{-6}$ s$^{3}$) is a constant coefficient. The calculated mass flux $F$ is partitioned into bins 1–4 as 10%, 30%, 35%, and 25%, respectively, based on observations reported in Ono.
et al. (2003). The empirical equation in (5) and parameters $a$ and $u^*$ are derived from previous field experiments (Nickling and Gillies 1993). The fractional erodibility $A$ ranging between 0.0 and 1.0, represents the model grid area fraction of the dust-erodible soil, and is derived from a 1-km-resolution land cover dataset produced by the U.S. Geological Survey (USGS). The dry bed of Owens Lake is currently a salt flat whose surface is a mixture of clay, sand, and a variety of minerals. In this study, it is assumed that the dry bed is equally dust erodible and the $A$ values have been reset to 1 in a source area similar to the one identified in Ono (2006).

The COAMPS model predicts ground wetness $w_s$ using a soil model (Louis 1979). Dust lifting is allowed only when the ground wetness is under a threshold value, $w_{st} = 0.3$, which was an empirical value from previous COAMPS simulations of aerosol lifting over desert areas (Liu et al. 2007). It is noteworthy that for this study the simulated PM-10 concentration is relatively insensitive to the ground wetness threshold due to the fact that Owens Valley is an arid valley and the ground wetness is around 0.2 or less over most of the valley.

According to (5), the key variable in dust lifting is the friction velocity, which is approximately proportional to the surface wind speed, and is also dependent on the static stability in the surface layer; the friction velocity is larger in a less stable surface layer. In COAMPS, the friction velocity is calculated from the 10-m wind speed and Richardson number, which is determined by the vertical wind shear and stability, following Louis (1979). The threshold friction velocity used in (5) is substantially larger than those obtained from recent wind tunnel experiments (e.g., Roney and White 2006). The former is used to model a tipping point beyond which the vertical dust flux becomes significant and the latter corresponds to a friction velocity when the horizontal movement of particulates starts being observed in wind tunnels. It is noteworthy that wind tunnel experiments also showed that the threshold friction velocity varies with soil textures and the surface binding energy, which is dependent on humidity, temperature, and soil chemistry (Ono et al. 2003). These processes are not represented in the COAMPS aerosol model and are beyond the scope of this study.

At the surface, PM-10 is removed through both dry and wet deposition processes that are parameterized in the aerosol model. For dust lofting and transport inside the valley, in the absence of precipitation, only the dry deposition process is relevant, which is assumed to be proportional to the particulate mass flux divergence in the lowest model layer, $\Delta z$; that is,

$$\frac{\partial C}{\partial t} = -v_d C/\Delta z,$$

where $\Delta z = 10$ m in this study and the deposition velocity, $v_d = u^*_z/U_{10}$, is calculated from the friction velocity $u^*_z$ and the 10-m wind speed, $U_{10}$ (Stull 1988). Equation (6) represents the deposition associated with turbulence diffusion.

c. Model validation

For the purpose of model validation, the synoptic flow patterns derived from the 40.5-km grid of the COAMPS simulation have been compared with the corresponding National Centers for Environmental Prediction–National Center for Atmospheric Research
(NCEP–NCAR) reanalysis data (information online at www.esrl.noaa.gov/psd/data/reanalysis/reanalysis.html; see Figs. 4a and 4b). The agreement between the two suggests that the COAMPS simulation captures the synoptic-scale flow patterns, particularly the passage of the midlatitude trough, reasonably well. Our confidence in the COAMPS simulation is further reinforced by the agreement between the wind and potential temperature profiles derived from the upstream and in-valley radiosondes launched during T-REX and those obtained by interpolating the COAMPS output to the corresponding sounding times and locations (Fig. 5). The COAMPS simulation reproduces the strong westerlies near the moutaintop level and above. It also captures the presence of a stable layer before sunrise (Fig. 5) and the formation of a deep well-mixed layer in Owens Valley in the afternoon (not shown). Associated with the strong cross-mountain winds, large-amplitude waves were generated over Owens Valley, as observed by the Wyoming King Air and U.K. BAe-146 in the lower to upper troposphere and HIAPER flying in the upper troposphere and lower stratosphere.

COAMPS simulations with horizontal grid spacings of 2 km or less qualitatively captured these large-amplitude waves (Jiang and Doyle 2009; Doyle et al. 2011). The COAMPS 1.5-km grid (i.e., fourth mesh) also captures the enhancement of the westerlies over the valley floor in the afternoon and the transition from up- to down-valley winds after sunset near Independence, qualitatively in agreement with the measurements by the DRI AWS network (Fig. 8).

The simulated PM-10 concentrations, wind speeds, and wind directions over the 24-h period from 0000 to 2300 PST 25 March, interpolated to the seven GBUAPCD surface station locations, are shown in Fig. 10. The simulation captures the dramatic spatial and temporal variations of the PM-10 concentrations at the surface station locations. The simulated PM-10 concentration maxima are comparable with observations and the simulated surface wind speeds are in general weaker than observed. Specifically, COAMPS captures the diurnal variations of the PM-10 concentrations, wind speeds, and wind directions, which are qualitatively consistent with the surface station observations. However, a quantitative comparison of the observed and simulated winds and PM-10 concentration at each station reveals substantial discrepancies, which, to some extent, is expected. Previous observations and high-resolution simulations have indicated that, besides valley-scale circulations, kilometer-scale and turbulent-like subkilometer-scale circulations are ubiquitous in Owens Valley, likely due to finescale terrain variations, rotor circulations associated with BL separation, and differential heating over complex terrain (Grubišić and Billings 2007; Doyle et al. 2009). These highly time-dependent kilometer and subkilometer circulations, with life cycles on the order of minutes or less, likely account for the dramatic temporal and spatial variations of winds and PM-10 concentrations and may virtually be unpredictable (e.g., Lorenz 1969). Therefore, the goal of the COAMPS simulation is to simulate accurately the synoptic-scale forcing and valley-scale circulations.

4. The IOP-6 simulation

As shown in the previous section, the COAMPS-simulated large-scale patterns, and wind and potential temperature profiles, are in good agreement with the corresponding NCEP–NCAR reanalysis data and radiosonde observations obtained during T-REX. In addition, the 0.5-km spacing aerosol model qualitatively captures most of the salient features of the observed wind and PM-10 concentration variations. The model output with a 5-min time resolution is further diagnosed in this section to help us understand the physics and dynamics associated with the dust-lofting and transport processes, particularly, the diurnal variation of winds and PM-10 concentrations.

The diurnal variation is evident in the area-integrated dust emission rates (Figs. 11a and 11b), which show a broad maximum between the late morning and early
afternoon (referred to as midday hereinafter) and a more pronounced maximum in the late afternoon. For the midday period, approximately half of the dust emitted into the atmosphere is removed almost immediately through the dry deposition process. There is an approximately 30-min time lag in the midday deposition maximum and emission maximum, implying an average dust residence time on the order of 2000 s. A significant fraction of PM-10 is transported across the northern model boundary, apparently due to the up-valley winds beneath the mountaintop level, and, consequently, only a very small fraction is transported over the Inyo Mountains. For the late afternoon maximum, approximately two-thirds of the emitted dust particulates are removed from the surface layer by dry deposition over a short time period. It is noteworthy that, under strong winds and unstable conditions, the PM-10 deposition speed, \( v_d \), becomes significantly larger than the terminal velocity \( v_f \) [Eq. (6)]. The time lag between the two emission rates and the two depositional rate maxima is less than 5 min, the model output time interval. The substantially larger deposition-to-emission ratio in the afternoon can be explained by Eq. (6), which yields a deposition time scale of \( \Delta z U_{10}/u_{*}^2 \). In the afternoon, the valley air is more turbulent and characterized by a deep well-mixed layer. Accordingly, \( U_{10}/u_{*}^2 \) becomes significantly smaller than in the morning, and it follows that a larger percentage of PM-10 is removed through dry deposition. A significant amount of PM-10

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**FIG. 11.** (a) Plot of the area-integrated emission and deposition rates, and horizontal fluxes of particulate bin 1 at the northern and eastern model boundaries vs PST time. (b) As in (a), but for bin 4. (c) Plot of the total mass loading for bins 1 and 4 vs PST time. (d) Plot of the particulate residence time vs PST time for bins 1 and 4.
is transported across the Inyo Mountains and out of the domain through the eastern boundary during the late afternoon period, associated with the strong cross-valley winds (i.e., westerlies). The total PM-10 loading inside the model domain increases with time after sunrise and reaches a maximum approximately before local noon (Fig. 11c). The PM-10 loading begins to decrease sharply after sunset, as the emission rate is diminished.

Although the terminal velocity of bin 4 is 100 times that of bin 1, the variations of the emission and deposition rates for the two bins are quite similar, implying that the gravitational sedimentation is relatively insignificant relative to the dry deposition process. This can also be seen by comparing two time scales: the surface layer deposition time scale, \( \tau_d = \Delta z U_{10}/u_a^* \), and the gravitational sedimentation time scale, \( \tau_s = H/v_f \). Using the average values derived from the model output, \( U_{10} \sim 10 \text{ m s}^{-1} \), \( u_a \sim 0.6 \text{ m s}^{-1} \), the mean dust plume depth \( H \sim 1000 \text{ m} \), and \( v_f \sim 0.8-0.008 \text{ cm s}^{-1} \), we obtain \( \tau_d \sim 275 \text{ s} \) and \( \tau_s \sim 5 \times (10^4-10^6) \text{ s} \). If the average time it takes for dust particles to leave the surface layer is 1–3 min, approximately 20%–50% percent of the particulates in the surface layer will be removed by dry deposition. Clearly, the gravitational sedimentation process is too slow to be important. We can also estimate the particulate residence times for each bin using the definition of \( \tau_i = \Lambda_i/D_i \), where \( \Lambda_i \) and \( D_i \) are the dust loading and the area-integrated depositional rate for bin \( i \). For the midday period, the residence time for both bins 1 and 4 is in the range of 2000–4000 s (Fig. 11d), which is in agreement with the residence time estimated from the time lag between the emission and deposition maxima above. Corresponding to the emission and deposition maxima between 1530 and 1600 PST, the residence time exhibits a minimum, approximately 500 s, associated with fast depositional removal of dust in the afternoon. After sunset, the residence time increases dramatically to nearly 20,000 s (note that the particulate fluxes along the side boundaries are ignored in estimating the residence time), implying that fine particulates can be suspended in the lower troposphere for hours after leaving the surface layer. The residence time for particulates in bin 4 is noticeably shorter than those in bin 1 (Fig. 11d) between 1900 and 2100 PST. Physically, the dust emission becomes negligible after sunset and the PM-10 concentration in the surface layer decreases quickly with time. Accordingly, the deposition rate becomes small, and the residence time becomes significantly longer.

To further illustrate the difference in the PM-10 transport and dispersion for the midday and late afternoon periods, the every 5-min surface winds and PM-10 concentrations for each bin are ensemble averaged over the 0600–1500 PST (i.e., midday), 1500–1900 PST (i.e., late afternoon), and 1900–0600 PST (i.e., nocturnal) periods, respectively, using the 5-min output frequency data. The winds averaged over the midday period reveal that, while the surface winds over high terrain are westerlies or southwesterlies, the surface winds are primarily southeasterly (i.e., up-valley winds; see Fig. 12) in the valley. The surface PM-10 concentration is characterized by two maxima, located along the southern and northern edges of Owens (dry) Lake, respectively. The concentration near the northern edge is significantly smaller than that along the southern edge, where the surface winds show a pronounced maximum, likely due to the gap wind acceleration effect associated with airflow passing through the narrow pass between the sierras and the Coso Range. Dust particulates are transported primarily northward along the valley. The average winds for the late afternoon period are characterized by the coexistence of the cross-valley westerlies and up-valley winds. The dust “plumes” are oriented primarily across the valley (Fig. 12b), resembling those in Fig. 6. A substantial portion of the dust is transported across the Inyo Mountains into Death Valley National Park. The concentration of bin 4 shows similar patterns to bin 1 except that it is larger (Fig. 12d). In the evening, the surface winds are very weak over the valley floor and accordingly the dust concentration is substantially smaller than during the daytime (Fig. 12c).

On 25 March 2006, strong waves were observed above Owens Valley, which likely played a role in modulating the dust lofting and transport inside Owens Valley. A vertical cross section of wind, potential temperature, and the bin 1 concentration are shown in Fig. 13. In the midday period, the prevailing cross-valley winds stay aloft and could not reach the valley floor. Boundary layer separation occurs under the influence of a large-amplitude wave. A mean rotor structure is evident under the wave crest, attended with flow reversal (i.e., easterlies) above the valley floor (Fig. 13a). Beneath the strong cross-valley flow, the valley flow is predominantly southerly (i.e., up valley). The PM-10 particulates are largely confined in the valley and are transported along the valley. In late afternoon, the westerlies aloft plunge into the valley and reach the western portion of the valley floor (Fig. 13c). Consequently, the mountain wave above Owens Valley becomes significantly stronger, under which a weak rotor is evident, characterized by a reversed cross-valley flow and nearly neutral stability. The PM-10 particulates are lifted to about 5 km MSL and a substantial portion of the dust is transported across the Inyo Mountains to Death Valley National Park (Fig. 13d). It is noteworthy that the actual instantaneous winds inside Owens Valley are highly three-dimensional and the westerlies propagate
across the valley floor in places. Jiang and Doyle (2008) examined the surface winds observed near Independence (Fig. 1a) (within Owens Valley) during March–April 2004. They found that during IOPs characterized by prevailing westerlies above the sierra mountaintop, a transition between a relatively quiescent or weak along-valley flow in the morning and a strong westerly flow over the valley floor in the afternoon occurred frequently. The westerlies typically penetrated into the valley at around 1400 PST and retreated back to the western slope of the valley after sunset.

The difference between the dust transport and dispersion in the midday and late afternoon periods can be further seen in cross sections shown in Fig. 14. In the morning, the valley air is relatively stable and the turbulence is relatively weak (Fig. 14a). In the late afternoon, an approximately 2-km-deep well-mixed layer is evident and the valley air is significantly more turbulent.
(Fig. 14b). Large-amplitude mountain waves over Owens Valley and in the lee of the Inyo Mountains are evident in the afternoon cross-valley sections. A PM-10 maximum is present over the eastern valley floor downwind of the mean rotor where the separated BL reattaches to the valley floor, implying the important role wave-induced valley-scale circulations play in dust transport. The cross-valley sections also indicate that a significant fraction of dust particulates are transported over the Inyo Mountains, assisted by strong vertical motion induced by mountain waves and turbulence associated with strong surface heat flux during the afternoon (Fig. 14c). Aloft, the color-shading boundaries of the dust concentration tend to follow the potential temperature contours, as the waves are nearly steady and isentropes are a good approximation of streamlines. A comparison between Figs. 14c and 14d...
indicates that more particulate mass in bin 4 makes its way across the Inyo Mountains than in bin 1.

The surface PM-10 concentrations, averaged for the midday and afternoon periods, in general, decrease with the downwind distance (Figs. 15a and 14b). For the midday period, the surface concentration shows a maximum near 40 km associated with emission from the northern edge of the lake. To the north of the maximum, the logarithm of the surface concentration decreases almost linearly with the downwind (i.e., northward)
distance, implying an exponential decay of the surface dust concentration with downwind distance. The e-folding decay distance, estimated from the slope of the surface concentration curve in Fig. 15a, is approximately 6.6 km. For the late afternoon period, the surface concentration decreases westward and the logarithm of the concentration exhibits two different slopes (Fig. 15b). In the valley, the e-folding distance estimated from the mean slope is approximately 5 km. Over and to the east of the Inyo Mountains, the concentration decreases much more slowly, with an e-folding distance of 43 km.

Also included in Figs. 15a and 15b are the vertically averaged PM-10 concentrations before 6 km MSL, defined as $C(x, y) = \int z_{6km} c(x, y, z) dz/(6 - z_{6km})$, where $\langle c(x, y, z) \rangle$ is the mean concentration for the midday or late afternoon period and $z_{6km}$ is the terrain height. As expected, the vertically averaged PM-10 concentration is smaller than the surface concentration. However, the column-averaged concentration decreases with the downwind distance much more slowly than the surface concentration.

Shown in Fig. 15c are the dust plume depths for the along-valley and cross-valley cross sections, defined as $H(x, y) = \int z_{sfc} (c(x, y, z)) dz/\int_{6km}^{z_{sfc}} (c(x, y, z)) dz$. For the midday period, overall, the variation of the plume height with the along-valley distance is small except over the northern edge of the lake where strong emission reduces the plume height by increasing the PM-10 concentration near the surface. For the afternoon period, the mean dust plume is shallower due to the large PM-10 concentration near the surface (Fig. 15). The plume height also shows significant variation with the eastward distance, with a minimum over the eastern valley floor where BL reattachment occurs. In the lee of the Inyo Mountains, the dust plume thickens suddenly associated with the wave-induced vertical stretching and the significant reduction of PM-10 concentration near the surface.

5. Conclusions

The transport, dispersion, and deposition of fine dust particles originating from Owens (dry) Lake during the 2-month-long T-REX intensive observational period have been examined, with emphasis on the impacts of mesoscale dynamics and turbulence on dust lofting and transport. The hourly PM-10 concentration observed during March–April 2006 exhibits a strong diurnal variation with a pronounced maximum in late afternoon. As reported in previous studies, over the valley floor, the surface winds are primarily in the along-valley direction. However, the PM-10 concentration weighted wind direction reveals a cross-valley (i.e., southwesterly) component, indicating that, although the westerlies are less frequent in the valley, they are related to some strong dust events.

The characteristics of the dust event that took place on 25 March 2006 (i.e., T-REX IOP 6) are further investigated using the surface observations and a high-resolution mesoscale aerosol model simulation. The observed PM-10 concentration for IOP 6 exhibits an interesting bimodal distribution with a primary maximum in the late afternoon and a secondary maximum in the late morning. The morning PM-10 maximum is clearly induced by the moderate up-valley winds over the valley floor. In the afternoon, the wind speeds in five of the seven stations weaken to approximately half of their morning peak values. However, strong cross-valley winds reach the western part of the valley, where the other two stations located closest to the western valley slope recorded severe downslope winds (i.e., southwesterlies). The PM-10 concentrations observed at some stations are significantly

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**FIG. 15.** Plot of the surface (solid) and vertical average (dashed) bin 1 concentrations vs downwind distance for the (a) morning and (b) late afternoon plumes. The plume axes for the morning and afternoon are indicated in Fig. 12d. The plume depths, defined as $H(x, y) = \int z_{sfc} (c(x, y, z)) dz/\int_{6km}^{z_{sfc}} (c(x, y, z)) dz$, where $\langle c(x, y, z) \rangle$ is the bin 1 concentration averaged over the midday or late afternoon period and $z_{sfc}$ is the terrain height, are shown for the (c) morning (solid) and afternoon (dashed) plumes.
larger than the corresponding peak concentrations in the morning, implying that, although the strong westerlies only reach the western portion of Owens (dry) Lake, they are very efficient in aerosol lofting, likely due to their large wind speed of $\sim (20–25) \text{ m s}^{-1}$ and the strong sensitivity of the dust-lofting flux ($F$) to the surface friction velocity (i.e., $F \sim u^{4}_{d} \sim U^{4}_{10}$).

The numerical simulation using the COAMPS aerosol model qualitatively captures the observed large-scale flow patterns, wind and potential temperature profiles, and mountain waves. The 5-min interval output from the fifth nested grid with a 500-m horizontal spacing over Owens Valley captures the strong spatial and temporal variations of surface PM-10 concentrations and winds, and reveals complex multiple-scale circulations inside the valley. The simulated area-integrated emission rate is characterized by two distinctive maxima: one in the midday period, induced by the up-valley winds over the valley floor, and the other, with a larger emission rate in late afternoon, associated with strong westerlies over the western part of the valley. Further diagnosis of the simulation reveals the roles that low-level winds, turbulence, and mountain waves play in fine particulate lofting, transport, and dispersion. In the morning, the relatively stable air in the valley is largely decoupled from the prevailing cross-valley winds above the mountains. The fine particulates blown off the dry bed of Owens Lake by the up-valley winds are transported primarily northwestward along the valley. The mountain waves aloft seem to have little impact on the along-valley dust plume. The dust in the air has a residence time on the order of 2000–4000 s and the surface concentration along the dust plume decays exponentially with the downwind distance with an $e$-folding decay distance of 6.6 km. The prevailing westerlies aloft plunge into the valley around 1500 PST, which largely account for the late afternoon PM-10 maximum observed by surface stations as well as simulated by the COAMPS aerosol model. The dust is transported both eastward across the Inyo Mountains by the westerlies and northwardwest along the valley by the low-level up-valley winds. The cross-valley dust transport is strongly modulated by the large-amplitude waves over Owens Valley and in the lee of the Inyo Mountains. The decrease in the surface PM-10 concentration with the eastward distance can be characterized by two $e$-folding decay distances: approximately 5 km over the valley floor and 43 km in the lee of the Inyo Mountains. The shorter decay distance in the valley is likely due to the strong low-level turbulence, which shortens the dry deposition time scale. The substantially longer $e$-folding decay distance in the lee of the Inyo Mountains is likely due to the vertical stretching of the dust plume by gravity waves in the lee of the Inyo Mountains, and is consistent with the much larger dust residence time (i.e., 10 000–40 000 s) in the late afternoon.

For PM-10 particles, even in the largest-size bin, the gravitational sedimentation speed is much smaller than the deposition speed and the wave-induced vertical motion. Therefore, the gravitational sedimentation effect on PM-10 transport is negligible in the vicinity of Owens (dry) Lake, and becomes more important far downstream after the dust leaving the surface layer.

In summary, this study confirms the importance of the up-valley winds in dust lofting and along-valley transport of PM-10 near Owens (dry) Lake. It also suggests that the importance of the afternoon westerlies in dust lofting may have been underestimated in previous studies. Although the westerlies are observed much less frequently in Owens Valley and may not be documented by those surface stations located near the valley center or on the eastern valley floor, they are likely responsible for some of the worst dust events in Owens Valley as a result of their significantly stronger wind speeds in comparison with typical up-valley winds and weaker stability over the valley floor in the afternoon. During an afternoon westerly dust event, assisted by turbulence and mountain-wave-induced vertical motion, a substantial fraction of the fine particles originating from Owens (dry) Lake can be transported across the Inyo Mountains into Death Valley National Park.

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