Investigating tropospheric effects and seasonal position variations in GPS and DORIS time-series from the Nepal Himalaya

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SUMMARY
Geodetic time-series from continuous GPS (cGPS) and 1 DORIS stations across the Himalaya of central Nepal show strong seasonal fluctuations observed on the horizontal and vertical components. Because the fluctuations determined at the different stations have similar phase but different amplitudes, these observations would imply that the secular shortening across the range is modulated by a seasonal strain. Given the geographic and climatic setting, there is however a possibility that the GPS positions be biased by tropospheric effects. We process these data using two different software packages and two different analysis strategies. Our analysis shows evidence for 1-strong seasonal fluctuation of zenithal delays consistent with in situ meteorological data and two strong horizontal tropospheric gradients in particular in the EW direction, that is, parallel to the mountain front at Gumba, also detected in DORIS results. We show that the tropospheric effects cannot however be the source of the observed seasonality of horizontal strain. This study supports the view that the seasonal strain in the Himalaya is real and probably driven by seasonal surface load variations. Our study adds support to the view that seasonal variations of seismicity in the Himalaya reflects seasonal variations of geodetic strain.

Key words: Time series analysis; Satellite geodesy; Transient deformation; Ionosphere/atmosphere interactions; Hydrology; Asia.

1 INTRODUCTION
Geodetic time-series often exhibit temporal variations (Blewitt et al. 2001). These variations may reflect the viscoelastic response of the lithosphere to surface loading related to continental water storage (Bawden et al. 2001; van Dam et al. 2001), atmospheric pressure (Kaniuth & Vetter 2005), snow accumulation (Heki 2001) or to transient deformation events, including earthquakes and slow slip events (e.g. Dragert et al. 2001; Douglas et al. 2005). Prominent temporal variations are in particular observed in horizontal and vertical geodetic time-series from the Nepal Himalaya and could reflect such processes (Bettinelli et al. 2006, 2008, Fig. 1). The time-series include strong seasonal fluctuations in addition to the secular rate related to the 19 ± 2.5 mm yr$^{-1}$ shortening across the Himalaya (Bettinelli et al. 2006; Bettinelli 2007). These variations are observed on all three-components (Figs 2 and 3) and may reflect seasonal strain potentially driving the seasonal variation of seismicity that was recently reported (Bollinger et al. 2007; Bettinelli et al. 2008).

Whether variations observed in GPS time-series positions reveal real ground deformation or processing artefacts is therefore an important issue to address a number of solid earth problems. This problem is largely explored through a peering approach at a global scale, (Dong et al. 2002). Locally, bias in periodic horizontal signals has been recognized to be related to unmodelled vertical signals (King et al. 2003). Atmospheric effects are among one of the dominant source of errors on GPS geodetic positions, and may severely limit the possibility to detect temporal variations. If not correctly modelled, atmospheric effects can indeed bias vertical positions (e.g. Beutler et al. 2001), but also horizontal positions in presence of atmospheric anisotropy, in particular humidity (Bar-Sever et al. 1998). The accuracy to which tropospheric effects are estimated and corrected has improved over the years but the possibility for bias probably remains (Davis et al. 1985; Beutler et al. 1989; Sjoberg 1992; Bock & Doerflinger 2001). It is now recognized that GPS data can be a reliable source of information on the tropospheric water content, as demonstrated from a number of methodological studies over the last 10 yr (e.g. Walpersdorf et al. 2007). As a matter
of fact, dense networks of continuous GPS (cGPS) stations make it possible to carry on tropospheric tomography studies (Flores et al. 2000; Walpersdorf et al. 2004; Nilsson et al. 2007), or to correct efficiently atmospheric artefacts in interferometric synthetic radar images (Li et al. 2005).

In this study, we focus on tropospheric effects and the potential biases that they may induce on geodetic positions in the Himalayan region where the Monsoon regime induces particularly large fluctuations of tropospheric water content. We use data from four continuous GPS stations, which have been in operation across the Himalaya of central Nepal since 1997 (Bettinelli et al. 2006), and from the IGS station (Dow et al. 2005) near Lhasa (Fig. 1). We also use data from the DORIS station deployed at Mount Everest base camp as a permanent tracking station of the International DORIS Service (IDS, Tavernier et al. 2006). Given the increase in topography across the range, the quite abrupt contrast between the humid foreland to the arid Tibet plateau and the monsoon regime (Barros & Lang 2003; Jade et al. 2005; Bookhagen & Burbank 2006), the potential for seasonal tropospheric artefacts is high.

Hereafter, we first describe the dataset assembled for this study and the processing strategy adopted to highlight the influence of tropospheric effects and possible potential processing bias. Next, we describe the results, compare the tropospheric delays estimated from the GPS data with the tropospheric water content estimated from in situ meteorological data, and discuss the eventual impact of tropospheric effects on geodetic positions. The study shows that the seasonal geodetic signal reported by Bettinelli et al. (2008) cannot be explained by mismodelling of tropospheric delays and reflect real geodetic strain and that this geodetic deformation is induced by surface load variations associated with the hydrological cycle.

2 DATA

Three permanent GPS stations, SIMRA, DAMAN and GUMBA (Fig. 1) were installed in 1997 by the DASE/LDG and the Department of Mines and Geology (DMG) of Nepal and have been operating nearly continuously since then. These data are freely available on the Tectonics Observatory website (http://www.tectonics.caltech.edu/). All measurements were made with Ashtech-sensor dual-frequency geodetic receivers and using choke-ring antennas to mitigate possible multipaths effects. The sampling rate was 30 s. Stations Daman and Gumba are installed directly on bedrock. Station Simra, in the Terai, is settled on alluvium but it is this latter station which undergoes the smallest horizontal seasonal variations, as will be shown later. This dataset was previously analysed by Bettinelli et al. (2006) with data from: (1) the cGPS station NAGA deployed near Nagarkot by CIRES (University of Colorado) and the Survey of Nepal, which has been in operation sporadically between 1997 and 2001, (2) the DORIS station (Tavernier et al. 2006) near Mount Everest and (3) all available GPS campaigns (Jouanne et al. 1999, 2004; Larson et al. 1999).

We also used data from a DORIS station (EVEB) close to Mount Everest base camp in Nepal (Fig. 1). These data are freely available on the IDS Web site at http://ids.cls.fr/html/doris/
ids-station-series.php3. This station is using a Starc antenna and is installed on bedrock. It is in continuous operation since 1992 May 22 as part of the permanent DORIS tracking network (Fagard 2006).

We determine velocities in ITRF2000 (Altamimi et al. 2002) and next relative to the stable Indian plate (Figs 2 and 3), as defined by Bettinelli et al. (2006), using data from 19 additional regional IGS stations (Table 1).

3 DATA PROCESSING

To investigate the sensitivity of the results to the choice of the software package and to the processing approaches, we processed the GPS data with two different software packages (Bernese software from University of Bern and GIPSY/OASIS from Jet Propulsion Laboratory), using different tropospheric strategies.
3.1 Bernese data processing using network approach

All available cGPS measurements were initially processed (Bettinelli et al. 2006), using the Bernese V4.2 software (Beutler et al. 2001). Results were obtained directly in the ITRF2000 reference frame (Altamimi et al. 2002), using IGS final precise orbits (Beutler et al. 1999), and Earth Orientation Parameters (EOPs). We used a cut-off elevation angle of 10°. The antenna phase centre offsets and the phase centre corrections were computed using the models provided by the IGS (National Geodetic Survey web site http://www.ngs.noaa.gov/). We determined a free network solution. Random-walk-style perturbations were allowed for some parameters whose errors were found to be correlated with time (e.g. EOPs and the antenna heights at a few sites). For more details about this procedure and estimation of uncertainties, the reader is referred to Shen et al. (2000) and http://gipsy.jpl.nasa.gov/qoca/. Time-series of stations coordinates were derived from this procedure to ensure a proper alignment of the daily realizations of the terrestrial reference system of the original Bernese results.

### 3.2 GIPSY/OASIS using PPP approach

We also processed all the GPS data using the GIPSY/OASIS in a very different mode, using this time a Precise Point Positioning (PPP) technique (Zumberge et al. 1997). We used the more recent GMF model for the tropospheric mapping function (Boehm et al. 2006) and estimated horizontal tropospheric gradients at each station. GPS data at a lower elevation than in the Bernese processing were also used (cut-off angle was 7°). The horizontal tropospheric gradient takes care of the possible asymmetry of the local atmosphere (few metres above the ground and up to 1–5 km maximum) at time scale of few minutes to a day and can be modelled as below, using the same conventions as Bar-Sever et al. (1998)

\[
D_L = m_h(e) D_{\text{ho}} + m_w(e) D_{\text{wz}} + m_d(e) \cot(e) [G_N \cos(\phi) + G_E \sin(\phi)],
\]

where \(D_L\) is the tropospheric delay in the line of sight (satellite to ground station), \(e\) is the elevation of the satellite above the local horizon, as seen by the ground station, \(m_h\) is the hydrostatic mapping function (GMF in our example), \(D_{\text{ho}}\) is the total zenith hydrostatic delay, \(m_w\) is the wet mapping function, \(D_{\text{wz}}\) is the zenithal wet delay, \(m_d = m_w\) (GMF in our case), \(G_N\) and \(G_E\) is the tropospheric gradients (respectively in the south–north and west–east directions), and \(\phi\) the azimuth.

In our GIPSY/OASIS GPS data processing, \(D_{\text{wz}}, G_N\) and \(G_E\) are estimated every 5 min as randomwalk variables, using tight constraints compatible with regular atmospheric conditions.

Furthermore, several studies have shown that the tropospheric gradient improves the ZTD estimation (Iwabuchi et al. 2003) and that influence of tropospheric effects on horizontal components can be mostly removed, and repeatability improved (Miyazaki et al. 2003). Anisotropy in the lower atmosphere cannot be completely modelled only by ZTDs. In such a case, remaining errors would naturally map into GPS residuals (Champion et al. 2004). This approach is more rigorous and GPS-results were previously compared by previous authors to other sources of information such as VLBI or Water vapour radiometer (Gradinarsky et al. 2000; Snajdrova et al. 2006) showing good agreement. In our study, the estimated gradients are well determined and found significant when compared to their formal error. For one of the station (GUMBA), the horizontal gradients, when studied over the full period of data (1998.0–2005.0) show a significant offset from zero in the west direction (Fig. 5), parallel to the Himalaya chain. This offset is statistically significant and could reflect transport of moisture by E–W winds forced by the E–W striking front of the High Himalaya range which rises up.
just north of the station). To our knowledge, no systematic study has been made to interpret such horizontal tropospheric gradients in terms of meteorology and systematic direction of moisture transport. Our explanation is only tentative and should be considered with caution since other causes might be advocated. For example, multipath may also map into this estimated parameter. Finally, we also had a close look at our GPS residuals over the observed time span. They do not show any strong seasonal variations, which could be a sign of tropospheric mismodelling.

3.3 DORIS data processing

The DORIS data from EVEB station (91 km northeast of GUMB) were processed using the GIPSY/OASIS software by the IGN/JPL analysis group (Willis et al. 2006). This solution takes advantage of the latest analysis improvements described in Willis et al. (2007). Results for all DORIS stations are also freely available on the IDS website at http://ids.cls.fr/html/doris/ids-station-series.php3.

For consistency with the processing of the GPS data, we also estimated horizontal tropospheric gradients for using the data from 2007. This analysis also shows a significant non-zero estimation in the west direction, however with a smaller amplitude (1.5 mm at EVEB using the DORIS data versus 3.0 mm at GUMB using the GPS data). The DORIS tropospheric gradients are noisier (typically 1.5 mm for a daily estimation), but they are sufficiently precise to detect a clear offset from a zero value (that would correspond to a total anisotropy of the atmosphere), using almost a year of daily solutions. These results confirm that the GPS tropospheric gradients are probably related to a tropospheric anisotropy rather than to a local multipath problem.

4. RESULTS

4.1 Temporal variations of geodetic positions and strain

Besides a secular trend related to tectonics, the continuous GPS and DORIS time-series show obvious seasonal variations over the 7 yr covered by the data (Figs 2 and 3). Although the GPS data strategies are very different in our Bernese and GIPSY/OASIS solutions, the resulting time-series show very similar linear trends and seasonal variations (Figs 6 and 7). The seasonal variations are particularly prominent on the northern component, that is, in the direction perpendicular to the Himalayan range. Calculated on the raw signals, the mean peak to peak amplitudes resulting from the Bernese and the GIPSY/OASIS data processing are of the same order, respectively, 21 and 24 mm on the north component of GUMBA, 17.2 and 16.1 mm for DAMA, 13.5 and 15.5 mm for LHSA. In order to enhance and characterize the seasonal variations, we removed the best-fitting secular rate (Fig. 3). To do so, we have adjusted the time-series with an analytical function (Yoshioka et al. 2004), which considers that the fluctuations are reasonably well adjusted from a sine function and its first harmonics

\[ y(t) = a + b \times t + c \sin \left( \frac{2\pi t}{T} + \phi_1 \right) + d \sin \left( \frac{4\pi t}{T} + \phi_2 \right). \]

where \( b \) is the secular rate, \( c, T \) and \( \phi_1 \) are the amplitude, period and phase of the periodic perturbations (\( \sim \)annual) and \( d \) and \( \phi_2 \) the amplitude and phase of its second harmonics (\( \sim \)semi-annual). This formulation is appropriate given the obvious quasi-annual component, the small interannual variability and the quasi-harmonic shape of the annual perturbation. It yields a very good fit to the time-series (Fig. 3 and Table 2) with the period of the fluctuation being close to annual. The semi-annual terms are much smaller than the annual terms by almost an order of magnitude and very often not significant (Table 2). We observe that peak to peak amplitudes, resulting of this adjustment, of the annual term decreases from north to south, being of the order of 2.5 mm at SIMR, 6 ± 0.6 mm at DAMA 5.9 ± 0.7 mm at NAGA, 9.6 ± 0.2 mm at GUMBA, 12.7 ± 1.6 mm at EVEB and 6.37 ± 0.2 mm at LHSA. These oscillations are more or less equivalent every year. The annual variations show in fact a saw tooth pattern, which cannot be matched exactly by a sine function. The durations of southward displacements also seem systematically longer than the duration of northward displacements. The semi-annual term helps to reproduce this feature but a

<table>
<thead>
<tr>
<th>Station</th>
<th>Component</th>
<th>( b ) (mm yr(^{-1}))</th>
<th>( c ) (mm)</th>
<th>( d ) (mm)</th>
<th>( T ) (d)</th>
<th>( \phi_1 ) (d)</th>
<th>( \phi_2 ) (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHAS</td>
<td>North</td>
<td>12.8 ± 1.0</td>
<td>6.37 ± 0.20</td>
<td>0.22 ± 0.06</td>
<td>365 ± 0.007</td>
<td>347 ± 2</td>
<td>76 ± 3</td>
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<tr>
<td></td>
<td>East</td>
<td>45.3 ± 1.0</td>
<td>2.65 ± 0.10</td>
<td>0.08 ± 0.06</td>
<td>364 ± 0.010</td>
<td>165 ± 3</td>
<td>75 ± 4</td>
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<tr>
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<td>Up</td>
<td>7.6 ± 3.0</td>
<td>8.59 ± 0.10</td>
<td>−0.42 ± 0.22</td>
<td>364 ± 0.001</td>
<td>295 ± 2</td>
<td>14 ± 5</td>
</tr>
<tr>
<td>EVEB</td>
<td>North</td>
<td>23.5 ± 0.6</td>
<td>12.7 ± 1.60</td>
<td>0.19 ± 1.02</td>
<td>355 ± 0.020</td>
<td>341 ± 6</td>
<td>70 ± 6</td>
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<tr>
<td></td>
<td>East</td>
<td>36.5 ± 1.2</td>
<td>20.1 ± 0.30</td>
<td>−0.69 ± 0.96</td>
<td>346 ± 0.003</td>
<td>159 ± 8</td>
<td>69 ± 7</td>
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<tr>
<td></td>
<td>Up</td>
<td>−6.1 ± 4.1</td>
<td>14.8 ± 0.50</td>
<td>−1.76 ± 1.02</td>
<td>365 ± 0.004</td>
<td>320 ± 2</td>
<td>49 ± 8</td>
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<tr>
<td>GUMB</td>
<td>North</td>
<td>25.74 ± 0.3</td>
<td>9.60 ± 0.20</td>
<td>−0.63 ± 0.36</td>
<td>364 ± 0.004</td>
<td>358 ± 2</td>
<td>87 ± 5</td>
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<td>East</td>
<td>36.15 ± 0.3</td>
<td>3.97 ± 0.20</td>
<td>−0.32 ± 0.69</td>
<td>365 ± 0.008</td>
<td>178 ± 3</td>
<td>88 ± 6</td>
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<tr>
<td></td>
<td>Up</td>
<td>4.4 ± 1.0</td>
<td>12.8 ± 0.04</td>
<td>−0.06 ± 0.10</td>
<td>365 ± 0.001</td>
<td>301 ± 5</td>
<td>30 ± 3</td>
</tr>
<tr>
<td>NAGA</td>
<td>North</td>
<td>30.13 ± 0.3</td>
<td>5.91 ± 0.70</td>
<td>−0.16 ± 0.40</td>
<td>410 ± 0.030</td>
<td>354 ± 3</td>
<td>83 ± 5</td>
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<td>East</td>
<td>35.08 ± 0.3</td>
<td>5.49 ± 1.20</td>
<td>−0.26 ± 4.40</td>
<td>374 ± 0.100</td>
<td>180 ± 2</td>
<td>90 ± 6</td>
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<tr>
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<td>Up</td>
<td>0.7 ± 1.0</td>
<td>13.1 ± 1.20</td>
<td>−0.65 ± 3.60</td>
<td>383 ± 0.008</td>
<td>202 ± 4</td>
<td>111 ± 5</td>
</tr>
<tr>
<td>DAMA</td>
<td>North</td>
<td>31.90 ± 0.3</td>
<td>6.01 ± 0.60</td>
<td>−0.28 ± 0.24</td>
<td>355 ± 0.007</td>
<td>343 ± 4</td>
<td>72 ± 4</td>
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<tr>
<td></td>
<td>East</td>
<td>37.08 ± 0.3</td>
<td>4.57 ± 0.20</td>
<td>−1.04 ± 0.05</td>
<td>365 ± 0.007</td>
<td>163 ± 6</td>
<td>73 ± 5</td>
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<tr>
<td></td>
<td>Up</td>
<td>0.6 ± 1.0</td>
<td>14.4 ± 0.20</td>
<td>−2.37 ± 0.30</td>
<td>355 ± 0.003</td>
<td>355 ± 4</td>
<td>84 ± 5</td>
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<tr>
<td>SIMR</td>
<td>North</td>
<td>32.75 ± 0.3</td>
<td>2.48 ± 1.7</td>
<td>0.21 ± 0.84</td>
<td>346 ± 0.200</td>
<td>335 ± 2</td>
<td>64 ± 4</td>
</tr>
<tr>
<td></td>
<td>East</td>
<td>37.88 ± 0.3</td>
<td>4.60 ± 0.20</td>
<td>−0.65 ± 0.40</td>
<td>337 ± 0.007</td>
<td>155 ± 6</td>
<td>65 ± 4</td>
</tr>
<tr>
<td></td>
<td>Up</td>
<td>0.30 ± 1.0</td>
<td>20.3 ± 0.80</td>
<td>4.54 ± 2.00</td>
<td>355 ± 0.007</td>
<td>101 ± 2</td>
<td>10 ± 2</td>
</tr>
</tbody>
</table>

Notes: Coefficients \( b \) correspond the velocity in mm yr\(^{-1}\). Coefficients \( c \) and \( d \) correspond, respectively to the amplitudes of the annual and semi-annual periodic variations. Coefficient \( T \) corresponds to the annual period, \( \phi_1 \) the phase of the annual period and \( \phi_2 \) the phase of the semi-annual period, expressed in days.

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satisfying fit to the data can be obtained with only the annual term (Table 2).

4.2. Baseline approach

Several IGS stations have apparent seasonal variations, as detectable from SOPAC (e.g. SOPAC, see Williams et al. 2004, http://sopac.ucsd.edu/processing/: BAHR, WUHN). In principle, such a problem may affect station coordinates from a local network based on such IGS stations. To verify that our results do not depend on the fiducial network that we used, we also carried out a simpler baselines analysis of the regional network using only the four stations in Central Nepal and LHASA. These data were processed with Bernese. Strong seasonal variations show up on all baselines, in particular for the baseline LHASA to GUMBA (Figs 4a and b). This is clear indication that a reference frame bias cannot explain the observed seasonality of our GPS time-series.

4.3. Comparison of GPS solutions with and without horizontal tropospheric gradients

The total zenith tropospheric delays estimated from the inversion of the GPS data using Bernese data processing are shown in Fig. 8. Tropospheric delay peaks in the summer are due to a dramatic increase in the percentage of moisture during the monsoon (Figs 8 and 9). It can be noted that the estimated ZTD consist of the followings.
A constant term, which depends mostly on altitude (the higher constant term is observed at the lowest station SIMR, the smaller at the highest, LHASA). This constant term is probably driven by the dry component of the tropospheric delay, which can be approximated, combining formulas from Davis et al. (1985), Elgered et al. (1991) and perfect gas laws, by

\[ ZTD_{\text{dry}} = 1.013 \times 2.27e^{-0.0000116h} \]  

(3)

where \( ZTD_{\text{dry}} \) is the dry tropospheric delay (in m), and \( h \) the altitude of the station (in m). This equation predicts an almost linear behaviour in the high altitude range of our stations due to the exponential decrease of the pressure with altitude.

(2) A seasonally varying term whose amplitude also depends on altitude (the larger amplitudes variations are obtained for the station at the lowest altitude, SIMR; and the smaller is obtained for the station with the highest altitude, LHASA) (see Table 3).

In order to evaluate the impact of analysis strategy on the ZTD determination, following Iwabuchi et al. (2003), we compare in Fig. 9 the ZTD determination from Bernese data processing (without any estimation of any horizontal tropospheric gradient) and GIPSY/OASIS (estimating a horizontal tropospheric gradient). We note that the amplitude of the seasonal variations are well above the differences between the two time-series (Table 4).
4.4. Comparison of zenith tropospheric delays with meteorological in situ measurements

Here we compare our ZTD estimates with estimates derived from in situ data (pressure, temperature and relative humidity) taking advantage of the availability of good quality local meteorological data. We were able to gather met data from stations close to SIMR (met station Bara, distance = 8 km), NAGA (met station Bhaktapur distance = 9 km) and DAMA (met station Makwanpur, distance = 27 km). Unfortunately, there is no meteorological station observing near our most northern GPS station (GUMB). From the available in-situ meteorological data, we computed equivalent tropospheric delays based on Saastamoinen (1974). As shown in Fig. 9, for all three stations NAGA, SIMR and DAMA, the GPS-derived ZTD agree quite well with the in-situ derived ZTD in terms of phase and amplitude, as well as for the constant term, while no a priori bias was removed in our comparison. The two estimates compare well with a mean difference on residuals of $-0.05, 0.001$ and $-0.006$ m, and standard deviation of $0.07, 0.03$ and $0.05$ m for stations SIMR, NAGA and DAMA, respectively. As expected, the mean difference and standard deviation values are higher for the station with the lower altitude, SIMR. The variations of the in situ meteorological data are consistent with variations from GPS-derived tropospheric delays.

The GPS-derived total zenith delay are indeed significantly correlated with the ZTD derived from the meteorological data (coefficient correlation and above 0.6 for DAMA and above 0.8 for NAGA and SIMR stations) (Table 5). This degree of correlation was unexpected as the surface meteorological data only represents the troposphere just above the station, while the GPS results integrate this information on the complete column from the station to the satellite. The lowest correlation is obtained for DAMA and cannot be interpreted as a dependency with station altitude as NAGA station is almost at the same altitude. A closer look at the individual ZTD results of this station shows that the correlation is lower for this station due to a lowest correlation for extreme conditions (highest and lowest ZTD values, basically representing lowest and highest humidity conditions). The distance to the meteorological station is also the largest.

In Table 5, only GPS Bernese ZTD estimations are considered as the correlation between Bernese and GIPSY derived ZTD is over 0.94. The slope $\lambda$ provided in Table 5 is computed as the average value over the full observation period, using the following simple formula:

$$ZTD_{\text{meto}}(t) = \lambda ZTD_{\text{GPS}}(t) + ZTD_0$$

Table 5 shows that the estimated slope value are significantly different from 1 (except for the NAGA station), but not by an order of magnitude. This shows that even if the full tropospheric content of the column between the receiver on the ground and the satellite cannot be reliably predicted from the meteorological ground measurements, these two types of measurements do compare quite well in the Himalayan setting.

4.5 Comparison of temporal variations of zenith tropospheric delays and station positions

The comparison of the detrended station coordinate horizontal residuals with the total tropospheric delays shows that they are clearly not in phase (Fig. 10). Table 3 shows that the phase in the annual signal of the tropospheric delays is about 120 d and consistent for almost all stations in the GPS network. Table 2 shows that the annual signals observed in the station coordinates residuals are different from 120 d. Only SIMR vertical coordinates may be affected by an annual signal with a 120 d phase. However, station coordinates annual signals basically present a 350 d phase for north and 160 d for east, that is different in phase from the tropospheric annual signal. In addition, as demonstrated above, the tropospheric model has no significant influence on the amplitude of the seasonal horizontal variations. We conclude that the seasonal variations of station horizontal coordinates cannot be explained by mismodelling errors in the troposphere. Finally, the observed phase delay derived from the DORIS station coordinate time-series at Everest (EVEB) are very consistent with the GPS results (350 d for north and 160 d for east). In addition, the phase differences between the EW and NS are consistent with the model proposed by Bettinelli et al. (2008). The model does predict an elliptical seasonal trajectory at each station, and not a displacement along a line, because the spatial distribution of surface loading does vary with time leading to different phases on the EW and NS component.

5 Conclusions

Permanent geodetic monitoring in the Himalaya reveals that secular interseismic strain is modulated by strong seasonal variations observed in GPS and DORIS time-series. Although seasonal variations in GPS time-series are commonly observed and could arise form a variety of artefacts, the fact that it is better observed in the horizontal component than in the vertical component is a specific feature of this network. Baseline analysis shows that the observed seasonality is not an artefact of the densification procedure used to express position results in a well-defined terrestrial reference frame. Results obtained from processing the same GPS data using two different software packages (Bernese and GIPSY/OASIS), and adopting different analysis strategies for terrestrial reference realization and for tropospheric correction, show strong horizontal tropospheric gradients, probably reflecting orogenic forcing on
moisture transport, and seasonal variation of the total zenith delays in surprisingly good agreement with those predicted from in situ meteorological measurements.

Our analysis demonstrates that the observed horizontal annual signals are not an artefact of the GPS processing related with tropospheric mismodelling. The amplitude of the horizontal seasonal geodetic displacements increases northwards, so that the shortening rate across the range is lower in the summer than in the winter. The geodetic data thus points to a local source capable of producing horizontal contraction in the winter and horizontal extension in the
summer, superimposed on the secular shortening rate across the Himalaya. As proposed by Bettinelli et al. (2008) this pattern is consistent in phase and amplitude with the effect of surface load variation as estimated from GRACE and TOPEX/Poseidon data (Fig. 11). The observed and predicted variations show extension across the range (northward horizontal displacements relative to stable India) to loading of the Ganges foreland basin by increasing water storage during the spring and summer and compression (southward horizontal displacements relative to stable India) in the Fall and Winter as the water storage decreases. The good agreement between the model and the GPS data both in amplitude and phase shows that the times series presented are not biased significantly by tropospheric artefact. This study shows that in certain favourable setting the effect of surface hydrology might be better detected on the horizontal components than on the vertical components. Our findings also add support to the view that the seasonal variations of seismicity observed in the Himalaya, the seismicity rate being twice higher in the Winter than in the Summer (Bollinger et al. 2007), are driven by seasonal variations of stressing rates, an observation that has important implications as to the mechanism of earthquakes nucleation (Bettinelli et al. 2008).

**ACKNOWLEDGMENTS**

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**Figure 8.** Time-series of total zenith tropospheric delays at the five cGPS stations analysed in this study obtained from the Bernese GPS data processing are presented here.

**Figure 9.** Comparison of time-series of total zenith tropospheric delays at the five CGPS stations analysed in this study obtained from the two GPS data processing Bernese (blue squares), and Gipsy/OASIS (red circles), and those calculated using meteorological data provided by the Nepal Department of Meteorology and Hydrology (green dots) and calculated from Saastamoinen 1974. See Fig. 1 for location of meteorological data.
Table 3. Coefficients of eq. (1) used to fit the zenith tropospheric delay time-series estimated from the Bernese data processing.

<table>
<thead>
<tr>
<th>Station</th>
<th>c (m)</th>
<th>d (m)</th>
<th>T (d)</th>
<th>ϕ1 (d)</th>
<th>ϕ2 (d)</th>
<th>χ²</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHAS</td>
<td>0.112</td>
<td>0.004 ± 0.2</td>
<td>363</td>
<td>119 ± 2</td>
<td>29 ± 3</td>
<td>0.015</td>
</tr>
<tr>
<td>GUMB</td>
<td>0.150</td>
<td>0.010 ± 0.05</td>
<td>366</td>
<td>118 ± 5</td>
<td>39 ± 3</td>
<td>0.0009</td>
</tr>
<tr>
<td>NAGA</td>
<td>0.180</td>
<td>−0.008 ± 0.8</td>
<td>364</td>
<td>120 ± 4</td>
<td>32 ± 5</td>
<td>0.0018</td>
</tr>
<tr>
<td>DAMA</td>
<td>0.200</td>
<td>0.004 ± 0.2</td>
<td>362</td>
<td>120 ± 4</td>
<td>32 ± 3</td>
<td>0.002</td>
</tr>
<tr>
<td>SIMR</td>
<td>0.360</td>
<td>0.020 ± 1.5</td>
<td>360</td>
<td>125 ± 3</td>
<td>42 ± 5</td>
<td>0.038</td>
</tr>
</tbody>
</table>

Notes: Coefficients c and d correspond, respectively, to the amplitudes of the annual and semi-annual periodic variations. Coefficients T, ϕ1 and ϕ2 correspond, respectively, to the period and to the annual and semi-annual phases, expressed in days.

Table 4. Residuals between ZTD Gipsy and Bernese estimated solutions.

<table>
<thead>
<tr>
<th>Station</th>
<th>Shift (m)</th>
<th>Standard deviation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GUMB</td>
<td>0.0147</td>
<td>0.0075</td>
</tr>
<tr>
<td>DAMA</td>
<td>0.0040</td>
<td>0.0070</td>
</tr>
<tr>
<td>SIMR</td>
<td>0.0076</td>
<td>0.0092</td>
</tr>
</tbody>
</table>

Table 5. Comparison between Zenith Total Delay (ZTD) derived from surface meteorological data and GPS observation. Correlation coefficient and slope, λ, between the 2 ZTD time-series, as defined in eq. (4).

<table>
<thead>
<tr>
<th>GPS station (acronym)</th>
<th>Altitude (m)</th>
<th>ZTD correlation (unitless)</th>
<th>Slope, λ (unitless)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAMA</td>
<td>2,151</td>
<td>0.650</td>
<td>0.590 ± 0.046</td>
</tr>
<tr>
<td>NAGA</td>
<td>2,105</td>
<td>0.827</td>
<td>0.995 ± 0.033</td>
</tr>
<tr>
<td>SIMR</td>
<td>71</td>
<td>0.850</td>
<td>0.530 ± 0.038</td>
</tr>
</tbody>
</table>

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REFERENCES


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Figure 10. Detrended northward displacements, and vertical displacements at the four CGPS stations SIMR, DAMA, NAGA, GUMB (black dots). Total zenith tropospheric delays estimated during the processing with BERNESE V4.2 (bottom) are shown for comparison (black dots). Red lines correspond to the best fit with a sinus function (taking into account only the annual term). Vertical black lines show the pick of the tropospheric delay.


Figure 11. Comparison of seasonal variation of geodetic displacements and water level in the Ganges basin (bottom graph). Water level variations of some major rivers in the Ganges basin measured by Topex-Poseidon (yellow dots) and equivalent water thickness derived from GRACE (blue dots). Purple shaded areas show seasonal geodetic displacements computed from the variation of surface load due to seasonal variation of water storage (2σ uncertainty) assuming an elastic half-space with an elastic shear modulus of 40 GPa, and a Poisson coefficient of 0.25 (Bettinelli et al. 2008).


Tavernier, G. et al., 2006. The International DORIS Service, genesis and early achievements, J Geod., 80(8–11), 403–417.


