

**ХАРАКТЕРИСТИКИ ДВОЙНОГО НАТРИЕВОГО СЛОЯ НАД ХАЙКОУ,
КИТАЙ (20.0° N, 110.1° E)****CHARACTERISTICS OF DOUBLE SODIUM LAYER OVER HAIKOU,
CHINA (20.0° N, 110.1° E)****Дали Ян***Хайнаньский педагогический университет,
Хайкоу, Китай, 147803434@qq.com***Теминь Чжан***Хайнаньский педагогический университет,
Хайкоу, Китай, 78833508@qq.com***Цзихун Ван***Национальный центр науки о космосе,
Академия наук КНР,
Пекин, Китай, jhwang@nssc.ac.cn***Цзяньцин У***Хайнаньский педагогический университет,
Хайкоу, Китай, 415623408@qq.com***Линьмао Ван***Хайнаньский педагогический университет,
Хайкоу, Китай, 415746442@qq.com***Сюй Цзоу***Хайнаньский педагогический университет,
Хайкоу, Китай, 25878671@qq.com***Хунянь Пэн***Хайнаньский педагогический университет,
Хайкоу, Китай, mdjphy@163.com***Dali Yang***Hainan Normal University,
Haikou, China, 147803434@qq.com***Tiemin Zhang***Hainan Normal University,
Haikou, China, 78833508@qq.com***Jihong Wang***National Space Science Center,
Chinese Academy of Sciences,
Beijing, China, jhwang@nssc.ac.cn***Jianqing Wu***Hainan Normal University,
Haikou, China, 415623408@qq.com***Linmao Wang***Hainan Normal University,
Haikou, China, 415746442@qq.com***Xu Zou***Hainan Normal University,
Haikou, China, 25878671@qq.com***Hongyan Peng***Hainan Normal University,
Haikou, China, mdjphy@163.com*

Аннотация Изучено свойство структуры двойного натриевого слоя (ДНС) в мезосфере и нижней термосфере лидаром на низких широтах в Хайкоу (20.0° N, 110.1° E), Китай. В период с апреля 2010 по декабрь 2013 г. в общей сложности 377 дней наблюдался 21 ДНС. ДНС были зарегистрированы на средних широтах Пекина и Уханя (Китай), но редко регистрировались на низких широтах. Также были проанализированы и рассмотрены такие характеристики ДНС, как время появления, максимальная высота, полуширина на половине высоты (ПШПВ), длительность и т. д. В то же время критическая частота f_oE_s и виртуальная высота $h'E_s$ спорадического E-слоя E_s наблюдались ионозондом над Даньчжоу (19.0° N, 109.3° E). Обсуждаются такие их характеристики, как, например, различия во времени, различия высоты по сравнению с ДНС. Для генерирования зондирующего пучка использовался лазер Nd:YAG с накачкой красителей. Длина волны лазера на красителях была установлена на 589 нм с помощью натриевой флуоресцентной клетки. Флуоресцентные фотоны обратного рассеивания из натриевого слоя были получены телескопом с главным зеркалом $\Phi 1000$ мм.

Ключевые слова: лидар, ионосферный слой, двойной натриевый слой.

Abstract. We study the property of double sodium layer structures (DSLs) in the mesosphere and lower thermosphere (MLT) by a lidar at the low-latitude location of Haikou (20.0° N, 110.1° E), China. From April 2010 to December 2013, 21 DSLs were observed within a total of 377 observation days. DSLs were recorded at middle latitudes of Beijing and Wuhan, China, but were rarely observed at low latitudes. We analyze and discuss characteristics of DSLs such as time of occurrence, peak altitude, FWHM, duration time, etc. At the same time, the critical frequency f_oE_s and the virtual height $h'E_s$ of the sporadic E layer E_s were observed by an ionosonde over Danzhou (19.0° N, 109.3° E). We discuss such their characteristics as differences of time, differences of altitude compared to DSLs. We used an Nd:YAG laser pumped dye laser to generate the probing beam. The wavelength of the dye laser was set to 589 nm by a sodium fluorescence cell. The backscattered fluorescence photons from the sodium layer were collected by a telescope with the $\Phi 1000$ mm primary mirror.

Keywords: lidar, ionospheric layer, double sodium layer.

INTRODUCTION

Earth's atmosphere has a thickness of about 120 km. The atmospheric layer between 80 and 110 km contains

neutral metal atoms such as sodium Na, iron Fe, potassium K, calcium Ca, etc. These neutral metal atoms can be detected by a ground-based lidar. The MLT composition is very complex. Meteor ablation occurs when me-

tears fly through this atmospheric layer, injecting metal particles into it and forming neutral metal layers. The density of these metal layers is affected not only by kinetic process, but by chemical process as well. Slipher et al. [1921] reported that the first discovery of sodium in the atmosphere was made in 1929. Bowman et al. [1969] first observed sodium layers in the atmosphere with a lidar. Climesha et al. [1978] first observed the occurrence of a sporadic sodium layer in the atmosphere. Gardner, Voelz [1985] has reported that sodium layers can be disturbed by gravity waves observed with a lidar in the same way as they can be impacted by a tidal wave [Gardner et al., 1986]. Kwon et al. [1987] first observed sodium layers during the daytime. Gardner et al. [1988] have reported that sodium layers are confined to a height 80–110 km and have complex physical, chemical, and kinetic interactions with other atoms, molecules, and ions. According to [Gong et al., 2003], if a sodium layer appears at 105–125 km and is clearly separated from the normal sodium layer (80–105 km), it is called the double sodium layer structure (DSL). Wang et al. [2012] have reported that 17 DSLs were observed during 319 nights; it is equivalent to the 5.3 % probability of finding DSLs at a mid-latitude station (Beijing, China, 40° N, 116° E). In this paper, we report the observations of DSLs from April 2010 to December 2013, and we study characteristics of DSLs at low latitudes.

EQUIPMENT

A sodium resonance lidar is located in Haikou (20.0° N, 110.1° E), China. A tunable Nd:YAG pumped dye laser was used to generate a probing beam. The wavelength of the dye laser was set to 589 nm by using a sodium fluorescence cell. The energy, divergence, and repetition rate of the laser beam were ~42 mJ per pulse, 1 mrad, and 30 Hz respectively. The backscattered fluorescence photons from the sodium layer are collected by a telescope with the primary mirror of diameter 1000 mm. The field of view of the telescope was normally set to ~2 mrad, and the bandpass of the optical filter was ~1 nm. A cooled PMT, fast amplifier, and time-resolved photon counter were used for signal detection, and a computer was used for data collection. Each lidar file contains 5000 laser pulses with an altitude resolution of 97 m. This corresponds to about 3 min for the 30 Hz repetition rate of the laser.

Data have been acquired by the DPS-4 ionosonde over Danzhou, China (19.0° N, 109.1° E), the station closest to the lidar. In this configuration, the lidar and ionosonde detected nearly the same range in the mesopause region. It records data automatically every 15 min, and its frequency scans from 0.5 to 15 MHz for 150 s to create a data file. For comparison, we have chosen data obtained with both the ionosonde and the lidar at Haikou from April 2010 to December 2013. The ionosonde SAO files provide information on E_s -layer parameters such as f_oE_s and $h'E_s$.

OBSERVATIONS

Referring to Figure 1, DSLs were observed over Haikou, China on March 4, 2012 at 16:15 UT. This Figure clearly shows that the second sodium layer appeared

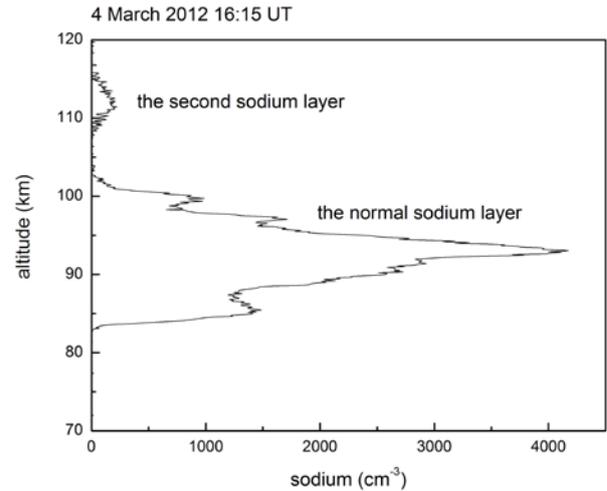


Figure 1. A typical DSLs structure observed at 16:15 UT on 4 March 2012 over Haikou

at an altitude of 108.0 to 115.2 km. The sodium layer had a peak density of 208 cm⁻³ and an altitude of 112.1 km. Its full width at half maximum (FWHM) was 3.1 km. The normal sodium layer was at altitudes 82.9–102.7 km and its main peak was at 93.0 km, the sodium density was 4172 cm⁻³, and FWHM of the normal sodium layer was 4.9 km. The ratio of the DSL peak density was 4.9 %. The gap between the second sodium layer and the normal sodium one was from 102.7 to 108.0 km; the sodium density was nearly zero. The second sodium layer was independent of the normal sodium layer. According to [Gong et al., 2003], it was typical of DSLs.

We have found 21 DSLs in total for 377 days from April 2010 to December 2013; it is a 5.5 % probability of finding DSLs over Haikou, China. This result indicates the probability of DSL occurrence at low and middle latitudes. In addition, in the DSLs over Haikou the density of the second sodium layer was low, no more than 1000 cm⁻³. Table 1 lists the main parameters of the DSLs, including date, universal time of occurrence, etc.

To determine the characteristics of the DSLs over Haikou, we have statistically analyzed the four-year observation data presented in Figure 2. Figure 2, *a* shows a histogram of the number of DSLs for each month of observation. The DSLs are demonstrated to occur generally in May, June, July, and August, occasionally in March, November, and December; they are not observed in January, February, April, September, and October. This conclusion is similar to that made by Wang et al. in Beijing [Wang et al., 2012], where DSLs occur only in spring and summer. Figure 2, *b* shows the hours when the DSLs were observed. From the observation, DSLs more frequently appeared from 13:00 to 16:00 UT. Figure 2, *c* shows the peak altitude of the second sodium layer. The peak altitude was more likely to be lower than 110 km, and less likely to be higher than 110, which was quite different from the Beijing observations from 110 to 125 km [Wang et al., 2012]. FWHM of the second sodium layer, shown in Figure 2, *d*, was between 1.5 and 5.0 km.

At present, theoretical studies indicate that the sodium layer is closely related to the E_s layer. Since the second sodium layer is in DSLs, it is located between 105

Table 1

The main characteristics of DSLs at Haikou, China (20.0° N, 110.1° E)

No.	Date	Time ^a , UT	Density ^b , cm ⁻³	Peak altitude, km	FWHM ^c , km	Duration, min	RPD ^d , %
1	7 May 2010	15:27	429	108.6	3.9	50	9.8
2	8 May 2010	16:04	344	106.5	2.6	42	10.4
3	13 May 2010	17:04	344	108.3	1.7	111	12.4
4	19 June 2010	15:12	200	105.0	3.0	86	10
5	13 July 2010	<13:37	255	107.9	3.1	108	10.5
6	7 Nov. 2010	14:22	616	105.3	1.8	125	15.4
7	29 Dec. 2010	16:24	133	105.6	1.4	17	10.7
8	6 May 2011	<13:08	213	108.6	3.0	25	5.8
9	18 May 2011	15:04	293	107.3	2.1	47	6.5
10	29 May 2011	14:44	993	106.6	2.8	106	37.2
11	12 June 2011	14:51	141	108.2	2.1	159	2.4
12	17 June 2011	14:24	477	106.5	2.3	256	25.4
13	1 July 2011	15:48	53	115.1	1.9	92	3.2
14	3 July 2011	16:09	135	109.6	3.6	72	3.8
15	14 Aug. 2011	<12:30	103	106.5	1.9	57	6.1
16	22 Aug. 2011	15:17	140	109.4	3.1	67	6.7
17	4 March 2012	16:15	208	112.1	3.1	69	4.9
18	5 June 2012	14:58	454	109.2	4.6	119	13.5
19	1 July 2012	13:59	407	109.3	2.7	133	13.3
20	9 May 2013	<11:40	540	106.7	1.7	98	30.7
21	1 Dec. 2013	21:22	198	108.6	1.8	59	6.9

^aTime is the second sodium layer beginning.

^bDensity is the peak density of the second sodium layer.

^cFWHM is full width at half maximum of the second sodium layer.

^dRPD is the ratio of peak density between the second sodium layer and the normal sodium layer.

< denotes that the beginning of the second sodium layer was not detected.

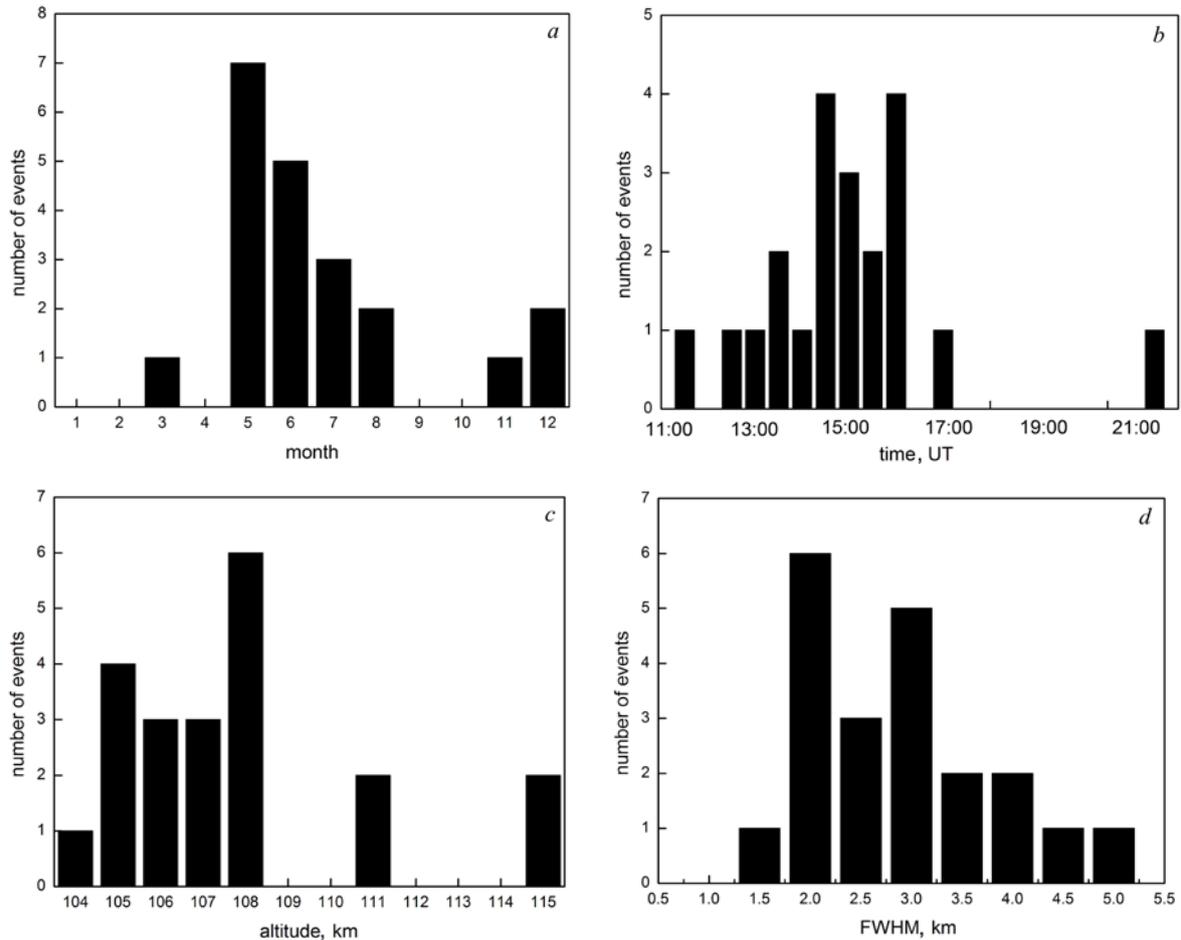


Figure 2. Statistics of DSLs: the month in which DSLs occurred (a); the time when DSLs occurred (b); altitude of the second sodium layer (c); FWHM of the second sodium layer (d)

Table 2

The main parameters of Es observed over Danzhou (19.0° N, 109.3° E).

No.	Date	$h'E_s$, km	f_oE_s , MHz	Duration, min	Time difference, min	Altitude difference, km
1	7 May 2010	–	–			
2	9 May 2010	–	–			
3	14 May 2010	106.3	5.38	60	–44	2.0
4	19 June 2010	113.8	5.58	135	–15	–8.8
5	13 July 2010	107.5	5.00	225	23	0.4
6	7 Nov. 2010	107.3	3.25	150	–76	–2.0
7	30 Dec. 2010	109.4	5.28	60	16	–3.8
8	6 May 2011	108.8	5.15	30	–8	–0.2
9	18 May 2011	109.4	4.40	180	–30	–2.1
10	29 May 2011	111.3	5.17	120	44	–4.8
11	12 June 2011	115.0	5.28	150	19	–6.8
12	17 June 2011	105.0	5.08	285	7	1.5
13	1 July 2011	110.0	3.50	60	–108	11.3
14	4 July 2011	112.5	3.55	135	–18	–2.9
15	14 Aug. 2011	108.8	5.30	120	–80	–2.3
16	22 Aug. 2011	111.3	5.50	75	20	–1.9
17	5 March 2012	–	–			
18	5 June 2012	–	–			
19	1 July 2012	107.5	3.77	90	–10	–2.0
20	9 May 2013	103.8	4.30	150	–113	–7.1
21	2 Dec. 2013	–	–			

Notes. “–” means that there are no E_s data. Time difference is the time between DSL and E_s peaks; the negative value indicates that first E_s appeared and then DSLs. Altitude difference is the second sodium layer of DSLs and $h'E_s$; the negative value suggests that $h'E_s$ is earlier than DSLs.

and 120 km in the ionosphere. We have analyzed the change in E_s with the occurrence of DSLs. Table 2 lists the main parameters of E_s observed over Danzhou (19.0° N, 109.3° E), when DSLs occurred over Haikou. When DSLs were observed, we compared the simultaneous E_s with complete data records. Table 2 presents 16 events in total, including $h'E_s$, f_oE_s , E_s duration, etc. The time difference is between DSLs and E_s ; the negative value means that first E_s appeared and then DSLs. The altitude difference is between the second sodium layer and E_s ; the negative value implies that E_s was higher than DSLs. As can be seen in Tables 1 and 2, E_s is strongly sporadic in the presence of DSLs. When DSLs occurred, 62.5 % of f_oE_s exceed 5 MHz. The time difference between DSLs and $h'E_s$ is within ± 60 min (75.0 %). We can also see that the altitude difference is within ± 2 km (62.5 %), within ± 5 km (87.5 %). According to the analysis of E_s , DSLs are closely related to E_s .

DISCUSSIONS

Since the lidar and the ionosphere were not located at the same place, weather conditions and equipment of the two places were more uncertain. There was a smaller amount of recorded data from the two places for the same time. We have figured out that DSLs and E_s interrelate and have determined the time difference and the altitude difference for the DSLs and E_s data. We selected the DSLs observed on May 13, 2010, and the data on E_s were also relatively complete. As shown in Figure 3, *a*, the density and altitude distributions were recorded from 13:30 to 21:30 UT. As can be seen from the Fig-

ure, the DSLs lasted for 111 min from 17:04 to 18:55 UT; during this period, the DSLs appeared three times (indicated by the arrow). The first DSLs began at 17:04 UT, the density of the second layer was up to 344 cm^{-3} at 17:27 UT, and the altitude was 108.2 km. The second DSLs followed with an interval of 22 min between the two DSLs, the altitude of the second sodium layer was 108.8 km. At 18:28 UT, the third DSLs occurred, and the altitude of the second sodium layer was 106.0 km. Figure 2, *b* shows the distribution of f_oE_s and $h'E_s$ over Danzhou. From 13:15 to 15:00 UT, there was no E_s observed. At 15:15 UT, f_oE_s dropped to 4.35 MHz and $h'E_s$ increased to 117.5 km. Thus there were three consecutive E_s , the first E_s at 16:00 UT, f_oE_s at 4.60 MHz, and $h'E_s$ at 113.8 km. The second E_s was at 16:45 UT, f_oE_s increased to 5.38 MHz, and $h'E_s$ decreased to 106.3 km. The third E_s was at 17:45 UT with the f_oE_s intensity of 5.31 MHz and $h'E_s$ at 112.5 km. The second and third f_oE_s were more intense, and two stronger E_s were 60 min apart. After 18:00 UT, the f_oE_s intensity started to decrease. At 21:15 UT, the f_oE_s intensity increased to 4.17 MHz and $h'E_s$ was at 103.8 km. According to the above observations, there were three E_s and three DSLs. The E_s occurred, on average, 60 min earlier than the DSLs and the altitude difference between $h'E_s$ and the second sodium layer was, on average, within 8 km. The occurrence of DSLs is shown to be related to E_s .

CONCLUSION

DSLs were observed with a lidar over Haikou, China (20.0° N, 110.1° E) from April 2010 to December 2013.

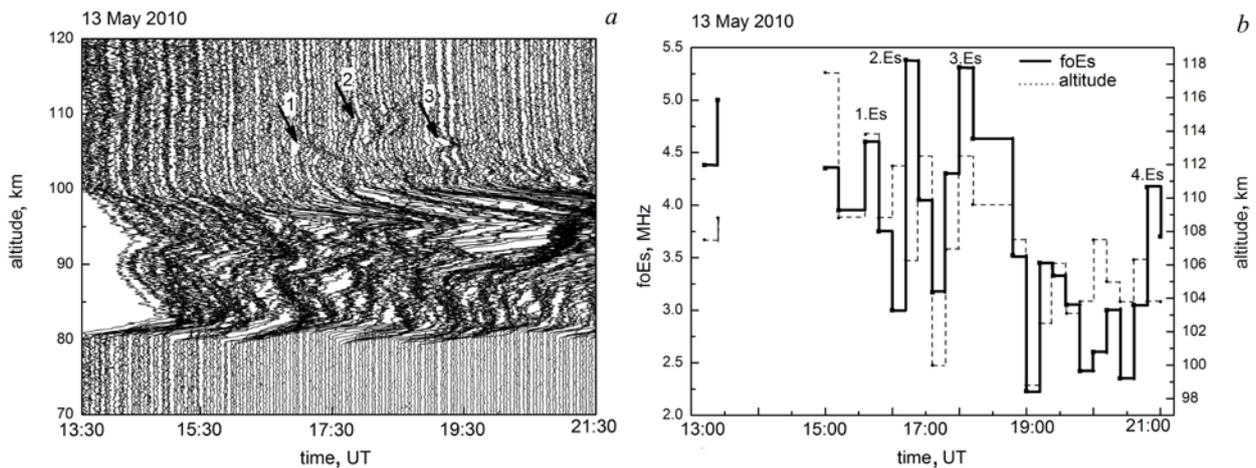


Figure 3. Distribution of the peak density and altitude during the occurrence of the second sodium layer over Haikou between 13:30 and 21:30 UT (a); distribution of f_oE_s and $h'E_s$ observed over Danzhou on May 13, 2010 from 13:00 to 21:00 UT (b)

We have found 21 DSLs during 377 observation days, which amounts to a 5.5 % probability. The probability of occurrence of DSLs at low latitudes is consistent with that at middle latitudes. DSLs occur generally in May, June, July, and August. In addition, the density of the second sodium layer of DSLs was low, no more than 1000 cm^{-3} . According to the analysis of DSLs and E_s , DSLs are closely related to E_s . The time difference between DSLs and $h'E_s$ is within $\pm 60 \text{ min}$ (75.0 %). We can also see that the altitude difference is within $\pm 2 \text{ km}$ (62.5 %) and within $\pm 5 \text{ km}$ (87.5 %).

This research is supported by National Natural Science Foundation of China under grant No. 41364005 and the Open Fund for State Key Laboratories under grant No. Y62612A87S. We acknowledge the State Meridian Project database for providing the data. We thank teachers and students of the lidar project team.

REFERENCES

- Bowman M.R., Gibson A.J., Sandford M.C.W. Observation of mesospheric Na atoms by tuner laser radar. *Nature*. 1969, vol. 221, no. 1, pp. 456–458.
- Clemesha B., Kirchoff V., Simonich D., Takahashi H. Evidence of an extra-terrestrial source for the mesospheric sodium layer. *Geophys. Res. Lett.* 1978, vol. 5, iss. 10, pp. 873–876. DOI: [10.1029/GL005i010p00873](https://doi.org/10.1029/GL005i010p00873).
- Gardner C.S., Voelz D.G. Lidar measurements of gravity wave saturation effects in the sodium layer. *Geophys. Res. Lett.* 1985, vol. 12, iss. 11, pp. 765–768. DOI: [10.1029/GL012i011p00765](https://doi.org/10.1029/GL012i011p00765).

Gardner C.S., Voelz D.G., Sechrist C.F., Segal A.C. Lidar studies of the night-time layer over Urbana Illinois. Seasonal and nocturnal variations. *J. Geophys. Res.* 1986, vol. 91, iss. A12, pp. 13659–13673. DOI: [10.1029/JA091iA12p13659](https://doi.org/10.1029/JA091iA12p13659).

Gardner C.S., Senft D.C., Kwon K.H. Lidar observations of substantial sodium depletion in the summertime Arctic mesosphere. *Nature*, 1988, vol. 332, pp. 142–144.

Gong S.S., Yang G.T., Wang J.M., Cheng X.W., Li F.Q., Wan W.X. A double sodium layer event observed over Wuhan, China by lidar. *Geophys. Res. Lett.* 2003, vol. 30, iss. 5, pp. 13–13-4. DOI: [10.1029/2002GL016135](https://doi.org/10.1029/2002GL016135).

Kwon K.H., Gardner C.S., Senft D.C., Roesler F.L., Harlander J. Daytime lidar measurements of tidal winds in the mesospheric sodium layer at Urbana, Illinois. *J. Geophys. Res.* 1987, vol. 92, iss. B8, pp. 8781–8786.

Slipher V.M. Emissions in the spectrum of the light of the night sky. *Publ. Astron. Soc. Pac.* 1929, vol. 41, pp. 262–263.

Wang J., Yang Y., Cheng X., Yang G., Song S., Gong S. Double sodium layers observation over Beijing, China. *Geophys. Res. Lett.* 2012, vol. 39, iss. 15, pp. L15801-1–L15801-5. DOI: [10.1029/2012GL052134](https://doi.org/10.1029/2012GL052134).

How to cite this article:

Dali Yang, Tiemin Zhang, Jihong Wang, Jianqing Wu, Linmao Wang, Xu Zou, Hongyan Peng. Characteristics of double sodium layer over Haikou, China (20.0° N, 110.1° E). *Solnechno-zemnaya fizika*. 2019. Vol. 5. Iss. 2. P. 30–34. DOI: [10.12737/szf-52201904](https://doi.org/10.12737/szf-52201904).