Vertical Crustal Displacements Due to Surface Fluid Changes

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Abstract  Using the model data for surface mass changes of the atmosphere, ocean, soil moisture and snow depth, the vertical crustal displacements of 25 fiducial stations in China were calculated according to the loading theory. From the spectral analysis of the results, we can see that the periods of displacements are 12 months and the semi-periods are 6 months. The results also show that the maximum seasonal displacements can reach 20 mm and even larger. The covariance analyses and significance tests show that the coefficients of 96 percent of the stations are significant at the 0.1 significance level. The results show that one of the reasons of the vertical crustal displacements is the changing surface fluid loads.

Keywords  vertical crustal displacements; fluid loading effects; GPS; significance analysis

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Introduction

Temporal and spatial variations of the surface mass redistribution among the surface fluids include the atmosphere, ocean and continental water. Such redistribution causes the changes of surface loads, which causes the Earth’s crustal elastic deformation[1]. Recently, large-scale deformation has been investigated by GPS technology[2-6].

The investigation of the surface shape changes caused by the surface fluid mass redistribution is of high significance. For example, the loads at the polar region on the solid Earth will change with the changes of glaciers and ice sheet masses. Hence, the study of the deformation caused by the polar mass changes contributes to the study of the global sea level changes[1].

In this study, we focus on the vertical crustal deformations at seasonal timescale responding to surface seasonal mass redistributions, not taking into account factors such as wind, volcanoes, ocean currents and earthquakes.

1  Theoretical background

The vertical displacement $V$, induced by fluid redistribution at a surface position $(\theta, \phi)$, can be described in the center of mass of the reference frame by the convolution of load Love numbers and the spherical harmonic expansion of surface load[7].

$$\Delta \sigma(\theta, \phi) = \sum_{\ell=1}^{\infty} \sum_{m=0}^{\ell} \sum_{s=-\ell}^{\ell} M_{nmq} Y_{nmq}(\theta, \phi)$$

$$V = \frac{4\pi a^3}{M_E} \sum_{\ell=1}^{\infty} \sum_{m=0}^{\ell} \sum_{s=-\ell}^{\ell} \frac{h_n}{2n+1} M_{nmq} Y_{nmq}$$

where $\Delta \sigma$ is the load; $c$ and $s$ are the spherical harmonic coefficients; $M_{nmq}$ is the harmonic coefficient of the surface load; $Y_{nmq}$ is the real-valued spherical harmonic function normalized with geodetic convention; $a$ is the Earth’s radius; $M_E$ is the Earth’s mass; $h_n$ the surface load Love number.

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2 Surface mass loads

The atmospheric pressure is from the National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) re-analysis sub-dataset and is the monthly mean surface pressure. The atmospheric load $f$ can be estimated from the atmospheric pressure:

$$f(\theta, \phi) = p(\theta, \phi) / g$$

where $p$ is the atmospheric pressure; and $g$ is the mean surface gravity.

The ocean load is estimated from the ocean bottom pressure. The ocean bottom pressure is calculated from the sea surface height, temperature and salinity. Outputs of the estimation of the circulation and climate of the ocean (ECCO) were produced by the Massachusetts Institute of Technology (MIT), Jet Propulsion Laboratory (JPL) and the Scripps of the Institution of Oceanography (SIO). The ocean load is given by:

$$P_b = g \rho_0 \zeta + g \int_0^\infty \rho dh - \frac{\rho g}{S} \int_V \delta \rho dV$$

where $\rho_0 = 1025 \text{ kg} \cdot \text{m}^{-3}$ is the mean density of the upper sea water; and $S$ and $V$ represent the ocean surface area and volume, respectively.

The soil moisture and snow depth are outputs from the Land Data Assimilation System (LDAS) and were produced by the Climate Prediction Center (CPC) of the National Oceanic and Atmospheric Administration (NOAA). LDAS data is supported by hourly precipitation, surface pressure, soil moisture and reanalyzed horizontal vector wind from NCEP. LDAS results include four-layer soil moisture under ground surface.

3 Spectral results

According to the elastic Earth loading theory, the seasonal vertical displacements due to surface fluid mass loads were estimated at the GPS sites of Crustal Movement Observation Network of China (CMONOC) from March 1999 to October 2003. The results show that the peak/bottom values of vertical displacements at all of the fiducial stations are larger than 10 mm, and the maximum is 20 mm at some stations. Partial result of the stations are shown in Fig.1.

For most stations, the largest contributor of vertical displacements is the atmospheric load. The larger the soil moisture, the least the ocean load. WUHN station is an example (Fig.2). However, the contributor of soil moisture may be larger than at the atmosphere vertical displacements, such as at the KMIN station.
This indicates that we cannot neglect the contribution of the soil moisture load when we decipher the reasons of the vertical crustal motions.

To further analyze the characteristics of the effects of the fluid loads, spectral analyses were adopted, which needed zero mean from the original data and samples at equal intervals. In this study, the fluid data are outputs of a model and the linear trend is comparatively low; the linear parts of the vertical displacements were truncated; the values were monthly and equally sampled, which satisfies the spectral analysis needs.

Letting \( \{x[n]\} \) denote the time series of the vertical displacements, the complex frequency spectra \( \{X[j]\} \) comprised of real and virtual parts can then be directly calculated with fast Fourier transformation (FFT). Hence, the amplitude spectra, the phase spectra and the power spectra can be estimated. The formula is as follows

\[
A(j) = |X(j)| = \sqrt{X_r^2(j) + X_i^2(j)} \quad (5)
\]

\[
\phi(j) = \arctan \left( \frac{X_i(j)}{X_r(j)} \right) \quad (6)
\]

\[
G(j) = |X(j)|^2 = A^2(j) \quad (7)
\]

Fig.3 and Fig.4 are the images of the fluid loading effects and the period images of relation between power and frequency (period/month), respectively, at the BJFS station. However, we cannot make out the real values of the period. For further analyses, the period was estimated and shown in a new coordinate, where time (year/period) is at the \( x \)-axis and power is at the \( y \)-axis. It is clear in Fig.5(a) that the period of the BJFS station is 12 months when the reference epoch is March 1999. As shown in Fig.1, it is obvious that there is a 6-month semi-period aside from a 12-month period. To verify such fact, FFT was performed and the results revealed that the semi-period actually exists, as given in Fig.5(b). The results show that all the 25 stations of CMONOC has a 12-month period and a 6-month semi-period.
4 Comparison between surface fluid loading effects and GPS results

Because of the influence of the geophysical signal of the solid and polar tides, and due to the seasonal movements of surface masses such as those on the atmosphere, oceans, snow, ground water and glaciers, GPS data has obvious seasonal characteristics. Today, it is possible to detect them with several more years of continuous daily observation data\textsuperscript{[10-14]}. A great deal of GPS data has been accumulated at the stations of the International GNSS Service for Geodynamics (IGS) but has been few in China. The CMONOC, with 25 fiducial stations running since 1997, contained much precise data. The results of the seasonal height changes were gained through time serial analysis method and is shown in Fig.1.

4.1 Correlation analyse

To find out the correlation between the surface fluid loading effects and GPS observation, correlation analyses were conducted while the index was the correlation coefficient. The results in Table 1 show that when the reference epochs were March 1999, except for the HLAR, SUIY and TASH stations, the other 22 stations’ correlation coefficients are larger than 0.5, especially at KMIN, LHAS, LUZH and XIAG stations (larger than 0.75). However, the correlation coefficients change as the reference epochs change. The reason is that the CMONOC was setup in 1999, and the observation quality in a short period of time is not high. So, the correlation coefficients improve after the observation data during 1999 to 2000 were cut out.

| Station | Reference epoch/ (month/year) | Correlation coefficient | Significance level 0.1 |
|---------|-------------------------------|-------------------------|------------------------|
| HLAR    | 03/1999                       | 0.36                    | 0.350                  |
|         | 01/2002                       | 0.60                    | 0.549                  |
| KMIN    | 04/1999                       | 0.82                    | 0.348                  |
|         | 05/2000                       | 0.79                    | 0.348                  |
| LHAS    | 03/1999                       | 0.82                    | 0.393                  |
|         | 03/2000                       | 0.78                    | 0.342                  |
| LUZH    | 03/1999                       | 0.78                    | 0.342                  |
|         | 05/2001                       | 0.92                    | 0.470                  |
| QION    | 03/1999                       | 0.73                    | 0.342                  |
|         | 02/2001                       | 0.91                    | 0.449                  |
| SUIY    | 03/1999                       | 0.37                    | 0.351                  |
|         | 01/2002                       | 0.77                    | 0.561                  |
| TASH    | 03/1999                       | 0.07                    | 0.345                  |
|         | 01/2001                       | 0.18                    | 0.449                  |
| XIAG    | 03/1999                       | 0.80                    | 0.342                  |
|         | 05/1999                       | 0.85                    | 0.348                  |

4.2 Regression analyses and significance tests

To verify the linearity between the fluid loading effects and GPS measurements, regression analyses and significance tests were done, and the results display that the 24 stations’ correlation coefficients, except at TASH station, are significant at the 0.1 level. This shows the fact that strong linearity exists between fluid loading effects and GPS measurements. Therefore, from the point view of fluid mass redistri-
bution, we can interpret the seasonal crustal vertical movement.

5 Conclusions

Space-geodesy technology is more and more applied to crustal deformation monitoring, which provides a kind of geodesy constraint. The fluid loading effects and GPS measurements at 25 stations of CMONOC show correlation coefficients that are significant at the 0.1 level, which implies strong linearity between the two. However, there are still a few deviations at exceptional stations such as at TASH because the atmosphere pressure data had been assimilated by a model and not directly observed. Hence, the data themselves have the characteristics of the period, and deviate greatly from the real observation in some local regions. Furthermore, GPS height is related to some basic problems such as coordinate frame, synthesized adjustment of GPS data processing, precision of geoid, the Earth’s rotation and so on. This pushes us to determine the reasons of the vertical crustal deformation, and the factors above are the localization of such research\[15\].

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