Performance of WRF Large-Eddy Simulations in summertime CBL characteristics over the Taklimakan Desert: A Real Test Case

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characteristics over the Taklimakan Desert: A Real Test Case

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41 **Abstract**

42   During the summer season over Taklimakan Desert, the maximum height of the CBL

43 (convective boundary layer) can exceed 5,000 m, which appeared to play critical roles in

44 simulating the regional circulation and weather. In this paper, we use a combination of WRF-LES

45 (Weather Research and Forecasting Model Large-Eddy Simulation)，the GPS radiosonde and

46 eddy-covariance station to evaluate the performance of WRF-LES in the deep convective PBL

47 case over the central Taklimakan. Results show that the model reproduces reasonably well the

48 evolution of PBL processes. However, simulations are relative warmer and moister than those

49 observed due to the over-predicted surface fluxes and largescale advection. Tests are further

50 performed with multiple configurations and sensitive experiments. Sensitivity tests to Lateral

51 Boundary Condition(LBC) showed that the model results are very sensitive to changes in time

52 resolution and domain size of Specified LBC. It is found that larger domain size varies the

53 distance of the area of interest from the LBC, is efficient to reduce the influences of large forecast

54 error near the LBC. However, more frequently updated LBC is desirable to inhibit model error

55 near the LBC. On the other hand, model error increased as the distance between the area of

56 interest and the lateral boundaries decreased. Furthermore，comparing model results using the

57 original surface land parameterized sensible heat flux(SH) with Noah land-surface scheme and

58 those of sensitive experiment, it is concluded that the desert CBL is very sensitivity to SH

59 produced by surface land scheme during summer day time. A reduction in SH can correct

60 overestimate of the potential temperature profile. However, increasing SH significantly reduce the

61 total time needed for CBL increase to a relative low altitude (< 3 km) at the middle and

62 preliminary stage of the development of CBL rather than produce higher CBL at the late stage

63   Keyword: WRF, Large Eddy Simulation, Convective Boundary Layer, Taklimakan

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1　Introduction

　　The Taklimakan Desert, locates at the south center of the province of Xinjiang, China, is the world's second-largest flow desert and has profound influences on the regional weather and climate. Because of the extreme near-surface temperatures, the Taklimakan PBL (planetary boundary layer) commonly reaches 4–6 km during boreal summer(Wang et al.), making it probably the deepest on earth. The deep PBL, which is significantly higher than that of the surrounding mountains and oases, appeared to play important roles on regional circulation and weather. In the northwest of china, the ability to accurately forecast in Taklimakan Desert especially the PBL processes is an important problem.

　　The large desert (such as Sahara, Taklimakan et al.) atmosphere is always a key component of the climate system. The surface heating from intense solar radiation leads to the development of a near-surface thermal low pressure system, commonly referred to as the heat low(Engelstaedter et al. 2015). However, despite of the vital role of the desert playing in the climate system, observations are extremely sparse, and thin data that exist are mostly from the surrounding of the desert due to the poor work and natural(Marsham et al. 2011). This fundamentally restrict the development of understanding desert and surrounding area, and leads to large discrepancies to analyses and significant biases in operational numerical weather prediction (NWP) models, given the scarcity of observation being assimilated by operational systems. The ability of these local models to simulate real-world cases is often hindered by a lack of favorable data needed to assess the performance of model results(Garcia-Carreras et al. 2015). To fill in the gaps of Taklimakan desert，the field observation experiment was held during the month of July 2016 in Tazhong, which is located

88   at center of Taklimakan, by the Institute of Desert Meteorology (IDM), Chinese

89   Meteorological Administration (CMA), Urumqi(Liu et al. 2012; WANG et al. 2016a; Wang

90   et al. 2016b). This will also give the opportunity to evaluate the performance of the deep PBL

91   process in NWP models over Taklimakan.

92   On the other hand, atmospheric motions interweave small-scale, complex and multiscale

93   nonlinear interactions. Due to the limited resolution (time and space) mesoscale atmospheric

94   models are still unable to explicitly represent all these processes(Talbot et al. 2012). Such

95   processes include turbulent motions, which are too small-scale to be explicitly resolved in the

96   atmospheric model by a simplified process. Furthermore, turbulent mixing throughout the

97   PBL can heavily impacted NWP forecasting (Shin; Hong 2011; Shin; Hong 2015).

98   One way to tackle complex turbulent flows in weather forecast models is Large eddy

99   simulation (LES) which explicitly resolve energy-containing turbulent motions that are

100   responsible for most of the turbulent transport(Moeng et al. 2007). It has been used

101   intensively to examine detailed turbulence structure, to generate statistics, and to perform

102   physical-process studies(Garcia-Carreras et al. 2015; Heinold et al. 2013; Heinold et al. 2015;

103   Heinze et al. 2015; Sun; Xu 2009). However, most LES applications to the PBL have been

104   limited to idealized physical conditions. Recently, some studies attempt to test LES and assess

105   its performance in simulating real cases(Liu et al. 2011; Talbot et al. 2012). Liu et al. (2011)

106   suggests that WRF-LES is a valuable tool for simulating real world microscale weather flows

107   and for development of future real-time forecasting system, although further LES modeling

108   tests, such as elucidate whether inaccurate synoptic forcing or coarse resolution, are highly

109   recommended. Talbot et al. (2012) suggested that the ability of WRF-LES to simulate

110　　real-world cases are hindered by a lack of favorable synoptic forcing. The initial(ICS) and

111　　lateral boundary conditions(LBCS) was found to be more critical to the LES results than

112　　subgrid-scale turbulence closures. Thus, the LBCS of can significantly alter high-resolution

113　　LES status through inflow boundaries(Rai et al. 2017).

114　　　　However, most of research above on LES over desert has been limited to idealized

115　　physical conditions(Garcia-Carreras et al. 2015) or conducted real case outside

116　　Taklimakan(Liu et al. 2011; Talbot et al. 2012). The aim of this study is the attempt to

117　　applicate LES in a real deep CBL case over Taklimakan. An important aspect of the ongoing

118　　this paper is to examine assess the skillfulness of WRF-LES in relative coarse resolution

119　　(333m) over Taklimakan dessert in simulating real cases of deep desert PBL process during

120　　boreal summer events in Taklimakan. First we use a combination of WRF-LES and the GPS

121　　radiosonde and surface fluxes calculated by an eddy-covariance method taken in the central

122　　Taklimakan to evaluate the performance of WRF-LES in real case. Then we assess the

123　　potential errors related to LBC. Moreover, we aim to evaluate the relative contribution of

124　　uncertainties in surface model to the typical behavior of PBL processes by conducting the

125　　sensitivity experiments. Thus, the sensitivity of the performance to surface sensible heat flux

126　　(SH) is also studied. Section 2 gives a brief description of synoptic of the study case, and we

127　　described data and model configuration and design of numerical experiments used in this

128　　study. We presented the results of numerical simulations in Section 4. Finally, we summarize

129　　conclusions in Section 5.

130　**2　Method**

131　　**2.1　Model configuration**

132   The WRF model of version 3.8.1 (Skamarock et al. 2008) is utilized here at

133   sub-kilometer resolutions to simulate the extreme CBL event in Taklimakan desert. The

134   model is integrated for 12h, starting from 0800 BJT (Beijing Time) 01 Jul 2016. We

135   conducted one-way nest WRF from mesoscale down to LES-scales. All domains were 51

136   levels extended to 50 hPa. Height for lowest 20 levels are 1130.473, 1157.705, 1207.765,

137   1294.703, 1423.873, 1591.895, 1795.526, 2021.868, 2272.33, 2558.433, 2882.675, 3248.113,

138   3658.499, 4118.481, 4633.882, 5212.111, 5855.802, 6517.111, 7151.295, 7757.151. The

139   model horizontal spacing is 12km 3km 1km and 0.33km for d01 d02 d03 and d04. The sizes

140   of model grids are 411 ×321 791x651 211x201 and 403x406 respectively. Figure 1 shows

141   the domain for all experiments except for BDY_T3. Smaller grid sizes (205 X 208) are used

142   in experiment BDY_T3 to verify the effect of domain size on LES simulation.

143   The initialized condition and lateral boundary conditions are provided to the coarsest

144   mesoscale simulations from NCEP Global Data Assimilation System (GDAS) Final

145   Operational Global Analyses. The analyses are 0.25-degree by 0.25-degree grids prepared

146   operationally every six hours and available on the surface, at 32 mandatory (and other

147   pressure) levels from 1000 millibars to 10 millibars (National Centers for Environmental

148   Prediction 2015).

149   The model physical options include the WSM5 microphysics scheme (Hong; Lim 2006),

150   the Yonsei University (YSU) planetary boundary layer scheme (Hong; Pan 1996), the Kain–

151   Fritsch cumulus parameterization scheme(Kain 1993; Kain 2004), RUC (Rapid Update Cycle)

152   land-surface model(Smirnova Tatiana et al. 2000; Smirnova et al. 1997), the Rapid Radiative

153   Transfer Model (Mlawer et al. 1997) longwave, and the Dudhia shortwave radiation scheme

154 (Dudhia 1989). The cumulus parameterization scheme is only applied to the d01(12km) grid

155 domain to parameterize the convective rainfall. While, the large-eddy-simulation (LES) is

156 only applied to d04(0.333km).

157   Table 1 shows the list of experiments. Experiment 1 was the control experiment, denoted

158 as CTRL. The experiment 2 (6-hour update LBC, denoted BDY_T2) and experiments 3(with

159 domain sizes 205 X 208, denoted BDY_T2) were conducted the same as CTRL with different

160 domain sizes and LBC update frequency. In experiment 4 (denoted HFX_%75) and 5

161 (denoted HFX_%125), the SH (sensible heat flux) was reduced to 75% and 125% of that in

162 the control experiment in the RUC land-surface scheme, to highlight the impact of SH on

163 deep CBL at Taklimakan desert, respectively. In experiment 6 (denoted Noah), Noah

164 land-surface model(Chen; Dudhia 2001a, 2001b) was used to replace the RUC land-surface

165 model in CTRL experiment to discriminate the influence of different land-surface model on

166 deep CBL.

167   **2.2   Data**

168   The model simulations are compared to the Tazhong field experiment, which was held

169 during the whole month of July 2016 in Tazhong, by the Institute of Desert Meteorology

170 (IDM), Chinese Meteorological Administration (CMA), Urumqi. The main station was

171 located at 86.63° E, 39.03° N. The location is relatively flat with few hills and covered by

172 sand combined with grass (Figure 1), and the deep PBL of our simulation was under a

173 cloudless sky and dry environment. Instruments are described as follows:

174   1) surface fluxes: The eddy correlation system was a R3-50 supersonic anemometer

175 developed by Gill Company, UK, deployed at a height of 10 m. The data acquisition

176   frequency was 20 Hz, and the surface sensible heat flux was calculated by the

177   eddy-covariance method.

178   2) vertical profiles measured using soundings: Upper air soundings of temperature,

179   pressure, humidity, and wind speed and direction were conducted 3-6 times per day with the

180   GPS sounding system developed by No. 23 Institute of China Aerospace Science & Industry

181   Corp. (CASIC23). The sounding times were 01:15, 07:15, 10:15, 13:15, 16:15 and 19:15

182   respectively.

183   **2.3   Synoptic**

184   Figure 2 shows the synoptic patterns at 0800 BJT 1 July 2016 at 850 700 500 and 100

185   hPa. There were cyclonic vortex from 850 to 500 hPa center at 55°N (Figure 2a ,b and c).

186   Taklimakan was located east of cyclonic vortex and embedded in east–west-elongated ridge

187   at 0800 BJT 1 July. To the southwest, influenced by the South Asia High, which was centered

188   over the eastern Iranian Plateau, the upper air over the Taklimakan Desert was controlled by

189   the westerly jet stream at 100hPa (Figure 2 d). The low-pressure system at low level, which

190   is termed of heat low (Figure 3), dominated most area of southern Xinjiang and resulted in

191   continuous high temperature over the desert. This situation favored the subsidence motion and

192   served as a triggering mechanism for deep PBL in the region in the coming 2–3 days (not

193   show).

194   **3   Results**

195   **3.1   Validation of the deep CBL structure**

196   Time series of surface variables at Tazhong station from CTRL simulation for 01 July

197   2016 are presented in Figure 4a, b. Results show that discrepancies of thermodynamic surface

198   variables (the surface temperature, sensible and latent fluxes) between model and observation

199   are large during simulation. The SH (surface sensible heat flux) is far less in observation

200   (maximum: 243 W m^{-2}) relative to model (maximum: 613 W m^{-2}). This represents SH from

201   WRF simulation is 2.5 times than that of observation when both of which reach its maximum.

202   On the other hand, model shows a significant cold bias for the surface temperature. The

203   surface temperature is much higher in observation (maximum: 70 °C) relative to model

204   (maximum: 50 °C). To further verification the surface variables, RMSE (root mean squared

205   error) and BIAS (mean bias) are calculated including integration hours from 3 to 12 h for

206   Tazhong station in Table 2. As mentioned earlier, model show yields significantly

207   overestimate of SH (RMSE 263.636 W/m^2, BIAS:250.14 W/m^2) and dramatically

208   underestimated of surface temperature (RMSE 14.65℃, BIAS:-13.37 ℃).

209   Two possible reasons result in model SH far above that of observation: (1) The

210   mismatches of land-use between the model and the observation. WRF use land-use categories

211   to assign certain static parameters and initial values to each grid cell, for example, albedo,

212   surface roughness, and so on(Schicker et al. 2016). However, As in Figure 1c, the EC station

213   is surround by mixing land of grass and sand. The complex underlying surface may not be

214   adequately reproduced by model and can have an impact on the overestimate of SH in this

215   case. (2) It is should be noted that the SH and LH (latent heat flux) based on eddy

216   correlation might be underestimated(LeMone et al. 2013). Researchers found that if the other

217   two terms in the budget—net radiation and flux into the soil were accurate, used data for the

218   whole experiment to find the H + LE for Tazhong station are equal to an average of 75% of

219   what would be required for balancing the surface energy budget.

220   Despite the large differences on surface, near-surface variables (2m temperature, relative

221   humidity and 10m wind speed, Figure 4 e f g) are closer to measurements than those from

222   surface, their values are relatively higher than those observed. The time series evolution of 2m

223   temperatures nearly follow those of the observations (RMSE:1.66, BIAS:1.61); but model

224   produce warmer surfaces by about 3 K at the beginning of model integration, and 1K when

225   model and observation both reach their maximum temperature, respectively.

226   Results indicate that, model-produced near-surface relative humidity is close to

227   observations at initial time (Figure 4 f). However, the humidity from the model keeps

228   increasing at the first few hours of model integration, when observations decrease. After 3

229   hours' spin-up, the model reproduces reasonably well the evolution of humidity, in agreement

230   with observation (RMSE:1.22), but their values are relative higher than those

231   observed(BIAS:1.11).

232   One reason for this discrepancy is the overestimate of soil moisture during simulation.

233   Soil moisture can severely impact near-surface humidity. The overestimate of the soil

234   moisture contents in the initial condition of the model, which are only offered to the model at

235   initial time, may result in considerable differences in near-surface layer humidity (Talbot et al.

236   2012). In the present simulations, model results are reported to produce grossly overestimate

237   soil moisture. At the model initialization for the CTRL simulation, EC station at Tazhong

238   station indicated a value of the 5-cm-deep soil moisture of 0.230 m^3/m^3, while the model

239   initial value is 0.6 m^3/m^3 (Figure 4 d). This large overestimate of soil moisture results in LH

240   (Figure 4 b, f) from the model continue to increase. As a result, near-surface of model is far

241   moister than that of observation at the first few hours of model integration. An interesting

242　result to note is that the model simulation has the abilities to correct some of the bias due to

243　the initial condition of the surface; The results from CTRL experiment are closer to

244　observation after 3 hours' spin-up.

245　　　The model simulated potential temperature are compared to GPS sounding

246　measurements at Tazhong during 0800~2000 BJT 01JULY2016 in Figure 5 (solid lines). One

247　should note that radio-sounder floating about 7 Km away from Tazhong, when radio-sounder

248　reach 6 Km height. Thus, for comparison, the profiles of model simulations are averaged

249　station in a radius of 3.5 Km. At 0800 BJT, when the model is initialized, the nocturnal

250　inversion reaches 300m (not shown). By 1100 BJT, this inversion is eroded in the model in

251　agreement with observations, and both reaching about 300m at 1100 BJT (Figure 5 a).

252　However, the simulated CBL grows faster in the morning due to larger SH than observation,

253　reaching 3500m (3000m in the observations) at 1400 BJT (Figure 5 b). At 1700 BJT (Figure 5

254　c), the simulated and observed CBL heights exceed 4000m and 5000m respectively. This

255　indicates that the simulated CBL grows more slowly in the afternoon than measurement.

256　Compared to measurements, the model is initially cooler with faster heating rate in the

257　morning. As a result, model is warmer than measurements in the afternoon. Eventually, model

258　agrees with observations at the end of the day. One possible minor reason is the differences of

259　potential temperature lapse rate above the top of mixing layer between observation and

260　simulation. Simulated stronger inversion layer restrain the development of CBL, which will

261　be discussed below.

262　　　Moreover, in terms of CBL temperatures, the model initially simulates a cooler and drier

263　CBL than that observed, at 1100 BJT01 JUL (Figure 5a). Compared to the observed potential

264 temperature profile, the CBL seems to appear earlier in model forecasts result based on

265 obvious warming in surface layer. One should note that RL (residual layer) may play a key

266 role in the deep PBL at Taklimakan desert. At 1100 BJT, when the CBLH was about 300 m in

267 observation as show above, potential temperature in the were about 317 in PBL and 320 K in

268 RL, respectively. When the potential temperature in CBL increased to the value in RL (320

269 K), the CBL merged with the RL, and the height of PBL reach 3000m in the observations at

270 1400 BJT. These results are in good agreement with Han et al. (2012). By analysis of

271 observation of a CBL in the Badanjilin region, they found a rapid development process of

272 CBL after 1200 LST, which appeared to be a jump of CBLH when the inversion layer

273 vanished.

274 When the SH reaches its maximum at 1400 BJT (Figure 5b), potential temperature

275 profile is closer to measurements than at initial time, and their values are higher than those

276 observed. By 2000 BJT (Figure 5d), CBLH in the model reaches its maximum value, which is

277 consistent with observation, despite of approximately 0.4K cooler on the lower

278 levels(<2.5Km). As mentioned, one cause of the higher temperatures produced with

279 model would be the large difference in the surface heat fluxes. It was concluded that

280 the surface sensible heat flux from the land surface parameterization is the crucial

281 factor affecting the CBL process during summer day time. Differences in surface SH

282 would create differences in the vertical development of the PBL. Thus, the large

283 surface SH difference between the model and observation may lead to differences in

284 CBL growth during daytime and in its peak depth during the simulation. Fortunately,

285 one can artificially modify the surface SH computed by surface-land model, which

286　controls the calculation of surface fluxes. Sensitive simulations will be realized and

287　discussed in next section.

288　　　Figure 5 also shows Vertical profiles of vapor mixing ratio (dash lines) at Tazhong

289　station. The simulated profiles with lower RL are much drier than observation from 1500 to

290　3500m at 1100 BJT. The vertical mixing results in the uniform structure of vapor mixing ratio

291　within CBL, so the differences between simulated and observational profiles are reduced

292　remarkably when CBL reach above 4000m at 1400 BJT. Differences are generally less than

293　1g/Kg at 1100 BJT reaching a maximum of 0.3g/Kg at 1400 BJT. However, measured PBL

294　moisture shows an inverse layer at lower PBL(≤2000m) range from 2.8 to 3.6 g/Kg, which is

295　not captured by model. Furthermore, as the convective boundary layer grows, the inversion

296　moisture structure below 3000m develops to and maintains below 3000m during 1400~2000

297　BJT. By the end of the day, the model-simulated CBL humidity show moister than

298　observation, because model cannot reproduce the inverse moisture layer within CBL.

299　　　Inverse humidity may be caused by the joint of the heterogeneous humidity Pattern and

300　Large-scale advection over the underlying surface. For instance, interaction of oasis with

301　desert environment may resulted in the inverse humidity layer in desert PBL. Thus, one

302　possible reason for the discrepancy between model and observation caused by the error in

303　land-use type. The USGS land-use in ARW-WRF is based on AVHRR (Advanced Very High

304　Resolution Radiometer) 1km resolution satellite data during1992-1993. For our case, this

305　land-use data may be outdated in Taklimakan. Besides such changes, misclassifications are

306　found in the USGS land-use data, the default land-use dataset in WRF(Schicker et al. 2016).

307　This is also confirmed by the discrepancies of land-use between simulation and measured at

308   the Tazhong station in the previous figure. Large-scale advection of dry air can affect the

309   profile of moisture. Moisture will also be variable in the horizontal, so advection at the low

310   level could contribute to the dry at bottom and moisture at the upper of PBL between 1100

311   and 2000 BJT at the bottom of the PBL.

312   The mismatch between the model and the observations in terms of moisture that is

313   present means that the effect of land-use type and Large-scale advection needs to be

314   quantified and that more detailed data of Taklimakan (land and atmosphere) might be

315   necessary to realize a more realistic performance. Extra care should also be taken with sparse

316   and the limited data in the periphery of the Taklimakan(ter Maat et al. 2012).

317   **3.2   Sensitive to Lateral Boundary Condition(LBC)**

318   After verifying the details of the LES simulations, we assess the sensitivity of the LES

319   simulations to time resolution and domain size of Specified LBC. For one-way nest, Specified

320   LBC is obtained from coarser model simulation. The analysis and all forecast times from a

321   previously-run larger-area model simulation are used to specify the LBC. The primary cause

322   of differences in PBL structure was diagnosed as differences in domain size and frequency

323   provided by the coarser resolution. The aim is to assess the sensitivity of the finer large-eddy

324   simulations to time frequency and domain size of Specified LBC forcing by larger-area model

325   simulation; Details of the three simulations (CTRL, BDY_T2 and BDY_T3) are given in

326   section 2.

327   Figure 5 compare the profiles of the simulated potential temperature and vapor mixing

328   ratio profiles from LBC sensitivity experiments and observation. Results indicate that, there is

329   a distinct relationship between LBC and CBL development. All model-produced profiles are

330   nearly the same at initial time (not show). However, the comparison results reveal that

331   discrepancies among different experiments are large for CBL. The results indicate that larger

332   domain size and more time frequency LBC leads to a warmer and drier PBL, but a cooler and

333   moister free troposphere. Such sensitivity is monotonic with respect to LBC (Figure 5).

334   Furthermore, in the next three hours, the differences between the sensitive experiments keep

335   increasing with time (Figure 5 a, b). The potential temperature profiles within CBL become

336   divergence at 1100 BJT. However, the results show more convergence at afternoon as CBL

337   continues to grow (Figure 5 c). Finally, largest discrepancies are found by end of the day

338   (Figure 5 d) where the model CBL potential temperature is warmer by up to about 0.7K and

339   0.9K in BDY_T2 and BDY_T1 respectively, compared to measurements.

340   Figure 6 shows cross sections along 39.03°N of horizontal winds, superposed with theta

341   and vapor mixing ratio. Overall, the lower frequently updated LBC is desirable to cold zone

342   near the LBC, which results in cold advection of the temperature and moisture to the area of

343   interest (Figure 6   b, c). Larger domain size, which varies the distance of the area of interest

344   from the LBC, is efficient to reduce the influences of large forecast error near the LBC to the

345   area of interest (CMP Figure 6   a, c). The results suggest that the model results are sensitive

346   to changes in time resolution and domain size of Specified LBC. The mismatch among

347   sensitive experiments is present means that the effect of LBC needs to be quantified to realize

348   a more realistic performance in the sub-kilometer simulations.

349   To further examine the impact of LBCS on the turbulence of deep Taklimakan desert

350   CBL, the instantaneous vertical velocity fields for the horizontal are displayed in . By 1400

351   BJT, the convection of CTRL simulation obviously intensified under strong surface heating

352   (Xu et al. 2018).   Thus, the maximum vertical velocity reaches 9 m/s and the depth of mixed

353   layer grows to about 4.3 km (a).   The distances between the boundary layer rolls

354   correspondingly increase to about 12 km and the height of the peak updraughts is raised to

355   just under 4 km.   The cellular shape of updraughts and downdraughts characteristic of

356   boundary layer rolls is obvious in the horizontal view with the strength of convection.

357   BDY_T2 and BDY_T3 experiments (b, c) both reproduce motions with much weaker

358   maximum and minimum values at boundary of domain. In BDY_T3 experiment, Tazhong

359   station at center of the model has been directly influenced by the inflow cold advection

360   produced by low frequency LBCS and results in much weaker maximum and minimum value

361   of w (about 6 m/s). However, despite the underestimate of potential temperature, the w fields

362   for BDY_T2 experiment look similar to the CTRL w in plain view, and the horizontal extent

363   of the updrafts/downdrafts agrees with the CTRL as can be inferred from . To further examine

364   vertical structure of desert CBL, vertical cross-sections along Tazhong station ($39°N$) of w

365   are presented in Figure 8. Wide and regularly spaced updrafts along A1- A2 split into the

366   stronger and more irregular motions in CTRL and BDY_T2. The updrafts are much weaker in

367   the BDY_T3 experiment, as can be seen from Figure 8 c. Peak updrafts on BDY_T3 are about

368   4 m/s much weaker than on CTRL (9 m/s) and BDY_T2 (8 m/s). For BDY_T2 and BDY_T3,

369   the distant of the inflow boundary is wider, and the intensity of the convection is weaker at

370   the boundary. Compared with BDY_T2, the horizontal distribution of vertical velocity at

371   Tazhong station in BDY_T3 experiments is much weaker.

372   **3.3   Simulations with different surface sensible heat flux (SH) and surface-land**

373   **models**

374　　　　The import cause of differences in PBL structure was diagnosed above as differences in

375　　SH predicted by the surface-land schemes. The SH is one of the key factor affecting the

376　　CBLH during summer day time. Thus, the difference between model and observation may

377　　lead to differences in PBL growth during daytime; To further confirm whether this indeed

378　　occurs, three additional sensitive simulations were realized based on the CTRL experiment.

379　　For Noah experiment Noah land-surface model is used to replace RUC land-surface model in

380　　CTRL experiment, and for HFX-125%, HFX -75% SH is %125 and %75 that of CTRL（HFX

381　　-100%）experiment, while the other parameters remain the same.

382　　　　The results from Figure 10 and Table 2 showed that HFX-75% successively improved

383　　the simulation of SH with RMSE:151.12, compared that of 263.64, 357.11 in CTRL and

384　　HFX-125%. Of interesting is that experiment with Noah surface-land yielded the best

385　　performance among all of the cases in SH, surface temperature and air temperature. However,

386　　Noah surface-land model show large discrepancies with observation in Soil moisture, and

387　　results in dramatically overestimate of LH and relative humidity compared to CTRL.

388　　　　Further examining potential temperature and vapor mixing ratio (Figure 9) indicate that

389　　with smaller SH leads to a cooler, moister lower PBL and a warmer, drier free atmosphere.

390　　Such sensitivity is monotonic with respect to SH. Overall, the CBL structure from the

391　　HFX-75% and Noah experiments match the GPS measurements better than the CTRL

392　　（HFX-100%）simulations. Potential temperature profiles from CTRL（HFX-100%）and

393　　HFX-125% are consistently warmer than the observation by about 0.4 and 0.5 K respectively,

394　　while results from HFX-75% and Noah are within about 0.2K at 1400 BJT (Figure 9 b). The

395　　results suggest that the model results are sensitive to changes SH from land-surface model.

396   However, simulations converge at the end of the day, but remain differences at 2000 BJT

397   (Figure 9 d). HFX-75% and Noah with weaker surface sensible heat flux can still produce the

398   deep CBL nearly the same as CTRL and HFX-125%. This indicates that SH may not the

399   dominant factor for the deep CBL over the Taklimakan desert.

400   Results of simulations on desert PBL in the morning agree with the previous studies of

401   sensitivities land-surface model for other areas (Hu et al. 2010; Zhang et al. 2017). However,

402   during 1700~2000 BJT 01July (Figure 9b, d), all experiments produce nearly the same CBLH

403   and moisture in agreement with observation in the PBL. The effects of SH on the evolution of

404   Taklimakan PBL structures during this period are needed to be further examined and

405   discussed. So, the question is: why are simulations insensitive to land-surface process by the

406   end of the day? As in Stull (1988), the development of CBL is mainly influenced by the effect

407   of thermodynamic and turbulent entrainment without considering large scale factors such as

408   large scale advection or subsidence. Besides the surface sensible heat, the intensity of

409   entrainment process determines the increasing rate of CBL. Thus, the entrainment rate w_e is a

410   valuable indicator for the development of PBL structure.

411   The rate of growth of the convective boundary layer is mainly determined by the

412   entrainment rate w_e at the inversion layer without considering large scale vertical motion. w_e

413   usually has a positive correlation with heat flux amount at the inversion layer $\overline{\left(w'\theta_v'\right)}_h$, and

414   large LES experiments show $\overline{\left(w'\theta_v'\right)}_h$ is about 0.2 times the surface flux of buoyancy

415    $\overline{\left(w'\theta_0'\right)}$. During the period from 1100 to 1400 BJT, larger SH is obviously correlated with

416   stronger turbulent entrainment and warmer air from free atmosphere (FA) entraining into ML.

417   As a result, CBL develop rapidly and is warm too fast in the early simulation phase due to the

418   obviously increasing temperature and strong vertical mixing in model. Of interesting is that

419   reduction in SH reproduces better desert PBL evolution in the early simulation phase, as

420   SH-75% and Noah produce the smallest simulation errors in both temperature and moisture.

421   However, one should note that CBLH and potential temperature for SH-75% and Noah have

422   reached above 5000 m and 323.2 K respectively at 1700 BJT (Figure 9 a). For the rest of the

423   day, the increase rate of CBL height slows down due to the deep CBL(>5000m) which require

424   more heat for the growth of PBL depth; Moreover, w_e decrease with increasing inversion

425   intensity, which inhibits the mixing and entrainment processes. These two factors obviously

426   limit the growth of CBL when CBLH is over 5000 m in this deep desert CBL case. Therefore,

427   increasing SH from 75% to 125% significantly reduce the total time needed for CBL increase

428   to a relative low altitude (< 5 km) at the middle and preliminary stage of the development of

429   CBL rather than produce higher CBL at the late stage. When height of CBL over Taklimakan

430   desert exceeds 5000 m, it might not change with proportion to SH fluxes (Figure 9 d). As a

431   result, PBL of WRF simulations are basically the same, and not sensitive to SH fluxes by the

432   end of the day.

433   **4   Summary**

434   This paper assesses the performance of the Weather Research and Forecasting Model

435   (WRF) Large-Eddy Simulations(LES) in deep convective PBL case over Taklimakan Desert.

436   Tests are performed with multiple configurations and sensitive experiments. Sensitivity tests

437   to Lateral Boundary Condition(LBC) showed that the model results are sensitive to changes

438   in time resolution and domain size of Specified LBC. It is found that larger domain size varies

439   the distance of the area of interest from the LBC, is efficient to reduce the influences of large

440   forecast error near the LBC.

441   Consequently, with the configuration used in this study, the model reproduces

442   reasonably well the evolution of PBL processes. The model shows discrepancies between the

443   main CBL characteristics in the morning including the thermal and moisture structure. The

444   model simulates the relatively colder and drier morning CBL well, underestimating it by up to

445   1.5K near-surface layer at Tazhong station. In the case of the underestimation of moisture by

446   only up to 1 g/kg in the near-surface layer. The overestimation of CBL profile may be caused

447   by discrepancy between model and measurement initially. This indicates that the results are

448   sensitive to the model initial conditions. An interesting result to note is that the model

449   simulation seems to be able to correct some of the bias due to the initial condition. In the

450   afternoon, the model correctly reproduce the thermal structure, but simulations are relative

451   warmer and moister than those observed. Potential temperature profile at CBL appears

452   warmer by up to about 0.4K compared to the observations. While the model overestimates the

453   afternoon moisture seriously, it mainly overestimates vapor mixing ratio by about 1 to 2 g/Kg

454   in the CBL. Largest discrepancies are found in 0~3Km where the model vapor is twice as

455   moist (up to about 3g/Kg above AGL) as observed.

456   Furthermore, three additional sensitive simulations were realized to further confirm

457   whether large differences of SH lead to differences in ABL growth during daytime, based on

458   the CTRL experiment.   The results suggest that the model results are sensitive to changes

459   SH and different land-surface models. The large difference between the model and

460   observation may lead to differences in CBL growth during daytime. From these results, it was

461   concluded the surface sensible heat flux is an important factor affecting the CBL depth over

462   Taklimakan during summer day time. However, its peak depth during the simulation show

463   less sensitive to SH because of decreasing w_e by the end of the day.

464   The future work aimed to study several other deep CBL cases over Taklimakan to

465   summarize their common features. Furthermore, we hope to utilize high resolution model and

466   observation to describe the fine characteristics of a typical deep Taklimakan CBL particularly

467   the turbulent and vertical mixing and its impact on regional weather forecast. This research is

468   aimed to improve the understanding of deep CBL over Taklimakan and its influence on

469   regional weather and climate.

470   **Conflict of Interests**

471   The author declares that there is no conflict of interests regarding the publication of this paper.

472   **Acknowledgments**

476

477   Captions:

478   Figure 1 Simulation domains used in ARW model with terrain height (shaded, units:m); (b) land

479   use categories for domain D03 and D04.

480   Figure 2 Horizontal distribution of geopotential height (solid, units: dagpm), wind speed (shaded,

481   units: knot), and wind barbs from the NCEP FNL analysis at 0800 BJT 1 Jul 2016 at (a)

482   850 hPa, (c) 700 hPa, (e) 500 hPa, and (d) 100hPa.

483   Figure 3 NCEP FNL 700hPa potential temperature (colors) and mean sea level pressure (white

484   lines) at 0800 BJT 1 Jul 2016. The black dot shows the location of Tazhong station at

485   Xingjiang province.

486   Figure 4 Time series of simulated surface variables from innermost domain of simulations

487   and surface observations at Tazhong station (83.63° E, 39.03° N) initial at 0800

488   BJT 01July 2016 (a) sensible heat flux (W/m^2), (b) latent heat flux(W/m^2), (c) 2-m

489   temperature (∘C), (d) surface temperature (∘C), (e) 2-m Relative Humidity(%) and (f)

490   10-m wind speed (m/s) with corresponding observations.

491   Figure 5 Vertical profiles of potential temperature (solid line, units: K) and vapor mixing

492   ratio(dash line, units: g/Kg)from innermost domain of simulations and observation of

493   GPS sounding at Tazhong station (83.63° E, 39.03° N) at (a)1100 (b) 1400 (c)

494   1700 (d) 2000 BJT 01 Jul2016.

495   Figure 6 cross sections along 39.03°N of horizontal winds (barbs, units: m/s), at intervals of 5 m/s,

496   superposed with theta (shaded, units: K) and vapor mixing ratio(contour, units: g/Kg), from (a)

497   BDY_T1, (c) BDY_T2, (e) BDY_T3 experiments at1400 BJT 01JUL2016, (b), (d), (f) are the

498   same as (a), (c), (e), but for 2000 BJT 01JUL2016.

499   Figure 7 Instantaneous vertical velocity fields (shading: m/s) at 3000 m for (a) BDY_T1 (CTRL), (b)

500   BDY_T2, (c) BDY_T3, and (d) Noah at 1400 BJT, 1 July 2016.
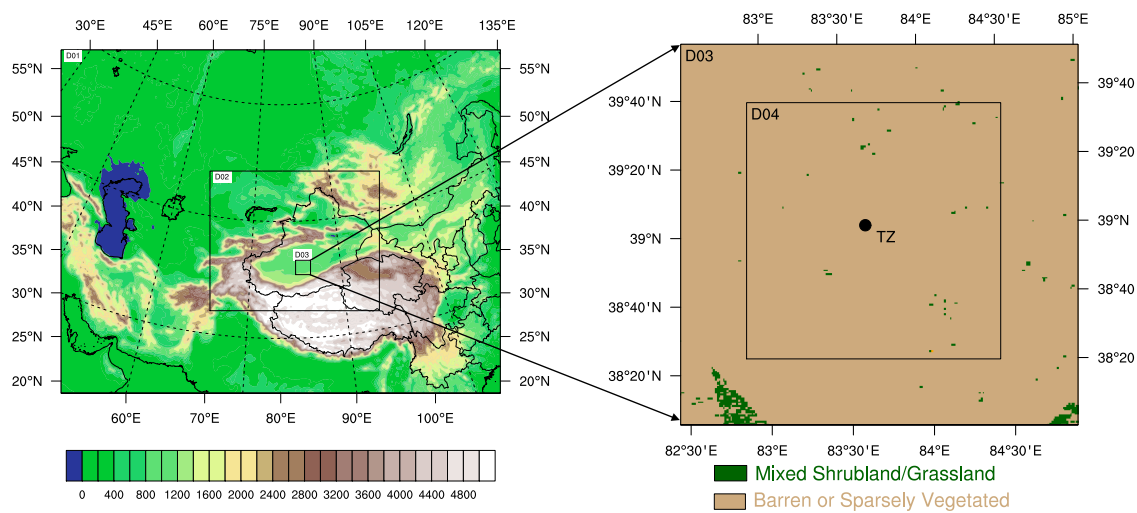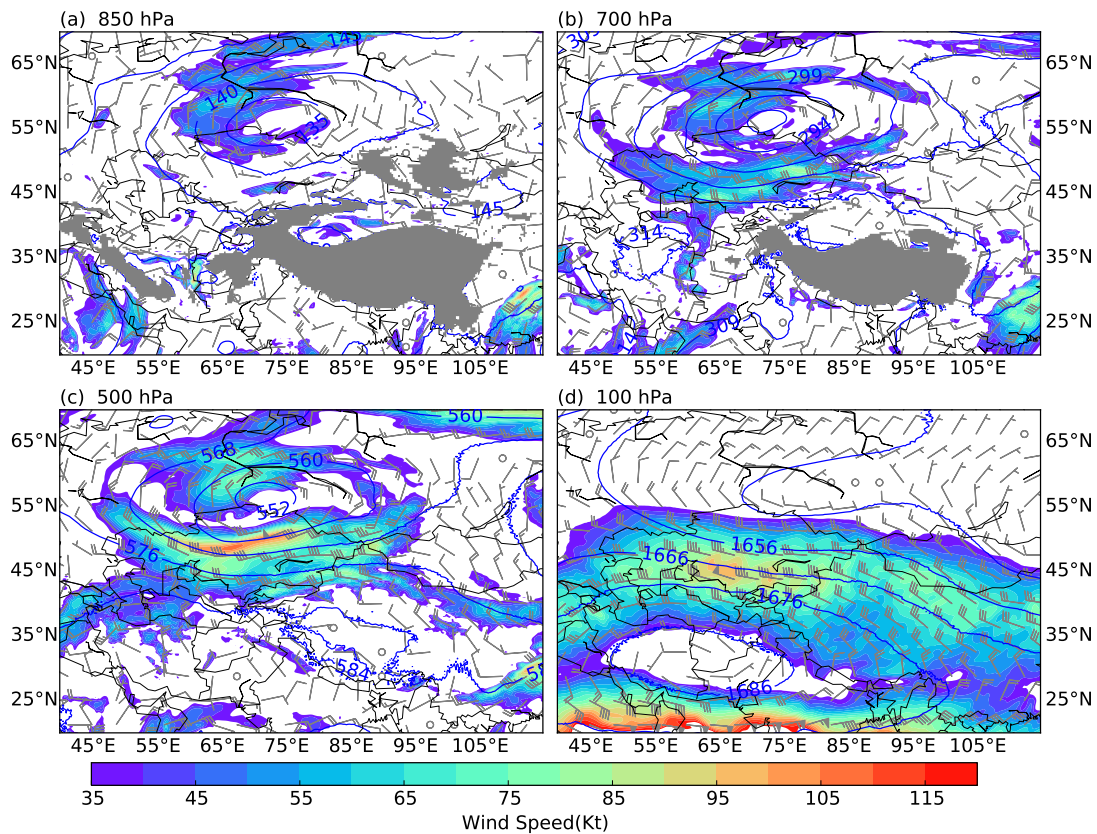
501   Figure 8 Vertical cross-section of instantaneous vertical velocity fields (shading: m/s) along

502   A1-A2 in for for (a) BDY_T1 (CTRL), (b) BDY_T2, (c) BDY_T3, and (d) Noah at 1400 BJT,

503   1 July 2016.

504   Figure 9 The same as Figure 5, but for SH flux sensitive and Noah land-surface experiment.

505   Figure 10 The same as Figure 4, but for SH flux sensitive and Noah land-surface experiment.

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509 （a） （b）

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511 （c）

512 Figure 1 Simulation domains used in ARW model with terrain height (shaded, units:m); (b)

513 land use categories for domain D03 and D04; (c) photograph of Tazhong station

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Figure 2 Horizontal distribution of geopotential height (solid, units: dagpm), wind speed

(shaded, units: knot), and wind barbs from the NCEP FNL analysis at 0800 BJT 1 Jul 2016 at

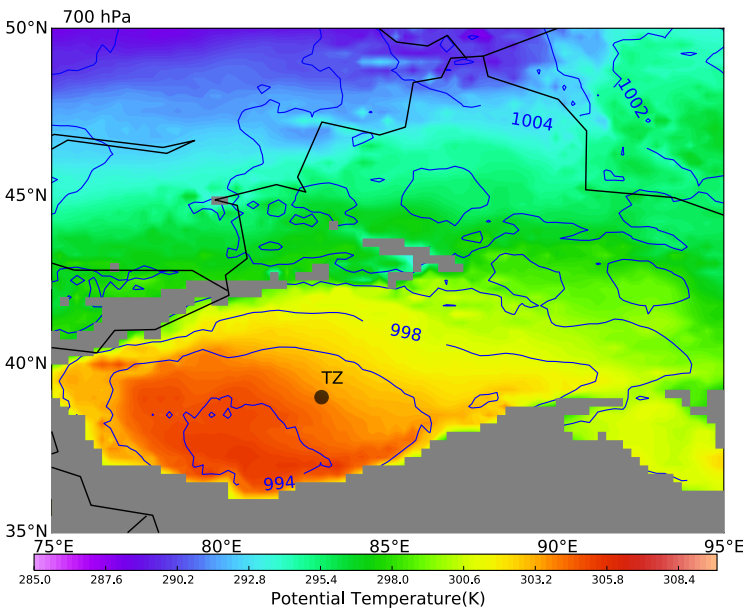(a) 850 hPa, (c) 700 hPa, (e) 500 hPa, and (d) 100hPa.

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522   Figure 3 NCEP FNL 700hPa potential temperature (colors) and mean sea level pressure (white lines) at
523   0800 BJT 1 Jul 2016. The black dot shows the location of Tazhong station at Xingjiang province.

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Figure 4 Time series of simulated surface variables from innermost domain of simulations

and surface observations at Tazhong station (83.63° E, 39.03° N) initial at 0800 BJT 01July

2016 (a) sensible heat flux (W/m^2), (b) latent heat flux(W/m^2), (c) 2-m temperature (◦C), (d)

surface temperature (◦C), (e) 2-m Relative Humidity(%) and (f) 10-m wind speed (m/s) with

corresponding observations.

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Figure 5 Vertical profiles of potential temperature (solid line, units: K) and vapor mixing

ratio(dash line, units: g/Kg)from innermost domain of simulations and observation of GPS

sounding at Tazhong station (83.63°E, 39.03°N) at (a)1100 (b) 1400 (c) 1700 (d) 2000 BJT

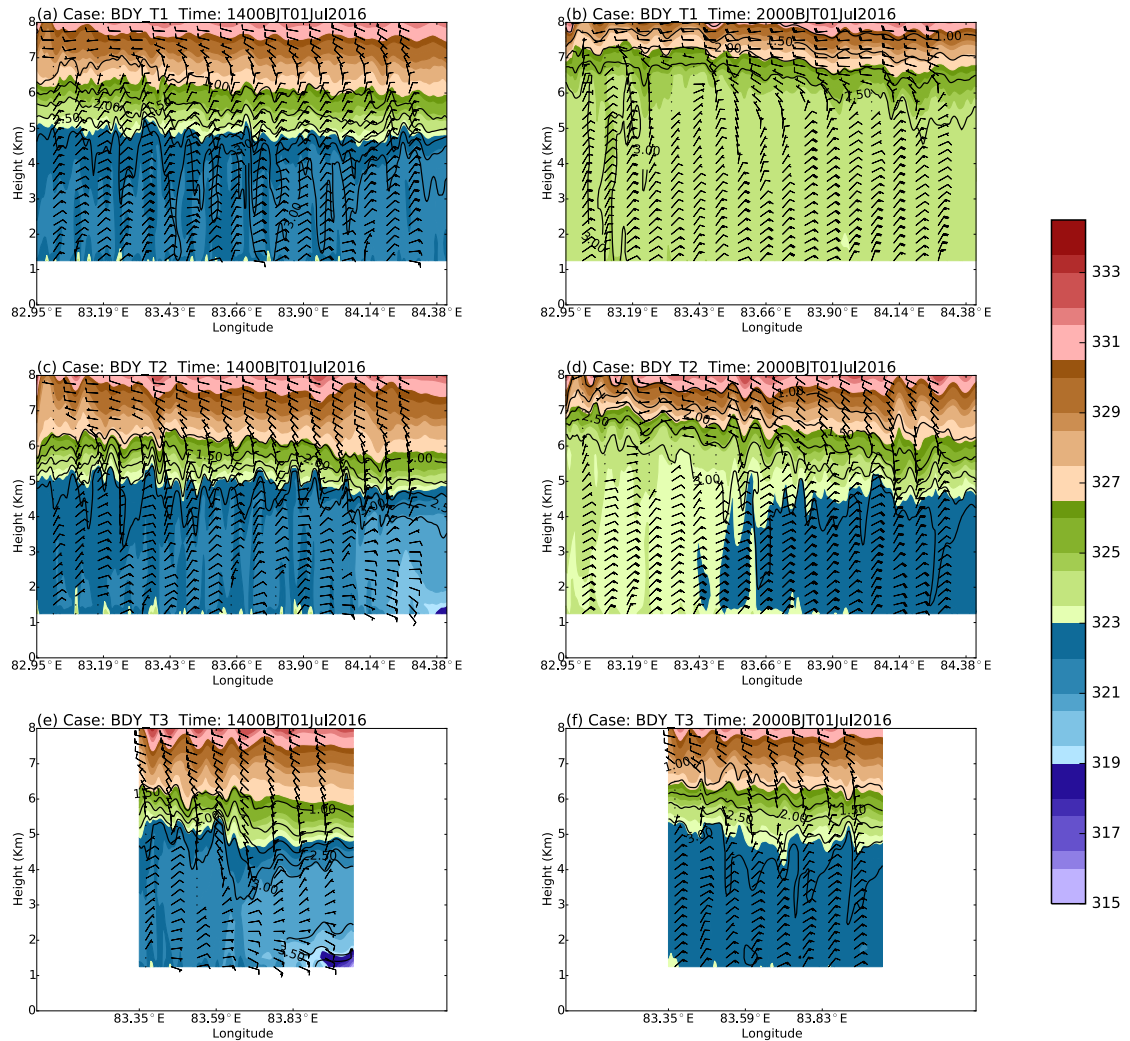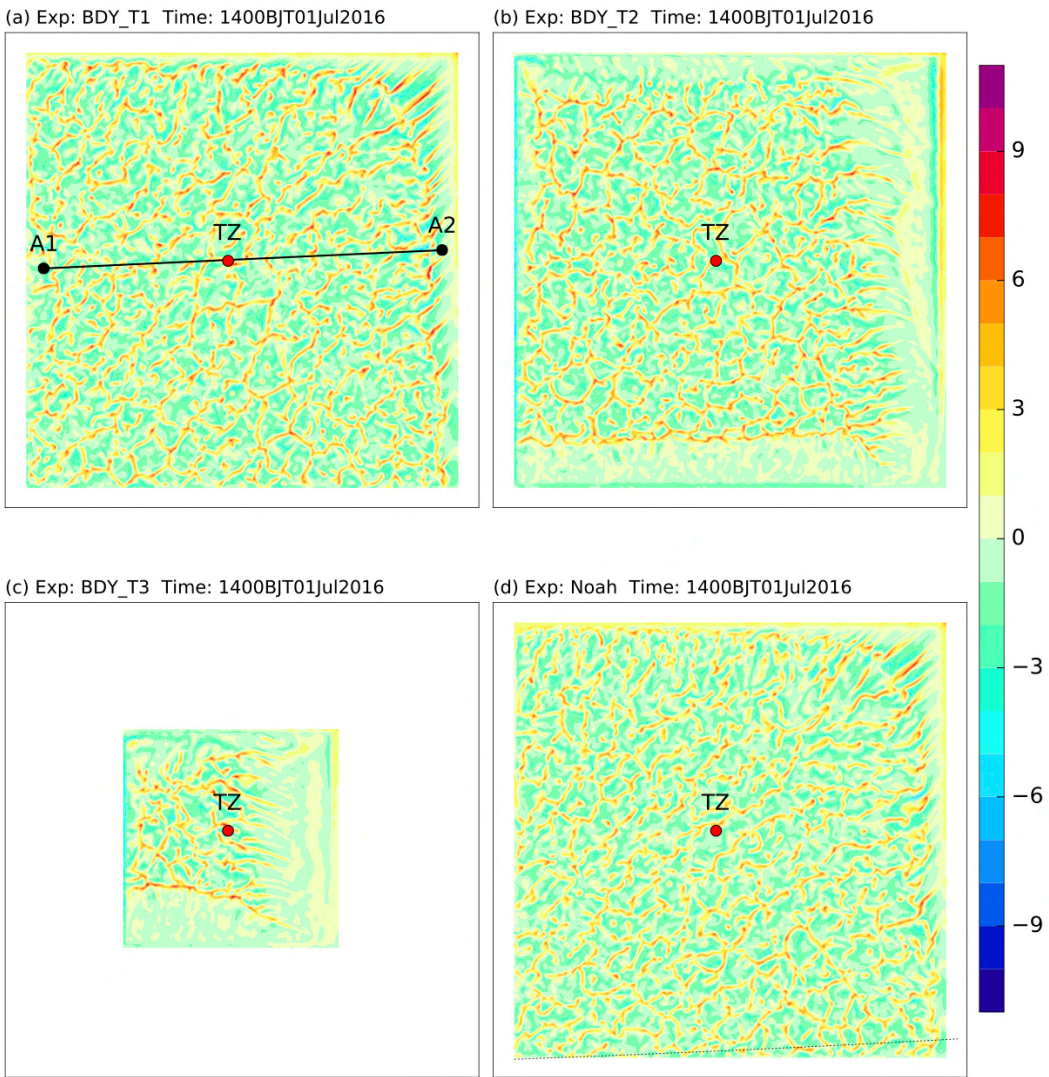01 Jul2016. The profile of model output are averaged in a radius of 3.5km.

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Figure 6 cross sections along 39.03°N of horizontal winds (barbs, units: m/s), at intervals of 5

m/s, superposed with theta (shaded, units: K) and vapor mixing ratio(contour, units: g/Kg),

from (a) BDY_T1, (c) BDY_T2, (e) BDY_T3 experiments at1400 BJT 01JUL2016, (b), (d),

(f) are the same as (a), (c), (e), but for 2000 BJT 01JUL2016.

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(a) Exp: BDY_T1 Time: 1400BJT01Jul2016

(b) Exp: BDY_T2 Time: 1400BJT01Jul2016

(c) Exp: BDY_T3 Time: 1400BJT01Jul2016

(d) Exp: Noah Time: 1400BJT01Jul2016

545

546　Figure 7 Instantaneous vertical velocity fields (shading: m/s) at 3000 m for (a) BDY_T1 (CTRL), (b)

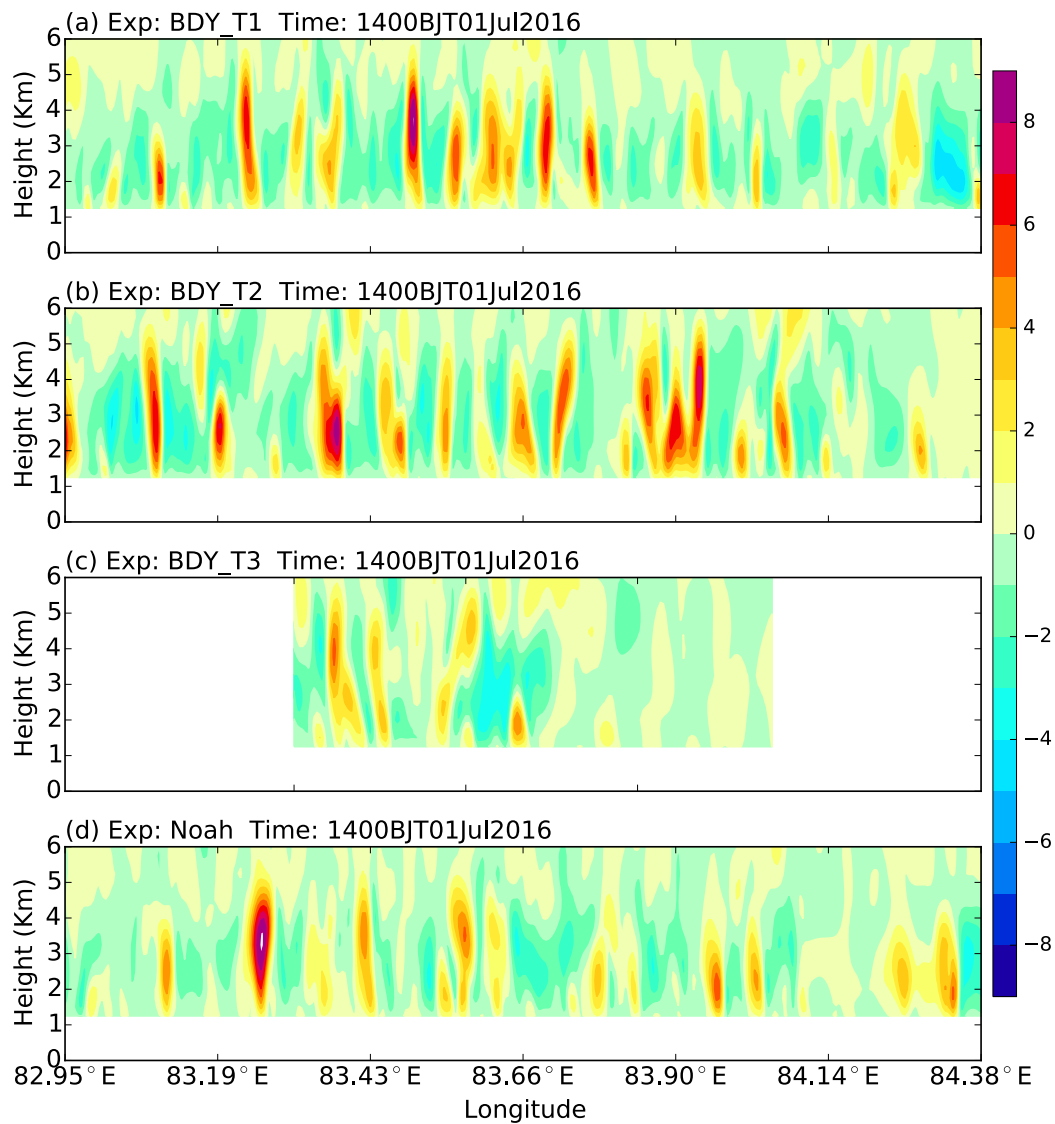547　BDY_T2, (c) BDY_T3, and (d) Noah at 1400 BJT, 1 July 2016.

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(a) Exp: BDY_T1 Time: 1400BJT01Jul2016

(b) Exp: BDY_T2 Time: 1400BJT01Jul2016

(c) Exp: BDY_T3 Time: 1400BJT01Jul2016
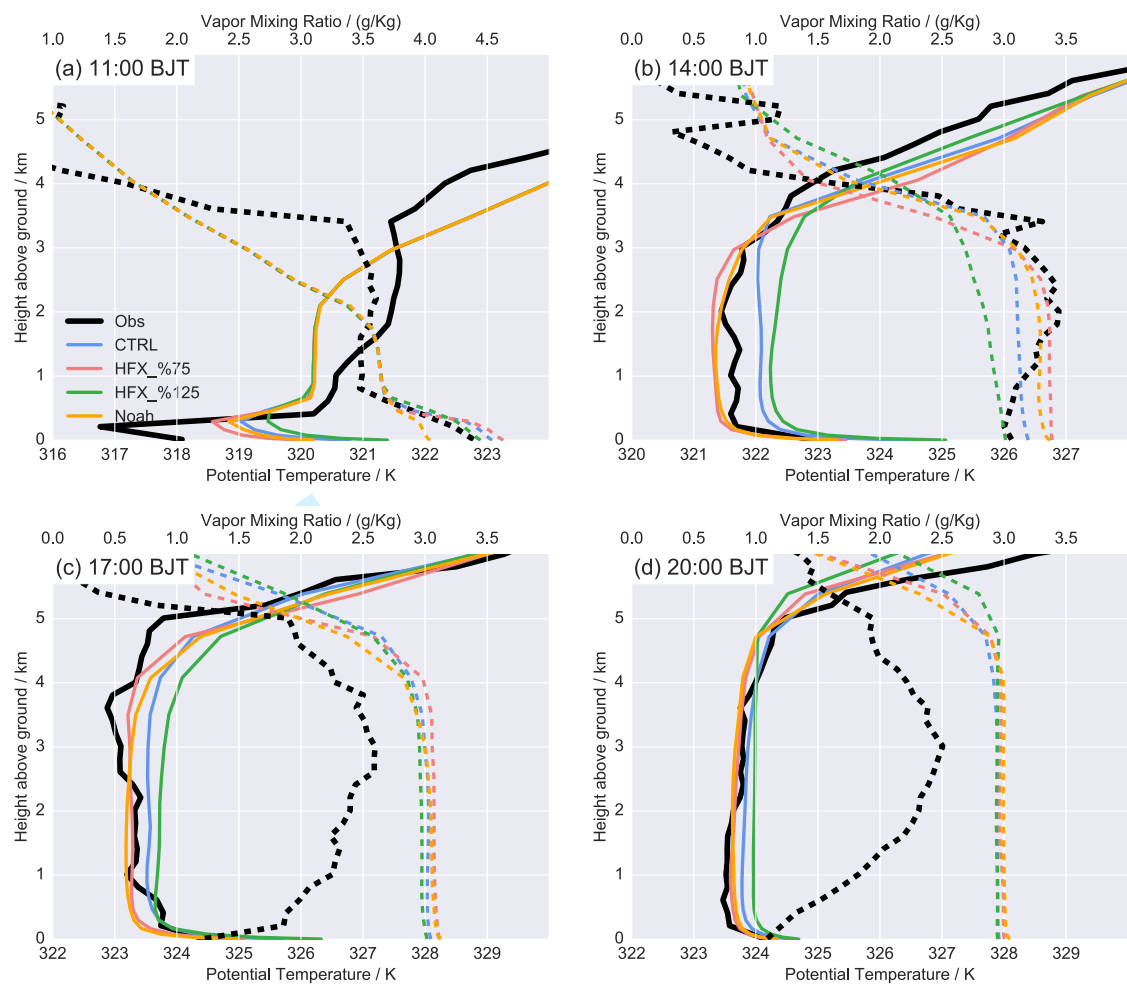
(d) Exp: Noah Time: 1400BJT01Jul2016

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Figure 8 Vertical cross-section of instantaneous vertical velocity fields (shading: m/s) along
A1-A2 in for for (a) BDY_T1 (CTRL), (b) BDY_T2, (c) BDY_T3, and (d) Noah at 1400 BJT, 1 July
2016.

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557 Figure 9 The same as Figure 5, but for SH flux sensitive and Noah land-surface experiment
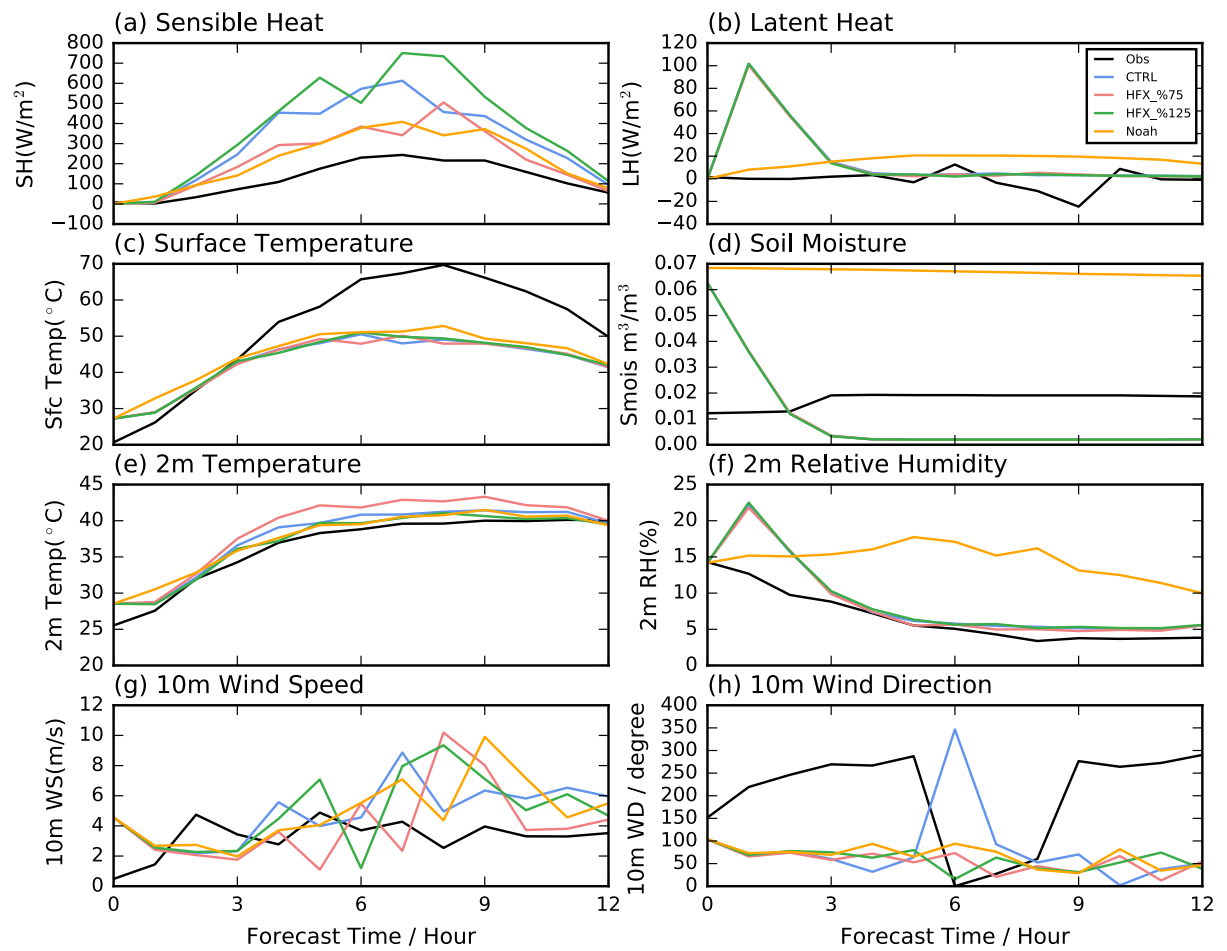
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560　Figure 10 The same as Figure 4, but for SH flux sensitive and Noah land-surface experiment.

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Experiment	Name	Remarks
1	BDY_T1(CTRL)	LBC of D04 is provide by d03 every 1 hour with model grids 403x406
2	BDY_T2	As BDY_T1, but LBC of D04 is provide by d03 every 6 hour
3	BDY_T3	As BDY_T2, but with model grids 205 x 208.
4	HFX_%75	As CTRL_T2, but with SH 75%.
5	HFX_%125	As CTRL_T2, but with SH 125% .
6	Noah	As CTRL_T2, but with Noah surface-land model.

563   Table 1. List of designed experiments.

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565

Variables	Sensible Heat		Latent Heat		Surface Temperature		Soil Moisture		2m Temperature		2m Relative Humidity		10m Wind Speed	
	RMSE	BIAS	RMSE	BIAS	RMSE	BIAS	RMSE	BIAS	RMSE	BIAS	RMSE	BIAS	RMSE	BIAS
Experiments														
CTRL	263.636	250.140	12.398	6.674	14.654	-13.373	0.017	-0.017	1.666	1.613	1.220	1.109	2.579	1.864
BDY_T2	249.395	240.660	12.383	6.253	14.116	-12.853	0.017	-0.017	1.912	1.817	1.275	1.162	2.943	1.307
BDY_T3	241.681	232.705	12.251	6.328	14.929	-13.737	0.017	-0.017	1.227	1.046	1.483	1.280	2.118	1.287
HFX_%75	151.119	134.594	12.544	6.354	14.740	-13.426	0.017	-0.017	3.078	3.016	0.956	0.826	3.335	0.874
HFX_%125	357.711	335.556	12.439	6.152	14.244	-13.043	0.017	-0.017	1.026	0.860	1.303	1.231	3.265	2.052
Noah	125.695	120.313	23.350	20.664	12.757	-11.502	0.048	0.048	1.046	0.983	10.116	9.904	2.788	1.795

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567   Table 2. Summary of surface and air variables verification including integration hours from 3 to 12 h for Tazhong station.

568

569 **Reference:**

570 Chen, F., and J. Dudhia, 2001a: Coupling an Advanced Land Surface–Hydrology Model with the
571 Penn State–NCAR MM5 Modeling System. Part II: Preliminary Model Validation. *Monthly Weather*
572 *Review*, **129,** 587-604.

573 ——, 2001b: Coupling an advanced land surface-hydrology model with the Penn State-NCAR
574 MM5 modeling system. Part I: Model implementation and sensitivity. *Monthly Weather Review*,
575 **129,** 569-585.

576 Dudhia, J., 1989: Numerical study of convection observed during the winter monsoon experiment
577 using a mesoscale two-dimensional model. *J. Atmos. Sci.*, **46,** 3077-3107.

578 Engelstaedter, S., R. Washington, C. Flamant, D. J. Parker, C. J. T. Allen, and M. C. Todd, 2015: The
579 Saharan heat low and moisture transport pathways in the central Sahara—Multiaircraft
580 observations and Africa-LAM evaluation. *Journal of Geophysical Research: Atmospheres*, **120,**
581 2015JD023123.

582 Garcia-Carreras, L., and Coauthors, 2015: The Turbulent Structure and Diurnal Growth of the
583 Saharan Atmospheric Boundary Layer. *Journal of the Atmospheric Sciences*, **72,** 693-713.

584 Han, B., S. Lü, and Y. Ao, 2012: Development of the convective boundary layer capping with a thick
585 neutral layer in Badanjilin: Observations and simulations. *Adv. Atmos. Sci.*, **29,** 177-192.

586 Heinold, B., P. Knippertz, and J. H. Marsham, 2013: Large Eddy Simulations of Nocturnal
587 Low-Level Jets over Desert Regions and Implications for Dust Emission. *EGU General Assembly*
588 *Conference*.

589 Heinold, B., P. Knippertz, and R. J. Beare, 2015: Idealized large-eddy simulations of nocturnal
590 low-level jets over subtropical desert regions and implications for dust-generating winds.
591 *Quarterly Journal of the Royal Meteorological Society*, **141,** 1740–1752.

592 Heinze, R., D. Mironov, and S. Raasch, 2015: Second-moment budgets in cloud topped boundary
593 layers: A large-eddy simulation study. *Journal of Advances in Modeling Earth Systems*, **7,** 510-536.

594 Hong, S.-Y., and H.-L. Pan, 1996: Nonlocal boundary layer vertical diffusion in a medium-range
595 forecast model. *Monthly weather review*, **124,** 2322-2339.

596 Hong, S.-Y., and J.-O. J. Lim, 2006: The WRF single-moment 6-class microphysics scheme (WSM6). *J.*
597 *Korean Meteor. Soc*, **42,** 129-151.

598 Hu, X.-M., J. W. Nielsen-Gammon, and F. Zhang, 2010: Evaluation of Three Planetary Boundary
599 Layer Schemes in the WRF Model. *Journal of Applied Meteorology and Climatology*, **49,**
600 1831-1844.

601 Kain, J. S., 1993: Convective parameterization for mesoscale models: The Kain-Fritsch scheme.
602 *The representation of cumulus convection in numerical models, Meteor. Monogr*, **46,** 165-170.

603 Kain, J. S., 2004: The Kain–Fritsch Convective Parameterization: An Update. *JOURNAL OF APPLIED*
604 *METEOROLOGY*, **43,** 170-181.

605 LeMone, M. A., M. Tewari, F. Chen, and J. Dudhia, 2013: Objectively Determined Fair-Weather CBL
606 Depths in the ARW-WRF Model and Their Comparison to CASES-97 Observations. *Monthly*
607 *Weather Review*, **141,** 30-54.

608 Liu, Y., Q. He, H. Zhang, and A. Mamtimin, 2012: Improving the CoLM in Taklimakan Desert
609 hinterland with accurate key parameters and an appropriate parameterization scheme. *Adv.*
610 *Atmos. Sci.*, **29,** 381-390.

611 Liu, Y., and Coauthors, 2011: Simultaneous nested modeling from the synoptic scale to the LES
612 scale for wind energy applications. *Journal of Wind Engineering and Industrial Aerodynamics*, **99,**

613   308-319.

614   Marsham, J. H., P. Knippertz, N. Dixon, D. J. Parker, and G. M. S. Lister, 2011: The importance of the

615   representation of deep convection for modeled dust - generating winds over West Africa during

616   summer. *Geophysical Research Letters*, **38**.

617   Mlawer, E. J., S. J. Taubman, P. D. Brown, M. J. Iacono, and S. A. Clough, 1997: Radiative transfer for

618   inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *J. Geophys.*

619   *Res.*, **102,** 16663-16682.

620   Moeng, C.-H., J. Dudhia, J. Klemp, and P. Sullivan, 2007: Examining Two-Way Grid Nesting for Large

621   Eddy Simulation of the PBL Using the WRF Model. *Monthly Weather Review*, **135,** 2295-2311.

622   National Centers for Environmental Prediction, N. W. S. N. U. S. D. o. C., 2015: NCEP GDAS/FNL

623   0.25 Degree Global Tropospheric Analyses and Forecast Grids. Research Data Archive at the

624   National Center for Atmospheric Research, Computational and Information Systems Laboratory.

625   Rai, R. K., L. K. Berg, B. Kosović, J. D. Mirocha, M. S. Pekour, and W. J. Shaw, 2017: Comparison of

626   Measured and Numerically Simulated Turbulence Statistics in a Convective Boundary Layer Over

627   Complex Terrain. *Boundary-Layer Meteorology*, **163,** 69-89.

628   Schicker, I., D. Arnold Arias, and P. Seibert, 2016: Influences of updated land-use datasets on WRF

629   simulations for two Austrian regions. *Meteorology and Atmospheric Physics*, **128,** 279-301.

630   Shin, H. H., and S. Y. Hong, 2011: Intercomparison of Planetary Boundary-Layer Parametrizations

631   in the WRF Model for a Single Day from CASES-99. *Boundary-Layer Meteorology*, **139,** 261-281.

632   Shin, H. H., and S.-Y. Hong, 2015: Representation of the Subgrid-Scale Turbulent Transport in

633   Convective Boundary Layers at Gray-Zone Resolutions. *Monthly Weather Review*, **143,** 250-271.

634   Skamarock, W. C., and Coauthors, 2008: A Description of the Advanced Research WRF Version 3. .

635   *NCAR/TN–475+STR, NCAR TECHNICAL NOTE*.

636   Smirnova Tatiana, G., M. Brown John, G. Benjamin Stanley, and D. Kim, 2000: Parameterization of

637   cold - season processes in the MAPS land - surface scheme. *Journal of Geophysical Research:*

638   *Atmospheres*, **105,** 4077-4086.

639   Smirnova, T. G., J. M. Brown, and S. G. Benjamin, 1997: Performance of Different Soil Model

640   Configurations in Simulating Ground Surface Temperature and Surface Fluxes. *Monthly Weather*

641   *Review*, **125,** 1870-1884.

642   Stull, R. B., 1988: An Introduction to Boundary Layer Meteorology. *Atmospheric Sciences Library*, **8,**

643   89.

644   Sun, J., and Q. Xu, 2009: Parameterization of Sheared Convective Entrainment in the First-Order

645   Jump Model: Evaluation Through Large-Eddy Simulation. *Boundary-Layer Meteorology*, **132,**

646   279-288.

647   Talbot, C., E. Bou-Zeid, and J. Smith, 2012: Nested Mesoscale Large-Eddy Simulations with WRF:

648   Performance in Real Test Cases. *Journal of Hydrometeorology*, **13,** 1421-1441.

649   ter Maat, H. W., E. J. Moors, R. W. A. Hutjes, A. A. M. Holtslag, and A. J. Dolman, 2012: Exploring the

650   Impact of Land Cover and Topography on Rainfall Maxima in the Netherlands. *Journal of*

651   *Hydrometeorology*, **14,** 524-542.

652   WANG, and Coauthors, 2016a: Summer atmospheric boundary layer structure in the hinterland of

653   Taklimakan Desert, China. *Journal of Arid Land*, **8,** 846-860.

654   Wang, M., X. Xu, and H. Xu: The possible influence of the summertime deep atmospheric boundary

655   layer process over the Taklimakan Desert on the regional weather. *(submitted to Quarterly Journal*

656   *of the Royal Meteorological Society)*.

657   Wang, M. Z., H. Lu, H. Ming, and J. Zhang, 2016b: Vertical structure of summer clear-sky
658   atmospheric boundary layer over the hinterland and southern margin of Taklamakan Desert: The
659   deep convective boundary layer of Taklamakan Desert. *Meteorological Applications*, **23,** 438-447.
660   Zhang, F., Z. Pu, and C. Wang, 2017: Effects of Boundary Layer Vertical Mixing on the Evolution of
661   Hurricanes over Land. *Monthly Weather Review*, **145,** 2343-2361.

662

Dear editors and reviewers,

We deeply appreciate the time and effort you've spent in reviewing our manuscript. Your comments are really thoughtful and helpful. Thus, we revised the manuscript, following your comments exactly. We have studied comments carefully and have made correction, which we hope meet with approval. Revised portion are marked in red in the paper. The main corrections in the paper and the responds to the reviewer's comments are as flowing:

Reviewer: 1

The paper is well written and presents works for PBL simulations using WRF framework. The authors explore the sensitivities of the model output due to lateral forcing of varying model sizes, frequency of the forcing, and surface heat flux. I would like the authors do some revisions on their manuscript. First, I have general comments here to address by the authors,

1. I encourage the author to reorganize the Method section as 2.1 Model configuration 2.2 Data 2.3 Synoptic

Thank you for the comments, we have reorganized the method section.

2. In Model configuration, please mention how long spin-up time was used. Did authors start all domains at same time? The authors also mention 51 vertical levels but you did not give what resolutions they are, particularly within the boundary layer. Please mention this.

Yes, we start all domains at same time. Height for lowest 20 levels are 1130.473, 1157.705, 1207.765, 1294.703, 1423.873, 1591.895, 1795.526, 2021.868, 2272.33, 2558.433, 2882.675, 3248.113, 3658.499, 4118.481, 4633.882, 5212.111, 5855.802, 6517.111, 7151.295, 7757.151.

3. The authors have presented several figures (vertical profiles and time series) but they have not mentioned how the plots are generated. Give details what the plots are representing – instantaneous or time/space averaged.

Thank you for the comments, we have added more details about profiles and series as follow:

Figure 4 Vertical profiles of potential temperature (solid line, units: K) and vapor mixing ratio(dash line, units: g/Kg)**from innermost domain of simulations and observation of GPS sounding at Tazhong station (83.63° E, 39.03° N)** at (a)1100 (b) 1400 (c) 1700 (d) 2000 BJT 01 Jul2016.

Figure 5 Time series of simulated surface **variables from innermost domain of simulations and surface observations at Tazhong station (83.63° E, 39.03° N)** initial at 0800 BJT 01July 2016 (a) sensible heat flux (W/m2), (b) latent heat flux(W/m2), (c) 2-m temperature (∘C), (d) surface temperature (∘C), (e) 2-m Relative Humidity(%) and (f) 10-m wind speed (m/s) with corresponding observations.

4. I guess the results from the innermost domain d04 are obtained without using perturbation near the inflow boundaries. It is not unexpected to see the difference in model output due to the varying grid size when the grid size reduces by more than half area. Similarly, more frequent forcing (1 hr) also provide more turbulence into the nested domain compared to 6 hr, as the model linearly interpolates tendencies between 6 hours. In this regard, it is always good to check how long fetch it took to develop the turbulence. Is the turbulence developed at the location where the model output is tapped? Have you checked results for other locations, may be far from the inflow boundaries where turbulence is well developed?

We have added instantaneous vertical velocity fields for the horizontal (Figure 7) and vertical cross-sections along Tazhong station (39∘N) of vertical velocity(Figure 8).

The instantaneous vertical velocity fields for the horizontal are displayed in Figure 7. By 1400 BJT, the convection of CTRL simulation obviously intensified under strong surface heating (Xu et al. 2018). Thus, the maximum vertical velocity reaches 9 m/s and the depth of mixed layer grows to about 4.3 km (Figure 7 a). The distances between the boundary layer rolls correspondingly increase to about 12 km and the height of the peak updraughts is raised to just under 4 km. The cellular

shape of updraughts and downdraughts characteristic of boundary layer rolls is obvious in the horizontal view with the strength of convection. BDY_T2 and BDY_T3 experiments (Figure 7 b, c).   both reproduce motions with much weaker maximum and minimum values at boundary of domain. In BDY_T3 experiment, Tazhong station at center of the model has been directly influenced by the inflow cold advection produced by low frequency LBCS and results in much weaker maximum and minimum value of w (about 6 m/s). However, despite the underestimate of potential temperature, the w fields for BDY_T2 experiment look similar to the CTRL w in plain view, and the horizontal extent of the updrafts/downdrafts agrees with the CTRL as can be inferred from Figure 7. To further examine the impact of LBCS on the simulation of desert CBL vertical cross-sections along Tazhong station (39∘N) of vertical velocity are presented in Figure 8. Wide and regularly spaced updrafts along A1- A2 split into the stronger and more irregular motions in CTRL and BDY_T2. The updrafts are much weaker in the BDY_T3 experiment, as can be seen from Figure 8 c. Peak updrafts on BDY_T3 are about 4 m/s much weaker than on CTRL (9 m/s) and BDY_T2 (8 m/s). For BDY_T2 and BDY_T3, the distant of the inflow boundary is wider, and the intensity of the convection is weaker at the boundary.   Compared with BDY_T2, the horizontal distribution of vertical velocity at Tazhong station in BDY_T3 experiments is much weaker.

5. I encouraged to run an additional simulation with different land-surface model as the authors mentioned that the heat flux and moisture quantities are playing the PBL growth.

Thank you for the comments, we have run an additional simulation with Noah land-surface model.

6. The authors tested with varying sensible heats in the simulation. I could not see the results of that in the manuscript. Could you present them together in figures 4-6 so that it helps reader to compare with other results?

Thank you for the comments and sorry for the mistake, Figure 8 and Figure 9 are the results from simulations with varying sensible heats. We have redrawn potential temperature and vapor mixing ratio into one figure. The new figure

also contains the results from Noah land-surface model as mentioned in comment 5.

7. In Fig. 7, I could not follow why the sizes of vertical cross-section is different between the panels in the first and the rest

Thank you for the comments and sorry for the mistake, we have reordered the Fig. 7(Figure 6 in the present manuscript), and modified BDY_T1 to BDY_T3. The sizes of vertical cross-section are different between the panels in BDY_T3 and the rest, because Sizes of BDY_T3 (205 X 208) is much smaller than the others(403X406).

8. I found cumbersome to go back and forth for the figures as the order of figures are random. Please put the figure in order. Similarly, the authors presented figures 8 and 9 in the list of figures, but I could not come across with those figures in the manuscript. Am I missing somewhere?

Thank you for the comments. We have reordered the figures. Figure 8 and Figure 9 are the results from simulations with varying sensible heats. Furthermore, we have put potential temperature and vapor mixing ratio into Figure 7.

9. When reading introduction, it looks like this work (desert case) is the first of its kind. Please make sure this. In addition, the authors may also mention complex terrain real case by Rai et al. (2017), where they did evaluate the turbulence statistics for the convective PBL in terms of turbulence model, domain size etc.

Thank you for the comments. We have cited the study, and changed the introduction.

Specific comments

1. Line 68: provide reference for '... 4-6 km during ...'.

Ok

2. Line 67 and 69: use either ABL or PBL and define it for the first time

Thank you for the comments. We have changed all ABL to PBL.

3. Line 129: why the section starts with 1, but not for introduction?

Thank you for the comments. We have changed introduction to the first section.

4. Line 144: define BJT

Thank you for the comments. We have changed BJT to BJT (Beijing Time)

5. Line 149-150: move to section model configuration

Ok

6. Line 164: make clear what is two experiments?

Thank you for the comments. We have changed 'Figure 1 shows the domain for two experiments.' to 'Figure 1 shows the domain for all experiments except for BDY_T3. Smaller grid sizes (205 x 208) are used in experiment BDY_T3 to verify the effect of domain size on LES simulation.'

7. Line 173: use space in '... millibars(National ....'. Check this throughout the manuscript as I found they occurs everywhere.

Ok

8. Line 185-186: check sentence syntax for 'For one-way nest, ...'

Thank you for the comments. We have changed 'For one-way nest, Specified LBC obtained from coarser model simulation.' to 'For one-way nest, specified LBC is obtained from coarser model simulation.'.

9. Line 218: define SH

We have change 'SH' to 'SH (surface sensible heat flux)'.

10. Line 245: see the period

Ok.

11. Line 279: it to It?

Ok.

12. Line 341-342: check the sentence syntax

Ok.

13. Line 351: the to The?

Ok.

Reviewer: 2

General comments

Characteristics of the convective boundary layer (CBL) over desert(s) are not

well defined due to lacking of observational data and high resolution numerical simulations. It definitely represents one of the research interests for the atmospheric boundary layer meteorology, weather, and climate. In this manuscript, the authors attempted to present the performance of WRF/LES on simulating the CBL structures and their evolution over the Taklimakan Desert during the summer daytime. They presented how the simulated vertical profiles of potential temperature and specific humidity were sensitive to the ingest frequency of lateral boundary conditions, and how the on simulated vertical profiles changed with surface heat fluxes. It is not surprised that the WRF/LES simulations with hourly update of lateral boundary conditions ingest showed better agreement with the observations (see Figure 4.b). The findings obtained from these two group sensitivity studies are not new at all. As indicated by the manuscript title, the study is supposed to focus on the performance of WRF/Chem. No enough meaningful evaluation results are provided in the manuscript to support the objective indicated by the manuscript title. The manuscript structure isn't well designed. Scientific questions are not clearly defined and insightful analyses are lacking. Extensive grammar errors make the manuscript very difficult to read and understand. No significant results were obtained from this study. Therefore, the manuscript is suggested to reject given the current status.

Major comments

1.   Observation-simulation comparisons (e.g., time series and vertical profiles) and statistical evaluations of the model simulation (considered as a base case) should be presented before the sensitivity studies (sections 3.1 and 3.2).

Thank you for the comment. We have reordered the section 3.1 and section 3.2.

2.   How are the lateral boundary conditions of the innermost domain

updated during the simulations? Is it not updated every integration time step? It is not useful to present sensitivity studies on impact of updated frequency of lateral boundary layer conditions on the WRF/LES results.

Thank you for the comments. We conducted one-way nest WRF from mesoscale down to LES-scales. For one-way nest, Specified LBC is obtained from coarser model simulation. For innermost, all forecast times from d03 simulation are used to specify the LBC. Limited by storage of our supercomputer, all model results are in 1hour interval.

As in Talbot et al. (2012), LES model fields are primarily influenced by their mesoscale meteorological forcing. Thus, in this study, we want to further examine the impact of uncertainties of LBC on LES simulation. The results suggest that the model results are sensitive to changes in time resolution and domain size of Specified LBC. The mismatch among sensitive experiments is present means that the effect of LBC needs to be quantified to realize a more realistic performance in the sub-kilometer simulations.

3.   Why the vertical profiles of specific humidity (Figure 5) are very different from those of potential temperature (Figure 4) within the CBL. Is this the real case? What are the main reasons causing such type of vertical distribution?

Yes, it's the real case. We also find inverse humidity in July 2017. Inverse humidity may be caused by the joint of the heterogeneous humidity Pattern and Large-scale advection over the underlying surface. For instance, interaction of oasis with desert environment may resulted in the inverse humidity layer in desert PBL.

4.   Why is the maximum observed surface sensible heat flux less than 250 W·m-2? This is not consistent with the boundary layer height (up to 5000 m). Is it possible to observe such low sensible heat flux over the desert?

Thank you for the comments,

(1) it is should be noted that the SH and LH based on eddy correlation might be underestimated. Researchers found that if the other two terms in the budget—net radiation and flux into the soil were accurate, used data for the whole experiment to find the H + LE are equal to an average of 75% of what would be required for balancing the surface energy budget(LeMone et al. 2013). Under this scenario, the government would soon recoup its investment and the debt pile would shrink.

(2) RL (residual layer) may play a key role in the deep PBL at Taklimakan desert. At 1100 BJT, when the PBLH was about 300 m in observation as show above, potential temperature in the were about 317 in PBL and 320 K in RL, respectively. When the potential temperature in CBL increased to 320 K because of heating from under layer surface, the CBL merged with the RL, and the height of PBL reach 3000m in the observations at 1400 BJT. These results are in good agreement with Han et al. (2012). By analysis of observation of a CBL in the Badanjilin region, they found a rapid development process of CBL after 1200 LST, which appeared to be a jump of PBLH when the inversion layer vanished.

（3） Results of simulations on desert PBL in the morning agree with the previous studies of sensitivities land-surface model for other areas (Hu et al. 2010; Zhang et al. 2017). However, during 1700~2000 BJT 01July (Figure 9b, d), all experiments produce nearly the same CBLH and moisture in agreement with observation in the PBL. The effects of SH on the evolution of Taklimakan PBL structures during this period are needed to be further examined and discussed. So, the question is: why are simulations insensitive to land-surface process by the end of the day? As in Stull (1988), the development of CBL is mainly influenced by the effect of thermodynamic and turbulent entrainment without considering large scale factors such as large scale advection or subsidence. Besides the surface sensible heat, the intensity of entrainment process determines the increasing rate of CBL. Thus, the entrainment rate w_e is a valuable indicator for the development of PBL structure.

The rate of growth of the convective boundary layer is mainly determined by the entrainment rate w_e at the inversion layer without considering large scale

vertical motion. w_e usually has a positive correlation with heat flux amount at the inversion layer $\overline{(w'\theta_v')_h}$, and large LES experiments show $\overline{(w'\theta_v')_h}$ is about 0.2 times the surface flux of buoyancy $\overline{(w'\theta_0')}$. During the period from 1100 to 1400 BJT, larger SH is obviously correlated with stronger turbulent entrainment and warmer air from free atmosphere (FA) entraining into ML. As a result, CBL develop rapidly and is warm too fast in the early simulation phase due to the obviously increasing temperature and strong vertical mixing in model. Of interesting is that reduction in SH reproduces better desert PBL evolution in the early simulation phase, as SH-75% and Noah produce the smallest simulation errors in both temperature and moisture. However, one should note that CBLH and potential temperature for SH-75% and Noah have reached above 5000 m and 323.2 K respectively at 1700 BJT (Figure 9a). For the rest of the day, the increase rate of CBL height slows down due to the deep CBL(>5000m) which require more heat for the growth of PBL depth; Moreover, w_e decrease with increasing inversion intensity, which inhibits the mixing and entrainment processes. These two factors obviously limit the growth of CBL when CBLH is over 5000 m in this deep desert CBL case. Therefore, increasing SH from 75% to 125% significantly reduce the total time needed for CBL increase to a relative low altitude (< 5 km) at the middle and preliminary stage of the development of CBL rather than produce higher CBL at the late stage. When height of CBL over Taklimakan desert exceeds 5000 m, it might not change with proportion to SH fluxes (Figure 9d). As a result, PBL of WRF simulations are basically the same, and not sensitive to SH fluxes by the end of the day.

5.　It is required to calculate statistical parameters for the model evaluation.

Thank you for your comments, we have added 'Summary of surface and air variables verification including integration hours from 3 to 12 h for Tazhong station.' in Table 2.

6.　L206-207: How the more frequently LBCs may cause the cold advection?

Sorry for the mistake, we have changed 'The more frequently updated LBC is

desirable to cold zone near the LBC, which results in cold advection of the temperature and moisture to the area of interest' to 'The lower frequently updated LBC is desirable to cold zone near the LBC, which results in cold advection of the temperature and moisture to the area of interest'.

Lower frequently LBCs may cause the cold advection, because earlier model results from d03 simulation are used to specify the LBC, which. In this case, BDY_T2 and BDY_T3 experiment LBC with 6 interval results from D03 produced cold zone in the lateral boundaries, and resulted in the cold advection.

7.   The authors pointed out that the soil moisture was over-estimated by the model and initial soil moisture is higher than the observations (see L242-243, L248-250). If this is the case, the sensible could be under-predicted.   However,   the   simulation   results   show   the over-prediction of sensible heat flux by the model (see L218-220).

Thank you for the comments. Yes, the large overestimate of soil moisture makes LH (Figure4 b, f) from the model continue to increase. As a result, near-surface of model is far moister than that of observation at the first few hours of model integration. However, an interesting result to be note is that the model simulation has the abilities to correct some of the bias due to the initial condition of the surface; The results from CTRL experiment are closer to observation after 3 hours' spin-up. Thus, the large overestimate of soil moisture at initial stage(0~3hours) may have little impact on the large over-prediction of sensible heat flux during 3~9 hours' simulation.

8.   As pointed out by the authors that the surface heat flux is the main driving force to the boundary layer growth. The model captured the boundary layer height quite well (see the control case in Figure 4.d) even the surface heat flux is significantly over-predicted by the model (see Figure 6).

Results of simulations on desert PBL in the morning agree with the previous studies of sensitivities land-surface model for other areas (Hu et al. 2010; Zhang et al. 2017). However, during 1700~2000 BJT 01July (Figure 9b, d), all experiments produce nearly the same CBLH and moisture in agreement with observation in the

PBL. The effects of SH on the evolution of Taklimakan PBL structures during this period are needed to be further examined and discussed. So, the question is: why are simulations insensitive to land-surface process by the end of the day? As in Stull (1988), the development of CBL is mainly influenced by the effect of thermodynamic and turbulent entrainment without considering large scale factors such as large scale advection or subsidence. Besides the surface sensible heat, the intensity of entrainment process determines the increasing rate of CBL. Thus, the entrainment rate w_e is a valuable indicator for the development of PBL structure.

The rate of growth of the convective boundary layer is mainly determined by the entrainment rate w_e at the inversion layer without considering large scale vertical motion. w_e usually has a positive correlation with heat flux amount at the inversion layer $\overline{\left(w'\theta_v'\right)}_h$, and large LES experiments show $\overline{\left(w'\theta_v'\right)}_h$ is about 0.2 times the surface flux of buoyancy $\overline{\left(w'\theta_0'\right)}$. During the period from 1100 to 1400 BJT, larger *SH* is obviously correlated with stronger turbulent entrainment and warmer air from free atmosphere (FA) entraining into ML. As a result, CBL develop rapidly and is warm too fast in the early simulation phase due to the obviously increasing temperature and strong vertical mixing in model. Of interesting is that reduction in SH reproduces better desert PBL evolution in the early simulation phase, as SH-75% and Noah produce the smallest simulation errors in both temperature and moisture. However, one should note that CBLH and potential temperature for SH-75% and Noah have reached above 5000 m and 323.2 K respectively at 1700 BJT (Figure 9a). For the rest of the day, the increase rate of CBL height slows down due to the deep CBL(>5000m) which require more heat for the growth of PBL depth; Moreover, w_e decrease with increasing inversion intensity, which inhibits the mixing and entrainment processes. These two factors obviously limit the growth of CBL when CBLH is over 5000 m in this deep desert CBL case. Therefore, increasing SH from 75% to 125% significantly reduce the total time needed for CBL increase to a relative low altitude (< 5 km) at the middle and preliminary stage of the development of CBL rather than produce higher CBL at the late stage. When height of CBL over

Taklimakan desert exceeds 5000 m, it might not change with proportion to SH fluxes (Figure 9d). As a result, PBL of WRF simulations are basically the same, and not sensitive to SH fluxes by the end of the day.

9.   Entrainment process could play an important role in the CBL development over the Desert. However, it hasn't discussed by the authors.

As in comment 8.

10.   There are too many grammar errors throughout the manuscript. It is difficult to list all the errors here.

We have carefully revised the manuscript according to the reviewers' comments, and also have rescrutinized to improve the English by a native English speaker.

Reviewer: 3

Major comments

1 Observation

The observation site is located in the center of desert. As the author says, the PBL there can reach 5000 m. Is this conclusion just based on the observation results given in fig.4 and 5? Or this results has been mentioned in other study from more atmospheric profiles? In my opinion, profiles only in one day cannot represent the common structures of low atmosphere as well as PBL. To state that the PBL in this desert can reach 5000 m frequently instead of occasionally, more profiles need to be given. Maybe the author can found some other similar research to support their conclusion.

The conclusion of desert PBL can reach 5000 m is based on the study of Wang et.al. They statics the PBL height of Tazhong and four surrounding stations (Minfeng, Korla, Ruoqiang and Kashgar, Figure b1) during July 2016. The number of days when

the ABL exceeds 4,000 m depth is 8, 9, 5, 4 and 2 respectively, and that of higher than 3,000 m is 20, 22, 13, 15, and 5 respectively.
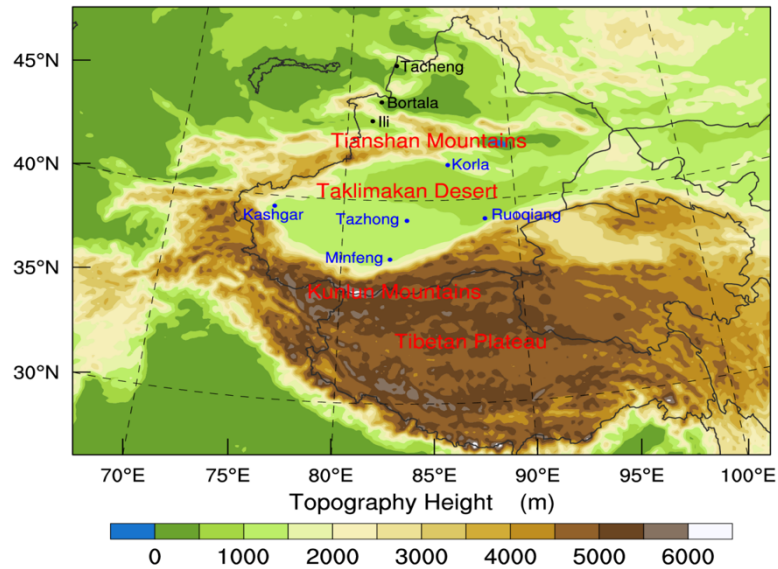
Figure b1. Location of the sounding stations.

Table 3. The number of days with deep boundary layers in the hinterland and the surrounding areas of the Taklimakan Desert in July 2016.

Height of the boundary layer	Tazhong	Minfeng	Korla	Ruoqiang	Karshgar
≥5000 m	1	1	1	1	0
≥4000 m	8	9	5	4	2
≥3500 m	15	17	6	9	4
≥3000 m	20	22	13	15	5
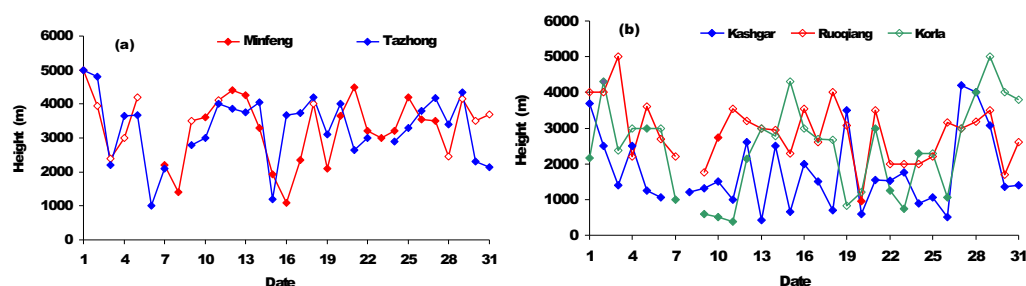
Figure b2. Curves of the daily height variations of the boundary layers in the hinterland and the surrounding areas of the Taklimakan Desert at 19:15 in July 2016.

(The solid symbols representing the height of the convective boundary layer while the hollow symbols representing the height of the residual mixed layer)

2 WRF-LES

The author compare the results from WRF-LES to that from radio sounder. It should be noted that the radiosounder also floated horizontally during its raising. The distance of horizontal displacement, generally 1-30 km if the radiosounder can reach 20 km high, depend on the horizontal wind. The horizontal movement can be ignored if the grid size of numerical model is larger than 20 km, but as for this study, the grid size is 330m, the effect of horizontal movement should be state in this study.

Yes, when radio-sounder reach 6km height, it floating about 7Km away. Thus, for more accuracy, we have averaged the profile of model output center at Tazhong station in 3.5km radius.

The author should also state why choosing WRF-LES, instead of LES or one-dimension PBL model, in study.

Thank you for the comment.

(1)   As in Xu et al. (2018), we have examined impact of PBL schemes on simulating deep PBL over Taklimakan dessert. Results show that there are still uncertainties, despite of using the state-of-the-art scale dependencies PBL scheme with reference data from LES.

(2)   The aim of this paper is to examine assess the skillfulness of WRF-LES in relative coarse resolution (333m) over Taklimakan dessert, in simulating real cases of desert PBL process during boreal summer events in Taklimakan.

WRF-LES can give the 3-D structure of lower atmosphere, but I note only fig.7 shows such results, and the corresponding statement in the manuscript seems contributed little to the main conclusion. I suggested that the authors add some discussion on the horizontal distribution of PBL or lapse rate of lower atmosphere over the desert region, and given a detailed description on the effect of advection in the night before the day of radio sound launched. By doing this, the difference in initial profile between observation and simulation may be better understand.

Thank you for the comment. We have added instantaneous vertical velocity fields for the horizontal (Figure 7) and vertical cross-sections along Tazhong station (39◦ N) of vertical velocity (Figure 8).

The instantaneous vertical velocity fields for the horizontal are displayed in Figure 7. By 1400 BJT, the convection of WRF-LES simulation obviously intensified under strong surface heating (Xu et al. 2018). Thus, the maximum vertical velocity reaches 9 m/s and the depth of mixed layer grows to about 4.3 km (Figure 7 a). The distances between the boundary layer rolls correspondingly increase to about 12 km and the height of the peak updraughts is raised to just under 4 km. The cellular shape of updraughts and downdraughts characteristic of boundary layer rolls is obvious in the horizontal view with the strength of convection. BDY_T2 and BDY_T3 experiments (Figure 7 b, c). both reproduce motions with much weaker maximum and minimum values at boundary of domain. In BDY_T3 experiment, Tazhong station at center of the model has been directly influenced by the inflow cold advection produced by low frequency LBCS and results in much weaker maximum and minimum value of (about 6 m/s). However, despite the underestimate of potential temperature, the fields for BDY_T2 experiment look similar to the CTRL in plain view, and the horizontal extent of the updrafts/downdrafts agrees with the CTRL as can be inferred from Figure 7. To further examine the impact of LBCS on the simulation of desert CBL vertical cross-sections along Tazhong station (39◦ N) of vertical velocity are presented in Figure 8. Wide and regularly spaced updrafts along A1-A2 split into the stronger and more irregular motions in CTRL and BDY_T2. The updrafts are much weaker in the BDY_T3 experiment, as can be seen from Figure 8 c. Peak updrafts on BDY_T3 are about 4 m/s much weaker than on CTRL (9 m/s) and BDY_T2 (8 m/s). For BDY_T2 and BDY_T3, the distant of the inflow boundary is wider, and the intensity of the convection is weaker at the boundary. Compared with BDY_T2, the horizontal distribution of vertical velocity at Tazhong station in BDY_T3 experiments is much weaker.

3 Land surface model

The difference in surface flux between simulation and observation seems to be too large, especially for the sensible heat flux (SH). The peak SH is about 250 Wm^2, but all simulations give the peak SH to be ~600 Wm^2. As the author mentioned, SH is a key factor to the development of convective boundary layer. If the land surface model give a similar SH as observed, is the 5000 m high PBL can still be given in all simulation cases? If not/so, why? Did the author verified all crucial parameterization schemes (like PBL, LSM eta.) before all simulations start? I also noted the simulated latent heat flux is also greater than the observed one, which infers the net radiation at land surface might be overestimated too. The author mentioned the USGS land use data might be problematic, but no detailed information has been given. For example, is the albedo between observation and simulation comparable? Only if the surface parameters and process are properly given, the PBL process, which is a combination of land surface process and free atmosphere dynamic processes, in numerical model can be more sound and meaningful.

If the land surface model give a similar SH as observed, is the 5000 m high PBL can still be given in all simulation cases? If not/so, why?

Results of simulations on desert PBL in the morning agree with the previous studies of sensitivities land-surface model for other areas (Hu et al. 2010; Zhang et al. 2017). However, during 1700~2000 BJT 01July (Figure 9b, d), all experiments produce nearly the same CBLH and moisture in agreement with observation in the PBL. The effects of SH on the evolution of Taklimakan PBL structures during this period are needed to be further examined and discussed. So, the question is: why are simulations insensitive to land-surface process by the end of the day? As in Stull (1988), the development of CBL is mainly influenced by the effect of thermodynamic and turbulent entrainment without considering large scale factors such as large scale advection or subsidence. Besides the surface sensible heat, the intensity of entrainment process determines the increasing rate of CBL. Thus, the entrainment rate w_e is a valuable indicator for the development of PBL structure.

The rate of growth of the convective boundary layer is mainly determined by the entrainment rate w_e at the inversion layer without considering large scale vertical motion. w_e usually has a positive correlation with heat flux amount at the inversion layer $\overline{(w'\theta_v')}_h$, and large LES experiments show $\overline{(w'\theta_v')}_h$ is about 0.2 times the

surface flux of buoyancy $\overline{(w'\theta_0')}$. During the period from 1100 to 1400 BJT, larger *SH* is obviously correlated with stronger turbulent entrainment and warmer air from free atmosphere (FA) entraining into ML. As a result, CBL develop rapidly and is warm too fast in the early simulation phase due to the obviously increasing temperature and strong vertical mixing in model. Of interesting is that reduction in SH reproduces better desert PBL evolution in the early simulation phase, as SH-75% and Noah produce the smallest simulation errors in both temperature and moisture. However, one should note that CBLH and potential temperature for SH-75% and Noah have reached above 5000 m and 323.2 K respectively at 1700 BJT (Figure 9a). For the rest of the day, the increase rate of CBL height slows down due to the deep CBL(>5000m) which require more heat for the growth of PBL depth; Moreover, w_e decrease with increasing inversion intensity, which inhibits the mixing and entrainment processes. These two factors obviously limit the growth of CBL when CBLH is over 5000 m in this deep desert CBL case. Therefore, increasing SH from 75% to 125% significantly reduce the total time needed for CBL increase to a relative low altitude (< 5 km) at the middle and preliminary stage of the development of CBL rather than produce higher CBL at the late stage. When height of CBL over Taklimakan desert exceeds 5000 m, it might not change with proportion to SH fluxes (Figure 9d). As a result, PBL of WRF simulations are basically the same, and not sensitive to SH fluxes by the end of the day.

Did the author verified all crucial parameterization schemes (like PBL, LSM eta.) before all simulations start?I also noted the simulated latent heat flux is also greater than the observed one, which infers the net radiation at land surface might be overestimated too. The author mentioned the USGS land use data might be problematic, but no detailed information has been given. For example, is the albedo between observation and simulation comparable? Only if the surface parameters and process are properly given, the PBL process, which is a combination of land surface process and free atmosphere dynamic processes, in numerical model can be more sound and meaningful.

(1)   Yes, we have verified PBL parameterization schemes. As in Xu et al. (2018), we have verified impact of different PBL schemes on the same case as this study.

(2)   We also added an experiment with Noah LSM to be compare to the RUC LSM used in CTRL experiment.

(3)   To verify the influence of landuse on overestimate of SH, the albedo of observation is calculated from upward show wave radiation and downward. Results show that albedo from observation (0.239) is in agreement with that of CTRL (0.21) experiment. This indicates that difference of landuse between model and observation are not the key reason for overestimate of SH.

(4)   However, One possible reason for inverse humidity may be caused by the error in landuse. Inverse humidity may be caused by the joint of the heterogeneous humidity Pattern and Large-scale advection over the underlying surface. For instance, interaction of oasis with desert environment may resulted in the inverse humidity layer in desert PBL.

4 Conclusions

One of the main conclusion is that the surface sensible flux is essential to the simulation of PBL, which is a common realization of PBL development because the buoyancy flux is main forcing of convective boundary layer rather than wind shear. However, from the sensitive experiment, when SH changed significantly, the shape of atmospheric profile did not show similar magnitude of change, and I guess the height of PBL did not increase/decrease for 25% (the author mentioned the change of PBL height should be 15% in Abstract, but I cannot found similar statement in section 3.3). How the height of PBL were defined should also be given in the manuscript. I noted that the residual layer at 1100 BJT is neutral and deep, is it the main reason for the deep PBL instead of SH? The author can refer to the work of Han in AAS in 2012.

Yes, RL(residual layer) may play a key role in the deep PBL.

(1) One should note that RL (residual layer) play a key role in the deep PBL at Taklimakan desert. At 1100 BJT, when the PBLH was about 300 m in observation as show above, potential temperature in the were about 317 in PBL and 320 K in RL, respectively. When the potential temperature in CBL increased to 320 K because of

heating from under layer surface, the CBL merged with the RL, and the height of PBL reach 3000m in the observations at 1400 BJT. These results are in good agreement with Han et al. (2012). By analysis of observation of a CBL in the Badanjilin region, they found a rapid development process of CBL after 1200 LST, which appeared to be a jump of PBLH when the inversion layer vanished.

　　(2) As in comment 4. The rate of growth of the convective boundary layer is mainly determined by the entrainment rate w_e at the inversion layer without considering large scale vertical motion. w_e usually has a positive correlation with heat flux amount at the inversion layer $\overline{\left(w'\theta_v'\right)}_h$, and large LES experiments show $\overline{\left(w'\theta_v'\right)}_h$ is about 0.2 times the surface flux of buoyancy $\overline{\left(w'\theta_0'\right)}$. During the period from 1100 to 1400 BJT, larger *SH* is obviously correlated with stronger turbulent entrainment and warmer air from free atmosphere (FA) entraining into ML. As a result, CBL develop rapidly and is warm too fast in the early simulation phase due to the obviously increasing temperature and strong vertical mixing in model. Of interesting is that reduction in SH reproduces better desert PBL evolution in the early simulation phase, as SH-75% and Noah produce the smallest simulation errors in both temperature and moisture. However, one should note that CBLH and potential temperature for SH-75% and Noah have reached above 5000 m and 323.2 K respectively at 1700 BJT (Figure 9a). For the rest of the day, the increase rate of CBL height slows down due to the deep CBL(>5000m) which require more heat for the growth of PBL depth; Moreover, w_e decrease with increasing inversion intensity, which inhibits the mixing and entrainment processes. These two factors obviously limit the growth of CBL when CBLH is over 5000 m in this deep desert CBL case. Therefore, increasing SH from 75% to 125% significantly reduce the total time needed for CBL increase to a relative low altitude (< 5 km) at the middle and preliminary stage of the development of CBL rather than produce higher CBL at the late stage. When height of CBL over Taklimakan desert exceeds 5000 m, it might not change with proportion to SH fluxes (Figure 9d). As a result, PBL of WRF

simulations are basically the same, and not sensitive to SH fluxes by the end of the day.

Minor comments
Some statements may confuse the readers, I listed them below.
1 P4L91" … mesoscale atmospheric models are still cannot…",-> unable to?

Ok, we have changed 'still cannot' to 'still unable to'.

2 P6L136 "The high-pressure system at low level, which is termed of heat low (Figure 3)," is this system high pressure or not?

We have changed "The high-pressure system at low level, which is termed of heat low (Figure 3)," to "The low-pressure system at low level, which is termed of heat low (Figure 3),"

Editor(s)' Comments to Author:

Editor: 1
Comments to the Author:
I have thought long-and-hard about this work since the reviews were so disparate (one reviewer suggested rejection). So I urge you to strongly consider carefully addressing the comments, particularly better examining the importance of land-surface processes and entrainment, as well as improving writing.
Ok
The 1st reviewer encouraged more sensitivity simulations and investigation, particularly in terms of importance of land-surface processes and inflow fetch.   Also the reviewer raised a lot of issue in terms of writing!   Please be very careful and make sure present your results nicely!
Ok
The 2nd reviewer is most critical. He suggested more examination of role of land surface fluxes and entrainment process on the development of CBL. Actually the 3rd reviewer suggested the same issue (e.g., importance of residual layer is nearly equivalent as the importance of entrainment in terms of CBL development). BTW, a lot of existing papers discussed the entrainment, which should be cited.
Also the 2nd reviewer pointed out the writing of the manuscript needs significant improvement, including organization, introduction, and grammar.
Ok
The 3rd reviewer suggested more discussion, particularly importance of land surface processes/fluxes on the development of PBL, as well as the role of pre-existing residual layer, and impact of horizontal drifting of the sounds.

Ok

Please put profiles of potential temperature and water vapor mixing ratio side by side since they can collectively indicate the boundary layer structure, that is, combine Figures 4 & 5;   Figures 8&9

Thank you for you comments, We have redraw Figures 4 & 5 and Figures 8&9 into Figure5 and Figure 7 respectively.

Reference

Hu, X.-M., J. W. Nielsen-Gammon, and F. Zhang, 2010: Evaluation of Three Planetary Boundary Layer Schemes in the WRF Model. *Journal of Applied Meteorology and Climatology*, **49,** 1831-1844.

LeMone, M. A., M. Tewari, F. Chen, and J. Dudhia, 2013: Objectively Determined Fair-Weather CBL Depths in the ARW-WRF Model and Their Comparison to CASES-97 Observations. *Monthly Weather Review*, **141,** 30-54.

Stull, R. B., 1988: An Introduction to Boundary Layer Meteorology. *Atmospheric Sciences Library*, **8,** 89.

Talbot, C., E. Bou-Zeid, and J. Smith, 2012: Nested Mesoscale Large-Eddy Simulations with WRF: Performance in Real Test Cases. *Journal of Hydrometeorology*, **13,** 1421-1441.

Wang, M., X. Xu, and H. Xu: The possible influence of the summertime deep atmospheric boundary layer process over the Taklimakan Desert on the regional weather. *(submitted to Quarterly Journal of the Royal Meteorological Society)*.

Xu, H., Y. Wang, and M. Wang, 2018: The Performance of a Scale-Aware Nonlocal PBL Scheme for the Subkilometer Simulation of a Deep CBL over the Taklimakan Desert. *Advances in Meteorology*, **2018,** 12.

Zhang, F., Z. Pu, and C. Wang, 2017: Effects of Boundary Layer Vertical Mixing on the Evolution of Hurricanes over Land. *Monthly Weather Review*, **145,** 2343-2361.

Performance of WRF Large-Eddy Simulations in summertime CBL

characteristics over the Taklimakan Desert: A Real Test Case

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40

41 **Abstract**

42   During the summer season over Taklimakan Desert, the maximum height of the CBL

43 (convective boundary layer) can exceed 5,000 m, which appeared to play critical roles in

44 simulating the regional circulation and weather. In this paper, we use a combination of WRF-LES

45 (Weather Research and Forecasting Model Large-Eddy Simulation)，the GPS radiosonde and

46 eddy-covariance station to evaluate the performance of WRF-LES in the deep convective PBL

47 case over the central Taklimakan. Results show that the model reproduces reasonably well the

48 evolution of PBL processes. However, simulations are relative warmer and moister than those

49 observed due to the over-predicted surface fluxes and largescale advection. Tests are further

50 performed with multiple configurations and sensitive experiments. Sensitivity tests to Lateral

51 Boundary Condition(LBC) showed that the model results are very sensitive to changes in time

52 resolution and domain size of Specified LBC. It is found that larger domain size varies the

53 distance of the area of interest from the LBC, is efficient to reduce the influences of large forecast

54 error near the LBC. However, more frequently updated LBC is desirable to inhibit model error

55 near the LBC. On the other hand, model error increased as the distance between the area of

56 interest and the lateral boundaries decreased. Furthermore, comparing model results using the

57 original surface land parameterized sensible heat flux(SH) with Noah land-surface scheme and

58 those of sensitive experiment, it is concluded that the desert CBL is very sensitivity to SH

59 produced by surface land scheme during summer day time. A reduction in SH can correct

60 overestimate of the potential temperature profile. However, increasing SH significantly reduce the

61 total time needed for CBL increase to a relative low altitude (< 3 km) at the middle and

62 preliminary stage of the development of CBL rather than produce higher CBL at the late stage

63   Keyword: WRF, Large Eddy Simulation, Convective Boundary Layer, Taklimakan

64

65

1   Introduction

66

67   The Taklimakan Desert, locates at the south center of the province of Xinjiang，China, is

68   the world's second-largest flow desert and has profound influences on the regional weather

69   and climate. Because of the extreme near-surface temperatures, the Taklimakan PBL

70   (planetary boundary layer) commonly reaches 4–6 km during boreal summer(Wang et al.),

71   making it probably the deepest on earth. The deep PBL, which is significantly higher than that

72   of the surrounding mountains and oases, appeared to play important roles on regional

73   circulation and weather. In the northwest of china, the ability to accurately forecast in

74   Taklimakan Desert especially the PBL processes is an important problem.

75   The large desert (such as Sahara, Taklimakan et al.) atmosphere is always a key

76   component of the climate system. The surface heating from intense solar radiation leads to the

77   development of a near-surface thermal low pressure system, commonly referred to as the heat

78   low(Engelstaedter et al. 2015). However, despite of the vital role of the desert playing in the

79   climate system, observations are extremely sparse, and thin data that exist are mostly from the

80   surrounding of the desert due to the poor work and natural(Marsham et al. 2011). This

81   fundamentally restrict the development of understanding desert and surrounding area, and

82   leads to large discrepancies to analyses and significant biases in operational numerical

83   weather prediction (NWP) models, given the scarcity of observation being assimilated by

84   operational systems. The ability of these local models to simulate real-world cases is often

85   hindered by a lack of favorable data needed to assess the performance of model

86   results(Garcia-Carreras et al. 2015). To fill in the gaps of Taklimakan desert，the field

87   observation experiment was held during the month of July 2016 in Tazhong, which is located

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88   at center of Taklimakan, by the Institute of Desert Meteorology (IDM), Chinese

89   Meteorological Administration (CMA), Urumqi(Liu et al. 2012; WANG et al. 2016a; Wang

90   et al. 2016b). This will also give the opportunity to evaluate the performance of the deep PBL

91   process in NWP models over Taklimakan.

92   On the other hand, atmospheric motions interweave small-scale, complex and multiscale

93   nonlinear interactions. Due to the limited resolution (time and space) mesoscale atmospheric

94   models are still unable to explicitly represent all these processes(Talbot et al. 2012). Such

95   processes include turbulent motions, which are too small-scale to be explicitly resolved in the

96   atmospheric model by a simplified process. Furthermore, turbulent mixing throughout the

97   PBL can heavily impacted NWP forecasting (Shin; Hong 2011; Shin; Hong 2015).

98   One way to tackle complex turbulent flows in weather forecast models is Large eddy

99   simulation (LES) which explicitly resolve energy-containing turbulent motions that are

100   responsible for most of the turbulent transport(Moeng et al. 2007). It has been used

101   intensively to examine detailed turbulence structure, to generate statistics, and to perform

102   physical-process studies(Garcia-Carreras et al. 2015; Heinold et al. 2013; Heinold et al. 2015;

103   Heinze et al. 2015; Sun; Xu 2009). However, most LES applications to the PBL have been

104   limited to idealized physical conditions. Recently, some studies attempt to test LES and assess

105   its performance in simulating real cases(Liu et al. 2011; Talbot et al. 2012). Liu et al. (2011)

106   suggests that WRF-LES is a valuable tool for simulating real world microscale weather flows

107   and for development of future real-time forecasting system, although further LES modeling

108   tests, such as elucidate whether inaccurate synoptic forcing or coarse resolution, are highly

109   recommended. Talbot et al. (2012) suggested that the ability of WRF-LES to simulate

110　real-world cases are hindered by a lack of favorable synoptic forcing. The initial(ICS) and

111　lateral boundary conditions(LBCS) was found to be more critical to the LES results than

112　subgrid-scale turbulence closures. Thus, the LBCS of can significantly alter high-resolution

113　LES status through inflow boundaries(Rai et al. 2017).

114　　However, most of research above on LES over desert has been limited to idealized

115　physical conditions(Garcia-Carreras et al. 2015) or conducted real case outside

116　Taklimakan(Liu et al. 2011; Talbot et al. 2012). The aim of this study is the attempt to

117　applicate LES in a real deep CBL case over Taklimakan. An important aspect of the ongoing

118　this paper is to examine assess the skillfulness of WRF-LES in relative coarse resolution

119　(333m) over Taklimakan dessert in simulating real cases of deep desert PBL process during

120　boreal summer events in Taklimakan. First we use a combination of WRF-LES and the GPS

121　radiosonde and surface fluxes calculated by an eddy-covariance method taken in the central

122　Taklimakan to evaluate the performance of WRF-LES in real case. Then we assess the

123　potential errors related to LBC. Moreover, we aim to evaluate the relative contribution of

124　uncertainties in surface model to the typical behavior of PBL processes by conducting the

125　sensitivity experiments. Thus, the sensitivity of the performance to surface sensible heat flux

126　(SH) is also studied. Section 2 gives a brief description of synoptic of the study case, and we

127　described data and model configuration and design of numerical experiments used in this

128　study. We presented the results of numerical simulations in Section 4. Finally, we summarize

129　conclusions in Section 5.

130　**2　Method**

131　　**2.1　Model configuration**

132   The WRF model of version 3.8.1 (Skamarock et al. 2008) is utilized here at

133   sub-kilometer resolutions to simulate the extreme CBL event in Taklimakan desert. The

134   model is integrated for 12h, starting from 0800 BJT (Beijing Time) 01 Jul 2016. We

135   conducted one-way nest WRF from mesoscale down to LES-scales. All domains were 51

136   levels extended to 50 hPa. Height for lowest 20 levels are 1130.473, 1157.705, 1207.765,

137   1294.703, 1423.873, 1591.895, 1795.526, 2021.868, 2272.33, 2558.433, 2882.675, 3248.113,

138   3658.499, 4118.481, 4633.882, 5212.111, 5855.802, 6517.111, 7151.295, 7757.151. The

139   model horizontal spacing is 12km 3km 1km and 0.33km for d01 d02 d03 and d04. The sizes

140   of model grids are 411 ×321 791x651 211x201 and 403x406 respectively. Figure 1 shows

141   the domain for all experiments except for BDY_T3. Smaller grid sizes (205 X 208) are used

142   in experiment BDY_T3 to verify the effect of domain size on LES simulation.

143   The initialized condition and lateral boundary conditions are provided to the coarsest

144   mesoscale simulations from NCEP Global Data Assimilation System (GDAS) Final

145   Operational Global Analyses. The analyses are 0.25-degree by 0.25-degree grids prepared

146   operationally every six hours and available on the surface, at 32 mandatory (and other

147   pressure) levels from 1000 millibars to 10 millibars (National Centers for Environmental

148   Prediction 2015).

149   The model physical options include the WSM5 microphysics scheme (Hong; Lim 2006),

150   the Yonsei University (YSU) planetary boundary layer scheme (Hong; Pan 1996), the Kain–

151   Fritsch cumulus parameterization scheme(Kain 1993; Kain 2004), RUC (Rapid Update Cycle)

152   land-surface model(Smirnova Tatiana et al. 2000; Smirnova et al. 1997), the Rapid Radiative

153   Transfer Model (Mlawer et al. 1997) longwave, and the Dudhia shortwave radiation scheme

154   (Dudhia 1989). The cumulus parameterization scheme is only applied to the d01(12km) grid

155   domain to parameterize the convective rainfall. While, the large-eddy-simulation (LES) is

156   only applied to d04(0.333km).

157   Table 1 shows the list of experiments. Experiment 1 was the control experiment, denoted

158   as CTRL. The experiment 2 (6-hour update LBC, denoted BDY_T2) and experiments 3(with

159   domain sizes 205 X 208, denoted BDY_T2) were conducted the same as CTRL with different

160   domain sizes and LBC update frequency. In experiment 4 (denoted HFX_%75) and 5

161   (denoted HFX_%125), the SH (sensible heat flux) was reduced to 75% and 125% of that in

162   the control experiment in the RUC land-surface scheme, to highlight the impact of SH on

163   deep CBL at Taklimakan desert, respectively. In experiment 6 (denoted Noah), Noah

164   land-surface model(Chen; Dudhia 2001a, 2001b) was used to replace the RUC land-surface

165   model in CTRL experiment to discriminate the influence of different land-surface model on

166   deep CBL.

167   **2.2   Data**

168   The model simulations are compared to the Tazhong field experiment, which was held

169   during the whole month of July 2016 in Tazhong, by the Institute of Desert Meteorology

170   (IDM), Chinese Meteorological Administration (CMA), Urumqi. The main station was

171   located at 86.63°E, 39.03°N. The location is relatively flat with few hills and covered by

172   sand combined with grass (Figure 1), and the deep PBL of our simulation was under a

173   cloudless sky and dry environment. Instruments are described as follows:

174   1) surface fluxes: The eddy correlation system was a R3-50 supersonic anemometer

175   developed by Gill Company, UK, deployed at a height of 10 m. The data acquisition

176 frequency was 20 Hz, and the surface sensible heat flux was calculated by the

177 eddy-covariance method.

178   2) vertical profiles measured using soundings: Upper air soundings of temperature,

179 pressure, humidity, and wind speed and direction were conducted 3-6 times per day with the

180 GPS sounding system developed by No. 23 Institute of China Aerospace Science & Industry

181 Corp. (CASIC23). The sounding times were 01:15, 07:15, 10:15, 13:15, 16:15 and 19:15

182 respectively.

183 **2.3   Synoptic**

184   Figure 2 shows the synoptic patterns at 0800 BJT 1 July 2016 at 850 700 500 and 100

185 hPa. There were cyclonic vortex from 850 to 500 hPa center at 55° N (Figure 2a ,b and c).

186 Taklimakan was located east of cyclonic vortex and embedded in east–west-elongated ridge

187 at 0800 BJT 1 July. To the southwest, influenced by the South Asia High, which was centered

188 over the eastern Iranian Plateau, the upper air over the Taklimakan Desert was controlled by

189 the westerly jet stream at 100hPa (Figure 2 d). The low-pressure system at low level, which

190 is termed of heat low (Figure 3), dominated most area of southern Xinjiang and resulted in

191 continuous high temperature over the desert. This situation favored the subsidence motion and

192 served as a triggering mechanism for deep PBL in the region in the coming 2–3 days (not

193 show).

194 **3   Results**

195 **3.1   Validation of the deep CBL structure**

196 Time series of surface variables at Tazhong station from CTRL simulation for 01 July

197 2016 are presented in Figure 4a, b. Results show that discrepancies of thermodynamic surface

9

198   variables (the surface temperature, sensible and latent fluxes) between model and observation

199   are large during simulation. The SH (surface sensible heat flux) is far less in observation

200   (maximum: 243 W m^{-2}) relative to model (maximum: 613 W m^{-2}). This represents SH from

201   WRF simulation is 2.5 times than that of observation when both of which reach its maximum.

202   On the other hand, model shows a significant cold bias for the surface temperature. The

203   surface temperature is much higher in observation (maximum: 70 °C) relative to model

204   (maximum: 50 °C). To further verification the surface variables, RMSE (root mean squared

205   error) and BIAS (mean bias) are calculated including integration hours from 3 to 12 h for

206   Tazhong station in Table 2. As mentioned earlier, model show yields significantly

207   overestimate of SH (RMSE 263.636 W/m^2, BIAS:250.14 W/m^2) and dramatically

208   underestimated of surface temperature (RMSE 14.65℃, BIAS:-13.37 ℃).

209   Two possible reasons result in model SH far above that of observation: (1) The

210   mismatches of land-use between the model and the observation. WRF use land-use categories

211   to assign certain static parameters and initial values to each grid cell, for example, albedo,

212   surface roughness, and so on(Schicker et al. 2016). However, As in Figure 1c, the EC station

213   is surround by mixing land of grass and sand. The complex underlying surface may not be

214   adequately reproduced by model and can have an impact on the overestimate of SH in this

215   case.   (2) It is should be noted that the SH and LH (latent heat flux) based on eddy

216   correlation might be underestimated(LeMone et al. 2013). Researchers found that if the other

217   two terms in the budget—net radiation and flux into the soil were accurate, used data for the

218   whole experiment to find the H + LE for Tazhong station are equal to an average of 75% of

219   what would be required for balancing the surface energy budget.

220   Despite the large differences on surface, near-surface variables (2m temperature, relative

221   humidity and 10m wind speed, Figure 4 e f g) are closer to measurements than those from

222   surface, their values are relatively higher than those observed. The time series evolution of 2m

223   temperatures nearly follow those of the observations (RMSE:1.66, BIAS:1.61); but model

224   produce warmer surfaces by about 3 K at the beginning of model integration, and 1K when

225   model and observation both reach their maximum temperature, respectively.

226   Results indicate that, model-produced near-surface relative humidity is close to

227   observations at initial time (Figure 4 f). However, the humidity from the model keeps

228   increasing at the first few hours of model integration, when observations decrease. After 3

229   hours' spin-up, the model reproduces reasonably well the evolution of humidity, in agreement

230   with observation (RMSE:1.22), but their values are relative higher than those

231   observed(BIAS:1.11).

232   One reason for this discrepancy is the overestimate of soil moisture during simulation.

233   Soil moisture can severely impact near-surface humidity. The overestimate of the soil

234   moisture contents in the initial condition of the model, which are only offered to the model at

235   initial time, may result in considerable differences in near-surface layer humidity (Talbot et al.

236   2012). In the present simulations, model results are reported to produce grossly overestimate

237   soil moisture. At the model initialization for the CTRL simulation, EC station at Tazhong

238   station indicated a value of the 5-cm-deep soil moisture of 0.230 m^3/m^3, while the model

239   initial value is 0.6 m^3/m^3 (Figure 4 d). This large overestimate of soil moisture results in LH

240   (Figure 4 b, f) from the model continue to increase. As a result, near-surface of model is far

241   moister than that of observation at the first few hours of model integration. An interesting

242   result to note is that the model simulation has the abilities to correct some of the bias due to

243   the initial condition of the surface; The results from CTRL experiment are closer to

244   observation after 3 hours' spin-up.

245   The model simulated potential temperature are compared to GPS sounding

246   measurements at Tazhong during 0800~2000 BJT 01JULY2016 in Figure 5 (solid lines). One

247   should note that radio-sounder floating about 7 Km away from Tazhong, when radio-sounder

248   reach 6 Km height. Thus, for comparison, the profiles of model simulations are averaged

249   station in a radius of 3.5 Km. At 0800 BJT, when the model is initialized, the nocturnal

250   inversion reaches 300m (not shown). By 1100 BJT, this inversion is eroded in the model in

251   agreement with observations, and both reaching about 300m at 1100 BJT (Figure 5 a).

252   However, the simulated CBL grows faster in the morning due to larger SH than observation,

253   reaching 3500m (3000m in the observations) at 1400 BJT (Figure 5 b). At 1700 BJT (Figure 5

254   c), the simulated and observed CBL heights exceed 4000m and 5000m respectively. This

255   indicates that the simulated CBL grows more slowly in the afternoon than measurement.

256   Compared to measurements, the model is initially cooler with faster heating rate in the

257   morning. As a result, model is warmer than measurements in the afternoon. Eventually, model

258   agrees with observations at the end of the day. One possible minor reason is the differences of

259   potential temperature lapse rate above the top of mixing layer between observation and

260   simulation. Simulated stronger inversion layer restrain the development of CBL, which will

261   be discussed below.

262   Moreover, in terms of CBL temperatures, the model initially simulates a cooler and drier

263   CBL than that observed, at 1100 BJT01 JUL (Figure 5a). Compared to the observed potential

264 temperature profile, the CBL seems to appear earlier in model forecasts result based on

265 obvious warming in surface layer. One should note that RL (residual layer) may play a key

266 role in the deep PBL at Taklimakan desert. At 1100 BJT, when the CBLH was about 300 m in

267 observation as show above, potential temperature in the were about 317 in PBL and 320 K in

268 RL, respectively. When the potential temperature in CBL increased to the value in RL (320

269 K), the CBL merged with the RL, and the height of PBL reach 3000m in the observations at

270 1400 BJT. These results are in good agreement with Han et al. (2012). By analysis of

271 observation of a CBL in the Badanjilin region, they found a rapid development process of

272 CBL after 1200 LST, which appeared to be a jump of CBLH when the inversion layer

273 vanished.

274   When the SH reaches its maximum at 1400 BJT (Figure 5b), potential temperature

275 profile is closer to measurements than at initial time, and their values are higher than those

276 observed. By 2000 BJT (Figure 5d), CBLH in the model reaches its maximum value, which is

277 consistent with observation, despite of approximately 0.4K cooler on the lower

278 levels(<2.5Km). As mentioned, one cause of the higher temperatures produced with

279 model would be the large difference in the surface heat fluxes. It was concluded that

280 the surface sensible heat flux from the land surface parameterization is the crucial

281 factor affecting the CBL process during summer day time. Differences in surface SH

282 would create differences in the vertical development of the PBL. Thus, the large

283 surface SH difference between the model and observation may lead to differences in

284 CBL growth during daytime and in its peak depth during the simulation. Fortunately,

285 one can artificially modify the surface SH computed by surface-land model, which

286   controls the calculation of surface fluxes. Sensitive simulations will be realized and

287   discussed in next section.

288   Figure 5 also shows Vertical profiles of vapor mixing ratio (dash lines) at Tazhong

289   station. The simulated profiles with lower RL are much drier than observation from 1500 to

290   3500m at 1100 BJT. The vertical mixing results in the uniform structure of vapor mixing ratio

291   within CBL, so the differences between simulated and observational profiles are reduced

292   remarkably when CBL reach above 4000m at 1400 BJT. Differences are generally less than

293   1g/Kg at 1100 BJT reaching a maximum of 0.3g/Kg at 1400 BJT. However, measured PBL

294   moisture shows an inverse layer at lower PBL(≤2000m) range from 2.8 to 3.6 g/Kg, which is

295   not captured by model. Furthermore, as the convective boundary layer grows, the inversion

296   moisture structure below 3000m develops to and maintains below 3000m during 1400~2000

297   BJT. By the end of the day, the model-simulated CBL humidity show moister than

298   observation, because model cannot reproduce the inverse moisture layer within CBL.

299   Inverse humidity may be caused by the joint of the heterogeneous humidity Pattern and

300   Large-scale advection over the underlying surface. For instance, interaction of oasis with

301   desert environment may resulted in the inverse humidity layer in desert PBL. Thus, one

302   possible reason for the discrepancy between model and observation caused by the error in

303   land-use type. The USGS land-use in ARW-WRF is based on AVHRR (Advanced Very High

304   Resolution Radiometer) 1km resolution satellite data during1992-1993. For our case, this

305   land-use data may be outdated in Taklimakan. Besides such changes, misclassifications are

306   found in the USGS land-use data, the default land-use dataset in WRF(Schicker et al. 2016).

307   This is also confirmed by the discrepancies of land-use between simulation and measured at

308   the Tazhong station in the previous figure. Large-scale advection of dry air can affect the

309   profile of moisture. Moisture will also be variable in the horizontal, so advection at the low

310   level could contribute to the dry at bottom and moisture at the upper of PBL between 1100

311   and 2000 BJT at the bottom of the PBL.

312   The mismatch between the model and the observations in terms of moisture that is

313   present means that the effect of land-use type and Large-scale advection needs to be

314   quantified and that more detailed data of Taklimakan (land and atmosphere) might be

315   necessary to realize a more realistic performance. Extra care should also be taken with sparse

316   and the limited data in the periphery of the Taklimakan(ter Maat et al. 2012).

317   **3.2   Sensitive to Lateral Boundary Condition(LBC)**

318   After verifying the details of the LES simulations, we assess the sensitivity of the LES

319   simulations to time resolution and domain size of Specified LBC. For one-way nest, Specified

320   LBC is obtained from coarser model simulation. The analysis and all forecast times from a

321   previously-run larger-area model simulation are used to specify the LBC. The primary cause

322   of differences in PBL structure was diagnosed as differences in domain size and frequency

323   provided by the coarser resolution. The aim is to assess the sensitivity of the finer large-eddy

324   simulations to time frequency and domain size of Specified LBC forcing by larger-area model

325   simulation; Details of the three simulations (CTRL, BDY_T2 and BDY_T3) are given in

326   section 2.

327   Figure 5 compare the profiles of the simulated potential temperature and vapor mixing

328   ratio profiles from LBC sensitivity experiments and observation. Results indicate that, there is

329   a distinct relationship between LBC and CBL development. All model-produced profiles are

330   nearly the same at initial time (not show). However, the comparison results reveal that

331   discrepancies among different experiments are large for CBL. The results indicate that larger

332   domain size and more time frequency LBC leads to a warmer and drier PBL, but a cooler and

333   moister free troposphere. Such sensitivity is monotonic with respect to LBC (Figure 5).

334   Furthermore, in the next three hours, the differences between the sensitive experiments keep

335   increasing with time (Figure 5 a, b). The potential temperature profiles within CBL become

336   divergence at 1100 BJT. However, the results show more convergence at afternoon as CBL

337   continues to grow (Figure 5 c). Finally, largest discrepancies are found by end of the day

338   (Figure 5 d) where the model CBL potential temperature is warmer by up to about 0.7K and

339   0.9K in BDY_T2 and BDY_T1 respectively, compared to measurements.

340   Figure 6 shows cross sections along 39.03°N of horizontal winds, superposed with theta

341   and vapor mixing ratio. Overall, the lower frequently updated LBC is desirable to cold zone

342   near the LBC, which results in cold advection of the temperature and moisture to the area of

343   interest (Figure 6   b, c). Larger domain size, which varies the distance of the area of interest

344   from the LBC, is efficient to reduce the influences of large forecast error near the LBC to the

345   area of interest (CMP Figure 6   a, c). The results suggest that the model results are sensitive

346   to changes in time resolution and domain size of Specified LBC. The mismatch among

347   sensitive experiments is present means that the effect of LBC needs to be quantified to realize

348   a more realistic performance in the sub-kilometer simulations.

349   To further examine the impact of LBCS on the turbulence of deep Taklimakan desert

350   CBL, the instantaneous vertical velocity fields for the horizontal are displayed in . By 1400

351   BJT, the convection of CTRL simulation obviously intensified under strong surface heating

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352   (Xu et al. 2018).   Thus, the maximum vertical velocity reaches 9 m/s and the depth of mixed

353   layer grows to about 4.3 km (a).   The distances between the boundary layer rolls

354   correspondingly increase to about 12 km and the height of the peak updraughts is raised to

355   just under 4 km.   The cellular shape of updraughts and downdraughts characteristic of

356   boundary layer rolls is obvious in the horizontal view with the strength of convection.

357   BDY_T2 and BDY_T3 experiments (b, c) both reproduce motions with much weaker

358   maximum and minimum values at boundary of domain. In BDY_T3 experiment, Tazhong

359   station at center of the model has been directly influenced by the inflow cold advection

360   produced by low frequency LBCS and results in much weaker maximum and minimum value

361   of w (about 6 m/s). However, despite the underestimate of potential temperature, the w fields

362   for BDY_T2 experiment look similar to the CTRL w in plain view, and the horizontal extent

363   of the updrafts/downdrafts agrees with the CTRL as can be inferred from . To further examine

364   vertical structure of desert CBL, vertical cross-sections along Tazhong station ($39°N$) of w

365   are presented in Figure 8. Wide and regularly spaced updrafts along A1- A2 split into the

366   stronger and more irregular motions in CTRL and BDY_T2. The updrafts are much weaker in

367   the BDY_T3 experiment, as can be seen from Figure 8 c. Peak updrafts on BDY_T3 are about

368   4 m/s much weaker than on CTRL (9 m/s) and BDY_T2 (8 m/s). For BDY_T2 and BDY_T3,

369   the distant of the inflow boundary is wider, and the intensity of the convection is weaker at

370   the boundary. Compared with BDY_T2, the horizontal distribution of vertical velocity at

371   Tazhong station in BDY_T3 experiments is much weaker.

372   **3.3   Simulations with different surface sensible heat flux (SH) and surface-land**

373   **models**

374   The import cause of differences in PBL structure was diagnosed above as differences in

375   SH predicted by the surface-land schemes. The SH is one of the key factor affecting the

376   CBLH during summer day time. Thus, the difference between model and observation may

377   lead to differences in PBL growth during daytime; To further confirm whether this indeed

378   occurs, three additional sensitive simulations were realized based on the CTRL experiment.

379   For Noah experiment Noah land-surface model is used to replace RUC land-surface model in

380   CTRL experiment, and for HFX-125%, HFX -75% SH is %125 and %75 that of CTRL（HFX

381   -100%）experiment, while the other parameters remain the same.

382   The results from Figure 10 and Table 2 showed that HFX-75% successively improved

383   the simulation of SH with RMSE:151.12, compared that of 263.64, 357.11 in CTRL and

384   HFX-125%. Of interesting is that experiment with Noah surface-land yielded the best

385   performance among all of the cases in SH, surface temperature and air temperature. However,

386   Noah surface-land model show large discrepancies with observation in Soil moisture, and

387   results in dramatically overestimate of LH and relative humidity compared to CTRL.

388   Further examining potential temperature and vapor mixing ratio (Figure 9) indicate that

389   with smaller SH leads to a cooler, moister lower PBL and a warmer, drier free atmosphere.

390   Such sensitivity is monotonic with respect to SH. Overall, the CBL structure from the

391   HFX-75% and Noah experiments match the GPS measurements better than the CTRL

392   （HFX-100%）simulations. Potential temperature profiles from CTRL（HFX-100%）and

393   HFX-125% are consistently warmer than the observation by about 0.4 and 0.5 K respectively,

394   while results from HFX-75% and Noah are within about 0.2K at 1400 BJT (Figure 9 b). The

395   results suggest that the model results are sensitive to changes SH from land-surface model.

396   However, simulations converge at the end of the day, but remain differences at 2000 BJT

397   (Figure 9 d). HFX-75% and Noah with weaker surface sensible heat flux can still produce the

398   deep CBL nearly the same as CTRL and HFX-125%. This indicates that SH may not the

399   dominant factor for the deep CBL over the Taklimakan desert.

400   Results of simulations on desert PBL in the morning agree with the previous studies of

401   sensitivities land-surface model for other areas (Hu et al. 2010; Zhang et al. 2017). However,

402   during 1700~2000 BJT 01July (Figure 9b, d), all experiments produce nearly the same CBLH

403   and moisture in agreement with observation in the PBL. The effects of SH on the evolution of

404   Taklimakan PBL structures during this period are needed to be further examined and

405   discussed. So, the question is: why are simulations insensitive to land-surface process by the

406   end of the day? As in Stull (1988), the development of CBL is mainly influenced by the effect

407   of thermodynamic and turbulent entrainment without considering large scale factors such as

408   large scale advection or subsidence. Besides the surface sensible heat, the intensity of

409   entrainment process determines the increasing rate of CBL. Thus, the entrainment rate w_e is a

410   valuable indicator for the development of PBL structure.

411   The rate of growth of the convective boundary layer is mainly determined by the

412   entrainment rate w_e at the inversion layer without considering large scale vertical motion. w_e

413   usually has a positive correlation with heat flux amount at the inversion layer $\overline{(w'\theta_v')}_h$, and

414   large LES experiments show $\overline{(w'\theta_v')}_h$ is about 0.2 times the surface flux of buoyancy

415    $\overline{(w'\theta_0')}$. During the period from 1100 to 1400 BJT, larger SH is obviously correlated with

416   stronger turbulent entrainment and warmer air from free atmosphere (FA) entraining into ML.

417   As a result, CBL develop rapidly and is warm too fast in the early simulation phase due to the

418 obviously increasing temperature and strong vertical mixing in model. Of interesting is that

419 reduction in SH reproduces better desert PBL evolution in the early simulation phase, as

420 SH-75% and Noah produce the smallest simulation errors in both temperature and moisture.

421 However, one should note that CBLH and potential temperature for SH-75% and Noah have

422 reached above 5000 m and 323.2 K respectively at 1700 BJT (Figure 9 a). For the rest of the

423 day, the increase rate of CBL height slows down due to the deep CBL(>5000m) which require

424 more heat for the growth of PBL depth; Moreover, w_e decrease with increasing inversion

425 intensity, which inhibits the mixing and entrainment processes. These two factors obviously

426 limit the growth of CBL when CBLH is over 5000 m in this deep desert CBL case. Therefore,

427 increasing SH from 75% to 125% significantly reduce the total time needed for CBL increase

428 to a relative low altitude (< 5 km) at the middle and preliminary stage of the development of

429 CBL rather than produce higher CBL at the late stage. When height of CBL over Taklimakan

430 desert exceeds 5000 m, it might not change with proportion to SH fluxes (Figure 9 d). As a

431 result, PBL of WRF simulations are basically the same, and not sensitive to SH fluxes by the

432 end of the day.

433 **4   Summary**

434   This paper assesses the performance of the Weather Research and Forecasting Model

435 (WRF) Large-Eddy Simulations(LES) in deep convective PBL case over Taklimakan Desert.

436 Tests are performed with multiple configurations and sensitive experiments. Sensitivity tests

437 to Lateral Boundary Condition(LBC) showed that the model results are sensitive to changes

438 in time resolution and domain size of Specified LBC. It is found that larger domain size varies

439 the distance of the area of interest from the LBC, is efficient to reduce the influences of large

440   forecast error near the LBC.

441   Consequently, with the configuration used in this study, the model reproduces

442   reasonably well the evolution of PBL processes. The model shows discrepancies between the

443   main CBL characteristics in the morning including the thermal and moisture structure. The

444   model simulates the relatively colder and drier morning CBL well, underestimating it by up to

445   1.5K near-surface layer at Tazhong station. In the case of the underestimation of moisture by

446   only up to 1 g/kg in the near-surface layer. The overestimation of CBL profile may be caused

447   by discrepancy between model and measurement initially. This indicates that the results are

448   sensitive to the model initial conditions. An interesting result to note is that the model

449   simulation seems to be able to correct some of the bias due to the initial condition. In the

450   afternoon, the model correctly reproduce the thermal structure, but simulations are relative

451   warmer and moister than those observed. Potential temperature profile at CBL appears

452   warmer by up to about 0.4K compared to the observations. While the model overestimates the

453   afternoon moisture seriously, it mainly overestimates vapor mixing ratio by about 1 to 2 g/Kg

454   in the CBL. Largest discrepancies are found in 0~3Km where the model vapor is twice as

455   moist (up to about 3g/Kg above AGL) as observed.

456   Furthermore, three additional sensitive simulations were realized to further confirm

457   whether large differences of SH lead to differences in ABL growth during daytime, based on

458   the CTRL experiment.   The results suggest that the model results are sensitive to changes

459   SH and different land-surface models. The large difference between the model and

460   observation may lead to differences in CBL growth during daytime. From these results, it was

461   concluded the surface sensible heat flux is an important factor affecting the CBL depth over

462　Taklimakan during summer day time. However, its peak depth during the simulation show

463　less sensitive to SH because of decreasing w_e by the end of the day.

464　　　　The future work aimed to study several other deep CBL cases over Taklimakan to

465　summarize their common features. Furthermore, we hope to utilize high resolution model and

466　observation to describe the fine characteristics of a typical deep Taklimakan CBL particularly

467　the turbulent and vertical mixing and its impact on regional weather forecast. This research is

468　aimed to improve the understanding of deep CBL over Taklimakan and its influence on

469　regional weather and climate.

470　**Conflict of Interests**

471　The author declares that there is no conflict of interests regarding the publication of this paper.

472　**Acknowledgments**

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477   Captions:

478   Figure 1 Simulation domains used in ARW model with terrain height (shaded, units:m); (b) land

479   use categories for domain D03 and D04.

480   Figure 2 Horizontal distribution of geopotential height (solid, units: dagpm), wind speed (shaded,

481   units: knot), and wind barbs from the NCEP FNL analysis at 0800 BJT 1 Jul 2016 at (a)

482   850 hPa, (c) 700 hPa, (e) 500 hPa, and (d) 100hPa.

483   Figure 3 NCEP FNL 700hPa potential temperature (colors) and mean sea level pressure (white

484   lines) at 0800 BJT 1 Jul 2016. The black dot shows the location of Tazhong station at

485   Xingjiang province.

486   Figure 4 Time series of simulated surface variables from innermost domain of simulations

487   and surface observations at Tazhong station (83.63° E, 39.03° N) initial at 0800

488   BJT 01July 2016 (a) sensible heat flux (W/m^2), (b) latent heat flux(W/m^2), (c) 2-m

489   temperature (∘C), (d) surface temperature (∘C), (e) 2-m Relative Humidity(%) and (f)

490   10-m wind speed (m/s) with corresponding observations.

491   Figure 5 Vertical profiles of potential temperature (solid line, units: K) and vapor mixing

492   ratio(dash line, units: g/Kg)from innermost domain of simulations and observation of

493   GPS sounding at Tazhong station (83.63° E, 39.03° N) at (a)1100 (b) 1400 (c)

494   1700 (d) 2000 BJT 01 Jul2016.

495   Figure 6 cross sections along 39.03°N of horizontal winds (barbs, units: m/s), at intervals of 5 m/s,

496   superposed with theta (shaded, units: K) and vapor mixing ratio(contour, units: g/Kg), from (a)

497   BDY_T1, (c) BDY_T2, (e) BDY_T3 experiments at1400 BJT 01JUL2016, (b), (d), (f) are the

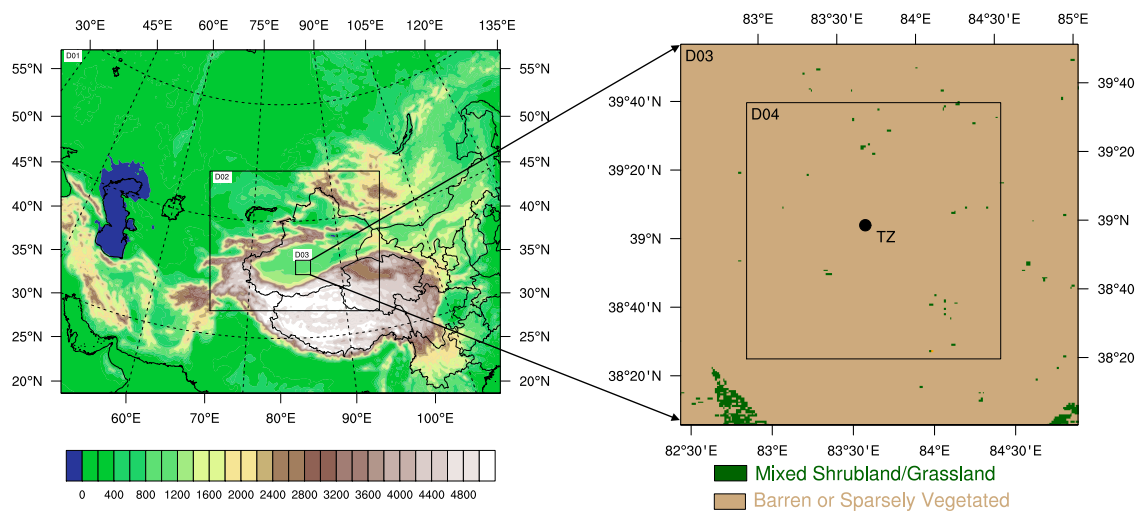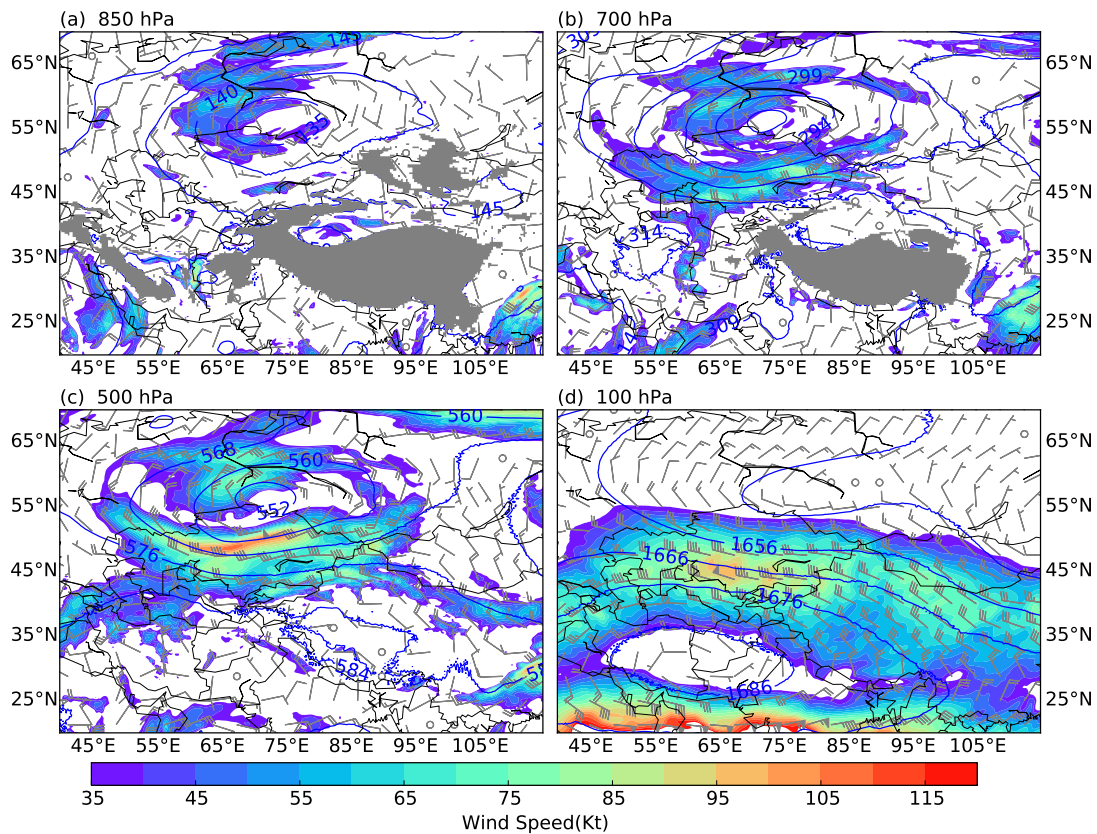498   same as (a), (c), (e), but for 2000 BJT 01JUL2016.

499   Figure 7 Instantaneous vertical velocity fields (shading: m/s) at 3000 m for (a) BDY_T1 (CTRL), (b)

500   BDY_T2, (c) BDY_T3, and (d) Noah at 1400 BJT, 1 July 2016.

501   Figure 8 Vertical cross-section of instantaneous vertical velocity fields (shading: m/s) along

502   A1-A2 in for for (a) BDY_T1 (CTRL), (b) BDY_T2, (c) BDY_T3, and (d) Noah at 1400 BJT,

503   1 July 2016.

504   Figure 9 The same as Figure 5, but for SH flux sensitive and Noah land-surface experiment.

505   Figure 10 The same as Figure 4, but for SH flux sensitive and Noah land-surface experiment.

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512　Figure 1 Simulation domains used in ARW model with terrain height (shaded, units:m); (b)

513　land use categories for domain D03 and D04; (c) photograph of Tazhong station

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Figure 2 Horizontal distribution of geopotential height (solid, units: dagpm), wind speed

(shaded, units: knot), and wind barbs from the NCEP FNL analysis at 0800 BJT 1 Jul 2016 at

(a) 850 hPa, (c) 700 hPa, (e) 500 hPa, and (d) 100hPa.

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522   Figure 3 NCEP FNL 700hPa potential temperature (colors) and mean sea level pressure (white lines) at

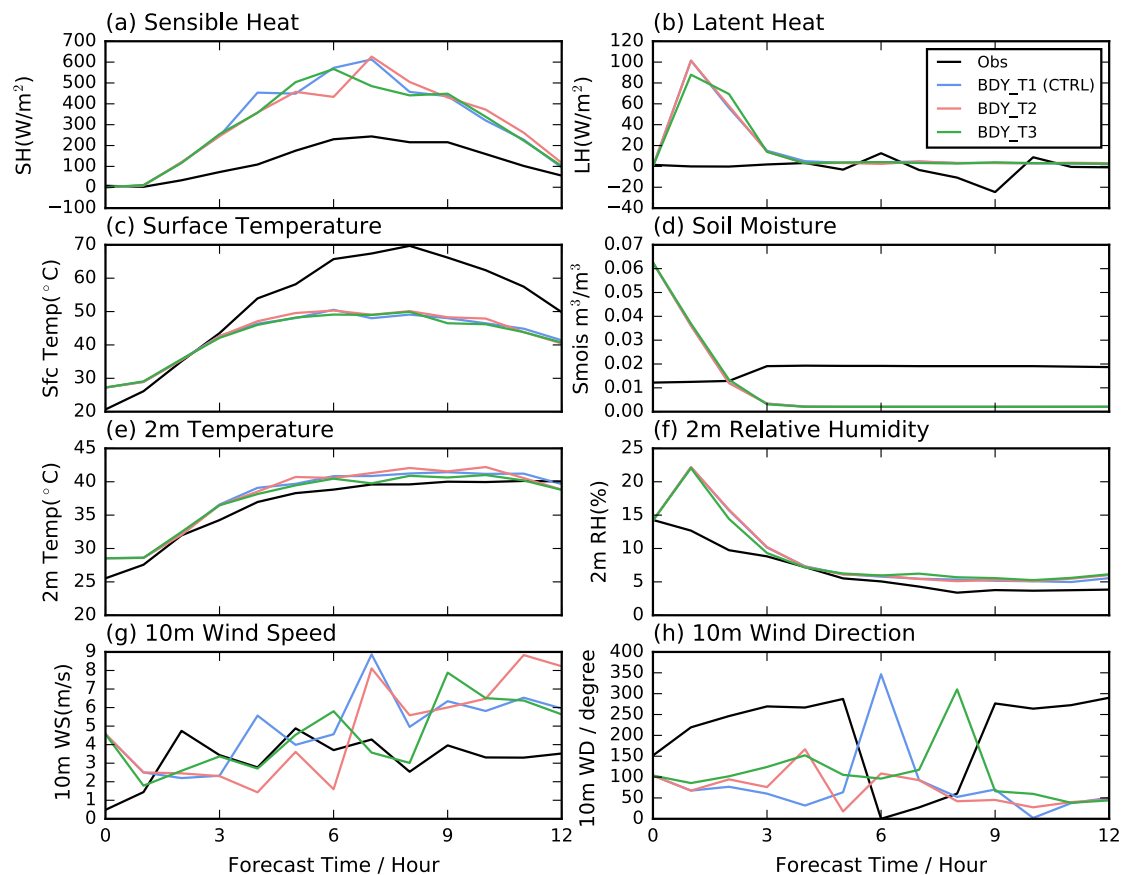523   0800 BJT 1 Jul 2016. The black dot shows the location of Tazhong station at Xingjiang province.

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Figure 4 Time series of simulated surface variables from innermost domain of simulations
and surface observations at Tazhong station (83.63° E, 39.03° N) initial at 0800 BJT 01July
2016 (a) sensible heat flux (W/m^2), (b) latent heat flux(W/m^2), (c) 2-m temperature (°C), (d)
surface temperature (°C), (e) 2-m Relative Humidity(%) and (f) 10-m wind speed (m/s) with
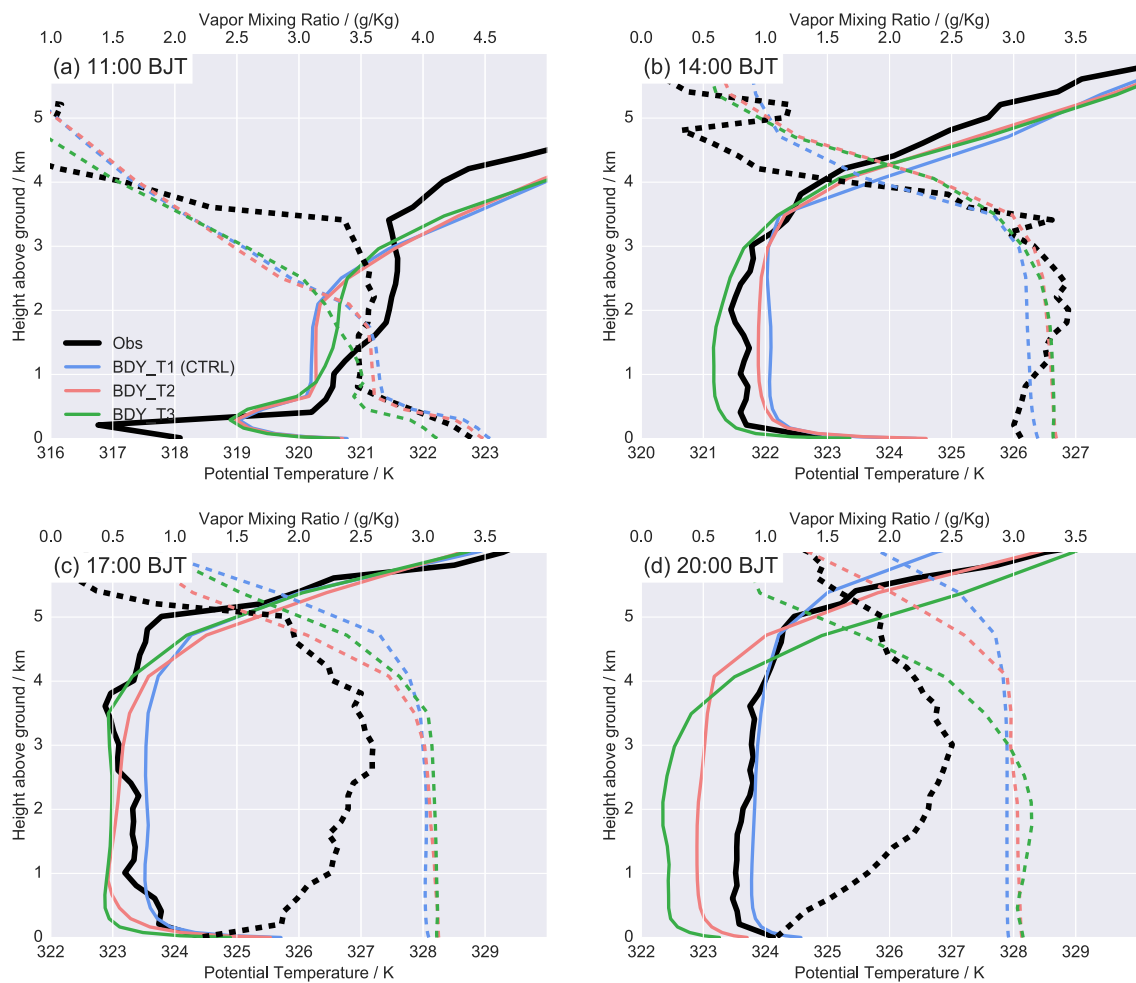corresponding observations.

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Figure 5 Vertical profiles of potential temperature (solid line, units: K) and vapor mixing ratio(dash line, units: g/Kg)from innermost domain of simulations and observation of GPS sounding at Tazhong station (83.63°E, 39.03°N) at (a)1100 (b) 1400 (c) 1700 (d) 2000 BJT 01 Jul2016. The profile of model output are averaged in a radius of 3.5km.
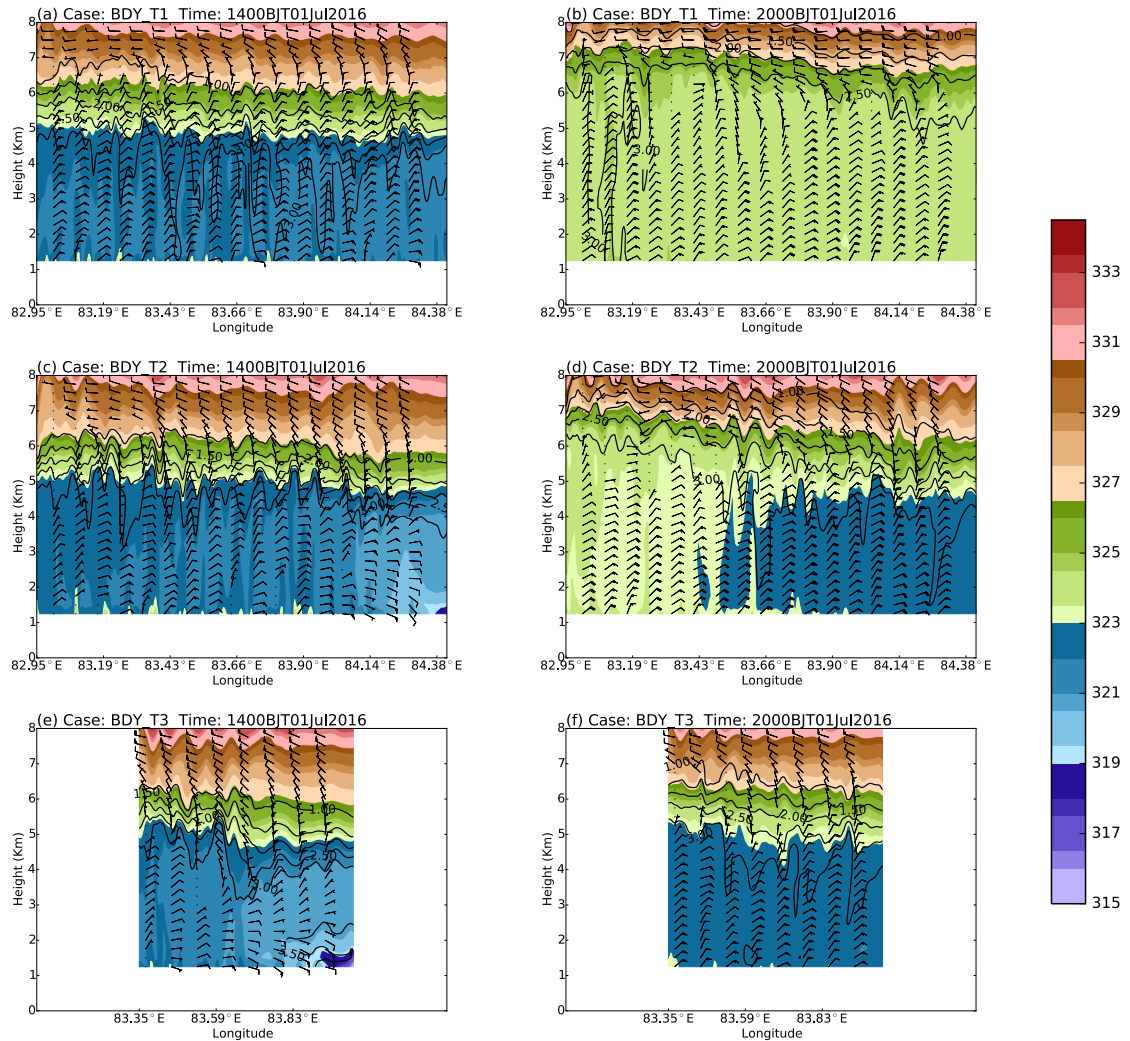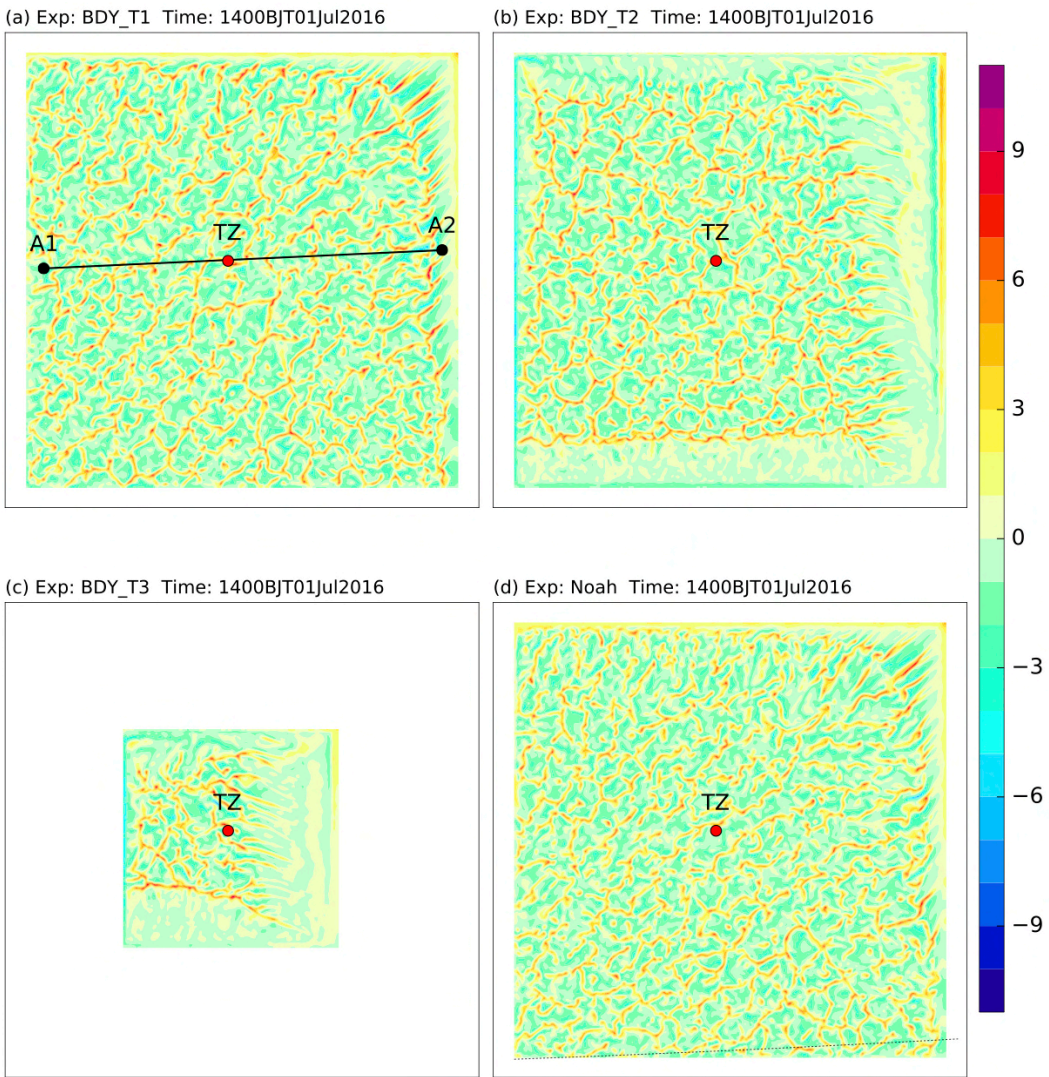
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Figure 6 cross sections along 39.03°N of horizontal winds (barbs, units: m/s), at intervals of 5

m/s, superposed with theta (shaded, units: K) and vapor mixing ratio(contour, units: g/Kg),

from (a) BDY_T1, (c) BDY_T2, (e) BDY_T3 experiments at1400 BJT 01JUL2016, (b), (d),

(f) are the same as (a), (c), (e), but for 2000 BJT 01JUL2016.

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(a) Exp: BDY_T1　Time: 1400BJT01Jul2016

(b) Exp: BDY_T2　Time: 1400BJT01Jul2016

(c) Exp: BDY_T3　Time: 1400BJT01Jul2016

(d) Exp: Noah　Time: 1400BJT01Jul2016

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546　Figure 7 Instantaneous vertical velocity fields (shading: m/s) at 3000 m for (a) BDY_T1 (CTRL), (b)

547　BDY_T2, (c) BDY_T3, and (d) Noah at 1400 BJT, 1 July 2016.

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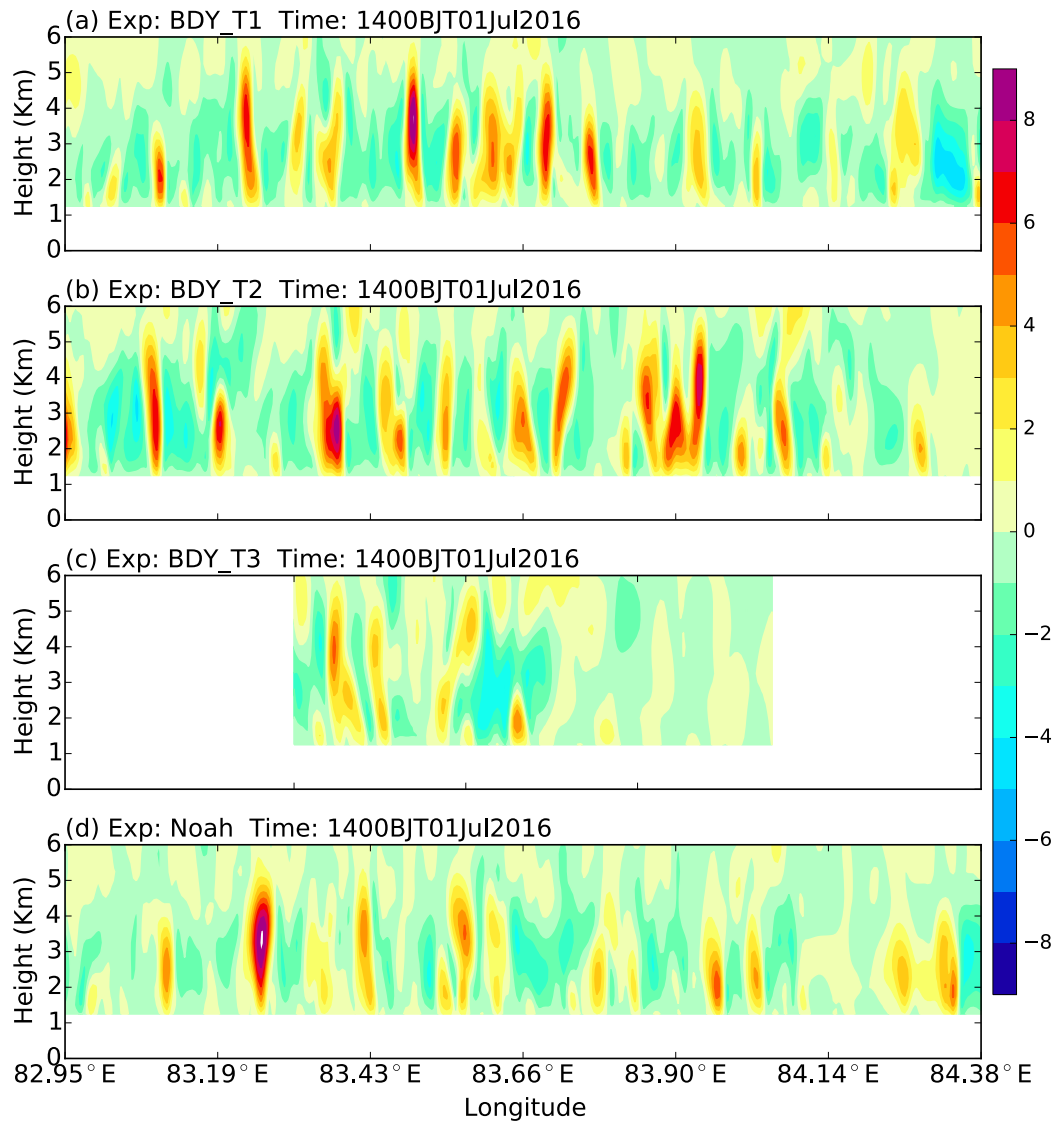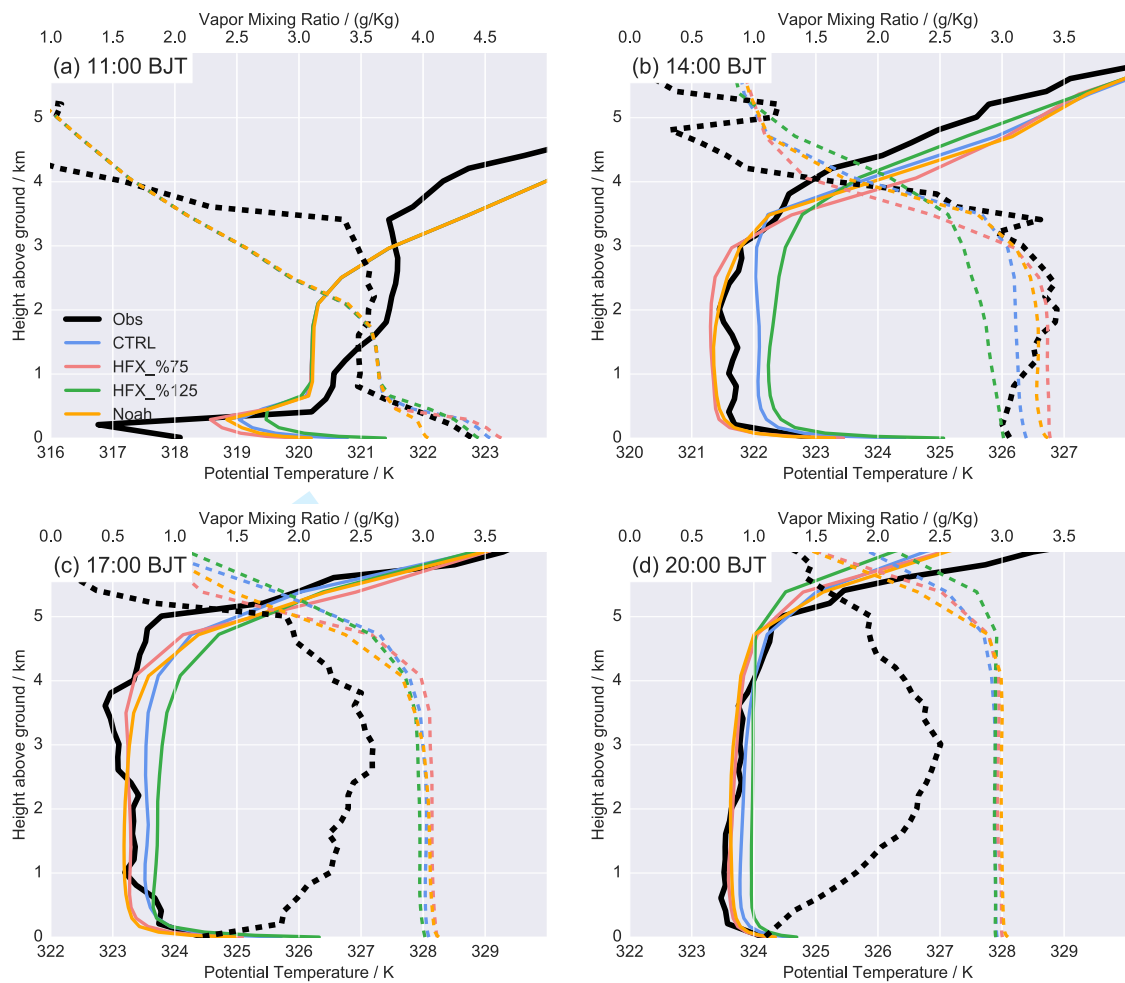
Figure 8 Vertical cross-section of instantaneous vertical velocity fields (shading: m/s) along
A1-A2 in for for (a) BDY_T1 (CTRL), (b) BDY_T2, (c) BDY_T3, and (d) Noah at 1400 BJT, 1 July
2016.

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557 Figure 9 The same as Figure 5, but for SH flux sensitive and Noah land-surface experiment
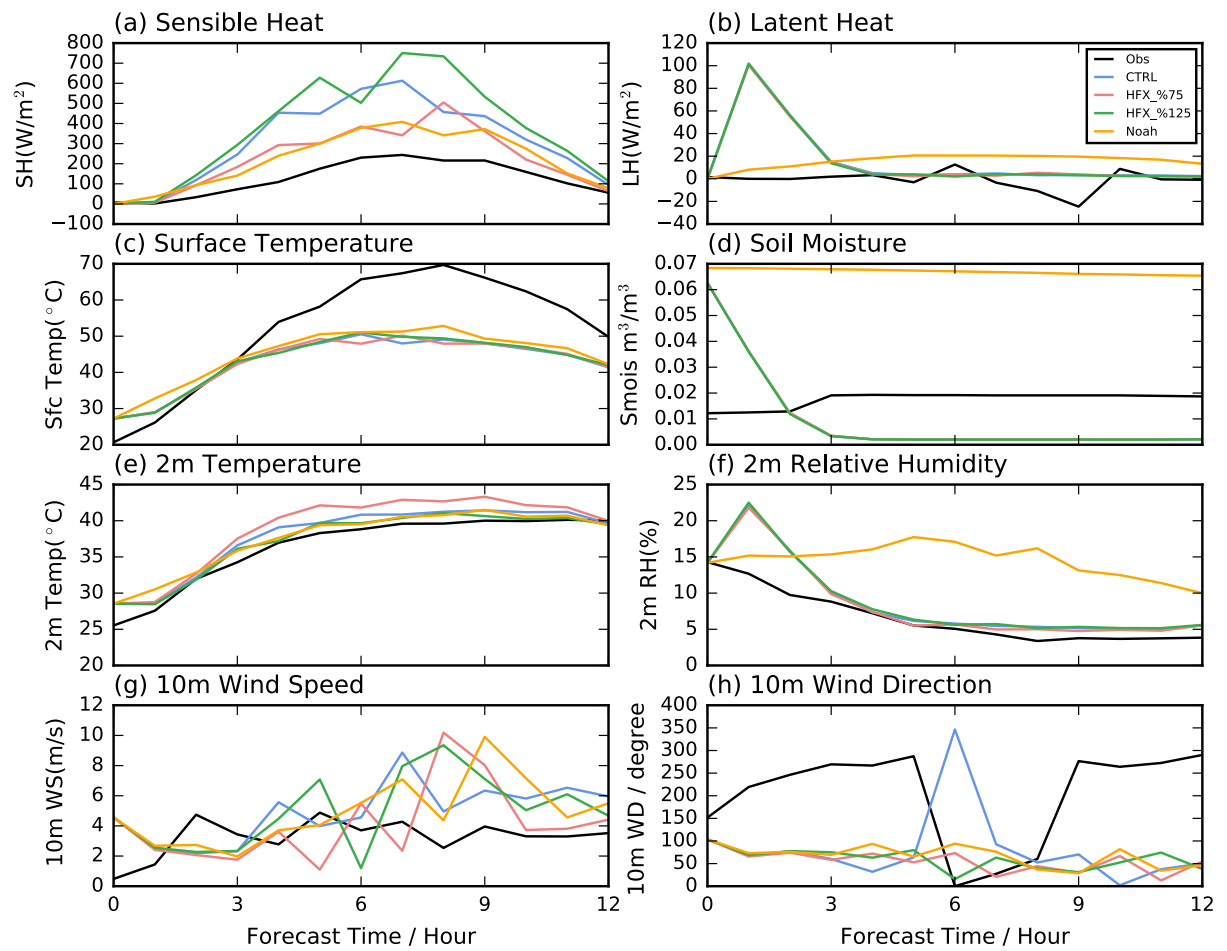
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560   Figure 10 The same as Figure 4, but for SH flux sensitive and Noah land-surface experiment.

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Experiment	Name	Remarks
1	BDY_T1(CTRL)	LBC of D04 is provide by d03 every 1 hour with model grids 403x406
2	BDY_T2	As BDY_T1, but LBC of D04 is provide by d03 every 6 hour
3	BDY_T3	As BDY_T2, but with model grids 205 x 208.
4	HFX_%75	As CTRL_T2, but with SH 75%.
5	HFX_%125	As CTRL_T2, but with SH 125% .
6	Noah	As CTRL_T2, but with Noah surface-land model.

563 Table 1. List of designed experiments.

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Variables	Sensible Heat		Latent Heat		Surface Temperature		Soil Moisture		2m Temperature		2m Relative Humidity		10m Wind Speed	
	RMSE	BIAS	RMSE	BIAS	RMSE	BIAS	RMSE	BIAS	RMSE	BIAS	RMSE	BIAS	RMSE	BIAS
Experiments														
CTRL	263.636	250.140	12.398	6.674	14.654	-13.373	0.017	-0.017	1.666	1.613	1.220	1.109	2.579	1.864
BDY_T2	249.395	240.660	12.383	6.253	14.116	-12.853	0.017	-0.017	1.912	1.817	1.275	1.162	2.943	1.307
BDY_T3	241.681	232.705	12.251	6.328	14.929	-13.737	0.017	-0.017	1.227	1.046	1.483	1.280	2.118	1.287
HFX_%75	151.119	134.594	12.544	6.354	14.740	-13.426	0.017	-0.017	3.078	3.016	0.956	0.826	3.335	0.874
HFX_%125	357.711	335.556	12.439	6.152	14.244	-13.043	0.017	-0.017	1.026	0.860	1.303	1.231	3.265	2.052
Noah	125.695	120.313	23.350	20.664	12.757	-11.502	0.048	0.048	1.046	0.983	10.116	9.904	2.788	1.795

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567   Table 2. Summary of surface and air variables verification including integration hours from 3 to 12 h for Tazhong station.

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Reference:

Chen, F., and J. Dudhia, 2001a: Coupling an Advanced Land Surface–Hydrology Model with the Penn State–NCAR MM5 Modeling System. Part II: Preliminary Model Validation. *Monthly Weather Review*, **129,** 587-604.

——, 2001b: Coupling an advanced land surface-hydrology model with the Penn State-NCAR MM5 modeling system. Part I: Model implementation and sensitivity. *Monthly Weather Review*, **129,** 569-585.

Dudhia, J., 1989: Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model. *J. Atmos. Sci.*, **46,** 3077-3107.

Engelstaedter, S., R. Washington, C. Flamant, D. J. Parker, C. J. T. Allen, and M. C. Todd, 2015: The Saharan heat low and moisture transport pathways in the central Sahara—Multiaircraft observations and Africa-LAM evaluation. *Journal of Geophysical Research: Atmospheres*, **120,** 2015JD023123.

Garcia-Carreras, L., and Coauthors, 2015: The Turbulent Structure and Diurnal Growth of the Saharan Atmospheric Boundary Layer. *Journal of the Atmospheric Sciences*, **72,** 693-713.

Han, B., S. Lü, and Y. Ao, 2012: Development of the convective boundary layer capping with a thick neutral layer in Badanjilin: Observations and simulations. *Adv. Atmos. Sci.*, **29,** 177-192.

Heinold, B., P. Knippertz, and J. H. Marsham, 2013: Large Eddy Simulations of Nocturnal Low-Level Jets over Desert Regions and Implications for Dust Emission. *EGU General Assembly Conference*.

Heinold, B., P. Knippertz, and R. J. Beare, 2015: Idealized large-eddy simulations of nocturnal low-level jets over subtropical desert regions and implications for dust-generating winds. *Quarterly Journal of the Royal Meteorological Society*, **141,** 1740–1752.

Heinze, R., D. Mironov, and S. Raasch, 2015: Second-moment budgets in cloud topped boundary layers: A large-eddy simulation study. *Journal of Advances in Modeling Earth Systems*, **7,** 510-536.

Hong, S.-Y., and H.-L. Pan, 1996: Nonlocal boundary layer vertical diffusion in a medium-range forecast model. *Monthly weather review*, **124,** 2322-2339.

Hong, S.-Y., and J.-O. J. Lim, 2006: The WRF single-moment 6-class microphysics scheme (WSM6). *J. Korean Meteor. Soc*, **42,** 129-151.

Hu, X.-M., J. W. Nielsen-Gammon, and F. Zhang, 2010: Evaluation of Three Planetary Boundary Layer Schemes in the WRF Model. *Journal of Applied Meteorology and Climatology*, **49,** 1831-1844.

Kain, J. S., 1993: Convective parameterization for mesoscale models: The Kain-Fritsch scheme. *The representation of cumulus convection in numerical models, Meteor. Monogr*, **46,** 165-170.

Kain, J. S., 2004: The Kain–Fritsch Convective Parameterization: An Update. *JOURNAL OF APPLIED METEOROLOGY*, **43,** 170-181.

LeMone, M. A., M. Tewari, F. Chen, and J. Dudhia, 2013: Objectively Determined Fair-Weather CBL Depths in the ARW-WRF Model and Their Comparison to CASES-97 Observations. *Monthly Weather Review*, **141,** 30-54.

Liu, Y., Q. He, H. Zhang, and A. Mamtimin, 2012: Improving the CoLM in Taklimakan Desert hinterland with accurate key parameters and an appropriate parameterization scheme. *Adv. Atmos. Sci.*, **29,** 381-390.

Liu, Y., and Coauthors, 2011: Simultaneous nested modeling from the synoptic scale to the LES scale for wind energy applications. *Journal of Wind Engineering and Industrial Aerodynamics*, **99,**

37

613   308-319.

614   Marsham, J. H., P. Knippertz, N. Dixon, D. J. Parker, and G. M. S. Lister, 2011: The importance of the

615   representation of deep convection for modeled dust‐generating winds over West Africa during

616   summer. *Geophysical Research Letters*, **38**.

617   Mlawer, E. J., S. J. Taubman, P. D. Brown, M. J. Iacono, and S. A. Clough, 1997: Radiative transfer for

618   inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *J. Geophys.*

619   *Res.*, **102,** 16663-16682.

620   Moeng, C.-H., J. Dudhia, J. Klemp, and P. Sullivan, 2007: Examining Two-Way Grid Nesting for Large

621   Eddy Simulation of the PBL Using the WRF Model. *Monthly Weather Review*, **135,** 2295-2311.

622   National Centers for Environmental Prediction, N. W. S. N. U. S. D. o. C., 2015: NCEP GDAS/FNL

623   0.25 Degree Global Tropospheric Analyses and Forecast Grids. Research Data Archive at the

624   National Center for Atmospheric Research, Computational and Information Systems Laboratory.

625   Rai, R. K., L. K. Berg, B. Kosović, J. D. Mirocha, M. S. Pekour, and W. J. Shaw, 2017: Comparison of

626   Measured and Numerically Simulated Turbulence Statistics in a Convective Boundary Layer Over

627   Complex Terrain. *Boundary-Layer Meteorology*, **163,** 69-89.

628   Schicker, I., D. Arnold Arias, and P. Seibert, 2016: Influences of updated land-use datasets on WRF

629   simulations for two Austrian regions. *Meteorology and Atmospheric Physics*, **128,** 279-301.

630   Shin, H. H., and S. Y. Hong, 2011: Intercomparison of Planetary Boundary-Layer Parametrizations

631   in the WRF Model for a Single Day from CASES-99. *Boundary-Layer Meteorology*, **139,** 261-281.

632   Shin, H. H., and S.-Y. Hong, 2015: Representation of the Subgrid-Scale Turbulent Transport in

633   Convective Boundary Layers at Gray-Zone Resolutions. *Monthly Weather Review*, **143,** 250-271.

634   Skamarock, W. C., and Coauthors, 2008: A Description of the Advanced Research WRF Version 3. .

635   *NCAR/TN–475+STR, NCAR TECHNICAL NOTE*.

636   Smirnova Tatiana, G., M. Brown John, G. Benjamin Stanley, and D. Kim, 2000: Parameterization of

637   cold‐season processes in the MAPS land‐surface scheme. *Journal of Geophysical Research:*

638   *Atmospheres*, **105,** 4077-4086.

639   Smirnova, T. G., J. M. Brown, and S. G. Benjamin, 1997: Performance of Different Soil Model

640   Configurations in Simulating Ground Surface Temperature and Surface Fluxes. *Monthly Weather*

641   *Review*, **125,** 1870-1884.

642   Stull, R. B., 1988: An Introduction to Boundary Layer Meteorology. *Atmospheric Sciences Library*, **8,**

643   89.

644   Sun, J., and Q. Xu, 2009: Parameterization of Sheared Convective Entrainment in the First-Order

645   Jump Model: Evaluation Through Large-Eddy Simulation. *Boundary-Layer Meteorology*, **132,**

646   279-288.

647   Talbot, C., E. Bou-Zeid, and J. Smith, 2012: Nested Mesoscale Large-Eddy Simulations with WRF:

648   Performance in Real Test Cases. *Journal of Hydrometeorology*, **13,** 1421-1441.

649   ter Maat, H. W., E. J. Moors, R. W. A. Hutjes, A. A. M. Holtslag, and A. J. Dolman, 2012: Exploring the

650   Impact of Land Cover and Topography on Rainfall Maxima in the Netherlands. *Journal of*

651   *Hydrometeorology*, **14,** 524-542.

652   WANG, and Coauthors, 2016a: Summer atmospheric boundary layer structure in the hinterland of

653   Taklimakan Desert, China. *Journal of Arid Land*, **8,** 846-860.

654   Wang, M., X. Xu, and H. Xu: The possible influence of the summertime deep atmospheric boundary

655   layer process over the Taklimakan Desert on the regional weather. *(submitted to Quarterly Journal*

656   *of the Royal Meteorological Society)*.

657   Wang, M. Z., H. Lu, H. Ming, and J. Zhang, 2016b: Vertical structure of summer clear-sky

658   atmospheric boundary layer over the hinterland and southern margin of Taklamakan Desert: The

659   deep convective boundary layer of Taklamakan Desert. *Meteorological Applications*, **23,** 438-447.

660   Zhang, F., Z. Pu, and C. Wang, 2017: Effects of Boundary Layer Vertical Mixing on the Evolution of

661   Hurricanes over Land. *Monthly Weather Review*, **145,** 2343-2361.

662