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ScienceDirect

Advances in Space Research xxx (2018) xxx–xxx

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

A refined regional empirical pressure and temperature model over China

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Received 24 February 2018; received in revised form 12 June 2018; accepted 17 June 2018

Abstract

Accurate pressure and temperature are indispensable in the GNSS water vapor retrievals. A refined regional empirical model, WHU_CPT, for estimating pressure, temperature and water vapor weighted mean temperature (T_m) with a horizontal resolution of 0.75° over China was developed. We found that the surface level reanalysis products are more reliable in reproducing surface temperature than pressure level products in the model construction. The model form was then determined individually for each meteorological variable by comparing performances of different models and by analyzing the Power Spectra Density of time series. Average RMS of pressure and temperature errors over China in WHU_CPT is about 4.07 hPa and 3.76 K, compared to 5.95 hPa and 5.92 K for GPT, 4.25 hPa and 5.14 K for GPT2, and 4.14 hPa and 5.14 K for GPT2w. Two T_m models were also developed in WHU_CPT. One is an empirical model, WHU_CPT (Tm1), which takes user location and time as inputs and the other one, WHU_CPT (Tm2), which additionally makes use of the measured temperature, is more suitable for users with surface temperature available. The mean RMS of T_m errors over China are about 4.45, 4.19, 3.81 and 2.97 K for the Bevis equation, GPT2w, WHU_CPT (Tm1) and WHU_CPT (Tm2).

Keywords: GNSS; Pressure; Temperature; Water vapor; Reanalysis

1. Introduction

Tropospheric delay is one of the major factors affecting the accuracy of electromagnetic distance measurements. In the geodetic analysis of Global Navigation Satellite System (GNSS) and Very Long Baseline Interferometry (VLBI) observations, the slant tropospheric delays are generally mapped into the zenith direction (Zenith Tropospheric Delay, ZTD) through mapping functions. ZTD can be divided into two parts, namely the hydrostatic part (Zenith Hydrostatic Delay, ZHD) and the non-hydrostatic part (Zenith Wet Delay, ZWD). Accurate a priori ZHD is usually needed in high-accuracy geodetic data processing. Preferably, they can be estimated from the in-situ measured pressure on the basis of models such as Hopfield (Hopfield, 1969) model or Saastamoinen (Saastamoinen, 1972) model with accuracy better than 1 mm. Pressures can also be derived from Numerical Weather Model (NWM). If neither of these two data is available, an empirical model is usually used, for example, the GPT model (Boehm et al., 2007).

GPT model was developed based on 3-year ECMWF (European Center for Medium-Range Weather Forecasts) reanalysis ERA-40 (Uppala et al., 2005) products. Pressures derived from GPT can also be taken as inputs in atmosphere pressure loading models and the derived temperatures can be used for determining annual thermal deformation of VLBI radio telescopes (Boehm et al., 2007). Parameters in GPT are expanded to spherical harmonics of degree and order nine, leading to a coarse horizontal resolution of about 20° and, therefore, restricted capability of representing large height variations and the associated changes of parameters. GPT2 (Lagler et al.,

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https://doi.org/10.1016/j.asr.2018.06.021
0273-1177/© 2018 Published by Elsevier Ltd on behalf of COSPAR.

Please cite this article in press as: Zhang, W., et al. A refined regional empirical pressure and temperature model over China. Adv. Space Res. (2018), https://doi.org/10.1016/j.asr.2018.06.021

2013) has a refined horizontal resolution of 5° which was built using 10-year of newer generation of reanalysis (ERA-Interim) products (Dee et al., 2011). Different from GPT, the semi-annual variations of parameters were additionally taken into account in GPT2 and the (semi-)annual phases were estimated instead of keeping fixed. In 2015, Boehm et al. (2015) introduced the water vapor weighted mean temperature (T_m) into GPT2w and parameters were expanded to a horizontal resolution of 1°. Diurnal variations can be taken into account for certain variables to further improve the performances of empirical models, such as TropGrid2 model (Schüler, 2014) and ITG model (Yao et al., 2015).

Due to the advantages of high-accuracy, high temporal resolution, low-cost and operations in all weather conditions, GNSS has been proved to be a powerful tool in atmospheric water vapor measuring (Bevis et al., 1992). T_m is a key factor to convert GNSS-derived ZTD to precipitable water vapor (PWV). The most commonly used method to estimate T_m is to follow the equation suggested by Bevis et al. (1992), namely $T_m = 70.2 + 0.72T_s$, where T_s denotes the surface air temperature. The coefficients of this equation were estimated from 8718 radiosonde profiles in North America. Several subsequent studies refined the Bevis equation based on more radiosonde profiles with more widely distributed stations (e.g. Ross and Rosenfeld, 1997; He et al., 2017) or focused on a regional area (e.g. Li et al., 1999, 2006, 2017a, 2017b; Lu et al. 2008). Wang et al. (2005) pointed out that biases of T_m using the Bevis equation can reach 6 K and they suggested estimating T_m based on NWM for a better accuracy, but this method relies on the external data source, i.e., the NWM products. Empirical T_m models which are independent from external data sources and generally take user location and time as inputs, were therefore developed, such as GWMT model (Yao et al., 2012), GPT2w model (Boehm et al., 2015), ITG model (Yao et al., 2015) and GWMT-D model (He et al., 2017).

Most of the current commonly used empirical models, e.g., pressure, temperature, and T_m, are intended to support global applications, which are usually not optimal in a specific region area. In China, with the development of the National BDS Augmentation Service System (NBASS) of China (Shi et al., 2017), the demands for regional enhanced empirical models are strong, and the increasingly abundant meteorological products provide a good opportunity to develop refined empirical models. In this work, a refined regional empirical model, WHU_CPT, that estimates pressure, temperature, temperature lapse rate, specific humidity and water vapor weighted mean temperature over China and the surrounding area was derived. There are two key issues for the empirical model constructions, i.e., the data source selection and model form determination. In the section Data Sources, the data sources used for model constructions will be analyzed and selected. Different model forms are compared and the most suitable model is determined in the section Model Determination. The performance of WHU_CPT will be evaluated and compared to the current commonly used models in the section Model Validation, followed by the section Discussions and Conclusions.

2. Data sources

Meteorological reanalysis products provide comprehensive global, multi-decadal records of historical atmosphere states using a single consistent numerical data assimilation scheme with various past observations. They have been used extensively in climate and weather research and applications. Meteorological reanalysis products are very suitable for empirical model constructions due to the advantages of high-accuracy, spatial integrity, and temporal continuity. Regarding the pressure and air temperature, some empirical models are constructed only on the basis of reanalysis pressure level products, such as GPT and GPT2, and other empirical models such as ITG are mainly derived on the basis of reanalysis surface products. However, none of these studies discussed the reason why they used pressure level products or surface level products.

In this section, we first estimated the pressure and temperature at about 200 synoptic meteorological stations over China using ERA-Interim reanalysis pressure level, denoted as ERA_pl, and surface level, denoted as ERA_sfc products in year 2014.

For using ERA_pl, when the synoptic meteorological station is above the lowermost pressure level, the temperature at the station is estimated by linear interpolation, while for station below the lowermost pressure level, the temperature at the station is estimated by linear extrapolation, using temperature lapse rate derived from the lowermost two pressure levels. The hydrostatic and ideal gas equations are used to adjust pressure from the nearest pressure level to the station as described in Wang et al. (2007).

For using ERA_sfc, the temperature at the synoptic station is estimated using reanalysis surface temperature and temperature lapse rate derived from the nearest two pressure levels. Pressure at the station is estimated based on surface pressure and adjusted in the same way as using ERA_pl.

Fig. 1 presents the Root Mean Square (RMS) of pressure and temperature differences between the reanalysis-based estimates and stations records (SYP) at about 200 stations over China in 2014. Taking SYP as references, pressures estimated from ERA_pl are slightly better than from ERA_sfc, with RMS of 0.9 and 1.0 hPa, respectively. However, temperature errors of ERA_pl estimates are considerably larger than ERA_sfc estimates, with RMS of about 3.4 and 2.0 K, respectively. For illustration, the temperature error time series of ERA_pl and ERA_sfc at one station (WMO ID 52533) are presented in Fig. 2 where we can easily find that ERA_sfc performs better than ERA_pl, especially in the winter time when the air temperature is lower.