Detecting the structure of marine atmospheric boundary layer over the Northern South China Sea by shipboard GPS sondes

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Abstract

Global Positioning System (GPS) sondes has been launched over the Northern South China Sea (NSCS) during the marine survey cruise each summer since 2006. These GPS-sounding data provide a great opportunity to monitor the vertical structure of marine atmospheric boundary layer (MABL) which is very important to the high-impact weather systems influencing the coastal regions. Our analysis on these GPS soundings reveals that the vertical structure of MABL over the NSCS is apparently correlated with the surface atmospheric stability. These MABL observations collected by GPS sondes are quite valuable for the forecasting of high-impact weather systems in the coastal regions of the southern China.

Keywords: GPS sondes; marine atmospheric boundary layer; surface atmospheric stability

1. Introduction

The vertical structure of marine atmospheric boundary layer (MABL), which contains most of the water vapor and energy flux in an atmosphere column, is one of the key factors that trigger the occurrence of some synoptic activities such as deep convections (Kloesel and Albrecht, 1989; Pyatt et al., 2005; Allappattu and Kunhikrishnan, 2010). Therefore, the observed information of the vertical structure of MABL could be very useful and important to the forecasts of heavy storms in the coastal regions such as the Northern South China Sea (NSCS). However, the observed data of MABL are sporadic due to the difficulties of implementing observations over ocean.

Atmospheric soundings are one of the most effective ways to observe the vertical structure of the atmosphere, including the vertical heating/moisture profiles and the features of mixing layer or inversion layer which are essential to the development of convective systems (Liu and Ding, 2000; Rappenglück et al., 2008; Tanimoto et al., 2015). Over ocean, although more difficult and expensive in deployment, atmospheric soundings can be still a feasible way to detect the vertical structure of MABL (Sweet et al., 1981; Hashizume et al., 2002; Tokinaga et al., 2006; Yu et al., 2009). Tokinaga et al. (2006) studied the structure of MABL over the regions of Kuroshio Extension using observations obtained from shipboard GPS sondes, and found large variation in the vertical structure of MABL which is closely related to the change of the surface atmospheric stability as measured by the sea–air temperature difference. The GPS sondes released during the 1998 South China Sea Monsoon Experiments (SCSME) provide the first opportunity for researchers to study the evolution of the vertical structure of the atmosphere over the SCS, and analysis results based on these GPS soundings indicate that the variations of the atmospheric stratification, mixed layer and MABL height over the SCS are associated with different South China Sea Summer Monsoon phases as well as different subregions of the SCS (Liu and Ding, 2000; Yu et al., 2009; Wang et al., 2010). However, the GPS sondes released in the SCSME are sporadic and thus the analysis results based on these limited data are somewhat preliminary, and the role of the GPS sounding observations over the NSCS in the forecasts of high-impact weather events over the coastal regions has not been investigated yet.

The Northern South China Sea Open Cruise (NSCOC), sponsored by the South China Sea Institute of Oceanology (SCSIO) and supported by National Science Foundation of China (NSFC), has been carried out each summer since 2004 (Yang et al., 2015; Zeng et al., 2015). Although the primary purpose of the cruise is to investigate the characteristics of the hydrographic and ecosystem in the NSCS using various instruments including Conductivity Temperature Depth (CTD), Acoustic Doppler Current Profilers (ADCP)
Table 1. Systematic characteristics of GPS-TK and CF-06-A radiosondes.

| Radiosonde type | Manufacturer and country | Temperature sensor | Humidity sensor | Weight/g |
|-----------------|--------------------------|--------------------|----------------|----------|
| GPS-TK          | Beijing (China)          | Range +125–40°C    | Range 0–100% RH| 150      |
|                 |                          | Resolution 0.04°C  | Resolution 0.4% RH|          |
|                 |                          | Response time 5 s  | Response time 8 s|          |
|                 |                          | Uncertainty N/A    | Uncertainty N/A|          |
| CF-06-A         | Beijing Chang Feng Micro Electronics Technology Co. (China) | Range +60–90°C | Range 0–100% RH| 270      |
|                 |                          | Resolution 0.1°C   | Resolution 1% RH|          |
|                 |                          | Response time 0.8 s| Response time 1.5 s|        |
|                 |                          | Uncertainty 0.5°C  | Uncertainty 5% RH|          |

Figure 1. The locations of the launching GPS sonde during the summer Northern South China Sea Open Cruise (NSCSOC) of 2006–2014.

and so on, a strategy was put forward to detect the vertical structure of MABL over the NCSC in 2006 by launching GPS sondes along survey sections of the cruise and has been implemented every summer since then. The GPS sondes used before and after 2012 (including 2012) are GPS-TK and CF-06-A, respectively. Table 1 shows the details of these two radiosondes (Xie et al., 2014). Figure 1 shows the locations of the GPS sondes launched during the 2006–2014 summer NSCSOC. It can be seen that most of the GPS sondes were launched near the coast of southeast China and along the latitude of 18°N. For each cruise, the launching time is at 0000, 0600, 1200, and 1800 UTC with an interval of 6 h in term of underway mode. These GPS sondes provide a great opportunity for us to investigate the MABL structure as well as its evolution over the NSCS.

2. The MABL structure over the NSCS

To see whether the height of MABL over the NSCS is closely associated to the surface atmospheric stability as that over the Kuroshio Extension shown in the study of Tokinaga et al. (2006), we analyze all GPS soundings and the corresponding sea surface temperature measured by CTD during 2010–2014 summer NSCSOC. The GPS soundings from 2006 to 2009 are excluded due to lack of SST, SAT, and sea surface wind speed observations, which are necessary in computing the air–sea temperature difference (S) and the surface latent and sensible heat fluxes (Qe, Qh). Data quality control is very important before the use of the GPS soundings. Xie et al. (2014) compared the GPS sondes (GPS-TK and CF-06-A) with the RS92-SGP and found that the temperature and relative humidity observed by GPS-TK have larger biases than those observed by CF-06-A. Therefore, the biases of temperature and relative humidity observed by GPS-TK are first corrected, and then a careful quality control is performed following the steps below: (1) the abnormal value of SST, SAT, and sea surface wind speed are eliminated with thresholds of 20–32 °C, 20–32 °C and 0–25 ms⁻¹, respectively, and the corresponding GPS sounding profiles are removed; (2) the GPS sounding profiles with large missing observations are also removed; (3) the GPS sounding profiles whose virtual potential temperature (θv) profiles fluctuate drastically are rejected since the MABL height is hard to obtain from these θv profiles. After the quality control check, 17 GPS sounding profiles are rejected and we have a total number of 122 GPS sounding profiles paired with corresponding SST observations by CTD. Following Zeng et al. (2004), we define the MABL height (h) as (1) the height where the vertical gradient of θv first becomes greater than or equal to 3 K km⁻¹ if MABL is unstable (with negative dθv/dh), or (2) the height where the bulk Richardson number first becomes greater than 0.3 based on the criterion of Vogezeang and Holtslag (1996) if MABL is stable. The obtained h needs to be further adjusted when it lies within the cloud layer: If h ≥ dc (cloud thickness), h is taken as the cloud top; If h < dc, h is taken as the cloud base. The cloud layer is taken as the layer where the relative humidity is larger than 97% as observed in broken cloud layers (Albrecht et al., 1985; Betts et al., 1995; Zeng et al., 2004). Among the 122 profiles, there is only one profile with stable MABL and only one profile with MABL height lying in the cloud layer. The observations less than 100 m are excluded in computing the MABL because of poor data quality, and the
Figure 2. Scatter plots between MABL height and (a) SST-SAT, and (b) surface turbulent heat flux \((Q_e + Q_h)\) during the summer NSCSOC of 2010–2014, with correlation coefficients of 0.44 (a) and 0.46 (b) exceeding 99% significant confidence level. The total number of GPS sounding profiles is 122 after quality control.

Figure 3. Composite vertical profiles of (a) virtual potential temperature (K) and (b) wind speed (m s\(^{-1}\)) for SST-SAT > 1.5°C (black line) and SST-SAT < 0.3°C (blue line) during the summer NSCSOC of 2010–2014. The total number of GPS sounding profiles with SST-SAT > 1.5°C is 28 while that with SST-SAT < 0.3°C is 26, after quality control.

observations are linearly interpolated to vertical level at 10 m intervals. The near-surface stability is defined as the air–sea temperature difference \(S = \text{SST-SAT}\) following Tokinaga et al. (2005). Figure 2(a) shows the scatter plot of the MABL height and the near-surface stability parameter \(S\). It can be seen that there is a good correlation between the MABL height and the near-surface stability parameter \(S\) with correlation coefficient of 0.44 (above the 99% confidence level), i.e. larger air–sea temperature difference is generally associated with larger MABL height. Figure 2(b) shows the scatter plot of the MABL height and the heat flux over the sea surface. The heat flux includes surface latent and sensible heat fluxes \((Q_e, Q_h)\) which are calculated using the aerodynamic bulk formula (Kondo, 1975). Similarly, good correlation (with correlation coefficient of 0.46, above the 99% confidence level) between the MABL height and the heat flux is found, too. This indicates that larger air–sea temperature difference induces strong turbulence over the sea surface and intensifies the vertical mixing. According to the vertical mixing mechanism proposed by Sweet et al. (1981) and Wallace et al. (1989), such an intensified vertical mixing transfers the heat flux from the sea surface to higher height and bring larger momentum from above to accelerate near-surface winds.

To further investigate the influence of the surface atmospheric stability on the MABL structure, we bin all sounding data into two categories based on the stability parameter \(S\): unstable category with \(S > 1.5\)°C and stable category with \(S < 0.3\)°C, and plot the composite vertical profiles of \(\theta_v\) and wind speed for the two categories, respectively, as shown in Figure 3. Obvious differences are found between the two categories: for the unstable situation \((S > 1.5\)°C\), it features a higher MABL height (\(\sim 0.58\) km) and intensified vertical mixing with weak vertical wind shear; for the neutral/stable one \((S < 0.3\)°C\), it features a lower MABL height (\(\sim 0.37\) km) and weak vertical mixing with strong vertical wind shear.

The MABL structure over the NSCS as well as its relationship with the near-surface stability observed by the GPS sondes is qualitatively in agreement with that over the extratropical front regions with strong SST gradient such as the Gulf Stream (Sweet et al., 1981), Antarctic Circumpolar Current (O’Neill et al., 2003), Kuroshio Extension (Tokinaga et al., 2006), and Agulhas Return Current (O’Neill et al., 2010). However, they are quantitatively different, due to much larger air–sea temperature difference in extratropical front regions than in tropical regions. For example, the maximum of air–sea temperature differences in the Kuroshio Extension was observed as large as 10°C, accompanied with a maximum MABL height of \(\sim 2\) km and surface turbulent heat flux of \(\sim 800\) W m\(^{-2}\) (Tokinaga et al.,...
2006). In contrast, the air–sea temperature differences observed in the SCS are mostly less than 2.5 °C with mean MABL height less than 1 km and surface turbulent heat flux less than 500 Wm⁻².

3. Conclusive remarks and discussion

The vertical structure of MABL is very important to the high-impact weather development influencing the coastal regions, but is usually hard to obtain due to the difficulties of implementing boundary layer observations over ocean. The shipboard GPS sondes launched over the NSCS during the marine survey cruise each summer since 2006, sponsored by SCSIO and supported by NSFC, provide a great opportunity to monitor the vertical structure of MABL.

Our analysis on these GPS soundings reveals that the vertical structure of MABL over the NSCS in summer is largely influenced by the near-surface atmospheric stability, i.e. a good correlation exists between the MABL height and the air–sea temperature difference. Good correlation between the MABL height and the heat flux is also found. Intensified vertical mixing with weak vertical wind shear occurs for unstable situation while weak vertical mixing with strong vertical wind shear is found for the neutral/stable situation. The observed structure of MABL over the NSCS as well as its relationship with the air–sea temperature difference is qualitatively similar to, thought quantitatively different with, that in extratropical front regions, and can be explained by the vertical mixing mechanism proposed by Sweet et al. (1981) and Wallace et al. (1989): larger air–sea temperature difference induces strong turbulence over the sea surface and intensifies the vertical mixing, and such an intensified vertical mixing transfers the heat flux from the sea surface to higher height and bring lager momentum from above to accelerate near-surface winds.

The observed information of MABL from GPS-sounding may play an important role in the forecasts of extremely heavy precipitation in the coastal regions. On the other hand, while we should continue to implement the strategy of deploying the GPS sondes during each year’s marine survey, other alternative means or network for detecting coastal MABL, such as drop-soundings by airplanes, could be also considered in the future. Moreover, the structure of MABL over the NSCS in winter needs to be monitored and analyzed in the future by implementing winter marine cruise.

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