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A COMPREHENSIVE REVIEW OF SEASONAL VERTICAL CRUSTAL MOVEMENTS FROM GPS OBSERVATIONS

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Abstract: This review focuses on understanding the factors and processes affecting Global Positioning System (GPS) vertical annual cycles and the use of GPS data for monitoring drought. Instead, through GPS techniques, annual oscillations of the Earth's crust due to hydrological, climatic and or environmental factors that affect surface deformation can be identified. In order to analyze seasonal vertical crustal movements using GPS observations, assessing patterns, causes, and implications for geophysical processes. These vertical displacements have been recently employed in hydrological contexts like Total Water Storage (TWS) inversion, and the indices from these vertical seasonal shifts seem effective for drought severity assessment. In recent years, extensive research and considerable scientific efforts have been dedicated to leveraging GPS technology as a tool for systematically recording and analyzing various natural processses, including extreme environmental events such as prolonged droughts and sudden, high magnitude earthquakes. However, despite these advancements, the intricate characteristics and underlying mechanisms governing the annual oscillatory movements of the Earth's crust remain largely elusive and not yet fully comprehended. Further, while GPS-based data analysis models have made significant progress in improving the accuracy of geodetic measurements, but still exhibit notable limitations, and precision imperfect, necessitating further refinements, methodological advancements, and the integration of complementary observational datasets to enhance their reliability and effectiveness for geophysical applications. This review also discusses the variation in these movements occurring at the regional level and reasons that finer models for such movements based on specific regional characteristics need to be developed. Future research will have to cause upgrades in the data models, including multi-source data, specifically GRACE satellite observation, and effective computational methods for exacting geodetic applications. By improving the precision of the GPS data analysis and integrating multi-source datasets, this research paves the way for more accurate and real-time environmental monitoring, offering valuable insights for disaster preparedness, water resource management, and climate resilience strategies. Also, these findings will provide a better understanding and guidance for future research in this scope of studies.

Keywords: vertical seasonalmovement; water resource management; drought monitoring; earthreference frame

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INTRODUCTION

Non-linear seasonal movements of the crust refer to the phenomenon where the Earth's crust exhibits non-linear characteristics during seasonal changes, such as varying amplitudes, irregular trajectories, and inconsistent velocity of movement. These movements are typically caused by seasonal climate changes, hydrological cycles, and geophysical processes (Heki & Jin, 2023). For example, winter ice and snow loads and summer precipitation can lead to elastic deformation of the crust, resulting in different modes and magnitudes of movement.

With the rapid development of Global Positioning System (GPS) observation technology and significant improvements in positioning accuracy, the information on crustal motion obtained from GPS observations plays an increasingly important role in the study of geodynamics. However, the crustal motion information derived from GPS observations is often influenced by non-linear seasonal movements, particularly prominent in vertical motion (Tsai, 2011; Yang et al., 2023). Currently, many researchers have applied GPS vertical seasonal motion information to water resource management, seismic activity monitoring, and the establishment of high-precision terrestrial reference frames (Azhari, 2020; Li et al., 2022; She et al., 2024). Nevertheless, there is still a lack of comprehensive studies systematically describing its related applications, and few studies have systematically summarized the current state of research on drought monitoring based on

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GPS vertical seasonal motion. Therefore, to gain a more comprehensive understanding of vertical seasonal movements based on GPS observations and their applications, we first use the bibliometric analysis method to analyze outlines of the causes and mechanisms of crustal seasonal movements. Secondly, it summarizes various related applications, particularly emphasizing those in drought monitoring, an area that has received comparatively less attention in prior research. Finally, the study concludes by synthesizing the research content and proposing future directions for studies related to vertical seasonal movements.The aim of this study is to conduct a comprehensive analysis of non-linear seasonal vertical crustal movements derived from GPS observations, exploring their causes, mechanisms, and applications, with a particular focus on drought monitoring. The study aims to synthesize current research and propose future directions for related studies.

LITERATURE REVIEW

The study of seasonal vertical crustal movements has gained prominence with the advancement of GPS technology. These movements exhibit non-linear characteristics, influenced by seasonal climatic changes, hydrological cycles, and geophysical processes. As climate-related phenomena such as snow and ice accumulation in winter, and seasonal precipitation, impact the crust, they induce elastic deformation. This results in varying amplitudes, irregular trajectories, and inconsistent velocity patterns of vertical crustal movements (Heki & Jin, 2023).

Causes and Mechanisms

Several studies have identified the primary causes behind these seasonal vertical movements. For example, Heki & Jin (2023) argue that the Earth's crust responds elastically to seasonal loading and unloading, such as the melting of ice or seasonal rainfall. This results in periodic upward or downward movements of the crust, which are often difficult to predict due to their non-linear nature. Additionally, Tsai (2011) and Yang et al. (2023) describe how the seasonal redistribution of water in the form of snow, rainfall, and groundwater contributes significantly to crustal deformation. These studies emphasize the need to differentiate between elastic deformation caused by climate variables and other forms of long-term geological movement.

Applications

Recent studies have focused on the application of GPS-derived vertical seasonal movements in various fields, including water resource management, seismic monitoring, and the establishment of high-precision terrestrial reference frames. Li et al. (2022) and She et al. (2024) highlight the utility of GPS data in accurately monitoring vertical displacement and its implications for earthquake prediction and water management. These findings are crucial for hydrological studies and flood control, where seasonal movements affect groundwater storage and surface water levels. However, a relatively underexplored application is the use of GPS-derived vertical seasonal movements for drought monitoring. Azhari (2020) suggests that seasonal vertical movements, such as those observed during periods of drought, can be used as an indicator of groundwater depletion. This could serve as an early warning system for water scarcity, particularly in regions with limited groundwater data. Despite the promising application of GPS in drought monitoring, there is a lack of comprehensive studies that systematize the relationship between vertical crustal movements and drought conditions.

Critical Analysis

The findings from the reviewed studies reveal significant progress in understanding the mechanisms driving seasonal vertical crustal movements. However, limitations exist in the research. Firstly, while the application of GPS technology has improved the precision of measurements, discrepancies between different GPS stations remain, especially in regions with complex geological structures. Tsai (2011) points out that local geological factors can distort vertical displacement measurements, making it difficult to generalize findings across different regions.

Moreover, while studies such as those by Li et al. (2022) and She et al. (2024) emphasize the potential of GPS for applications like seismic monitoring, the integration of GPS data with other geophysical data sets remains a challenge. The need for multi-source data fusion is critical to enhance the accuracy and reliability of GPS-derived measurements. Additionally, Azhari (2020) notes that while vertical movements provide valuable insights into drought conditions, there is insufficient research on the temporal relationship between vertical displacement and drought severity.

METHODS

In the Scopus database, using the advanced search query: `TITLE-ABS-KEY (GPS AND vertical AND displacement) AND SUBJAREA (eart) AND PUBYEAR > 2013 AND PUBYEAR < 2025 AND (LIMIT-TO ( EXACTKEYWORD, "Seasonal Variation" ) OR LIMIT-TO ( EXACTKEYWORD, "GPS") )`, a total of 334 English papers on Seasonal Crustal Vertical Movements Based on GPS Observations were retrieved (as of the search date, September 20, 2024). After reviewing the abstracts of these papers, 67 non-review English papers were selected (Figure 1). The number of papers on Seasonal Crustal Vertical Movements Based on GPS Observations shows an increasing trend, with related English papers primarily published in journals such as Journal of Geophysical Research-Solid Earth, Acta Geophysica Sinica, Geophysical Journal International, Geophysical Research Letters, Geodesy and Geodynamics, and Journal of Hydrology (Figure 2).

Seasonal Variation based on geodetic perspective

In the physical mechanisms causing seasonal changes in station displacements, accurate correction formulas for many geophysical factors have been provided, such as annual and semi-annual solid Earth tides, annual effects of polar tides, and tidal models (Lyard et al., 2006; Petit & Luzum, 2010). The influences of these annual effects have been incorporated into precise theoretical models allowing for their correction at the processing stage of GPS carrier phase data (functions are available in software packages like GAMIT, GIPSY, and Bernese). However, the effects generated by more subtle geophysical factors, due to their small magnitudes and reliance on geophysical models, are often overlooked. Through the analysis and speculation of some scholars in recent years, it is suggested that the non-linear changes in GPS station coordinate residuals may also be related to factors such as surface mass loading effects, seasonal temperature effects, and high-order ionospheric delays (Jiang et al., 2018; Li et al., 2024; Yehun et al., 2020).

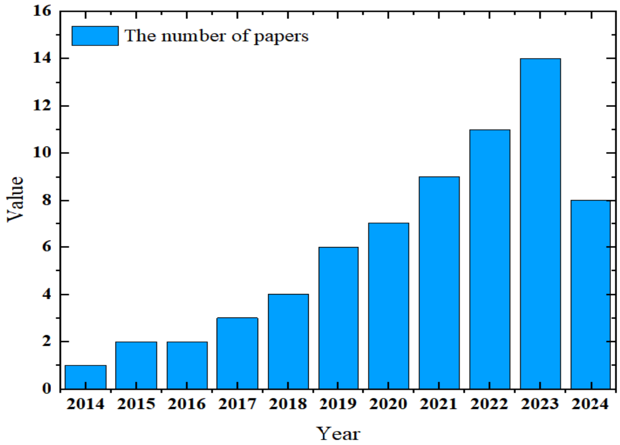


Figure1. Number of articles on seasonal crustal vertical movements based on GPS observations

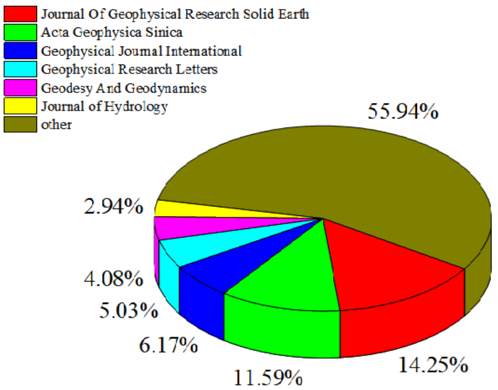


Figure 2. Proportion of journals publishing articles on seasonal crustal vertical movements based on GPS observations

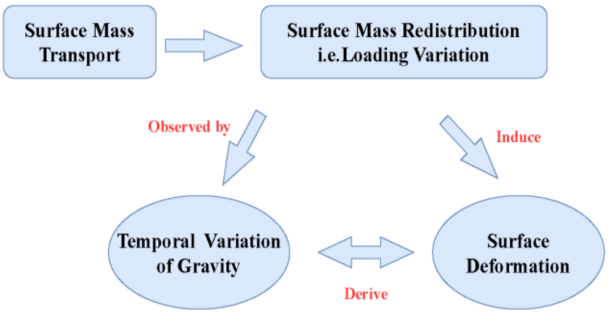


Figure 3. Process of mass transport and loading variation (Zhang, 2014)

Surface mass loading effects

As a large amount of material is transferred within the Earth's system over time, the redistribution of this material on the Earth's surface leads to changes in surface loading, resulting in temporal variations in gravity. Since the geoid of the Earth is defined as a surface of equal gravitational potential, changes in gravity affect height displacements. Therefore, changes in surface load due to mass redistribution ultimately result in elastic displacements of the Earth's surface (White et al., 2022; Zhang, 2014), as illustrated in Figure 3. Early studies have indicated that the surface load effect of materials is one of the significant factors contributing to the seasonal vertical displacements observed at GPS stations. Common types of surface load effects include atmospheric loading effects, non-tidal ocean loading effects, and terrestrial water loading effects. Seasonal variations in atmospheric pressure can lead to elastic deformation of the crust, resulting in periodic vertical changes of several millimetres to tens of millimetres at GPS stations, particularly pronounced in high-latitude and mountainous regions (Dong et al., 2002; Zhang et al., 2018). Non-tidal ocean loading mainly comprises changes in ocean water mass brought about by wind-driven effects, atmospheric pressure effects, and variations in seawater density. Studies have shown that non-tidal ocean loading primarily impacts coastal cities, with the response diminishing as the distance from the coastline increases (Van & Wahr, 1998; Zerbini et al., 2004). Variations in terrestrial water storage, encompassing changes in snowfall, soil moisture, groundwater, and surface water such as lakes and reservoirs, exert loads on the crust, leading to changes in GPS station displacements. The influence of terrestrial water loading on the vertical displacements of GPS stations ranges from millimetres to centimeters, exhibiting variations across different regions and seasons (Argus et al., 2017).

With the continuous advancement of related research and the further development of corresponding spatial geodetic technologies in recent years, the conclusion that material gravitational loading can stimulate non-tectonic seasonal surface movements has been further corroborated and refined. Chuanyin et al. (2018) identified that variations in atmospheric loading, non-tidal ocean loading, and terrestrial water mass loading are the primary factors triggering seasonal vertical deformations of the crust, contributing over 97%. Zhao et al. (2023), comparing the statistical distributions of continuous GPS time series, sought the optimal regional surface mass loading model to correct these GPS time series, thereby reducing their dispersion and enhancing the accuracy of uplift rate estimates. In summary, the impact of surface load effects on the vertical displacements of GPS stations is significant and exhibits marked seasonal variation. However, it is crucial to recognize that surface loading effects may differ across regions due to variations in geography, climate, and human activities. Existing studies may lack regional applicability, failing to account for the characteristics and disparities of different areas adequately. Consequently, future research should emphasize data sharing and collaboration, develop higher-precision models, and prioritize real-time monitoring of regional variability and dynamic changes.

Seasonal temperature effects

The thermal elastic deformation caused by changes in surface temperature also has an inducing effect on the annual displacement observed by GPS stations. Due to the Earth's revolution around the sun, there is a significant annual variation in surface temperature, which can also induce seasonal deformations on the surface. In the field of Earth science, related research on thermal elastic deformation Berger et al. (1975) proposed the first thermal elastic deformation model on a semi-infinite space. Ben-Zion and Leary (1986) extended the model and then established a decoupled layer semi-infinite space model.

Subsequently, some scholars used this model to estimate the thermal expansion effect caused by changes in surface temperature and its effect on the radial displacement of GPS stations. Dong et al. (2002), based on the half-plane analytical model, concluded that temperature change influences the annual amplitude variation of GPS station bedrock vertical displacement by less than 0.5mm. It is also suggested that temperature change is one of the factors causing periodic displacement changes in GPS stations. Yan et al. (2010) analyzed the effect of temperature changes on the vertical displacement of GNSS stations based on 23 GNSS reference stations in the Chinese Crustal Movement Observation Network, revealing that the maximum annual amplitude of its effect is 2.8mm. Lulu et al. (2018) discussed the influence of the thermal expansion effect on GNSS vertical displacement. They showed that the annual amplitude of thermal expansion vertical displacement for more than 50% of GNSS stations in mainland China is at least 1mm. Lu et al. (2024) demonstrated that by employing an improved comprehensive thermal expansion model (TEVD FSD), it is possible to assess better the non-linear variations of GNSS height products, particularly across different data processing strategies, thus significantly enhancing the explanatory power regarding the effects of surface temperature changes on thermal expansion.

While prevailing research affirms the impact of temperature on the seasonal movements of GPS, certain limitations persist in the research process. Firstly, the accuracy of the adopted thermal expansion model remains a concern, leading to periodic issues in the final results. Secondly, disparities in the materials utilized in the observation piles at diverse GPS stations in the research locale may yield significant deviations in the analysis outcomes across sites. Lastly, the intricate bedrock composition beneath GNSS stations may render a single thermal expansion model unsuitable for all stations, potentially affecting observation accuracy. Therefore, developing a new and refined thermal expansion effect model is crucial for more accurately mitigating temperature-induced influences on GNSS vertical displacement.

High-order ionospheric delays

Alongside load effects and temperature considerations, the non-linear alterations in GPS station coordinates may also be subject to influence from high-order ionospheric delays. Recent scholarly focus on precise GPS positioning has underscored the escalating emphasis on and exploration of high-order ionospheric delays' impact on GPS data processing precision. Kedar et al. (2003) highlighted that high-order ionospheric errors can introduce distinctive semi-annual signals in the north component of GPS sites. Expanding on this observation Yuan et al. (2008) posited that high-order ionospheric delays might engender semi-annual signals in the vertical domain. Petrie et al. (2010) elucidated the role of high-order ionospheric delays in instigating non-linear seasonal movements in GPS coordinate time series. Zhu Xin-hui et al. (2020) conducted a collective study implementing high-order ionospheric delays to evaluate their impact on GNSS station coordinate time series, delving into the influence of these delays on the non-linear alterations in GNSS station coordinates and quantifying their effects in scholarly discourse. To date, investigations into the influence of high-order ionospheric delays on non-linear seasonal changes affecting global GPS sites are relatively limited. Hence, a deeper exploration of high-order ionospheric delays' effects on non-linear seasonal displacements at global GPS sites stands to unveil a new pathway toward establishing a refined, high-precision global Earth framework.

Applications of Seasonal Deformation

As the exploration of the seasonal movement of the Earth's crust advances, a clearer understanding of crustal seasonal movements is emerging. Consequently, applications related to the seasonal movement of the Earth's crust are progressively maturing. In the ensuing discourse, we delve into the utilization of crustal nodal movement in water resource monitoring and management, earthquake activity analysis, regional crustal structure inversion, and bolstering the stability of the Earth reference framework.

Monitoring and management of water resources

GPS technology exemplifies remarkable capability in accurately documenting surface responses to seasonal changes in water content and other Earth crust loads, denoted as seasonal displacements. Conversely, through meticulous separation of other non-hydrological signal components (encompassing non-tidal atmospheric and oceanic loads, tectonic deformations, and post-glacial rebound effects), GPS can effectively facilitate the inversion of regional Total Water Storage (TWS) alterations. Analogous to insights from GRACE/GFO missions, GPS-derived TWS changes encapsulate diverse hydrological components like surface water, groundwater, and soil moisture. As a result, GPS-inferred TWS alterations find utility in hydrology, extreme climate change, and related research domains.

The novel application of GPS observations in hydrogeology, specifically inverting regional Total Water Storage (TWS) changes, warrants a comprehensive evaluation of its efficacy and potential. Argus et al. (2014) harnessed GPS vertical displacement to invert changes in land water storage in California, yielding inversion results congruent with GRACE data. Fu et al. (2015) employed GPS vertical displacement to assess alterations in land water storage in Washington and Oregon, showcasing a solid correlation between GPS-derived results and those from GRACE and hydrological model inversions. Comprehensive comparison and analysis of Yunnan's land water storage inversion results with GRACE, GLDAS, and TRMM data indicate the capability of current GPS stations in Yunnan as autonomous observation data for tracking land water storage changes during the GRACE and GRACE/GFO interconnecting periods (Siyuan et al., 2018). A method proposed by integrating independent component analysis (ICA) with GPS vertical coordinate time series facilitated the estimation of land water storage (TWS) changes in the Sichuan-Yunnan region of China, exhibiting high consistency with GRACE-derived water storage outcomes (Liu et al., 2022).Illustrating Yunnan Province in China as a case study for Total Water Storage (TWS) inversion, Figure 4 delineates the spatial distribution of the annual amplitude of TWS changes from December 2010 to February 2021 as inverted by GPS, GRACE/GFO, and the Global Land Data Assimilation System (GLDAS) land surface model. Notably, the GPS-inferred results align with GRACE/GFO and GLDAS estimates, disclosing a gradual waning trend of TWS alterations in Yunnan Province from southwest to northeast. The slightly larger overall amplitude of the GPS signal is ascribed to its heightened sensitivity to local hydrological load signals relative to GRACE/GFO.

GNSS (Figure 4a) shows the annual amplitudes of TWS changes in Yunnan Province as derived from GNSS observations. The color scale represents the magnitude of TWS changes, with red indicating the highest amplitudes and blue indicating the lowest. The spatial distribution suggests that the highest amplitudes are concentrated in the central and northern parts of the province. GRACE/GFO shows the annual amplitudes of TWS changes obtained from the GRACE/GFO mission. The color scale is similar to the GNSS diagram, with red representing high amplitudes and blue representing low amplitudes. The spatial pattern is generally consistent with the GNSS results, but with some differences in the magnitude and distribution of high-amplitude areas. GLDAS shows the annual amplitudes of TWS changes as simulated by the GLDAS model. The color scale remains the same, with red indicating high amplitudes and blue indicating low amplitudes. The spatial pattern shows a more uniform distribution of amplitudes compared to the GNSS and GRACE/GFO results, with higher amplitudes concentrated in the central and southern parts of the province. The investigations above underscore the pivotal role of GPS deformation time series accuracy and emphasize the significance of monitoring station density and distribution in optimizing GPS-inferred outcomes. While GRACE/GFO and GPS are instrumental tools in modern geodesy, harmonizing the inversion of Total Water Storage (TWS) alterations through cross-validation of these complementary technologies holds promise for enhancing the precision of terrestrial water storage change assessments. However, notable disparities stemming from methodological and scale differences necessitate a strategic fusion of these technologies to exploit their combined strengths, heralding an innovative research pathway toward attaining more precise changes in terrestrial water storage.

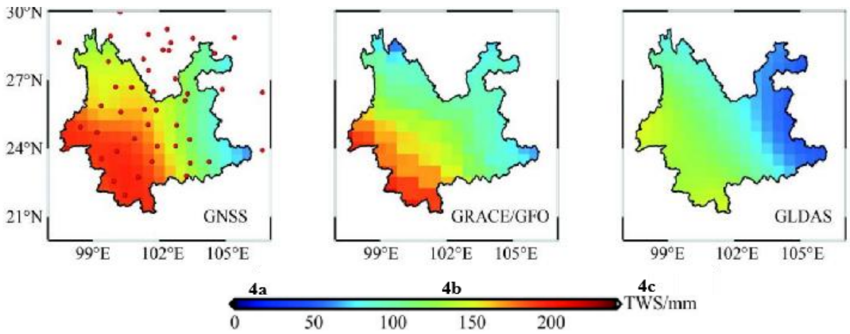
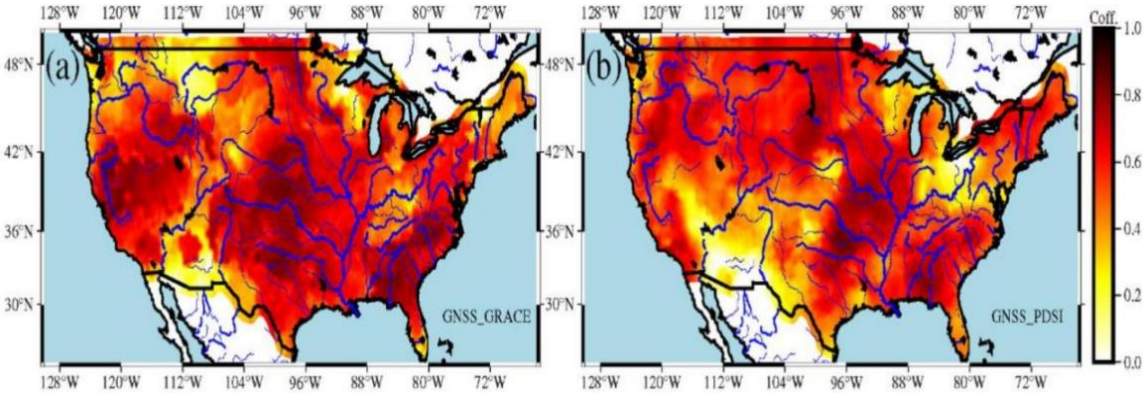


Figure 4. Annual Amplitudes of TWS Changes in Yunnan Province derived from different inversion strategies from Dec. 2010 to Feb. 2021, Heat map (Li et al., 2023)

Drought monitoring

The escalating prevalence of drought globally poses a significant threat to water resources and hydrological cycles, accentuating the need for robust monitoring strategies (He et al., 2021). Drought, typified through hydrological, meteorological, or agricultural lenses, encompasses various indices designed to effectively gauge and contrast drought severity and duration (Shi et al., 2023).Recent ground-based GPS observations furnishing vertical seasonal displacement data pertinent to hydrological cycles have been leveraged to fashion novel drought indices, underscoring the utility of GPS in monitoring drought intensity. For instance, Chew and Small (2014) devised a site-specific drought index (DIGPS) at each GPS station predicated on vertical surface seasonal displacement time series, serving as a pivotal indicator for hydrological drought surveillance. Ferreira et al. (2018) conducted a comparative analysis of drought indices derived from GRACE (DITWS) and vertical land deformations measured by GPS (DIVCD) for nationwide drought classification in Brazil over a relatively short period (7 years). While congruence between GRACE TWS and GPS displacement exceeded 90% at most sites, the correlation between DITWS and DIVCD stood at 82% of sites. Yao et al. (2019) devised a GPS drought index for the Yunnan region grounded on vertical seasonal motion coordinate time series, effectively capturing the region's drought characteristics. Jiang et al. (2022) pioneered a dynamic GPS imaging approach based on principal component analysis of vertical crustal displacements sensed by GPS from 2006 to 2020, amalgamated with climatological methods, culminating in a GPS-based Drought Severity Index (GPS-DSI).Figure 5 illustrates U.S. drought monitoring from 2006 to 2020 using vertical seasonal displacements from GPS data. It elucidates the spatial distribution features of the GPS-DIS derived from GPS and the GRACE-derived hydrological drought index (GRACE-DSI) (Figure 5 a), alongside the correlation coefficients between these indices and the meteorological drought index sc-PDSI (Figure 5 b). The depiction affirms robust correlations between GPS-DIS based on GPS and both GRACE-DSI and sc-PDSI indices across most U.S. regions.



a b

Figure 5. Spatiotemporal correlation between GPS-DSI, GRACE-DSI, and scPDSI time series. Panels (a) and (b) show the map of correlation coefficients for GPS-GRACE and GPS-scPDSI, respectively, Heat Map (Jiang et al., 2022)

Table 1 encapsulates the correlation analysis between the hydrological drought index GPS-DSI fashioned from vertical seasonal displacements using GPS, the hydrological drought index GRACE-DSI derived from GRACE, and the meteorological drought index sc-PDSI time series across 18 basins in the United States. Displaying correlation coefficients denoted as R1 for GPS-DSI and GRACE-DSI correlation and R2 for GPS-DSI and sc-PDSI correlation, the table underscores robust correlations among the three indices in a majority of U.S. basins, highlighting the viability and efficacy of leveraging GPS-detected vertical seasonal changes to probe extreme climate occurrences like drought.

Table 1. The correlation coefficient between the GPS-DSI, GRACE-DSI, and sc-PDSI in 18 basins in the United States

Region	**R1**	**R2**	**Region**	**R1**	**R2**
the New England	0.52	0.65	Missouri	0.65	0.75
Mid-Atlantic	0.72	0.47	Arkansas-White-Red	0.81	0.66
South Atlantic-Gulf	0.81	0.7	Texas-Gulf	0.70	0.57
Great Lakes	0.64	0.45	Rio Grande	0.60	0.32
Ohio	0.58	0.42	Upper Colorado	0.61	0.54
Tennessee	0.59	0.66	Lower Colorado	0.40	0.19
Upper Mississippi	0.74	0.72	Great Basin	0.78	0.53
Lower Mississippi	0.70	0.60	Pacific Northwest	0.57	0.72
Souris-Red-Rainy	0.71	0.69	California	0.81	0.67

The studies mentioned above underscore the significance of utilizing globally accessible GPS vertical seasonal deformations for drought severity monitoring. However, given the nuanced factors influencing GPS seasonal displacements, the accuracy of our constructed drought index hinges on the effective extraction of vertical seasonal displacements triggered by hydrological loads. Consequently, future research will pivot towards enhancing the precision and efficacy of extracting hydrological load displacements entwined with drought from GPS seasonal displacements to craft meticulous GPS drought indices.

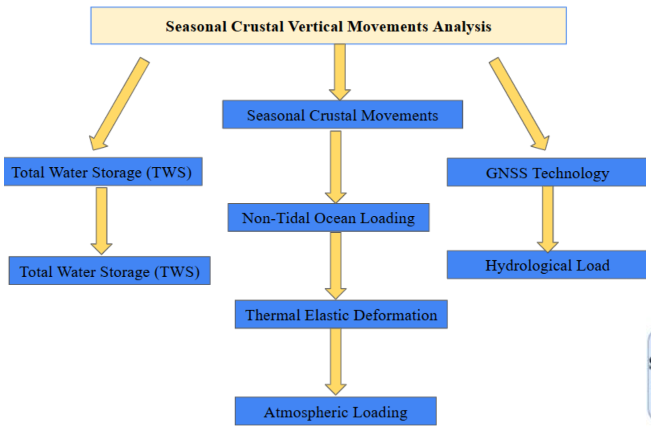


Figure 6. Seasonal crustal vertical movements analysis (Zhang, 2014)

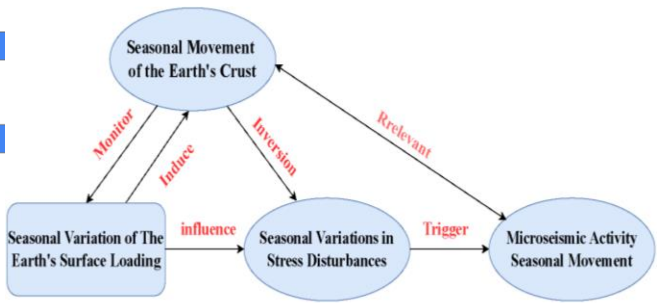


Figure 7. Relationship between seasonal vertical crustal deformation and seasonal variations of mass loading, crustal stress perturbation (Jiang et al., 2022)

Analysis of earthquake activity

The investigation into stress disturbances on seismic activity induced by diverse physical processes underscores the pivotal role of stress fluctuations arising from seasonal mass-loading variations. The magnitude of stress perturbations triggered by these seasonal mass loading changes is of sufficient scale to influence seismic events (Johnson et al., 2017). Simultaneously, the seasonal oscillation in crustal mass loading emerges as the primary catalyst for seasonal crustal motion, hinting at a potential correlation between seasonal crustal motion and regional seismic events, as elucidated in Figure 7.

Geophysicists have recently witnessed a burgeoning interest in unravelling the modulatory impact of seasonal crustal motion on seismicity. Heki (2003) scrutinized the seasonal crustal deformations instigated by snow load in the Japanese archipelago, positing that snow load interferes with strain accumulation amidst earthquakes, potentially precipitating seasonal seismic events in the region. Compared to pore pressure explanations, the snow load mechanism leans towards exerting a regional influence on seismic activity Bettinelli et al. (2008) elucidated the linkage between the seasonal fluctuation of hydrological load, the seasonal displacement of GPS stations, and seismic event traits in the Nepal region, shedding light on the intricate interplay between earthquake nucleation processes, stress accrual, and seismic activity. Drawing insights from California, USA, Kreemer & Zaliapin (2018) computed the seasonal signals of GPS stations, unveiling a robust correlation between the seasonal vertical displacement of regional GPS stations and seasonal surface strain. In conjunction with seismic event data, their analysis alludes to seasonal strain potentially catalyzing main shock episodes, amplifying earthquake magnitudes, and mitigating aftershocks. Nagale et al. (2022) leveraged data from GRACE and GPS to appraise the influence of seasonal loading on deformation amidst seismic episodes in Nepal, revealing a discernible correlation between seasonal water loading and seismic activity, whereby escalating hydrological loading mitigated seismic occurrences.

The findings underscore a significant association between water load variations and earthquake frequency, primarily attributed to the repercussions of seasonal pressure fluctuations. The dominant pressure exerted by water load alterations aligns with the background tectonic stress direction, potentially instigating a 10% surge in seismic events. This analytical framework serves as a viable model for elucidating the periodicity of earthquakes in the southeastern periphery of the Qinghai-Tibet Plateau. Collectively, these studies underline the correlation between seasonal motion and seismic activity, offering a novel angle for comprehending the triggers and intricate mechanisms governing earthquakes in the research domain.

Enhancing the stability of the earth reference frame

The technology of spatial geodesy possesses the capability for high-precision measurement of surface deformations and the Earth's gravitational field while also defining and maintaining the geodetic reference framework. It has made significant contributions to the fields of geoscience, particularly in monitoring crustal movements, the migration of surface fluid materials, and atmospheric delays (Bock & Melgar, 2016). A high-precision reference framework serves as a fundamental reference for the aforementioned geoscientific observations (Weiping et al., 2022). Research indicates that vertical seasonal movements of the crust can influence the stability of station coordinates within the Earth reference framework, resulting in periodic fluctuations in long-term coordinate time series. These fluctuations may affect the accuracy and long-term stability of the ITRF, particularly in geodesy applications that demand extremely high precision (Ferre, 2018). Specifically, failing to account for vertical seasonal movements in the ITRF solutions may lead to frame displacements, consequently impacting the accurate interpretation of global surface movements and variations in the Earth's gravitational field (Ming et al., 2023).

Thus, simulating and analyzing the non-linear changes of GPS stations has become a crucial task for refining the International Terrestrial Reference Frame (ITRF). Establishing a millimetre-level terrestrial reference frame has emerged as a new objective within the international geodetic community. In 2016, the International Earth Rotation and Reference Systems Service (IERS) released the ITRF 2014 (Altamimi et al., 2016). This framework has begun utilizing the characteristics of non-linear crustal motion as a fundamental model for expressing the crustal dynamics of GPS baseline stations. This approach incorporates post-seismic deformation modelling and the estimation of seasonal annual and semi-annual signals into the model of linear crustal movement while traditionally overlooking station non-linear movements.

Consequently, ITRF2014 represents significant advancements and improvements over previous iterations of the ITRF series, offering strong guidance and holding substantial significance for future research on millimetre-level terrestrial reference frames. The latest iteration, ITRF2020, was unveiled in April 2022. Compared to ITRF2014, this enhanced version not only includes station positions and velocities but also provides parameters for post-seismic deformation (PSD) and seasonal signals. ITRF2020 further refines the modelling of station non-linear movements, thereby enhancing the quality, consistency, and accuracy of the new framework (Altamimi et al., 2023). Given the current limited understanding of the factors inducing vertical seasonal movements in GPS, future research must focus on enhancing the correction accuracy for these vertical seasonal movements, particularly in high-latitude regions and areas experiencing significant load variations. Furthermore, integrating multi-source data, such as gravity field data from GRACE satellite observations, with advanced machine learning algorithms can more effectively capture and predict the complex characteristics of vertical seasonal movements, thereby further improving the performance of the ITRF reference framework.

CONCLUSION AND PROSPECTS

This review critically examines the causes and applications of GPS vertical seasonal movements, particularly emphasizing their emerging yet underexplored potential in drought monitoring. By elucidating the non-linear behaviour of crustal seasonal movements driven by climatic and hydrological factors, the study provides a foundational understanding of the intricate links between these geodetic observations and environmental changes. Although GPS-based surface deformation monitoring has enriched our insights into natural calamities like droughts and earthquakes, inherent constraints persist owing to incomplete elucidation of factors driving seasonal crustal movements and imperfections in GPS data processing models. Moving forward, refining data processing models, streamlining calculation procedures, and ameliorating error margins in computed results is imperative. Additionally, the mechanisms driving seasonal crustal movements exhibit regional variability, necessitating meticulous examination and in-depth exploration of the drivers of seasonal crustal motion in each specific geographic area. Such detailed analysis promises to provide a richer perspective on the complexities of seasonal crustal dynamics and enhance the robustness of geodetic applications across diverse regions, thereby advancing the use of GPS in environmental monitoring, resource management, and disaster mitigation efforts globally.

This study reported limitations by highlighting the inevitable challenges in accurate modeling of vertical crustal movements due to different regional environmental influences, which complicate GPS data interpretation. While seasonal displacements are detected very well with GPS observations, model data analysis per se, regarding percentages of today's analytical data, proves to be a limiting factor. Although the multi-source data availability such as the GRACE satellite observations may improve reliability, technical challenges in integrating these data sets still exist. But the complexity of the hydrological, climatic, and environmental processes affecting the Earth's crust is such that today the knowledge about how these processes influence each other is still incomplete. Moreover, although GPS has been observed to hold promise in drought severity monitoring, the differences in local conditions together with the resolution of available data may result in conflicting outcomes for the same across different regions. Addressing these concerns is a promising avenue for future research with improved computational methodologies to boost the reliability and applicability of GPS in monitoring natural processes.

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