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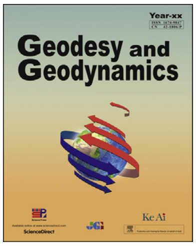

Establishment and analysis of global gridded $Tm - Ts$ relationship model

Zeying Lan[a], Bao Zhang[b,*], Yichao Geng[c]

[a] School of Management, Guangdong University of Technology, Guangzhou 510630, China
[b] School of Geodesy and Geomatics, Wuhan University, Wuhan 430079, China
[c] Guangzhou Urban Planning & Design Institute, Guangzhou 510060, China

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ABSTRACT

In ground-based GPS meteorology, Tm is a key parameter to calculate the conversion factor that can convert the zenith wet delay (ZWD) to precipitable water vapor (PWV). It is generally acknowledged that Tm is in an approximate linear relationship with surface temperature Ts, and the relationship presents regional variation. This paper employed sliding average method to calculate correlation coefficients and linear regression coefficients between Tm and Ts at every 2° × 2.5° grid point using Ts data from European Centre for Medium-Range Weather Forecasts (ECMWF) and Tm data from "GGOS Atmosphere", yielding the grid and bilinear interpolation-based TmGrid model. Tested by Tm and Ts grid data, Constellation Observation System of Meteorology, Ionosphere, and Climate (COSMIC) data and radiosonde data, the TmGrid model shows a higher accuracy relative to the Bevis $Tm - Ts$ relationship which is widely used nowadays. The TmGrid model will be of certain practical value in high-precision PWV calculation.

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1. Introduction

Water vapor, an important component of the atmosphere, is mainly distributed in the lower atmosphere, and water vapor in the troposphere constitutes approximately 99% of its total content. Though little in the atmosphere, water vapor plays a key role in a range of spatial and temporal scales of atmospheric processes, and closely relates to precipitation and climate change. The advection of water vapor and its latent heat by the general circulation of the atmosphere is an important component of the Earth's meridional energy balance [1]. A good understanding of the distribution of water vapor is very necessary for weather forecasting and climate prediction [2].

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* Corresponding author.
E-mail address: sggzhb@qq.com (B. Zhang).

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Askne and Nordius [3] first derived the relation between zenith wet delay (ZWD) and precipitable water vapor (PWV), making it possible to use GPS to detect water vapor. Bevis et al. [1] first proposed the concept of GPS meteorology, introduced the principle of using GPS to detect water vapor in detail, and proposed the method to calculate Tm, the key parameter to map ZWD to PWV, making GPS an important mean to detect water vapor. The relation between PWV and ZWD can be expressed as [1]:

$$\mathrm{PWV} = \Pi \cdot \mathrm{ZWD} \tag{1}$$

where Π is a water vapor conversion factor, which can be expressed as:

$$\Pi = \frac{10^6}{\rho_w R_v \left[(k_3/T_m) + k_2' \right]} \tag{2}$$

where ρ_w is the density of water, R_v is the specific gas constant for water vapor, k_2', k_3 are the atmospheric refractivity constants [4,5], Tm is the key variable to calculate the conversion factor Π which is related to temperature, pressure and vapor pressure, and can be precisely calculated by equation (3).

$$Tm = \frac{\int \frac{P_v}{T} \mathrm{d}z}{\int \frac{P_v}{T^2} \mathrm{d}z} = \frac{\sum \frac{P_{vi}}{T_i} \cdot \Delta h_i}{\sum \frac{P_{vi}}{T_i^2} \cdot \Delta h_i} \tag{3}$$

where P_{vi} and T_i are the average vapor pressure (unit: hPa) and average temperature (unit: K) of the atmosphere at the ith layer, respectively and Δh_i is the atmosphere thickness (unit: m) at the ith layer.

When we map ZWD to PWV, one of the largest error sources is Π calculation, whose relative error basically equals to that of Tm [6], so exact determination of Tm is very important to precise calculation of PWV.

We generally use the surface temperature Ts to calculate Tm by a linear relationship instead of equation (3), as temperature and vapor pressure profiles over a station can hardly be obtained. It has been found that Tm and Ts have a good linear correlation based on an analysis of 8718 radiosonde profiles at latitudes 27°N–65°N in America, and suggested that Tm is linearly related to Ts, i.e., $Tm = a + bTs$ [1]. Bevis et al. [1] noted that to get the best results, the constants a and b should be 'tuned' to specific areas and seasons, and offered the equation $Tm = 70.2 + 0.72Ts$ suitable for use in mid latitudes. Ross and Rosenfeld [7,8] noted that the $T_m - T_s$ relationship changes with station locations and seasons, based on a research of 23 years of radiosonde data from 53 stations. Wang et al. [9] established similar linear relationship for use in Wuhan region. Wang et al. [6] concluded that there is no significant difference between one-factor (Ts) and multi-factor (Ts; Ps: pressure; es: water vapor pressure) regression results, but the precision of regression relation based on local radiosonde data is higher than that of Bevis $Tm - Ts$ relation. Many scientists have analyzed the regional $Tm - Ts$ relation and established regional models [10–14]. Yao et al. [15] took seasonal and geographic variations into account, established the empirical model GWMT based on spherical harmonics, and well solved the problem of calculating Tm independent of measured meteorological parameters. Later in 2013, Yao et al. [16] made an improvement to GWMT and improved the accuracy of GWMT in sea areas. In 2014, Yao et al. [17] analyzed the relationship between Tm and multiple meteorological parameters and thus established the very accurate one-/multi-parameter-based models. Yao et al. [18] also published the latest and the most accurate empirical model in the same year. We can come to such conclusions from previous studies: it is of practical applicability to use Ts to calculate Tm according to regression relation; $Tm - Ts$ regression relation has evident regional characteristics; different data have significant influence on the establishment of $Tm - Ts$ linear relation.

In order to establish $Tm - Ts$ linear relation with regard for geographic variations on a global scale, this paper analyzed the correlation between the ECMWF Ts data and the "GGOS Atmosphere" Tm data. ECMWF provides gridded "2 meter temperature" data with resolution no higher than 0.75° × 0.75° daily at 0:00, 6:00, 12:00 and 18:00UTC, while "GGOS Atmosphere" provides 2° × 2.5° Tm grid data at the same time. This paper utilized 2° × 2.5° Tm and Ts data to calculate the regression coefficient a and b as well as the correlation coefficient r at the 91 × 144 grid points, and then the bilinear interpolation was employed to calculate a and b at any site. Based on these, the TmGrid model was established.

2. Analysis of the correlation between *Tm* and *Ts* and establishment of the TmGrid model

In order to get global smooth results of a, b and r, this paper employed the sliding window algorithm to calculate them. The size of the sliding window is 4° × 5°, i.e., data at the 3 × 3 grid points in the sliding window are used to calculate a, b and r which will be taken as results of the center point of the sliding window. Using this method, the global gridded $Tm - Ts$ relation model was established, i.e., TmGrid model.

The concrete realization course of TmGrid model can be described as follows: first, calculate a, b and r of the sliding window at the upper-left corner of the grids as results of the first grid point at this latitude; then move the sliding window by one point along the latitude, and calculate a, b and r of the sliding window as results of the second grid point at the latitude, and repeat until the last point of this latitude; move the sliding window by one grid once along the longitude, and calculate a, b and r of all grid points at this latitude according to methods outlined above, and so on until a, b and r at all grid points are calculated. Fig. 1 shows the smoothed correlation coefficient r in different areas of the world, while Fig. 2 shows the root mean square (RMS) error of the regression relation in different areas of the world.

From Fig. 1, we can see the correlation between Tm and Ts is mainly affected by latitudes, appears stronger at high latitudes, weaker at low latitudes, and reaches the weakest (below 0.5 at most areas) at latitudes 20°N–20°S. While the correlation also shows some differences at different longitudes.

From Fig. 2 we can see except for rare areas in the Indian Ocean, western Atlantic and eastern Pacific, the RMS errors of the regression relation are very small (basically below 4 K) in the other areas, even below 2 K at latitudes 20°N–20°S. The RMS errors, on the whole, are larger at high latitudes and smaller in the tropic areas. In general, the stronger the