



Ground Deformation Monitoring Using InSAR and Meteorological Time Series and Least-Squares Wavelet Software: A Case Study in Catania, Italy

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Abstract. Persistent Scatterers Interferometric Synthetic Aperture Radar (PS-InSAR) is an advanced satellite remote sensing technique which allows an effective monitoring of ground movement. In this work, PS-InSAR time series as well as precipitation and temperature time series in a region in Catania, Italy are utilized during 2018–2022, and their possible interconnections with land subsidence/uplift due to groundwater level change are investigated. First, the potential jumps in the displacement time series are removed, and then the Sequential Turning Point Detection (STPD) is applied to estimate the times when the velocity of the displacement time series changes. The results show a significant correlation between the frequency of turning points in displacement time series and precipitation trend change, particularly during the winter season. Furthermore, the Least-Squares Cross Wavelet Analysis (LSCWA) is applied to estimate the coherency and phase delay between the displacement and weather cycles in the time-frequency domain. The annual cycles of displacement and temperature show more coherency than the ones of displacement and precipitation across the study region. The results presented herein are important for infrastructure and water management planning.

1 Introduction

Rising and declining precipitation over time can potentially increase and decrease groundwater level, respectively (Jasechko et al., 2024). Excessive groundwater extraction during hot and dry seasons for various purposes, such as agriculture and industry, can result in seawater intrusion, streamflow reduction, and land subsidence (Jasechko et al., 2024). On the other hand, land uplift may be due to rising groundwater level as the result of increase in precipitations and reduction in groundwater pumping (Ghaderpour et al., 2024a). Catania plain, the widest alluvial plain in Sicily, has experienced land subsidence due to natural and anthropogenic causes, such as tectonic and volcanic activity, sediment compaction, fluid withdrawal, and dams (Anzidei et al., 2021). This plain has been studied by many researchers, especially from the structural and hydrogeological points of view (Spampinato et al., 2013; Guastaldi et al., 2014). European Ground Motion Service (EGMS) has recently provided PS-InSAR data derived from Sentinel-1 satellites for ground deformation monitoring across Europe with millimeter precision (Costantini et al., 2021). In the present study, trends, and seasonal components in PS-InSAR time series covering the plain are estimated and their potential interconnection with precipitation and temperature are investigated.

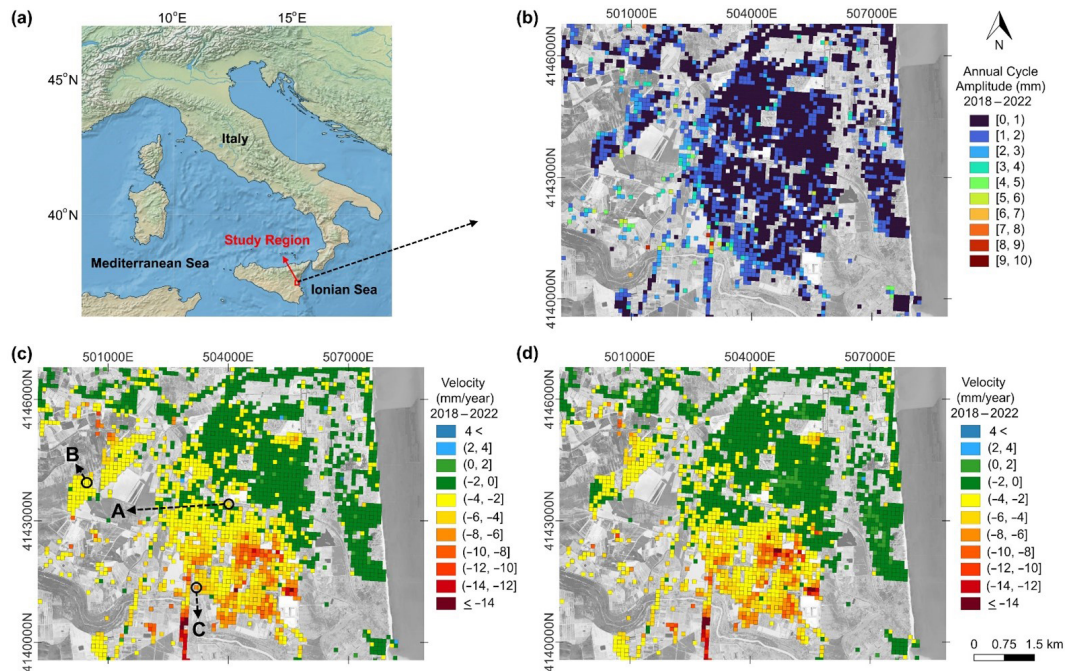


Figure 1. (a) Location of the study region, (b) the amplitude map of annual cycles in PS-InSAR vertical time series, (c, d) the velocity maps before and after removing the jump at the end of 2018, respectively. The maps are produced by QGIS (from © Google Maps 2015).

2 Materials and Methods

2.1 Study region

The study region is part of Catania plain, located in south-east of Sicily (Italy), Fig. 1. The region includes Catania international airport, industrial areas, villages, and agricultural lands. Improper water management had a negative impact on groundwater in the last decades, resulting in seawater intrusion and aquifers salinization (Guastaldi et al., 2014). The Ionian Sea is on the east side of the region. From a geological point of view, this region is located between Mount Etna and the Hyblean foreland, where alluvial clastic deposits crop out (Lentini, 1982). These deposits mainly lie on a thick sequence of Pleistocene marine marly clays, which are also part of the sedimentary basement of Mount Etna.

2.2 Datasets

The vertical displacement time series with a sampling rate of 6 d for period 2018–2022 and at a spatial resolution of 100 m from the EGMS Level 3 Ortho Product (<https://egms.land.copernicus.eu/>, last access: 20 March 2024) are utilized herein, derived from ascending and descending PS-InSAR time series and information of Global Navigation Satellite Systems (GNSS). The daily precipitation and temperature time series at Fontarossa, near the center of the study region, are downloaded from <https://www.3bmeteo.com/> (last access: 20 March 2024). For visualization purposes, the tem-

perature (average) and precipitation (cumulative) time series are resampled to 6 d intervals to match the sampling rate of displacement time series. For the STPD and frequency bar chart, the displacement time series are monthly resampled using the spline interpolation method, and monthly accumulated precipitation time series are also calculated (Ghaderpour et al., 2024a, b).

2.3 Methods

2.3.1 Jumps Upon Spectrum and Trend (JUST)

JUST is a robust method of detecting abrupt changes (jumps) in the time series. Its special case, implemented herein, uses the Ordinary Least-Squares (OLS) by a sequential least-squares fitting of a linear trend with two pieces within a translating window (Ghaderpour, 2021b).

2.3.2 Sequential Turning Point Detection (STPD)

STPD is developed for detecting trend Turning Points (TPs) in a time series. A TP is the location where the gradient of connected linear pieces, fitting the time series, changes with the assumption that no significant abrupt change exists. STPD is like the special case of JUST, but a linear trend with two connected pieces is sequentially fitted to the time series segments. Like JUST, the criterion for selecting a potential TP is minimizing the residual norm (Ghaderpour et al., 2024b).

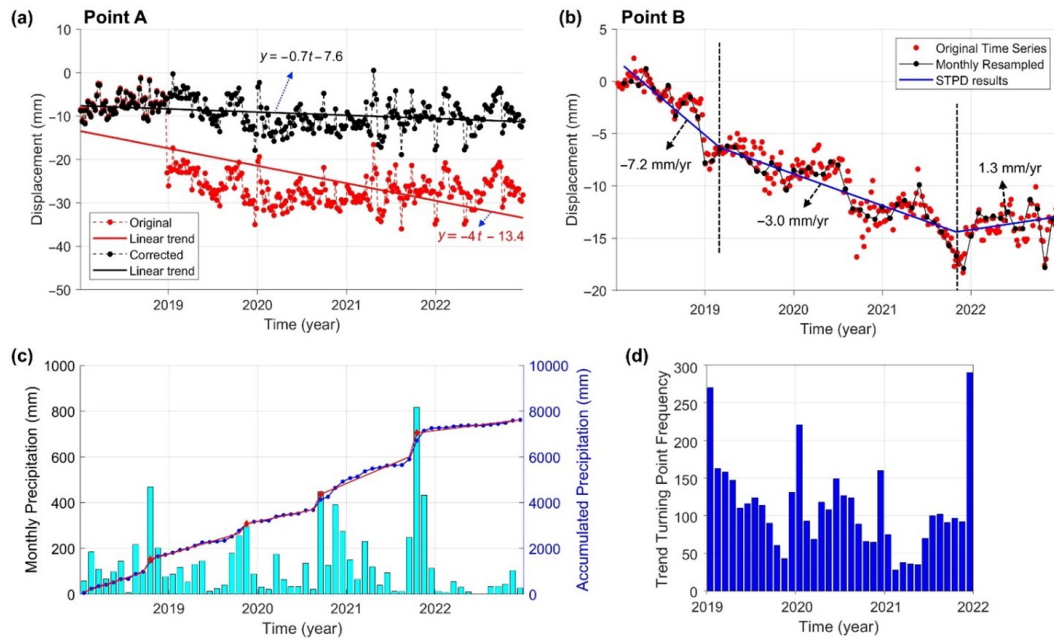


Figure 2. (a) Velocity of a time series before and after jump removal, (b) STPD result of a time series showing two TPs, (c) JUST result of precipitation showing 4 significant changes, (d) frequency bar chart for the set of all the time series whose locations are shown in Fig. 1. Note that the original and corrected segments before 2019 are the same in panel (a).

2.3.3 Least-Squares Cross Wavelet Analysis (LSCWA)

LSCWA decomposes time series into the time-frequency domain to estimate a cross-spectrogram (Ghaderpour et al., 2018). A spectrogram for each time series is estimated by fitting trend and sinusoidal functions to each segment within a translating window whose size is inversely proportional to frequency. Two spectrograms for the two time series are then cross-multiplied to obtain a cross-spectrogram which shows how much the periodic/aperiodic cycles of the two time series are coherent. LSCWA also provides phase delay information for cyclic components of the time series. The phase delay is usually depicted by white arrows on the cross-spectrograms, following the trigonometric principle. LSCWA is a tool in the LSWAVE software (Ghaderpour and Pagiatakis, 2019).

3 Results

3.1 Velocity Estimation Before and After Jump Removal

From implementing JUST, it is found that there is a jump with a significant magnitude at the end of 2018 for many of the time series across the region, likely due to the earthquake occurred on 26 December 2018 (Alparone et al., 2022). Panels (c) and (d) in Fig. 1 respectively show the velocity maps before and after correcting the jump at the end of 2018, where the results of Point A are illustrated in Fig. 2a. This highlights

the criticality of properly detecting and removing jumps before velocity estimation.

3.2 Turning Points and Jumps

Those time series with a significant jump at the end of 2018 are first corrected, then STPD is applied to all monthly resampled time series, including the corrected ones. An example of a time series with two TPs is depicted in Fig. 2b, where Point B is highlighted in Fig. 1c. Figure 2d shows the frequency bar chart of TPs for all the time series across the study region, where each bar shows the number of all the estimated TPs at a given calendar month. Due to extreme precipitation events, the accumulated precipitation time series exhibits significant jumps, so JUST is applied to estimate the dates when the precipitation trend has changed, considering the jumps (Fig. 2c). Note that the red points in Fig. 2c show the jumps (not TPs) in the accumulated time series due to extreme precipitation events, allowing the linear trend pieces to fit better the segments.

3.3 LSCWA

Figure 1b shows the amplitude map of annual cycles in the displacement time series, estimated by the least-squares spectral analysis (Ghaderpour, 2021b). LSCWA is then applied to the displacement and weather time series to further investigate the potential cause of annual and seasonal cycles in the displacement time series within the study region. One time series example corresponding to Point C in Fig. 1c is

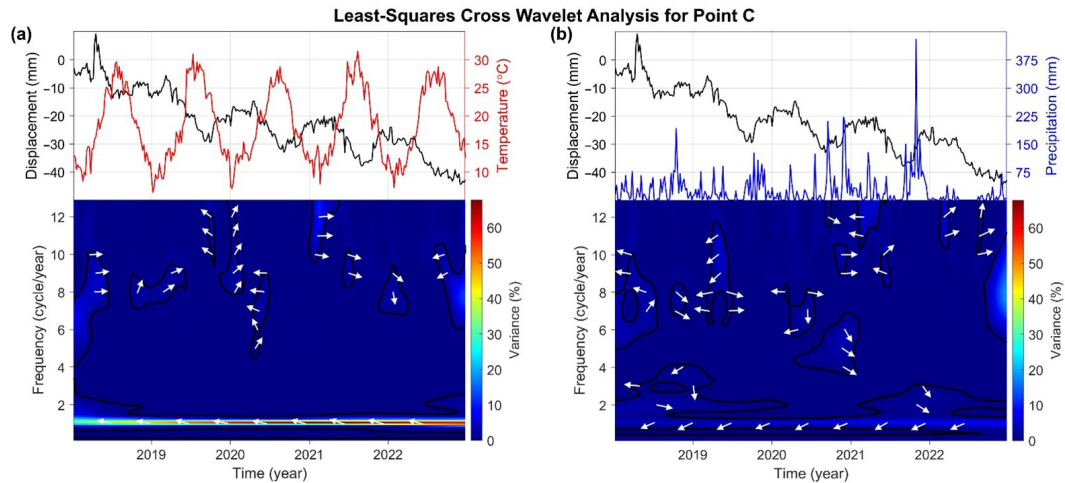


Figure 3. The LSCWA results for Point C near Centrale Elettrica Solare, displayed in Fig. 1c.

demonstrated in Fig. 3. The annual cycles in the displacement and temperature time series are relatively much more coherent than the ones in the displacement and precipitation time series across the study region, particularly for the reddish areas in Fig. 1b and Point C shown here; see the reddish horizontal peaks at 1 cycle/year in Fig. 3a and compare it with Fig. 3b. In Fig. 3, arrows pointing to the east and west indicate in-phase and out-of-phase, respectively. Arrows pointing to the north and south mean the weather cycle lag and lead the displacement cycle, respectively. Spectral peaks inside the black contour lines are statistically significant at 95 % confidence level.

4 Discussion and conclusions

Herein, ground deformation in Catania plain is studied using the tools in LSWAVE software applied to EGMS and weather data. From Fig. 2d, relatively higher numbers of TPs are observed during the winter. Many of these TPs have a positive direction, meaning that the subsidence rate has been decreased and in some cases land uplift is even observed. Interestingly, the jumps detected during the fall season, as shown in Fig. 2c, indicate that heavy precipitation could have played a role in the land uplift, although this aspect deserves further investigation focused on the hydrogeological setting of the study area. Moreover, tectonic dynamics must be considered since literature reports the presence of fault segments crossing the region (Ferrara and Pappalardo, 2004). The annual cycle of the displacement time series was almost out-of-phase with the annual cycles of temperature and precipitation in some areas, including the Centrale Elettrica Solare. This may be interpreted as relatively more land subsidence during the hot season and more land uplift during the cool season. This may also be partially due to thermal expansion and contraction of metal structures and solar power sys-

tems (Ghaderpour, 2021a). Moreover, the delay of about five months between annual cycles of precipitation and displacement time series could be due either to a delay between surface water and groundwater interaction, or to the groundwater travel time between the infiltration point and the aquifer existing within the study area. Land cover response to climate change could also be another contributing factor to the seasonal cycles of displacement time series as sensed from space (Ghaderpour et al., 2023). Historical groundwater level data for Catania plain are limited, but their analyses and correlation with climate and ground deformation are subjects to future studies.

Code availability. The software is publicly available online at <https://github.com/Ghaderpour/LSWAVE-SignalProcessing> (Ghaderpour, 2021; Ghaderpour and Pagiatakis, 2019).

Data availability. The Sentinel-1 based PS-InSAR time series utilized in this study are publicly available at <https://doi.org/10.2909/943e9cbb-f8ef-4378-966c-63eb761016a9> (European Environment Agency, 2023). The weather data are also available at <https://3bmeteo.com> (3BMeteo S.r.l, 2024).

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