

Article

Atmospheric Optical Turbulence Characteristics over the Ocean Relevant to Astronomy and Atmospheric Physics

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Abstract: Due to the space and time constraints of turbulence measurement equipment and the experiment scene, it is difficult to obtain the atmosphere refractive index structure constant over the ocean. In this paper, the characteristics of atmospheric optical turbulence in offshore and open ocean conditions are summarized by analyzing the meteorological data obtained from two ocean atmospheric optical parameter field experiments. Because of the influence of land undersurface, the turbulence strength in offshore conditions is roughly the same as that on land and presents different characteristics in open ocean. Compared with the offshore area, the turbulence strength over the open ocean near-surface decreases during the day and increases at night, and the diurnal variation characteristics weaken. The turbulence strength profiles over the offshore area show different characteristics at different times, where the turbulence strength in the morning is higher than that in the evening. By retrieving the meteorological factors affecting the turbulence, it is found that the temperature gradient and wind shear are in good agreement with turbulence strength in both offshore and open ocean areas. Furthermore, the integrated parameters for astronomy and optical telecommunication are derived from profiles over the offshore and open ocean areas. It is of great significance to research the turbulent characteristics of ocean atmosphere for optical transmission and astronomical observations.

Keywords: optical turbulence; astroclimatic parameter; atmospheric physics; ocean and atmospheric optics



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1. Introduction

Fluctuations in the refractive index of the atmosphere, also known as optical turbulence, are caused by the wind blowing over the earth's surface and the temperature gradient between the earth's surface and the above air [1]. Atmospheric turbulence is a primary reason for laser beam wandering and spreading. It affects the observation of astronomical telescopes by limiting imaging quality and interfering with the propagation of laser beams [2,3]. Atmospheric turbulence strength is generally characterized by the structural parameters of the refractive index (C_n^2). Appropriate knowledge of C_n^2 and further understanding of optical turbulence characteristics are essential for improving the performance of adaptive optics (AO) systems and conducting astronomical observations.

Since the 1960s, quantitative measurement of optical turbulence strength of the visible light range at different heights is required in modern astronomy to improve the visibility of the focus of existing telescopes and to find new locations where new instruments can

be installed [4]. Astronomical site selection is a long and arduous process that requires a lot of manpower, material resources and financial resources. In order to deploy powerful facilities for astronomical observations, it is necessary to carry out many atmospheric optical turbulence investigations on astronomical locations. Investigating the optical turbulence over the ocean helps to further understand the atmosphere of the environment. Previously, some studies have been conducted on the ocean atmosphere. The structures and characteristics of a windy atmospheric boundary layer during a cold air outbreak in the ocean region are investigated by Cheng, who found that the main structures and characteristics are the same as during strong wind episodes with cold air outbreaks on land [5]. Based on data from the board measurement test through South China Sea Monsoon Experiment-II during June 2019, for the first time, the spatiotemporal distribution of optical turbulence over the South China sea and its sea surface was analyzed comprehensively by Shao et al. [6]. However, this study lacks the measured optical turbulence profile data. Additionally, Wu analyzed the Tropical Rainfall Measuring Mission Microwave Imager data for the period 1998–2007, which reveals large subseasonal fluctuations in sea surface temperature during the summer monsoon onset [7]. A study that analyzed radiosonde data was performed by Abahamid at various different astronomical sites. This was the first time that a complete median and average C_n^2 and outer scale profile, from the ground up to 30 km, was available [8]. The WRF Model was used to forecast the routine meteorological parameters firstly, and then was calculated based on these parameters by the Bulk model from the Monin–Obukhov similarity theory over the ocean near-surface, which was introduced by Qing and Wu [9]. Using the data from Shack–Hartmann wavefront sensor and reanalysis data, Bolbasova et al. presented the first seasonal study of the vertical distribution of wind speed and daytime optical turbulence conditions at the Baikal Astrophysical Observatory [10]. Furthermore, Chen and Li offered an investigation relevant to latent heat flux exchanges at the air–sea interface, which play important roles in the formation and development of tropical cyclones over the ocean [11]. Sparks and Hon presented an analysis of the first boundary layer flight observations on the ocean by the Hong Kong Observatory comprising four eyewall penetrations, which derived the vertical flux of momentum and vertical momentum diffusivity from observed turbulence parameters [12]. Based on generalizations of numerous measurements and calculations, Lukin found that the outer scale of turbulence in the surface layer of the atmosphere depends not only on the height above the underlying surface but also on the type of atmospheric stratification [13]. At present, although certain investigations have been carried out on the atmosphere of the ocean, the understanding of atmospheric optical turbulence, especially high-altitude atmospheric optical turbulence, is still very insufficient.

In this paper, through two measurement experiments for turbulence performance, we obtained a large amount of atmospheric optical turbulence data over the ocean. By using measured atmospheric data, the spatiotemporal distribution of optical turbulence over the ocean and corresponding ocean surface was analyzed comprehensively. The influence of various factors on the vertical distribution of turbulence strength are concluded. Furthermore, the value from measurement and the model is used to calculate the coherence length (r_0), the seeing (ϵ), the isoplanatic angle (θ_0), and the wavefront coherence time (τ_0) over the ocean.

2. Experiment and Methodology

2.1. Experiment Details

The first experiment, an offshore atmospheric optical turbulence in-situ measurement experiment, was implemented from 17 November to 24 December in 2017 in the south of Hainan Island. A field campaign of balloon-borne radiosondes equipped with micro-thermometers and GPS was conducted by the Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences. All the flights were released during the early morning at 7:40 or late evening at 19:40. At the same time, the turbulence strength near the ground was obtained [14,15]. A comprehensive description of micro-thermometer and its specifications

are given in [16–19]. During the experiment, the micro-thermometer was installed on a meteorological tower with an altitude of 130 m above sea level, which faced the South China Sea. Furthermore, an ultrasonic anemometer was installed at a distance of 1 m. The turbulence strength derived from two instruments was compared and verified to ensure the validity of the experimental data. The replacement cycle of the temperature sensing foil wires is about 3 days to ensure its sensitivity.

The open ocean experiment on measurement of atmospheric turbulence aboard ships was developed from October to November in 2020 in the southern part of the South China Sea. During the experiment, the micro-thermometer for near-surface turbulence measurement was always working. In order to reduce the influence from the ship to the instrument, the micro-thermometer extended about 3 m out of the ship. To obtain vertical profile characteristics of optical turbulence over the open ocean, balloon-borne radiosondes equipped with micro-thermometers and GPS were also launched on the ship boat. Typical sunny weather was selected to analyze the optical turbulence strength characters on the open ocean. According to Taylor's freezing hypothesis, the air around the instrument can be regarded as stationary when the shaking amplitude of the ship is relatively small and the speed is relatively slow. The error of the turbulence strength measured by the micro-thermometer is small at this situation. In addition, in order to reduce the influence of salt aerosols on the platinum wires, we controlled the time period for replacing the platinum wires at about 3 days. Less aerosol accumulation makes the measured value more accurate. Similarly, an ultrasonic anemometer was installed at a distance of 1 m to ensure the validity of the experimental data. The photographs of balloon-borne micro-thermometer and experimental scenario picture of micro-thermometer are shown in Figure 1. The red point in the figure is the release position of our balloon-borne radiosondes.

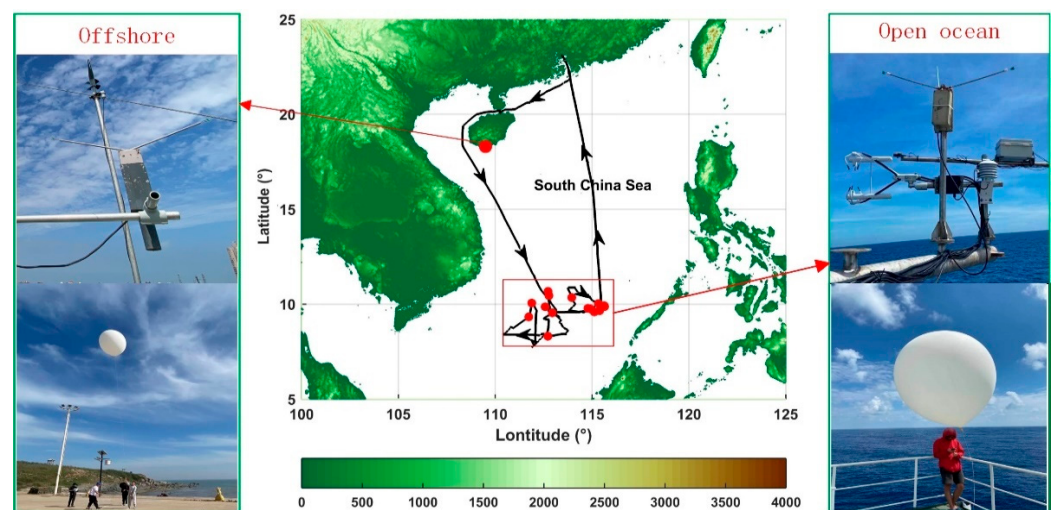


Figure 1. Photographs of a balloon-borne micro-thermometer and the micro-thermometer over the offshore (left) and open ocean (right).

2.2. Principle of C_n^2 Measurement

The values of C_n^2 measured by micro-thermometer are derived from a pair of horizontally separated micro-temperature probe wires. For visible and near-infrared wavelengths, the refractive index fluctuation mainly results from temperature fluctuation [17], and the C_n^2 is related to the corresponding temperature structure constant (C_T^2).

$$C_n^2 = \left(79 \times 10^{-6} \frac{P}{T^2} \right)^2 C_T^2 \quad (1)$$

where T is air temperature (K) and P is air pressure (hPa), Kolmogorov defined the C_T^2 as a constant of proportionality in the inertial subrange of the temperature structure function $D_T(r)$ and the C_T^2 can be described as following [3,20].

$$D_T(r) = \langle [T(x) - T(x+r)]^2 \rangle = C_T^2 r^{2/3}, l_0 \ll r \ll L_0 \quad (2)$$

where x and r denote the position vector, $\langle \dots \rangle$ represents the ensemble average, l_0 and L_0 are the inner and outer scales of turbulence and have units of m.

2.3. C_n^2 Estimation Model

C_n^2 estimation models are developed to convert standard meteorological data into the C_n^2 vertical profiles based on the basic theory of turbulence. According to Kolmogorov's theory, the Tatarski C_n^2 model [3] is

$$C_n^2 = a L_0^{4/3} M^2 \quad (3)$$

where a is a constant of 2.8 [17], L_0 is the outer scale, which is the largest scale of inertial range turbulence, and M is the potential refractive index gradient defined as

$$M = \frac{79 \times 10^{-6} P}{T^2} \frac{\partial \theta}{\partial h} \quad (4)$$

where M is related to atmospheric temperature (T), atmospheric pressure (P), and potential temperature (θ). h is the height above ground. From these Equations it can be noted that the vertical temperature gradient can be estimated from sounding data, and, thus, the selection of an appropriate L_0 is the key factor for estimating C_n^2 .

With the Tatarski model, several outer scale models have been proposed to estimate C_n^2 profiles from different atmospheric parameters. Among them, the HMNSP99 model is the most widely used [21–23]. The HMNSP99 model was developed at the Air Force Research Laboratory (AFRL) Holloman Spring 1998 and Holloman Spring 1999 thermosonde campaigns (New Mexico), and the statistical relationships relating L_0 parameterization to wind shear (S) and temperature lapse rate (dT/dh) [24]. The relationships are expressed as

$$L_0^{4/3} = \begin{cases} 0.1^{4/3} \times 10^{0.362+16.728S-192.347 \frac{dT}{dh}}, & \text{Troposphere} \\ 0.1^{4/3} \times 10^{0.757+13.819S-57.784 \frac{dT}{dh}}, & \text{Stratosphere} \end{cases} \quad (5)$$

where u and v are the north and east horizontal wind components.

2.4. Integrated Astroclimatic Parameters

The integrated value of C_n^2 allows us to predict the coherence length r_0 , the atmospheric optical quality in terms of seeing ε , as well as isoplanatic angle θ that depend on the local conditions at altitude h . The seeing ε is a crucial parameter that leads us to distinguish the most effective windows in the AO systems, which can be used to retrieve r_0 [25]. In addition, the wind speed and C_n^2 profiles are employed to calculate τ_0 , which shows how fast the turbulence is [26]. All the parameters are given as follows

$$r_0 = \left[0.423 \left(\frac{2\pi}{\lambda} \right)^2 \int_0^\infty C_n^2(h) dh \right]^{-3/5} \quad (6)$$

$$\varepsilon = 5.25 \lambda^{-1/5} \left(\int_0^\infty C_n^2(h) dh \right)^{3/5} \quad (7)$$

$$\tau_0 = 0.057 \lambda^{6/5} \left(\int_0^\infty |V(h)|^{5/3} C_n^2(h) dh \right)^{-3/5} \quad (8)$$

$$\theta = 0.057\lambda^{6/5} \left(\int_0^\infty h^{5/3} C_n^2(h) dh \right)^{-3/5} \quad (9)$$

3. Results and Discussion

3.1. C_n^2 Evolution Trend

The refractive index structure constant is the most important index indicating optical turbulence strength. To better investigate the surface turbulence strength, dual timelines are chosen here to characterize the variation of C_n^2 . The comparison of the variation of C_n^2 between offshore and open ocean areas is depicted in Figure 2. In the figure, both the x -axis and the y -axis are time axes, respectively representing 24 h of a day and 30 days of a month. As shown in Figure 2, the refractive index structure constant has a relatively typical ‘seesaw’ feature near the ocean surface in the offshore area. The turbulence strength is stronger between about 07:00 in the morning and 18:00 in the evening, and weaker at other times, which is basically in the range of 10^{-17} – $10^{-12} \text{ m}^{-2/3}$. The offshore experiment was mainly carried out in winter, and strong turbulence was measured during the daytime, which is consistent with the result of C_n^2 statistics estimated by Shikhovtsev [27]. Compared with values in the offshore area, C_n^2 over the open ocean in daytime, especially around noon, declines, in the nighttime increases, and is generally close to a constant value $2 \times 10^{-14} \text{ m}^{-2/3}$. The typical ‘seesaw’ feature disappears farther than 160 km from coast. According to the reference [27,28], the optical turbulence over open ocean is mainly controlled by air temperature gradient. It may be the result that the open ocean has lower air temperature compared with offshore during the daytime, which inhibits the development of turbulence. At night, the ocean surface temperature is higher than offshore, resulting in a larger temperature gradient, so the turbulence strength is enhanced. When the scientific research vessel is approaching land, the variation characteristics of C_n^2 are again consistent with the offshore area.

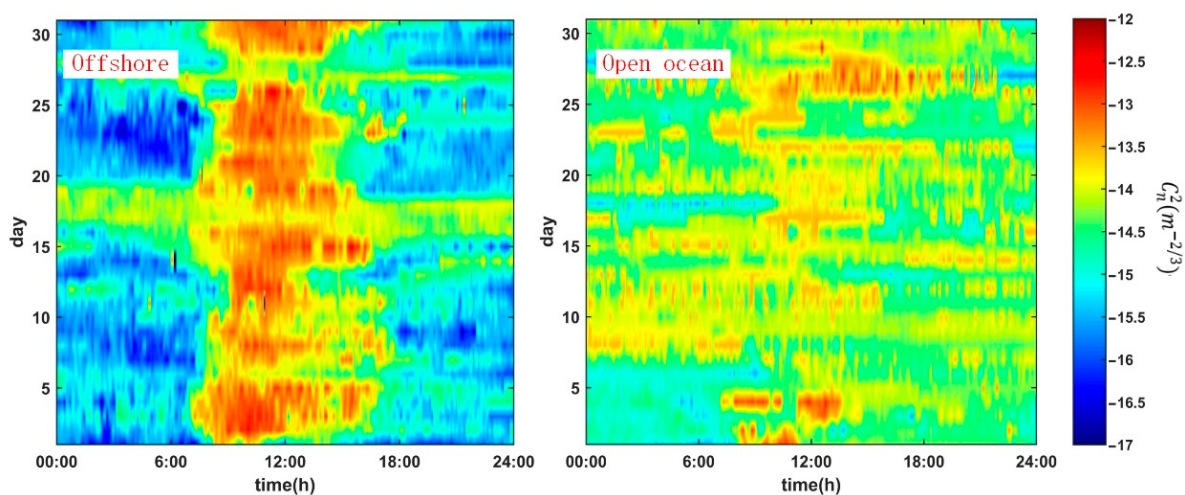


Figure 2. Distribution of diurnal curve of C_n^2 over the offshore and open ocean surface.

In order to obtain the variation characteristics of refractive index structure constant profile, eight balloon-borne radiosondes were launched at different moments during the open ocean. The result is shown in Figure 3, where the whole trend is turbulence strength decreasing with height at different time, but there are inverse increases at height intervals. The profiles reveal that the value of C_n^2 drops steeply with height near the ocean surface, then gradually increases from the boundary layer to the low stratosphere and again decreases with altitudes in the free atmosphere thereafter. The profile peaks correspond to the tropopause at around 15 km. Compared with C_n^2 profiles of different moments, it is concluded that optical turbulence strength is strongest at noon and at its maximum is close to $5 \times 10^{-13} \text{ m}^{-2/3}$. In contrast, optical turbulence strength is relatively weaker at about

09:00 and 19:00, the minimum reaches the magnitude of $10^{-19} \text{ m}^{-2/3}$. Furthermore, the turbulence strength at 10:00 and 16:00 is also relatively strong, but slightly less than the turbulence strength value at noon.

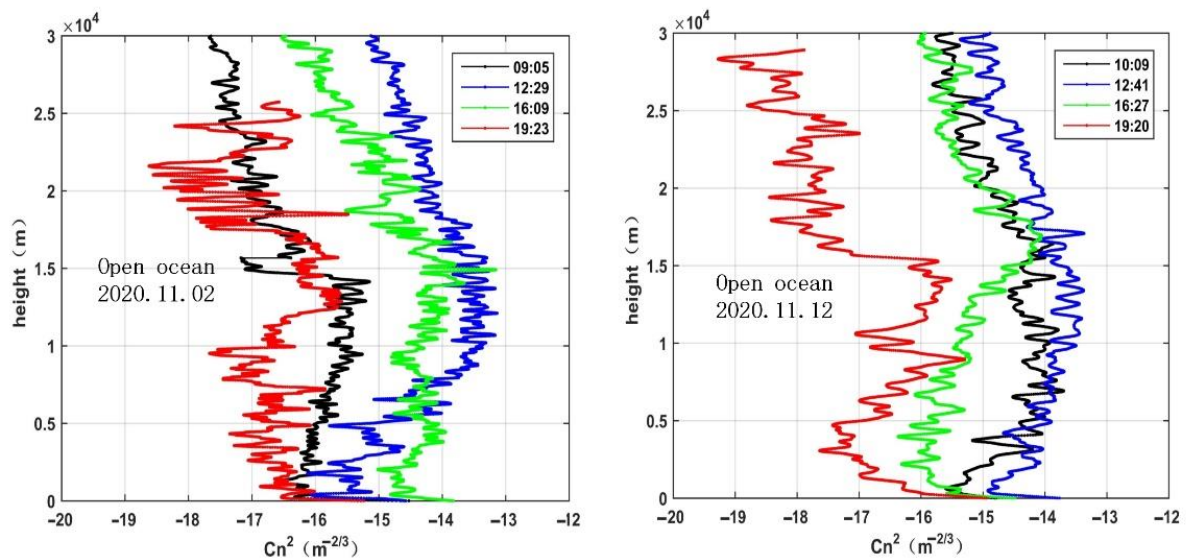


Figure 3. Vertical profiles distribution of C_n^2 over the open ocean.

Similarly, the profiles of two moments, 7:40 in the morning and 19:40 in the evening, measured by the balloon-borne micro-thermometer over the offshore area are illustrated in Figure 4. In the figure, the x -axis and y -axis, respectively, represent the number of soundings and the height above ground level. Thirty profiles are displayed at every moment. Note that no matter whether morning or evening, the optical turbulence near the ground is strong, and there exists the strong turbulent layers from 10 to 18 km. With a comparison of the turbulence strength in the morning and evening, it is well visible that the value of C_n^2 in the morning is larger. It is notable that the differences in C_n^2 between morning and evening are relatively small near the ocean surface, but significantly large from 10 to 18 km. In the morning, the turbulence strength of the near-surface layer and the strong turbulence layer from 10 to 18 km are at the same magnitude. Compared with the morning, the turbulence strength near the surface in the evening is greater than the 10 to 18 km layer.

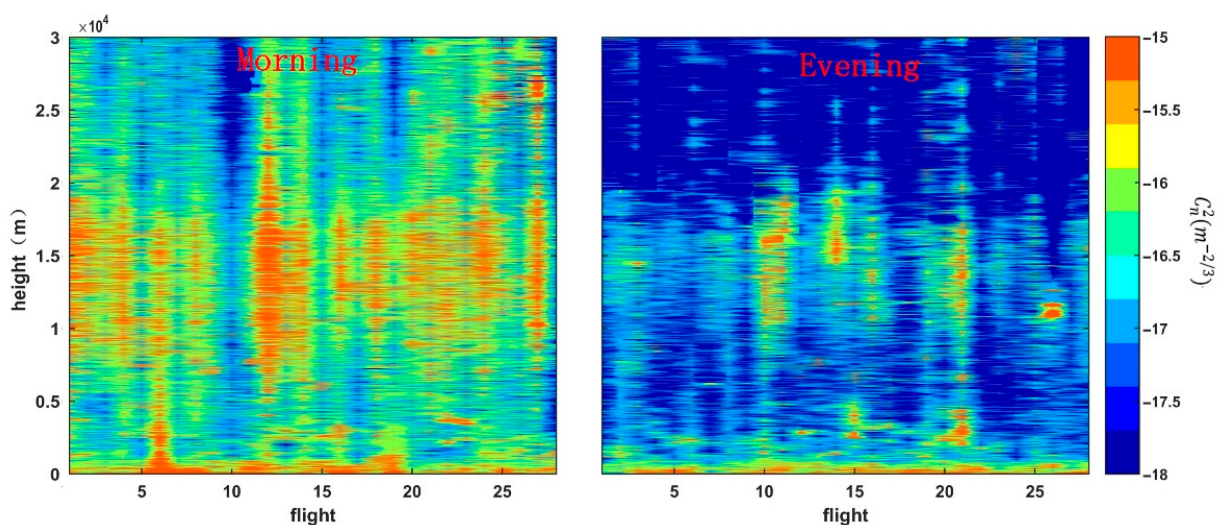


Figure 4. Vertical profiles distribution of C_n^2 at two moments over the offshore area.

3.2. Analysis of Influencing Factors

Based on the previous equation, it is known that the surface optical turbulence strength is proportional to the variance of air temperature variation at a fixed distance. However, for the turbulence strength profile, there are many associated factors. Previous research has shown that turbulence can be brought out by a buoyancy heat bubble and wind shear. According to the currently widely used HMNSP99 model, the relationship is investigated between the two factors and turbulence strength profile. The HMNSP99 model was developed from the statistics of the connection between the outer scale to wind shear and temperature lapse rate at the Air Force Research Laboratory. The model contained more atmospheric parameters and might be better in line with the nature of the actual development of turbulence. The introduction of using this model to estimate the strength of optical turbulence is given in [29]. Figure 5 shows the C_n^2 profiles of estimated and measured, as well as the profiles of temperature gradient, wind shear, outer scale, and potential refractive index gradient. These profiles came from different launched sites from the open ocean area and the corresponding launched time points of three balloon-borne radiosonde were 23 October, and 3 and 4 November 2020.

As shown in Figure 5, although the magnitude of the four parameters is different, the profile fluctuation changes in similar degrees. At the same height, the variance trends of the four parameters are similar. Comparing the temperature lapse rate profiles and the wind shear profiles, the variations in the two parameters below 15 km are quite different and have good consistency above 15 km, which may cause the HMNSP99 model to use two equations when estimating L_0 . As for the profiles of outer scale and potential refractive index gradient, the L_0 has a maximum value near the ground and around 15 km, while M shows an inverse increase above 15 km. Among the four parameters, the outer scale, whose variance trend is the closest to the turbulence strength, is obviously dominant since its value is higher than other parameters with the order of magnitude multiple. It can conclude that the profiles are related to several influence factors, but the outer scale has the biggest influence weight among them. The result shows that it is reasonable to use the HMNSP99 model to estimate C_n^2 profiles, which adds more meteorological parameters to obtain a relatively accurate outer scale. The differences between the model and the measurement are relatively small from 3 to 15 km. Differences in fine structure may be attributed to the surroundings that have a mutual effect on atmospheric conditions and, hence, on optical turbulence.

Figure 6 shows the profiles of the same characters with Figure 5 except that the experiment site is offshore and the corresponding releasing time points are 07:40 and 19:40, when the turbulence strength is in the weaker period. The variation characteristics of the turbulence strength profiles and four parameters' profiles with height is similar. However, there is little disagreement between the estimated results and the measurement results in the offshore area, where the C_n^2 estimated by the HMNSP99 model is closer to the measured value over 15 km. In general, the profiles obtained by the model are in accordance with the profiles obtained by the radiosonde measurement. Certainly, there is still some room to improve the estimated model.

From the previous discussion, we know that the outer scale contributes more than other parameters. Therefore, it is necessary to study the outer scale characteristics. Figure 7 shows the statistically averaged outer scale profiles of offshore and open ocean areas. Obviously, the outer scale profiles of two scenes are consistent in trend. The profiles reveal the L_0 drops steeply near the ground, then gradually increases with altitudes from the boundary layer to the upper troposphere, subsequently decreases with altitudes to the lower stratosphere, and, finally, increases in the free atmosphere. The value peaks of L_0 correspond to the tropopause with altitudes around 13 km. However, the outer scale of the offshore area is smaller than that of the open ocean overall, and this could be the result of the difference in the location and the release time of the balloons between two experiments.

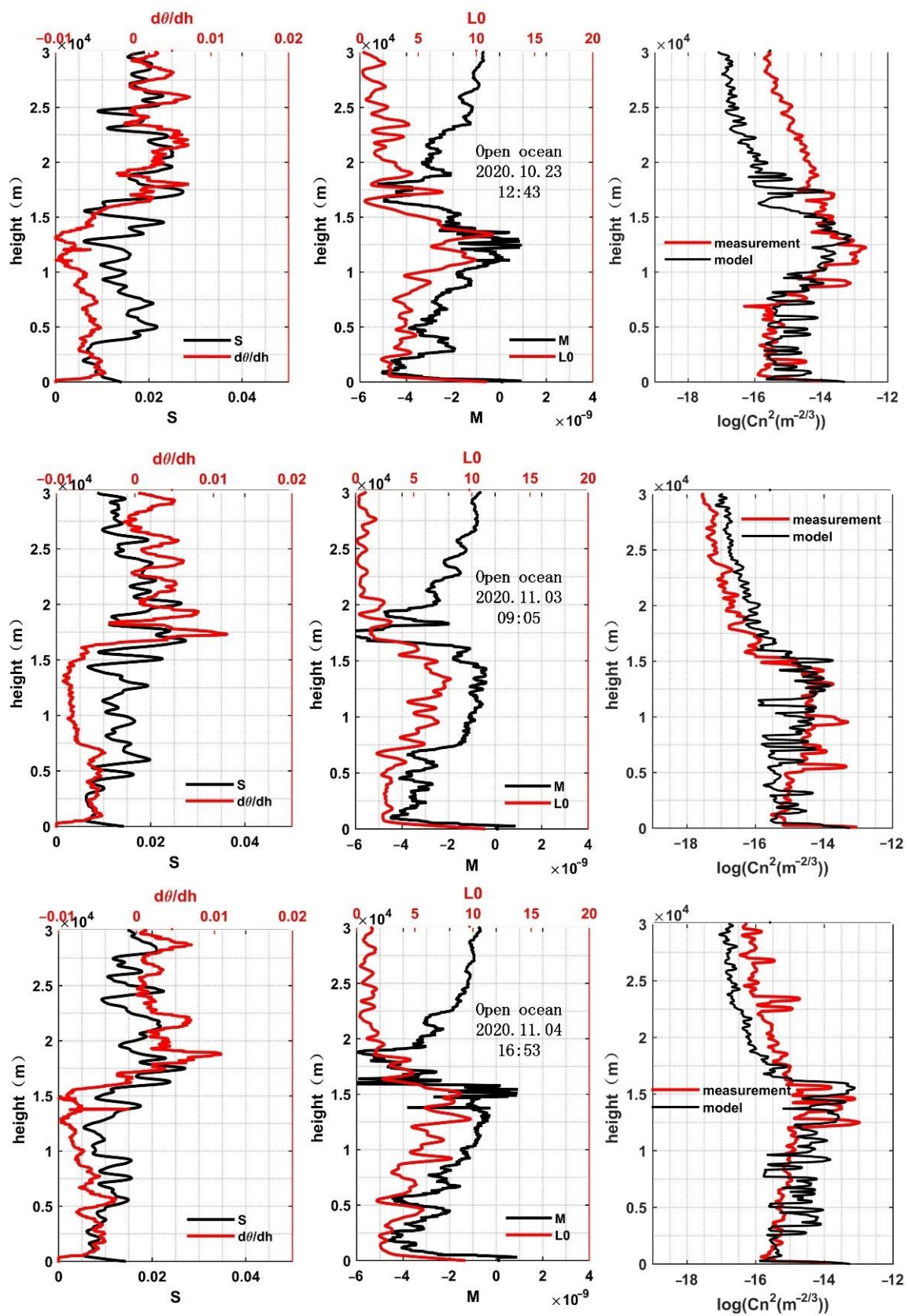


Figure 5. The profiles of temperature gradient, wind shear (left), outer scale and potential refractive index gradient (middle) as well as C_n^2 profiles of estimated and measured (right) in open ocean.

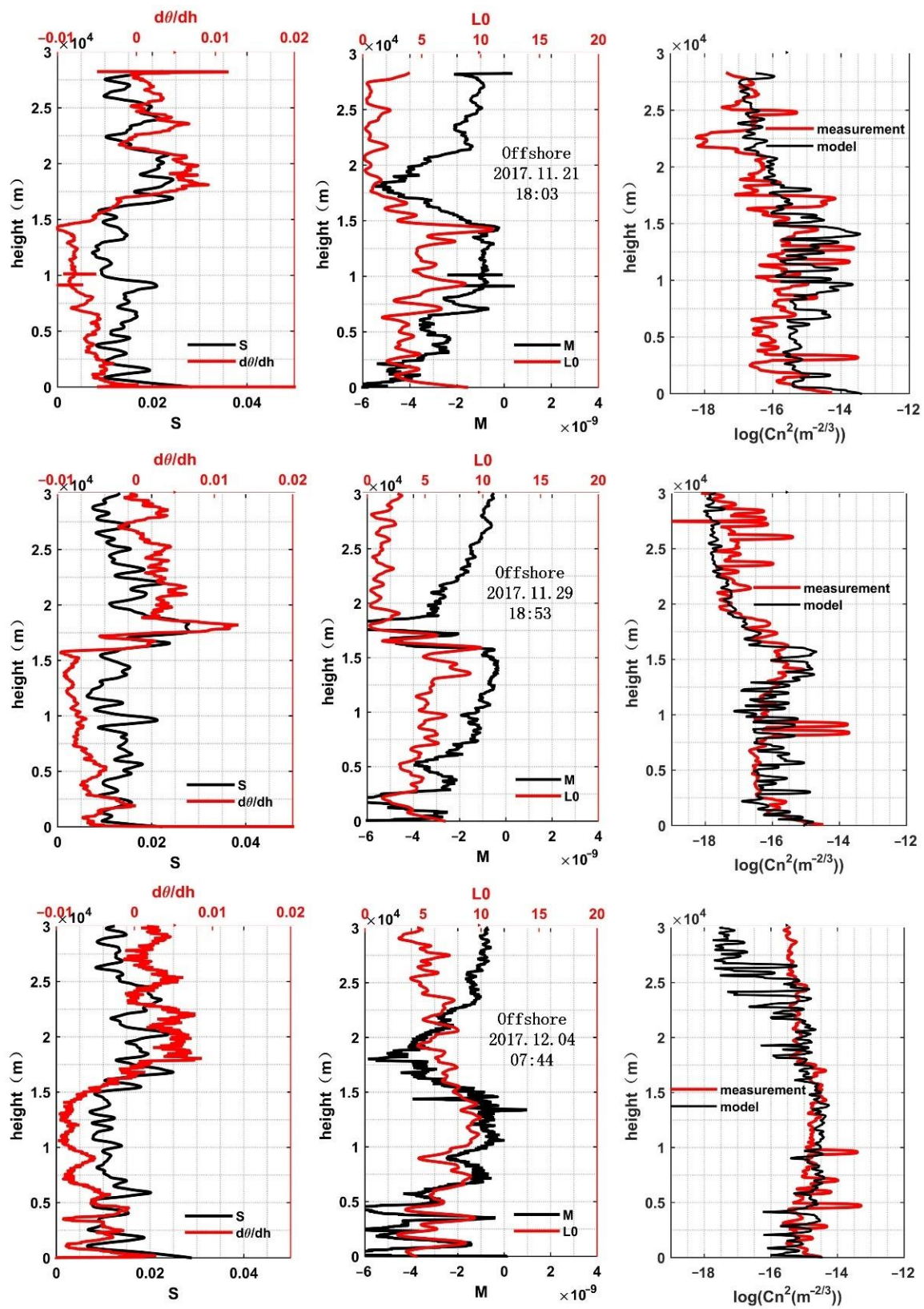


Figure 6. The profiles of temperature gradient, wind shear (left), outer scale, and potential refractive index gradient (middle), as well as C_n^2 profiles of estimated and measured (right) in offshore area.

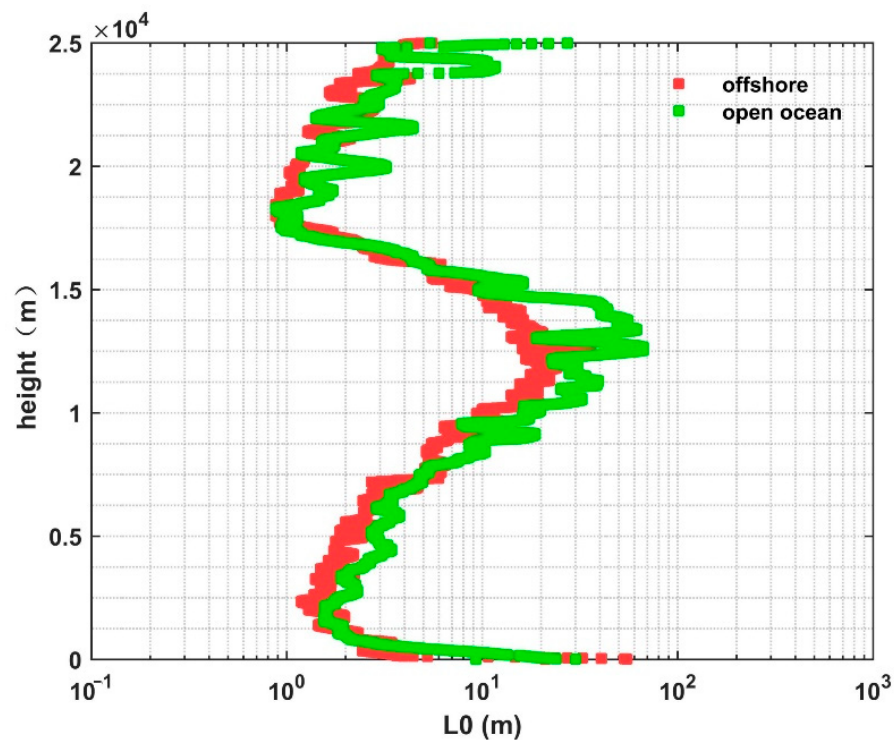


Figure 7. Statistically averaged outer scale profiles of offshore and open ocean.

3.3. Integrated Astroclimatic Parameters

The integrated parameters (coherence length r_0 , seeing ε , and isoplanatic angle θ , coherence time τ_0) derived from C_n^2 profiles are considered the main turbulence characterization parameters for astronomy and optical telecommunication [30–34]. The comparison of integrated parameters between the model and radiosonde is shown in Figure 8. For 532 nm light wave, the mean r_0 values from the radiosonde measurement are 2.45 cm and 1.05 cm at the offshore and open ocean, and the corresponding mean r_0 values from the model are 3.50 cm and 1.36 cm, respectively. Obviously, the mean r_0 from the radiosonde measurement at the open ocean is lower than the offshore area, which shows that the optical turbulence over open ocean is stronger than offshore. The result may be caused by our experimental site and the release time of the balloons. Contrary to r_0 , the ε of the open ocean is generally greater than that of the offshore, which once again verifies the strong turbulence over the open ocean. As shown in Figure 8, the θ of the open ocean and the offshore are similar, and most of the values are less than 0.5 arcsec. Furthermore, the characteristics of the coherence time τ_0 and the coherence length r_0 are almost the same, which shows that the development of turbulence over the open ocean is faster than that over the offshore area.

Furthermore, marine aerosols do have an impact on observations, but, compared with land, the atmospheric environment above the ocean is relatively stable and is less affected by humans. However, from the calculation results of the astronomical parameters, the optical turbulence is strong and the coherence length is small in the ocean, especially in the open ocean area, which is not conducive to astronomical observation. Therefore, the establishment of astronomical observation sites on the ocean has certain limitations. However, the results we have achieved are impressive and provide potential supports for the application of adaptive optics systems.

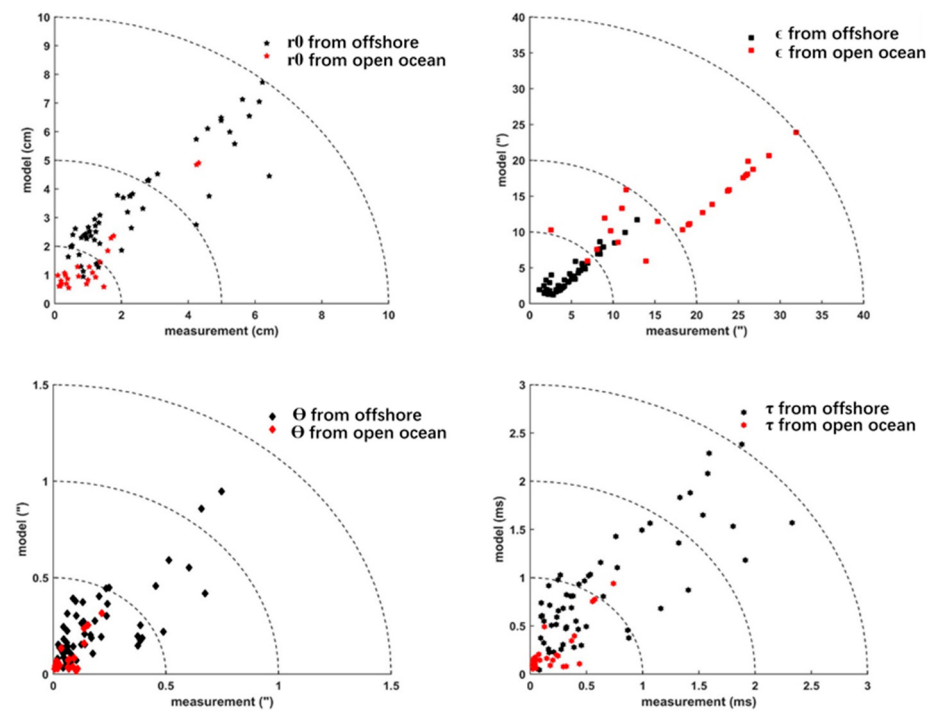


Figure 8. Integrated parameters (r_0 , ϵ , θ and τ_0) derived from C_n^2 profiles from offshore and open ocean.

4. Conclusions

In-depth research of ocean atmospheric turbulence is significant for discussion on laser beam propagating and astronomical observation. We investigated the strength of optical turbulence over the offshore and open ocean areas, the corresponding conclusions are as follows:

- (1) The refractive index structure constant has a relatively typical ‘seesaw’ feature near the ocean surface in the offshore area, which disappears farther than 160 km away from the coast. The optical turbulence strength from the ground up to 30 km is strongest at noon with a maximum value close to $5 \times 10^{-13} \text{ m}^{-2/3}$, and relatively weak at morning and dusk even near the magnitude of $10^{-19} \text{ m}^{-2/3}$ over the open ocean. For turbulence strength profiles of the offshore area, the value of C_n^2 in the morning is larger than that in the evening.
- (2) Over the offshore and open ocean areas, the variance trends of the C_n^2 profiles are similar near the same height, and the outer scale has the biggest influence weight among influence factors. It is reasonable to use the HMNSP99 model to estimate C_n^2 profiles, although there is still room for improvement. Furthermore, the value of the outer scale of the offshore area is smaller than that of the open ocean overall, which may be caused by the difference in the location and the release time of the balloons.
- (3) The mean r_0 from the radiosonde measurement at the open ocean area is smaller than offshore, which agrees with the finding that the optical turbulence of the open ocean from the ground up to 30 km is stronger than offshore. Otherwise, the characteristics of the coherence time τ_0 present that the turbulence strength develops faster over the open ocean. The establishment of astronomical observation sites on the ocean has certain limitations. The results we have achieved provide potential supports for the application of adaptive optics systems and astronomical observation.

Author Contributions: Conceptualization, M.X. and S.S.; software, M.X.; validation, formal analysis, M.X., S.S. and N.W.; investigation, M.X.; resources, L.Z.; data curation, L.Z. and Q.L.; writing original draft preparation, M.X.; writing-review and editing, M.X.; visualization, M.X.; supervision, S.S., Y.Z.

and N.W.; project administration, funding acquisition, S.S. All authors have read and agreed to the published version of the manuscript.

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