



# Statistical Study of the Latitudinal and Seasonal Variations of Intermediate Descending Layers over China

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**Abstract.** This paper presents a statistical investigation of intermediate descending layers (IDLs) in the ionospheric E region using multi-station digital-ionosonde observations at Mohe, Wuhan, and Fuke. The measurements reveal clear descending structures, strong seasonal variability, and pronounced latitude-dependent local-time morphology. Mohe and Wuhan commonly exhibit morning and afternoon occurrence enhancements, with the morning layer generally stronger than the afternoon layer, whereas Fuke shows a broader daytime distribution in which the afternoon enhancement can exceed the morning enhancement and multiple local maxima may occur. Lomb–Scargle analysis of IDL virtual height identifies prominent 12-h and 24-h periodicities, together with a weaker 8-h component in some cases. We interpret the asymmetric morning–afternoon structure as the result of superposed atmospheric tides: the early peak is preferentially associated with diurnal modulation, whereas the later peak is more closely related to semidiurnal modulation. At Mohe and Wuhan, the larger morning occurrence rate is consistent with constructive superposition of the diurnal and semidiurnal components during the morning and weaker reinforcement during the afternoon. At Fuke, the weaker and less stable semidiurnal signature, together with the afternoon-dominant and occasionally three-peak morphology, suggests that a secondary 8-h (terdiurnal) contribution may become relatively more important in shaping the local-time distribution, although the dominant height periodicity remains near 24 h. These results support a latitude-dependent tidal-modulation framework in which several tidal components jointly organize the occurrence and descent of IDLs through wind-shear-driven ion convergence.

## 1 Introduction

IDLs are also a nonnegligible layer emerging between E-layer and F1-layer, and it detaches from the bottom side of F-layer, moves downwards to gradually merge with Es-layer (Chen, 2024). A key evolutionary feature is their continuous descent over time. A typical IDL evolution includes the formation of a thin enhanced ionization layer, a downward motion lasting several hours, and a clear local time dependence. IDLs directly reflect the redistribution of E region plasma under neutral atmosphere and electrodynamic forcing. They therefore provide valuable information for understanding ionospheric structuring and layering mechanisms. In some events, sporadic E (Es) layers may coexist with IDLs and show dynamical connections.



30 However, IDLs represent an independent type of ionospheric dynamical structure. Their morphological characteristics and spatiotemporal evolution still require dedicated investigation.

The earliest observational reports of IDLs date back to the 1930s (Appleton, 1933; Ratcliffe and White, 1933; Schafer and Goodall, 1933). Early studies confirmed that this ionospheric structure occurs at altitudes of 130–170 km, between the E and F<sub>1</sub> layers. Later, radar and ionosonde observations were used to systematically investigate the spatiotemporal evolution of IDLs in different longitudinal sectors (MacDougall, 1974, 1978; Rodger et al., 1981; Szuszczewicz et al., 1995; Wilkinson et al., 1992). The wind-shear theory proposed by Whitehead (1961) and Axford (1963) provides a classical explanation for their formation. According to this theory, wind shear can drive the vertical transport and convergence of long-lived metallic ions, thereby forming layered ionospheric structures. Under steady-state conditions, the vertical ion drift velocity can be quantitatively described by the wind shear theory. This velocity is determined jointly by the horizontal components of the neutral wind (meridional and zonal winds) and the inclination angle of the geomagnetic field. The occurrence frequency of IDLs shows clear seasonal and local-time variations. In summer, the enhanced activity of sporadic E layers can mask the IDL signals, leading to a lower detection probability. IDLs are mainly generated during the daytime. Their development starts around sunrise, and the descending motion persists throughout the day. Furthermore, at low latitudes, the occurrence characteristics of IDLs are largely unaffected by solar activity. In contrast, a significant difference in IDL occurrence frequency is observed in the equatorial region between solar maximum (2003) and solar minimum (2009). This phenomenon may be related to the displacement of the magnetic equator. The dynamics of IDLs are jointly regulated by atmospheric tides, gravity waves, and electric fields. These factors together determine the generation, steady-state maintenance, and descending motion of the layers (Santos et al., 2021).

To address this gap, we performed a statistical investigation of IDL occurrence characteristics using simultaneous Digisonde observations from three stations spanning different latitudes in China. We systematically compared their seasonal occurrence, altitude evolution, local-time distribution, descent behavior, and dominant periodicities. The results demonstrate significant latitudinal variations in IDL characteristics and provide a statistical basis for understanding their climatological behavior.



## 55 2 Observations and Methods

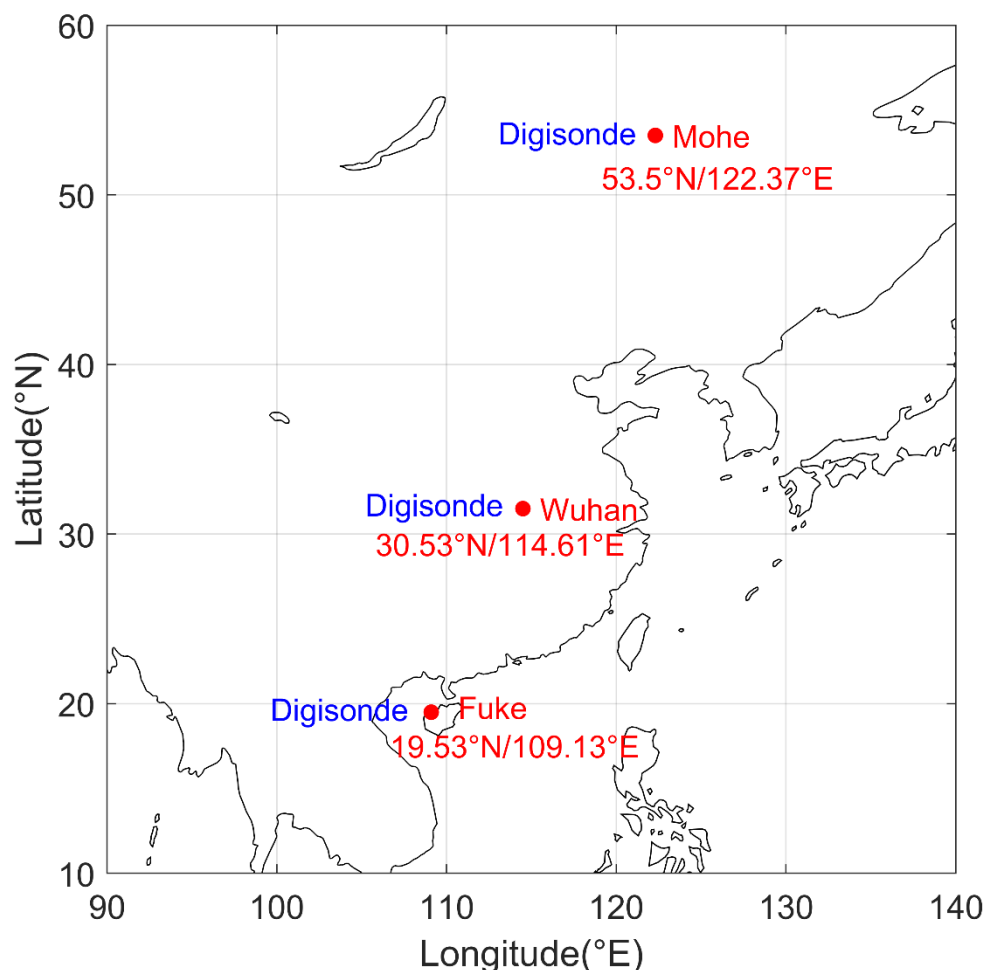


**Figure 1. Locations of the Digisonde stations at Mohe, Wuhan, and Fuke. The geographic coordinates of each station are indicated on the map.**

60 The statistical analysis is based on digital-ionosonde observations obtained from March 2020 to February 2021 at Mohe (53.5°N, 122.37°E), Wuhan (30.53°N, 114.61°E), and Fuke (19.53°N, 109.13°E). The three stations span high-, middle-, and low-latitude regions of China and are part of the Chinese Meridian Project observation network. Their locations are shown in Figure 1. The ionosondes operate over a frequency range of 1–20 MHz with a frequency step of 0.025 MHz. The original temporal resolution of the observations is 5 or 15 min, and the data are stored in the SAO Explorer Record Structure Format (RSF). To ensure consistency among the three stations, a uniform temporal resolution of 15 min was adopted for the statistical analysis. Files with incomplete sounding sequences or abnormal termination were excluded before further processing. IDL



events and their characteristic parameters were manually identified and scaled from the ionograms using SAO-Explorer. The maximum frequency of the continuous IDL trace is denoted as  $f_{\text{IDL}}$ , whereas  $h'_{\text{IDL}}$  represents the lowest virtual height of the IDL trace at which  $f_{\text{IDL}}$  is determined. To ensure consistent identification among the three stations, an IDL was identified when the bottom of the F1 layer detached downward and formed a distinct descending layer. In addition, a layer originating above 130 km and exhibiting continuous downward motion for more than 30 min was classified as an IDL. When a clear detachment from the F1 layer could not be observed, the event was still retained if the height and duration criteria described above were satisfied. An IDL event was tracked from its first appearance until the layer descended and became stable below approximately 105 km. After manual scaling, the derived ( $h'_{\text{IDL}}$ ) and ( $f_{\text{IDL}}$ ) sequences were inspected again to exclude ambiguous or incomplete events.

For an overview of the observed IDL climatology, monthly and seasonal occurrence variations at the three stations are presented in Figure 2. The seasons were defined as spring (March–May 2020), summer (June–August 2020), autumn (September–November 2020), and winter (December 2020–February 2021). The occurrence rate was calculated as the number of valid observation days with at least one detected IDL divided by the total number of valid observation days in the corresponding month or season. Figure 2 provides the statistical background for comparing the latitude-dependent occurrence characteristics of IDLs during the observation period. To investigate the local-time dependence of IDL occurrence, the observations were further analyzed using 15-min local-time bins. For each local-time bin, the IDL occurrence rate was calculated as the number of valid observations in which an IDL was detected divided by the total number of valid observations in that bin. Seasonal local-time distributions were then constructed to characterize the diurnal morphology of IDL occurrence and to compare the morning and afternoon occurrence enhancements among the three stations. To identify dominant periodic components associated with the observed local-time structures, Lomb–Scargle spectral analysis was applied separately to the seasonal  $h'_{\text{IDL}}$  series at each station. The analysis focused on periodicities within the 0–36 h range, with particular attention to the 8-, 12-, and 24-h components corresponding to terdiurnal, semidiurnal, and diurnal variability, respectively. The resulting normalized Lomb–Scargle spectra were used to compare the dominant periodic characteristics among different seasons and latitudes.

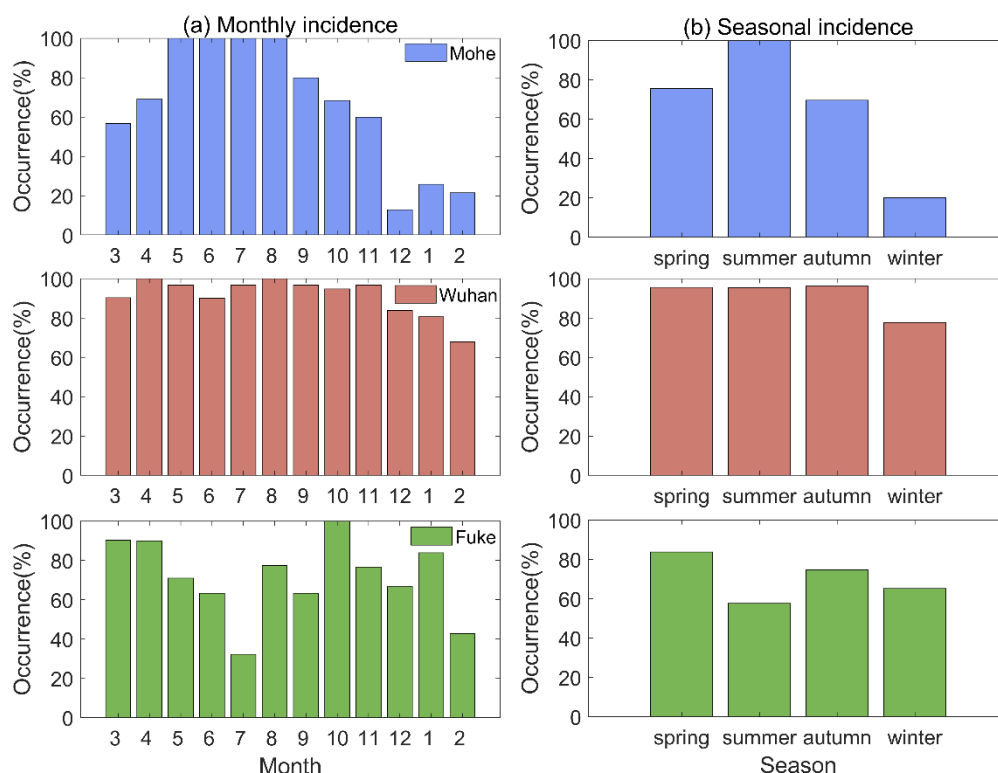


**Figure 2. Monthly (left column) and seasonal (right column) occurrence rates of the IDL at Mohe, Wuhan, and Fuke from March 2020 to February 2021. Rows from top to bottom correspond to the Mohe, Wuhan, and Fuke stations, respectively.**



### 3 Results

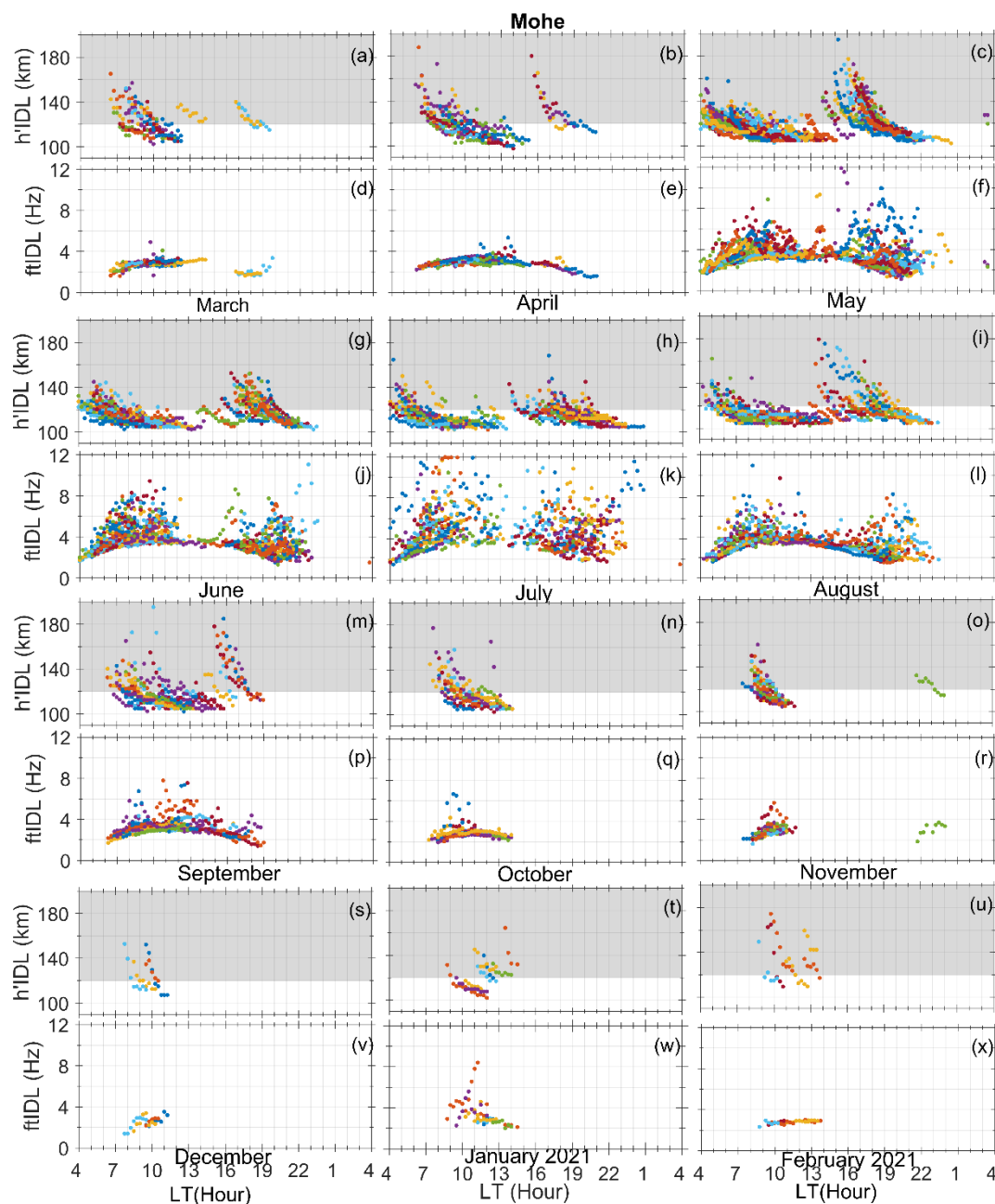
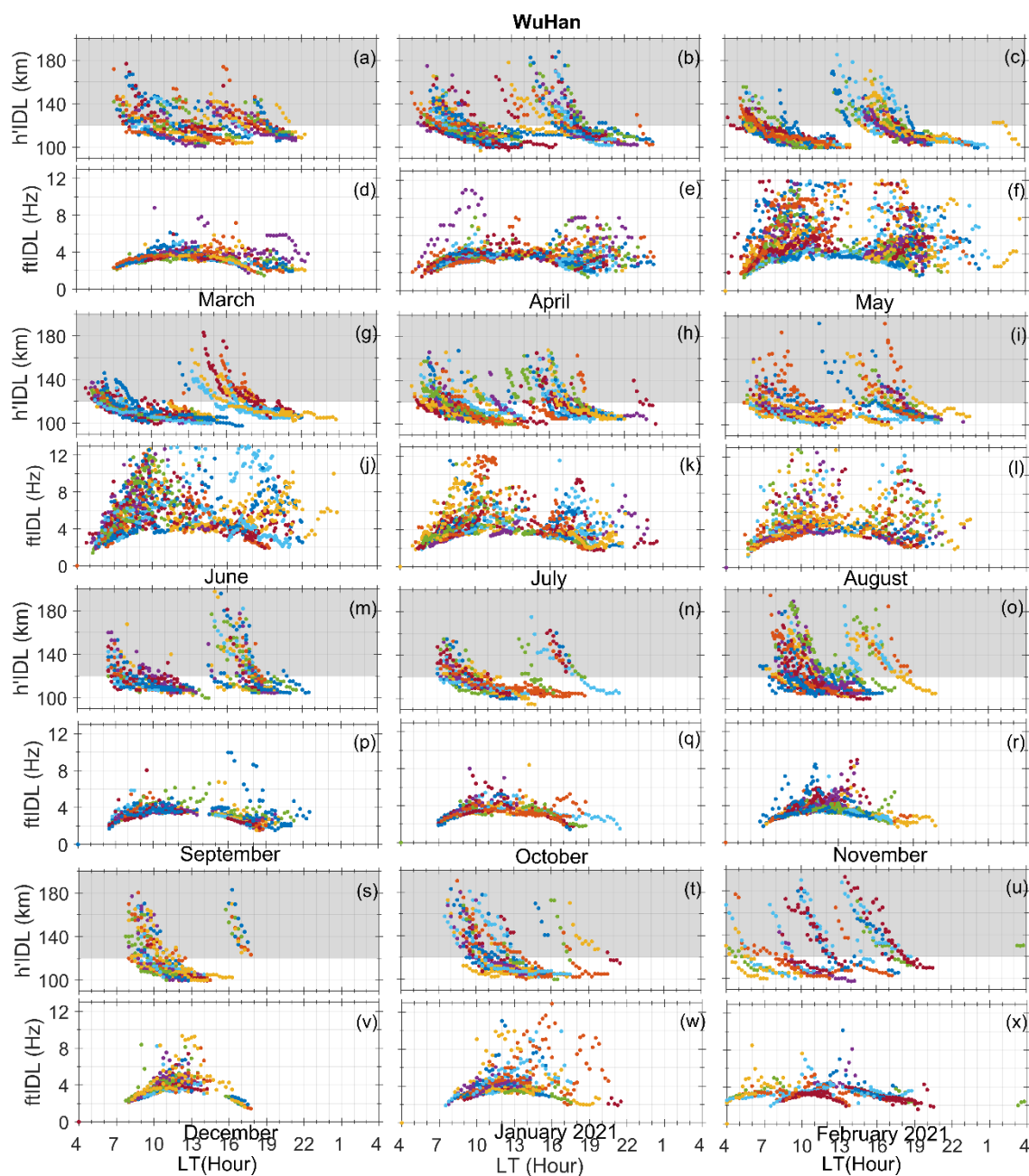


**Figure 3.** Monthly variations in the virtual height ( $h'_{IDL}$ ) and maximum frequency ( $ft_{IDL}$ ) of intermediate descending layers at Mohe from March 2020 to February 2021. For each month, the upper and lower panels show  $h'_{IDL}$  and  $ft_{IDL}$ , respectively, as functions of local time (LT). Different colors represent individual IDL events.



100 **Figure 4.** Monthly variations in the virtual height ( $h'_{IDL}$ ) and maximum frequency ( $ft_{IDL}$ ) of intermediate descending layers at Wuhan from March 2020 to February 2021. For each month, the upper and lower panels show  $h'_{IDL}$  and  $ft_{IDL}$ , respectively, as functions of local time (LT). Different colors represent individual IDL events.

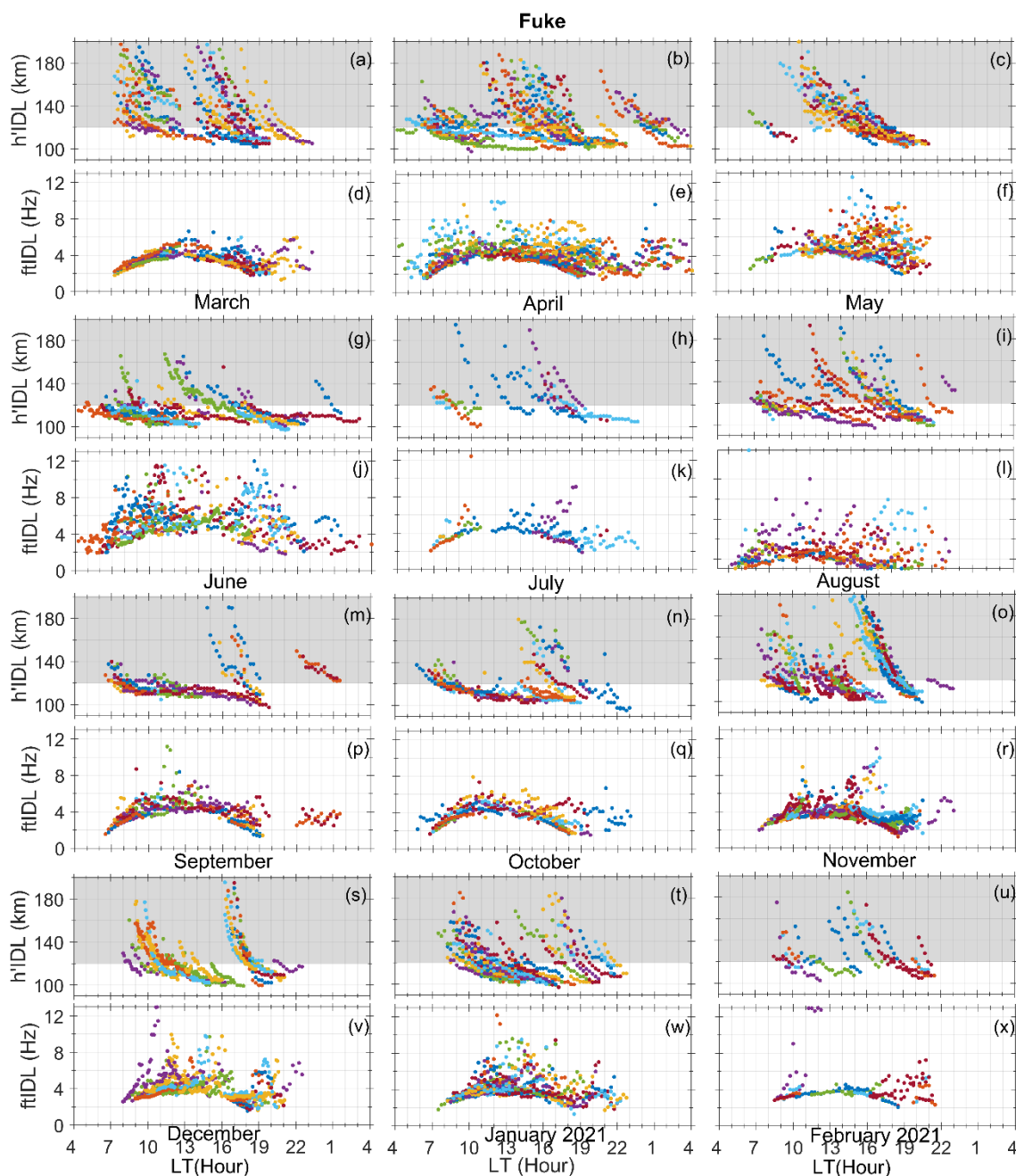


**Figure 5. Monthly variations in the virtual height ( $h'IDL$ ) and maximum frequency ( $ftIDL$ ) of intermediate descending layers at Fuke from March 2020 to February 2021. For each month, the upper and lower panels show  $h'IDL$  and  $ftIDL$ , respectively, as functions of local time (LT). Different colors represent individual IDL events.**



Figures 3–5 present the year-long evolution of individual IDL events at Mohe, Wuhan, and Fuke. At all three stations, most IDLs appear initially in the upper E region and subsequently descend to approximately 100–120 km over several hours, producing well-defined downward-sloping height–time trajectories. IDL occurrence is predominantly confined to daytime, although both the event density and local-time distribution exhibit pronounced seasonal and latitudinal differences. At Mohe, IDL activity is concentrated primarily in spring and summer. During these seasons, two groups of descending trajectories are frequently observed, with one occurring during the morning and the other during the afternoon or early evening. The afternoon branch becomes substantially weaker in autumn and is rarely observed in winter, when the total number of IDL events also decreases markedly. The corresponding  $f_{IDL}$  generally develops from relatively low values, increases during the evolution of the layer, and subsequently decreases as the event weakens. Wuhan exhibits much more persistent IDL activity throughout the year. Distinct descending trajectories are present in nearly all months, including winter, and both morning and afternoon/evening event groups can be identified during much of the year. The local-time coverage is broader than at Mohe, and many events descend from approximately 140–180 km toward the lower E region. The  $f_{IDL}$  values show substantial event-to-event variability, particularly during the more active months, while a general increase followed by a decrease is commonly observed during individual layer evolution. Fuke also exhibits persistent descending structures, but its local-time organization differs from that at the two higher-latitude stations. Individual events are distributed over a broader daytime interval, and the separation into distinct morning and afternoon branches is less regular. In several months, afternoon and evening descending events are comparable to or more prominent than the morning events, and multiple groups of descending trajectories can occur within the same day. Seasonal variability is also less monotonic than at Mohe, with reduced activity during parts of summer followed by renewed activity in autumn and winter.

Overall, Figures 3–5 reveal a clear latitudinal transition in IDL occurrence and evolution. Mohe is characterized by strong seasonal dependence and relatively well-organized morning–afternoon descending structures, Wuhan shows more persistent year-round activity with a broadly bimodal local-time pattern, and Fuke exhibits a wider and more complex daytime distribution with weaker separation between the morning and afternoon branches. Despite these regional differences, all three stations share the common feature of continuous downward motion from the upper E region toward lower altitudes. These event-scale characteristics provide the observational basis for the subsequent analyses of seasonal occurrence, local-time morphology, and dominant periodicities.

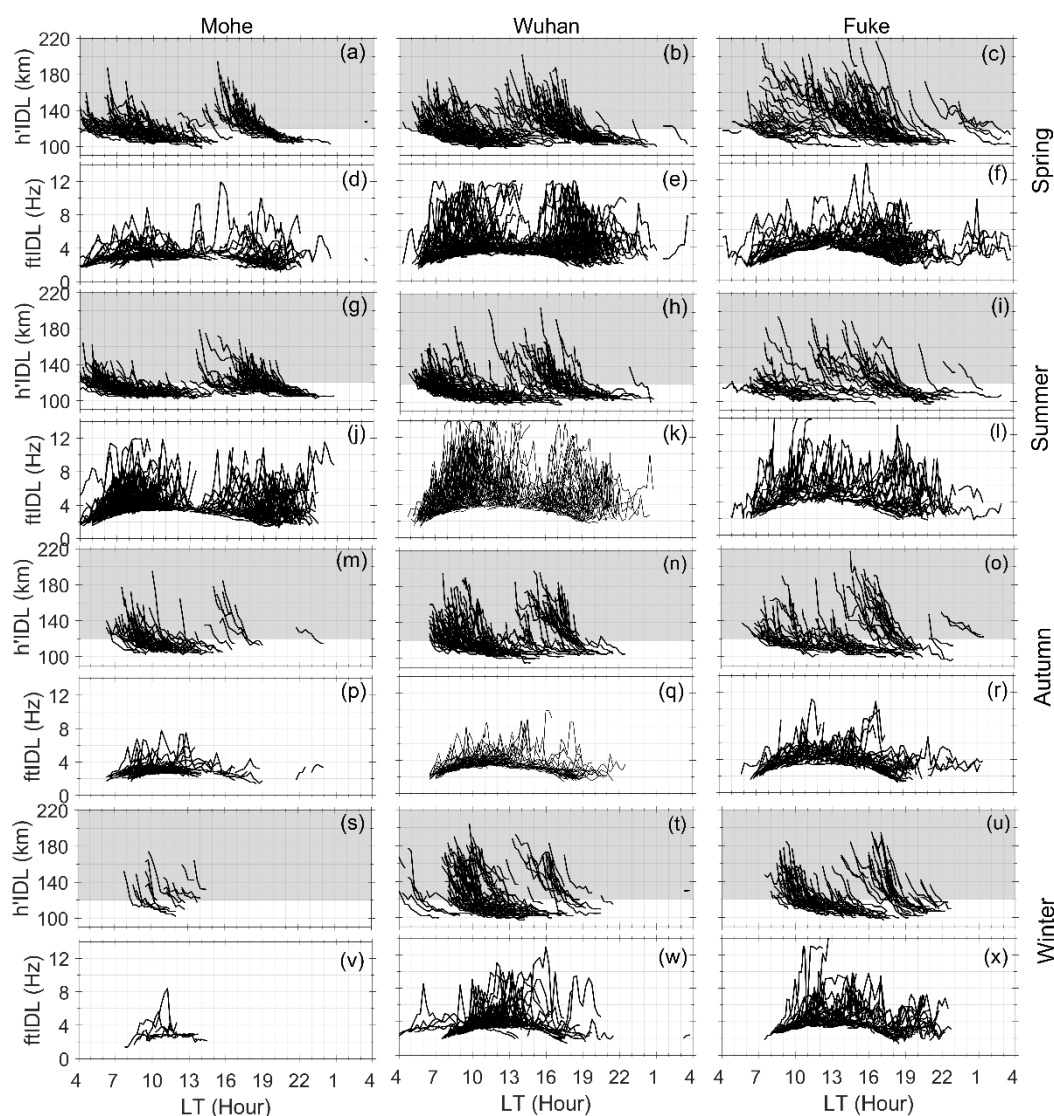


**Figure 6. Temporal variations of IDL height and maximum frequency over Mohe, Wuhan, and Fuke across seasons. Data from the Mohe, Wuhan, and Fuke stations are presented in the left, middle, and right columns, respectively. Panels (a)–(f) correspond to spring, (g)–(l) to summer, (m)–(r) to autumn, and (s)–(x) to winter.**

Figure 6 summarizes the seasonal evolution of ( $h'IDL$ ) and ( $ftIDL$ ) across the three latitude regions and provides a cross-station comparison of the event characteristics shown in Figures 3–5. The data are grouped into four seasons: spring (March–May 2020), summer (June–August 2020), autumn (September–November 2020), and winter (December 2020–February 2021). Overall, IDLs occur predominantly during daytime, with enhanced activity generally observed during the morning and afternoon/early evening. When ( $ftIDL$ ) reaches relatively high values, the corresponding ( $h'IDL$ ) is commonly located near



140 km. The local-time morphology shows clear latitudinal and seasonal differences. Mohe and Wuhan commonly exhibit a morning–afternoon double-peak structure, particularly during spring and summer, with the morning enhancement generally stronger than the afternoon enhancement. At Mohe, the afternoon branch weakens substantially in autumn and becomes much less evident in winter. Fuke differs from the two higher-latitude stations by exhibiting a broader daytime distribution, in which the afternoon enhancement can be comparable to or stronger than the morning enhancement, and more than two local maxima may occur in some seasons. The occurrence times also vary seasonally: at Mohe and Wuhan, the first enhancement generally occurs from morning to late morning and the second from afternoon to early evening, whereas at Fuke the occurrence is distributed over a broader daytime interval and the relative strength and number of local maxima vary more strongly with season. The (ftIDL) values also exhibit systematic temporal evolution during individual IDL events. In the bimodal pattern, the initial (ftIDL) of the afternoon layer is generally higher than that of the morning layer, with average initial values of approximately 4.41 and 2.6 MHz, respectively. During the subsequent evolution, (ftIDL) commonly increases during the early stage and then decreases as the layer weakens. For morning IDLs, the increase is generally more evident during the early stage, whereas afternoon IDLs tend to show a more gradual decrease after formation. In contrast, (ftIDL) variations are smaller and relatively stable during months characterized by a predominantly unimodal occurrence pattern.

## 4 Analysis and Discussion

### 4.1 Seasonal and latitudinal variations in IDL occurrence

160 The three stations show clearly different seasonal occurrence patterns. Seasonal variation is strongest at Mohe. IDLs remain common during most of the year at Wuhan, while their seasonal distribution is less regular at Fuke. As shown in Figure 2, IDL occurrence at Mohe increases strongly in spring and summer and decreases sharply in winter. Wuhan maintains a relatively high occurrence rate during most months. Fuke shows larger month-to-month changes and does not have the clear summer maximum seen at Mohe. All three stations were observed during the same one-year period, and the same criteria were used to identify IDLs. Thus, the differences are unlikely to be mainly caused by different observation periods or analysis methods. They more likely show that the background conditions controlling IDL formation change with latitude and season.

The stronger seasonal variation at the higher- and middle-latitude stations agrees with the known seasonal changes in the neutral atmosphere and E-region ion convergence. Atmospheric tides, especially the semidiurnal tide, change greatly with season in the mesosphere and lower thermosphere. These changes can affect the strength and vertical structure of wind shear, which causes metallic ions to converge into thin layers (MacDougall, 1978; Yuan et al., 2008). Earlier studies also found strong seasonal patterns in sporadic-E occurrence. They linked these patterns to tidal wind shear and the seasonal availability of meteoric metallic ions (Haldoupis et al., 2007). A global radio-occultation study also showed clear changes in Es intensity with latitude and season. Es intensity was highest at midlatitudes, and its summer values were two to three times the winter values (Yu et al., 2019). Using ionosonde data from Sanya, Wuhan, Beijing, and Mohe, Qiu et al. (2021) found that the descent rates of summer descending Es layers increase with both altitude and latitude. This result provides regional evidence that



lower-ionospheric processes over China vary with latitude. Es layers and IDLs are not the same type of structure, but both are closely linked to ion convergence caused by wind shear. These studies therefore provide a useful physical basis for the strong spring–summer increase and winter decrease found in the present IDL statistics. The continued occurrence of IDLs at Wuhan also suggests that favorable convergence conditions last for a larger part of the year than at Mohe. This difference may result from changes in the seasonal behavior of tidal winds with latitude.

At lower latitudes, the seasonal pattern becomes less regular, as shown by the Fuke observations. At the equatorial station of Thiruvananthapuram, Mridula and Pant (2022) found that IDLs occurred more often during the summer and winter solstices than during the equinoxes. They also found a higher occurrence probability during low solar activity. Earlier low-latitude studies showed that neutral-wind shear affects the occurrence and vertical motion of intermediate layers. Ionospheric electric fields and other electrodynamic processes can also affect these layers (Lee et al., 2003; Niranjana et al., 2010; Santos et al., 2021). These processes may change the simple seasonal pattern expected from tidal forcing alone. The irregular seasonal distribution at Fuke is therefore consistent with the combined effects of neutral-atmospheric forcing and low-latitude electrodynamics. Overall, the simultaneous observations at the three stations extend earlier single-station studies. They show that IDL seasonality changes with latitude: it is strong and clear at Mohe, weaker at Wuhan, and more irregular at Fuke. This change suggests that the roles of tidal wind shear, metallic-ion availability, and electrodynamic forcing differ among latitude regions.

## 4.2 Local-time morphology and tidal characteristics

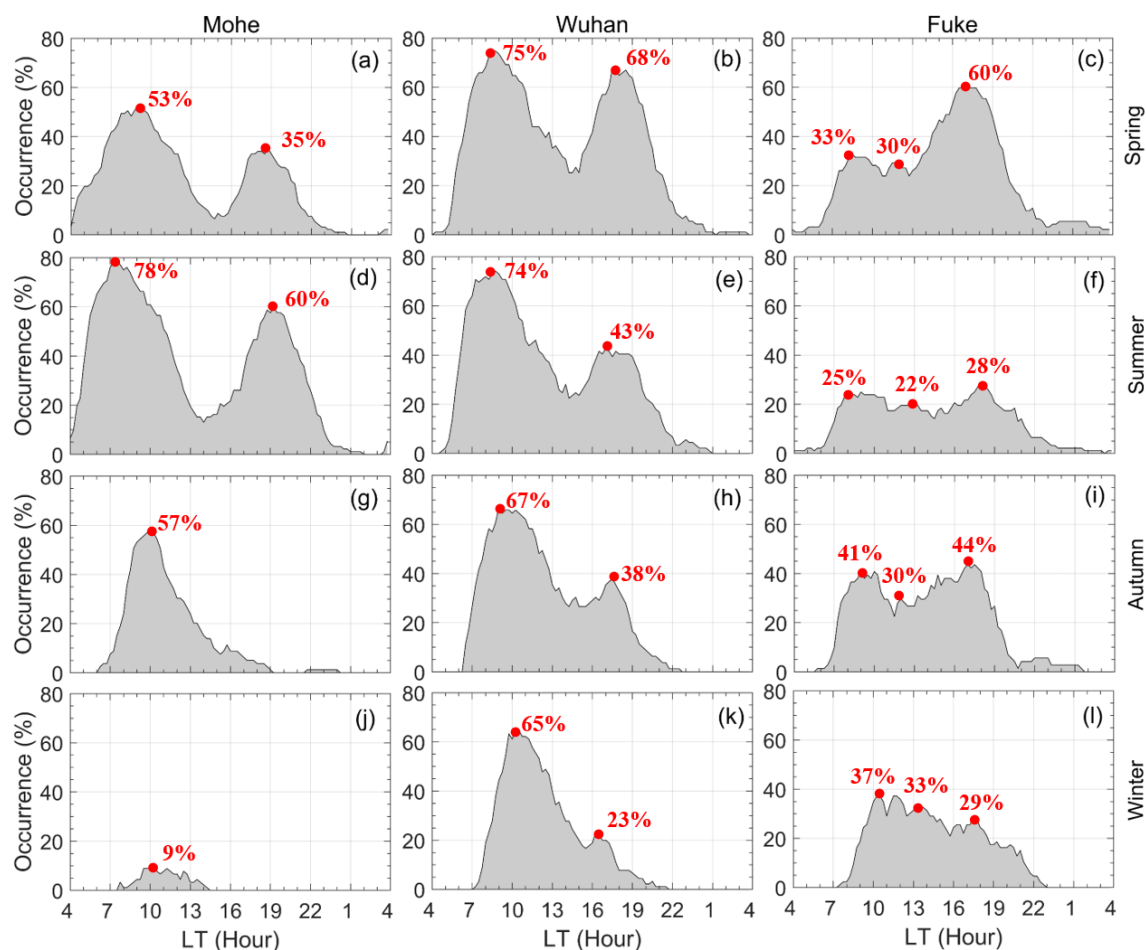
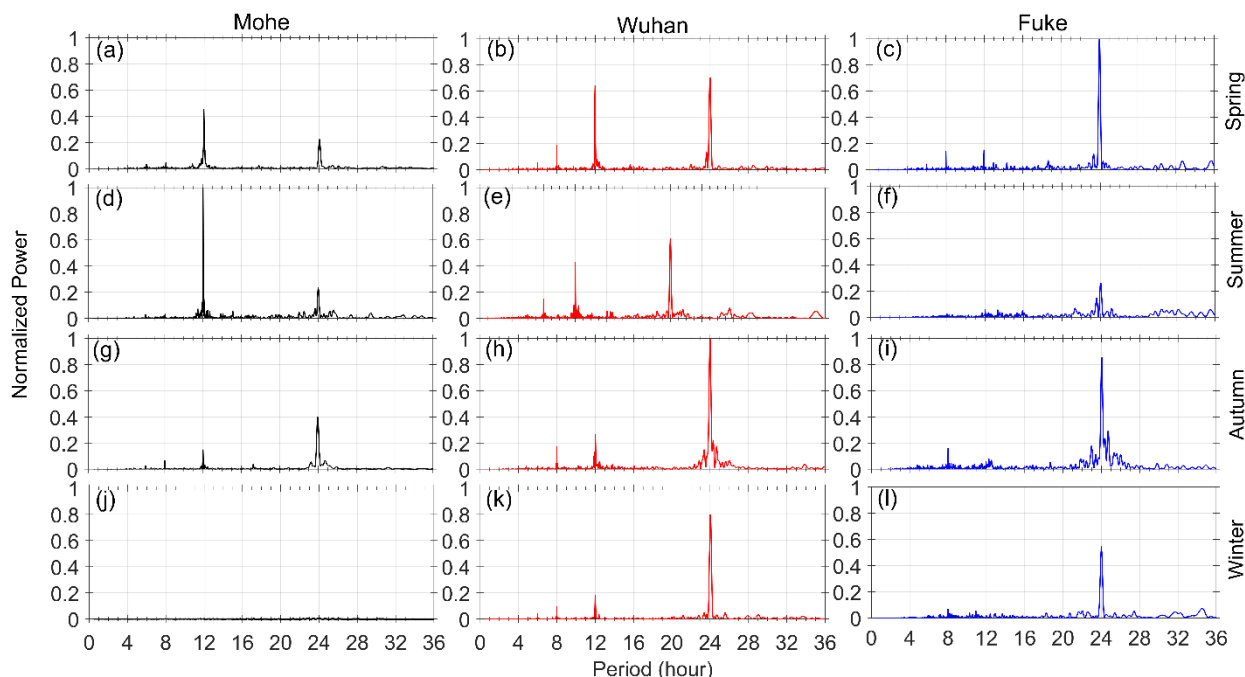


**Figure 7. Temporal variations in the occurrence rate of the IDL. The columns (from left to right) represent data from the Mohe, Wuhan, and Fuke stations, respectively. The rows (from top to bottom) indicate the Spring, Summer, Autumn, and Winter seasons.**

Figure 7 shows clear latitudinal and seasonal differences in the local-time occurrence morphology of IDLs. At Mohe, a distinct morning–afternoon double-peak structure is evident in spring and summer, with the morning enhancement generally stronger than the afternoon enhancement. The afternoon branch weakens markedly in autumn, and the distribution becomes predominantly morning-centered in winter as the overall IDL occurrence decreases. Wuhan exhibits a more persistent asymmetric double-peak pattern throughout the year. Although the timing and relative strength of the two peaks vary with season, the morning enhancement consistently exceeds the afternoon enhancement. In contrast, Fuke shows a broader and

more complex daytime distribution, with less clearly separated morning and afternoon branches. Multiple local maxima are present in several seasons, and the later daytime enhancement can be comparable to or stronger than the morning enhancement.



205 **Figure 8. Normalized Lomb-Scargle power spectra of IDL virtual height at Mohe, Wuhan, and Fuke from March 2020 to February 2021. Panels (a)-(c) correspond to spring, (d)-(f) to summer, (g)-(i) to autumn, and (j)-(l) to winter, respectively.**

The Lomb–Scargle spectra in Figure 8 show corresponding differences in the periodic characteristics of IDL virtual height. At Mohe, a pronounced 12-h component is observed in spring and becomes particularly prominent in summer, accompanied by a weaker component near 24 h. In autumn, the 24-h component becomes relatively more apparent, whereas no robust periodicity can be identified in winter because of the very limited IDL occurrence. Wuhan exhibits both 12- and 24-h periodicities, with the 24-h component generally stronger, particularly in autumn and winter. Weaker spectral features at shorter periods, including near 8 h, are also present in some seasons. At Fuke, the 24-h component is the most persistent spectral feature and is particularly pronounced in spring, autumn, and winter, while weaker 12-h and shorter-period components occur intermittently. These spectra therefore indicate that the relative contributions of diurnal-, semidiurnal-, and higher-frequency periodicities vary with both latitude and season.

Overall, Figures 7 and 8 demonstrate a systematic latitudinal transition in the temporal characteristics of IDLs. Mohe is characterized by a relatively well-defined morning–afternoon morphology and a prominent semidiurnal signature, especially in spring and summer; Wuhan shows persistent asymmetric double peaks together with mixed diurnal and semidiurnal periodicities; and Fuke exhibits a broader multi-peak local-time distribution associated with a persistent diurnal periodicity



220 and weaker higher-frequency components. The coexistence of 24-, 12-, and occasionally 8-h spectral features indicates that IDL variability contains multiple tidal-scale periodicities whose relative prominence changes with latitude and season.

### 4.3 Tidal modulation of IDL formation and descent

The formation and downward evolution of IDLs can be explained by the classical wind-shear theory. In the E region, long-lived metallic ions are affected by both the geomagnetic field and neutral winds. Vertical changes in the zonal and meridional  
 225 winds cause ion drifts to vary with height. This creates convergence levels where metallic ions gather and form thin ionization layers. When the wind-shear structure changes with time, these convergence levels can move vertically. The related ionization layers can then descend. Atmospheric tides are an important source of these changes. Tidal winds repeat with time, and their amplitude and phase change with altitude. Thus, wind shear directly causes ion convergence, while tides control when and where favorable shear conditions develop. Tides also control how the convergence levels change with time (Whitehead, 1961;  
 230 Axford, 1963; Osterman et al., 1994). A multi-instrument study of the 2017 sudden stratospheric warming event also found quasi-16-day variations from the lower thermosphere to the topside ionosphere over low-latitude East Asia. This result gives broader evidence of vertical coupling between the atmosphere and ionosphere (Liu et al., 2020).

The 24-, 12-, and 8-h periods in Figure 8 can be interpreted as signs of diurnal, semidiurnal, and terdiurnal tidal modulation, respectively. A 24-h diurnal tide produces one large-scale cycle each day. It can create a clear daily difference in the wind-shear environment. A 12-h semidiurnal tide repeats twice each day. It can therefore create two preferred periods of ion  
 235 convergence. This is consistent with the morning and afternoon occurrence peaks observed at Mohe and Wuhan. At Mohe, the strong 12-h component suggests that the semidiurnal tide is the main periodic component of the background forcing. The weaker 24-h component may help explain why the two occurrence peaks have different strengths. At Wuhan, the strong 24- and 12-h components show that both diurnal and semidiurnal tides are important. Both components can contribute to the  
 240 persistent but unequal morning and afternoon peaks. This interpretation agrees with earlier studies showing that diurnal and semidiurnal tidal winds can act together to control intermediate and descending ionization layers through periodic changes in wind shear (Fujitaka and Tohmatsu, 1973; Mathews and Bekeeny, 1979; Szuszczewicz et al., 1995).

The 8-h terdiurnal component provides a faster variation to the wind-shear field. An 8-h tide can repeat about three times each day. When it acts together with the 24- and 12-h components, it can create more periods of ion convergence and make the  
 245 local-time occurrence pattern more complex. This effect is especially important at Fuke. Figure 7 shows a wider daytime distribution and several occurrence peaks during some periods. Figure 8 also shows that the 24-h component remains dominant, while the 12-h component is weaker. The 8-h component should therefore be treated as a secondary modulation added to the dominant diurnal tide. It is not the main controlling component. When the semidiurnal component is weak, the effect of the 8-h component may become easier to identify. It may then change the timing and relative strength of the daytime occurrence  
 250 peaks. Similar 8-h variations have been found in observations of sporadic-E and related ionospheric layers and have been linked to terdiurnal tides (Haldoupis and Pancheva, 2006). Overall, the observations show a change with latitude. Semidiurnal



modulation is stronger at Mohe. Diurnal and semidiurnal tides both play important roles at Wuhan. At Fuke, the diurnal tide is dominant, while the terdiurnal tide provides a secondary contribution. These tidal components can act together to control the temporal and vertical changes in wind-shear convergence. This provides a clear physical explanation for the observed differences in IDL occurrence and descent with latitude.

## 5 Conclusions

The present multi-station observations reveal pronounced latitude- and season-dependent characteristics of intermediate descending layers over China. IDLs at all three stations generally form in the upper E region and descend toward approximately 100-120 km over several hours, but their occurrence climatology and local-time morphology vary systematically with latitude. Mohe exhibits the strongest seasonal dependence, with enhanced activity in spring and summer and markedly reduced occurrence in winter, whereas Wuhan maintains relatively persistent IDL activity throughout the year. Fuke shows a broader and less regular seasonal and local-time distribution, with afternoon occurrence occasionally exceeding the morning occurrence and multiple local maxima appearing in some seasons. The combined local-time statistics and Lomb-Scargle spectra further indicate a latitude-dependent transition in tidal modulation. At Mohe, semidiurnal forcing provides the dominant dynamical background, while diurnal modulation contributes to the asymmetric morning-afternoon occurrence pattern. At Wuhan, diurnal and semidiurnal tides jointly regulate the persistent double-peak structure, with their relative contributions varying seasonally. At Fuke, diurnal modulation is dominant, whereas the semidiurnal contribution is weaker. A secondary terdiurnal component may also contribute to the afternoon-enhanced and occasionally multi-peak morphology. These results suggest that the observed statistical differences in IDL occurrence and descent are organized by the seasonally and latitudinally varying superposition of atmospheric tides, acting through wind-shear-driven ion convergence, while background plasma and electrodynamic conditions further modulate the occurrence and detectability of individual layers.

## Data availability

The ionogram image data of Mohe and Wuhan and Fuke stations used to describe the text in the study can be publicly obtained through the Chinese Meridian Project (<https://data.meridianproject.ac.cn/>) in ionogram image of digital ionosonde (Chinese Meridian Project, 2011); The ionogram data is computed and processed by SAO software version 3.6.1 under Global Ionosphere Radio Observatory (GIRO) (<https://giro.uml.edu/didbase/>).



## Author contributions

280 MY conducted the data analysis and prepared the original draft of the manuscript. GC substantially revised the manuscript and contributed to the interpretation of the physical mechanisms underlying IDL formation and descent. XC and MZ organized the observational datasets. YJ contributed to manuscript editing and language refinement. All authors participated in discussing the results and reviewing the manuscript.

## Competing interests

The contact author has declared that none of the authors has any competing interests.

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