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A global weighted mean temperature model based on empirical orthogonal function analysis

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Abstract

A global empirical orthogonal function (EOF) model of the tropospheric weighted mean temperature called GEOFM_Tm was developed using high-precision Global Geodetic Observing System (GGOS) Atmosphere T_m data during the years 2008–2014. Due to the quick convergence of EOF decomposition, it is possible to use the first four EOF series, which consists base functions U_k and associated coefficients P_k, to represent 99.99% of the overall variance of the original data sets and its spatial-temporal variations. Results show that U_1 displays a prominent latitude distribution profile with positive peaks located at low latitude region. U_2 manifests an asymmetric pattern that positive values occurred over 30° in the Northern Hemisphere, and negative values were observed at other regions. U_3 and U_4 displayed significant anomalies in Tibet and North America, respectively. Annual variation is the major component of the first and second associated coefficients P_1 and P_2, whereas P_3 and P_4 mainly reflects both annual and semi-annual variation components. Furthermore, the performance of constructed GEOFM_Tm was validated by comparison with GTm_III and GTm_N with different kinds of data including GGOS Atmosphere T_m data in 2015 and radiosonde data from Integrated Global Radiosonde Archive (IGRA) in 2014. Generally speaking, GEOFM_Tm can achieve the same accuracy and reliability as GTm_III and GTm_N models in a global scale, even has improved in the Antarctic and Greenland regions. The MAE and RMS of GEOFM_Tm tend to be 2.49 K and 3.14 K with respect to GGOS T_m data, respectively; and 3.38 K and 4.23 K with respect to IGRA sounding data, respectively. In addition, those three models have higher precision at low latitude than middle and high latitude regions. The magnitude of T_m remains at the range of 220–300 K, presented a high correlation with geographic latitude. In the Northern Hemisphere, there was a significant enhancement at high latitude region reaching 270 K during summer. GEOFM_Tm is capable to represent the spatiotemporal variations of T_m, with the high accuracy and reliability in a global scale, therefore, will be of great significance to the real-time GNSS water vapor inversion and climate studies.

Keywords: Empirical orthogonal function (EOF); Weighted mean temperature; Accuracy and precision validation; Spatial-temporal characteristics

1. Introduction

Water vapor is a highly variable component of the Earth's atmosphere, which is mainly distributed at the bottom of the troposphere, constituting approximately 99% percent of total vapor. It is fundamental to the transfer of energy in the atmosphere and the formation, evolution of weather and changes of global climate (Rocken et al., 1997). Improved knowledge of the water vapor field and variation patterns is needed for a variety of atmospheric research, meteorology applications, especially for the real-time weather forecasting and extreme weather monitoring. Traditional methods for detecting water vapor, such as radiosonde and water vapor radiometer, cannot meet the increasing demands of meteorological application

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for the limited spatial and temporal resolution and expensive equipment. Nowadays, The Global Navigation Satellite System (GNSS) and the regional augmentation systems have the great potential to detect precipitable water vapor and its variations trend with a high spatiotemporal resolution as well as high precision. Currently, real-time GNSS precise point positioning (PPP) can obtain the coordinates in centimeter-level accuracy along with zenith tropospheric wet delay (ZWD), which can be regarded as an unknown value in parameters estimation process, by means of the precise ephemeris and clock corrections provided by numbers of analysis centers and associated organizations (Karabatić et al., 2011; Lu et al., 2015). In ground-based GNSS meteorology, ZWD of the troposphere can be converted into precipitable water vapor (PWV) that is defined as the total possible precipitation of vapor content in a unit area cylinder from the height of an observing station to the outer layer of the atmosphere. The relationship between ZWD and PWV is as follows:

$$\mathrm{PWV} = \prod \times \mathrm{ZWD} \tag{1}$$

$$\prod = \frac{10^6}{\rho_w R_v[(k_3/T_{\mathrm{m}}) + k'_2]} \tag{2}$$

where $\prod$ is the conversion coefficient for mapping ZWD onto PWV; ρ_w and R_v refer to the density of liquid water and gas constant for water vapor, respectively; k'_2, k_3 denote the atmospheric refractivity constants; T_m is the weighted mean temperature of the troposphere, playing a key role in determining the conversion coefficient $\prod$. It can be found that the precision of T_m will indirectly affect the precision and reliability of PWV obtained from GNSS water conversion. According to the error propagation law, when ZWD is 400 mm, if the mean square error of T_m is 5 K, it would result in the error of 1.1 mm to PWV (Yao et al., 2014).

For the significant role of T_m playing in real-time GNSS water vapor conversion, researchers from all over the world are devoted to studying the spatial-temporal characteristics of T_m and empirical modeling. Substantial achievements have been published (Bevis et al., 1992; Ross and Rosenfeld (1997); Li and Mao, 1998; Wang et al., 2005; Yu and Liu, 2009; Yao et al., 2012, 2013, 2014; Chen et al., 2014). Bevis et al. (1992) proposed a linear regression formula to calculate T_m from the ground atmospheric temperature T_s. The formula was more suitable for mid-latitudes due to the modeling data only came from 13 stations in the United States. Ross and Rosenfeld (1997) analyzed 23-year sounding data from 53 global radiosonde stations and discovered that the correlation between T_m and T_s changes with the geographic location and season. For the disadvantages of the single- and multi-factor regional models associated with meteorological elements, Yao et al. (2012) firstly established a globally applicable weighted mean temperature called GWMT using sounding data during years 2005–2009, which was based on the GPT model and Bevis linear regression formula. GWMT can calculate the T_m at any site by the geographic coordinate and day of year without the ground atmospheric temperature. Due to the limitation of the distribution of radiosonde stations, the reliability and accuracy of GWMT over the ocean and the Antarctic regions degraded. Therefore, Yao et al. (2013) adopted the simulated values determined by the combination of GPT model and Bevis liner regression formula in sea areas where sounding data is unavailable, along with sounding data, to recalculate the coefficients of model, then an improved model called GTm_II was established. Meanwhile, Chen et al. (2014) developed a global empirical model of T_m GTm_N using NCEP reanalysis data during years 2006–2012, which considers the annual and semiannual variation of T_m and the initial phase of each cycle. Yao et al. (2014) also took into account the annual and semiannual variation of T_m and the initial phase of each cycle, then developed a new global empirical model called GTm_III using GGOS Atmosphere T_m grid data of years 2005–2011.

The existing global models of the weighted mean temperature, such as GWMT, GTm_III and GTm_N are established based on the spherical harmonics function, which is artificially predefined orthogonal function. Empirical orthogonal function can naturally be determined by the original data set themselves. Therefore, the method of EOF analysis that will preserve the inherent characteristics of the original data and possesses the feature of quick convergence, is the preferred approach for global T_m modeling. Here, high accuracy T_m grid data provided by GGOS Atmosphere during the years 2008–2014 was used to develop a global weighted mean temperature model of the troposphere. The modeling data and EOF decomposition method are described in Section 2. The data processing techniques and specific procedures of model construction will be illustrated in Section 3. Further description on internal and external validation and analysis of temporal-spatial features of T_m are given in Sections 4 and 5, respectively. Section 6 lists a final summary and conclusions.

2. Data and method

This section illustrates the data sources used to develop an empirical model of the T_m and the preprocessing procedure necessary for further decomposition. In addition, a detailed description of EOF analysis is also covered here.

2.1. GGOS Atmosphere T_m data set and preprocessing

The GGOS Atmosphere can provide the gridded data of the global weighted mean temperature that can be used to convert wet zenith delays into precipitable water vapor with a temporal resolution of 6 h (at UT 00:00, 06:00, 12:00, 18:00) and a high spatial resolution of 2.5° in longitude and 2° in latitude, which is based on the data from European Center for Medium-Range Weather Forecasts (ECMWF) with a 6-h time resolution. The corresponding ellipsoidal heights H at each grid point with respect to