Spatiotemporal analysis of GNSS time series at the active volcano Ol Doinyo Lengai, Tanzania

Abstract:

In geodesy and geophysics, continuous Global Navigation Satellite Systems (GNSS) observations have been used globally to study different geodynamic processes. This study investigates the spatiotemporal patterns of the active Ol Doinyo Lengai using data from the network of permanent GNSS sites monitoring the volcano (the TZVOLCANO network) installed around the flanks of the volcano. I constrain surface motions using 6 GNSS sites distributed around volcano, continuously operating between 2016 and 2022. The daily positional time series were processed using GAMIT-GLOBK software then used the linear regression or fitting analyses in Python program to estimate the potential velocities from the GNSS position time series. The results suggest the inflation of the volcano. Both Temperature and precipitation show a significant correlation with the daily GNSS position.

1. Introduction

Satellite positioning (GNSS – Global Navigation Satellite System) is an important technology which has profoundly influenced the profession of surveying as well as a plethora of modern society's economic, scientific and social activities. With the improvement of positioning accuracy and the growing number of continuous operating reference stations (CORS), GNSS has found an increasingly wide utilization in the field of geodesy and geodynamics, such as seismic activity and earthquake studies (Grapenthin and Freymueller, 2011), volcano deformation monitoring (Dzurisin, 2006), plate motion and plate boundary strain accumulation (Stamps et al., 2021; Saria et al., 2013) and others. The measurements provide insights and information of the tectono-magmatic processes and other eruptive precursory events.

The GNSS time series in the horizontal direction are featured with the linear velocity caused by plate movement while the vertical direction is associated with more cyclical variation caused by geophysical phenomena such as non-tectonic deformation. GNSS time series details the positional change of a site over time depicting an ongoing geodynamic process. However, they are affected by climatic variables (for example, temperature, rainfall, drought and precipitation) within the region. Analyzing position time series is a key to understanding seismic events and monitoring any tectono-magmatic interactions by detecting transient movements due to magma movements that cause volcanic eruptions. Before using the GNSS positions, a careful understanding of their spatiotemporal correlation with climatic variables is required. The project tries to answer the following questions regarding to spatiotemporal analysis of GNSS time series with temperature and precipitation

1. How do daily positional time series change due to magma activity (magma source expansion or contraction)?
2. Are daily positions correlated with climate?
3. Does temperature affect the daily GNSS position?
4. Does precipitation affect the daily GNSS position?
5. Which climatic component is sensitive to daily position?
6. How many components explain almost 95% of the temperature signal?

Here I use the permanent GNSS monitoring network called Tanzania Volcano Network (TZVOLCANO) established in 2016 to monitor the active volcano Ol Doinyo Lengai and constrains the Natron fault. The network has four GNSS monitoring sensors installed on the flanks of the volcano, one sensor on the border fault (Natron Fault), one outside the influence of the volcano to have a local reference station, and one co-located seismic sensor (Figure 1). All data is transmitted through a remote satellite internet system telecommunication to a USA National Science Foundation Geodesy Facility entitled UNAVCO (www.unavco.org). The study also uses temperature and precipitation variables that were downloaded from the European Centre for Medium-Range Weather Forecasts (ECMWF) archive (Prof. Susanna Werth, personal communication, 2022). The Singular Value Decomposition (SDV) technique is used to investigate the correlation between positions and climatic variables.

2. Data and Methods

I use Continuous GNSS measurements, temperature and precipitation to study the mechanism of an ongoing deformation. GNSS provides daily observations and has capability to measure displacements on earth's surface with millimeter precision in three dimensional (3-D). Usually, deformation study involving continuous GNSS observation, it requires a minimum of three (3) years on continuous observation to estimate reliable geodetic velocity while for episodic measurement, a minimum of three epochs of measurements are required (Blewit et al., 2002). I use temperature and precipitation to identify if GNSS are correlated with these variables.

2.1 Geodetic Data

The input data in this study are 6 years of GNSS data from the TZVOLCANO network (Figure 1). The observations were processed using GAMIT-GLOBK software (Herring et al., 2018) to obtain the final positional time series and velocity solutions with their uncertainties from GNSS phase observables using double differencing. The GNSS time series are the input in the Python program to assess the spatiotemporal features as well as deformation patterns.

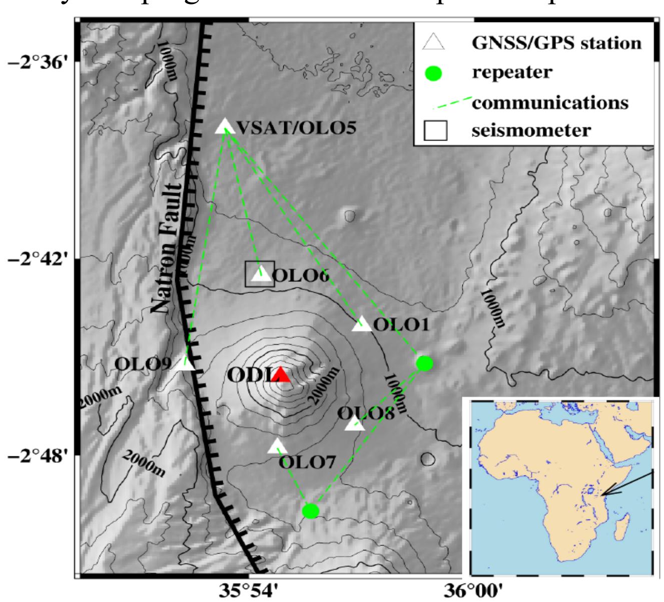

Figure 1. The TZVOLCANO network (ODL = Ol Doinyo Lengai). White triangles are CGNSS stations, the black square is a broadband seismometer, green circles are radio transmitters,

dashed green lines the communication pathways. The Natron Fault is depicted as a dashed black line.

2.1.1 GNSS surface motion from time series

Calculating surface motion from GNSS time series involves three steps first, to convert spatial coordinates, then plot and last fits the time series using Python program. The following steps were followed

i. **process_raw_and_export_csv.py**

   This script processes original data in each station by converting longitude and latitude time series to local east (E), north (N) and up (U) components (ellipsoidal height or vertical is unchanged). It also converts the time component and creates a new time (unit: year, with digits). This is used for plotting time series. The new information is then added to the dataframe. The unit for E, N, U is changed to mm as opposed to the original data being in meters.

ii. **auto_plot_timeseries.py**

   This python script loops through the newly created csv files in (i) above and plots the time series without fitting them.

iii. **auto_fit_velocity.py**

   This script reads the .csv files created in step (i) and fits the time series to compute velocities in local east, north and up components. The script is designated to have flexibility options just before fitting, the user will be prompted to provide a station as reference station (i.e., that station will be completely stationary in the fitted result). If no desired reference station (i.e., use the time series as is), type in 'None'. The referencing step will be skipped. New plotted time series with fitted velocities. This script also exported the velocity data as a csv file named: fitted_velocity_ref_(ref_site_name).csv. Figure 8-13 represents GNSS fitted time series.

2. 2 Temperature and Precipitation variables

Temperature and precipitation variables were downloaded from the European Centre for Medium-Range Weather Forecasts (ECMWF) archive (Prof. Susanna Werth, personal communication, 2022). Their time span is approximately six years (2017 to 2022).

3. Results.

3.1 GNSS Results

This study presents plots GNSS time series (Figure 2 -5) without fitting them just to understand the trend of the data from which the earth’s surface deformation can be estimated by fitting the data.

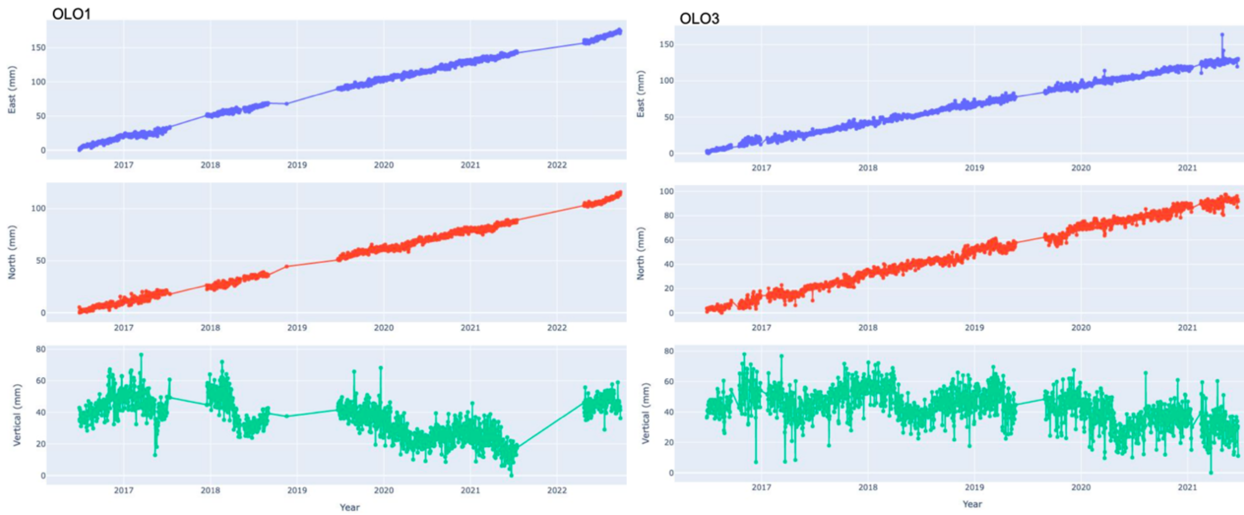

Figure 2. Time series for OLO1 (left) and OLO3 (right) before fitting

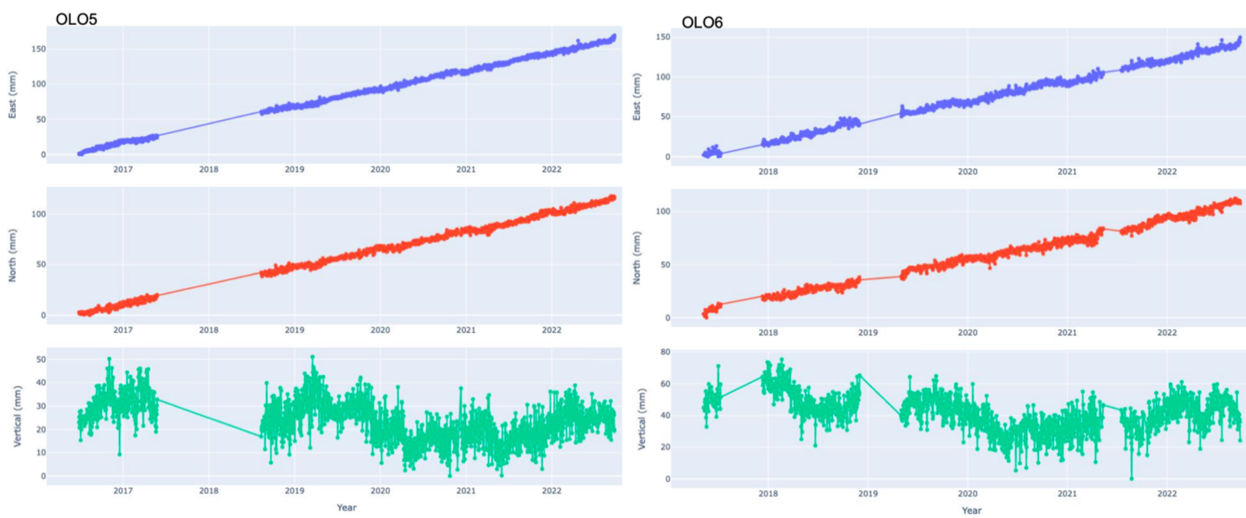

Figure 3. Time series for OLO5 (left) and OLO6 (right) before fitting

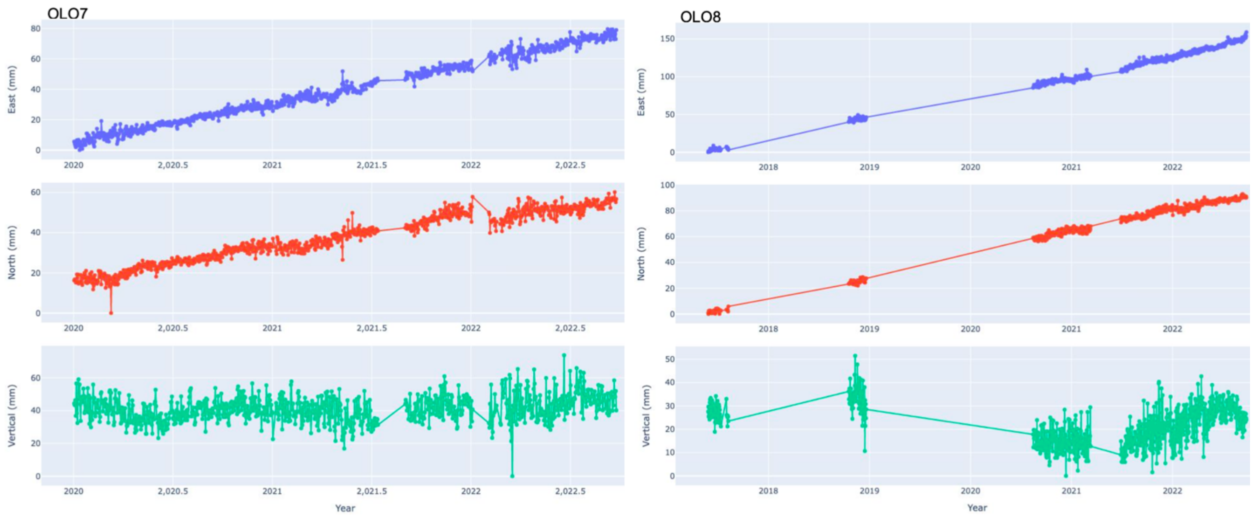

Figure 4. Time series for OLO7 (left) and OLO8 (right) before fitting

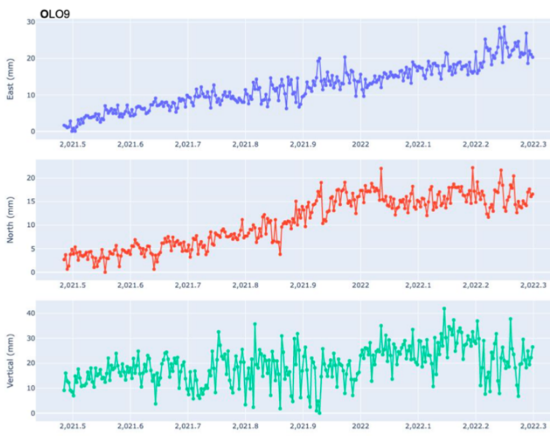

Figure 5. Time series for OLO9 before fitting

After plotting GNSS time series, I fit them so as to calculates the site velocities in east, north and vertical components. Figure 6 -9 represents the fitted time series to estimate the horizontal and vertical motions which suggests for the geodynamic process

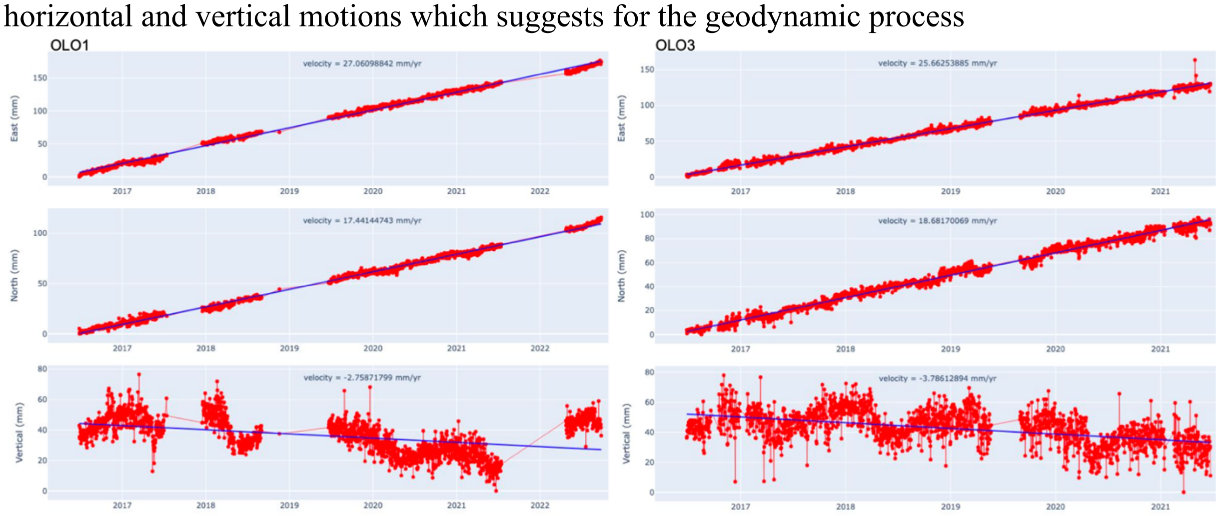

Figure 6. The fitted (blue line) time series for OLO1 (left) and OLO3 (right)

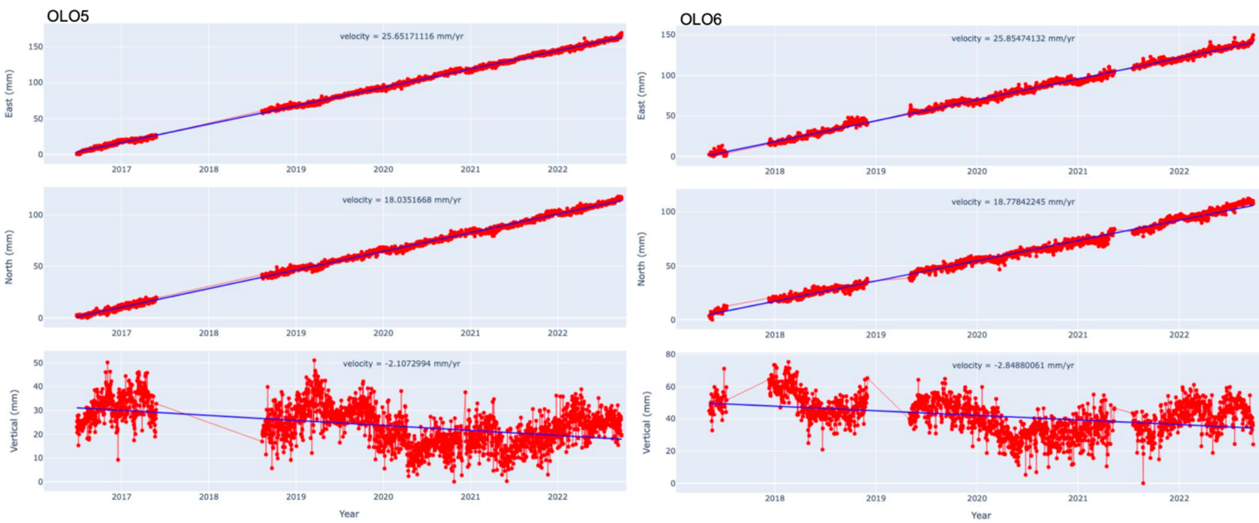

Figure 7. The fitted (blue line) time series for OLO5 (left) and OLO6 (right)

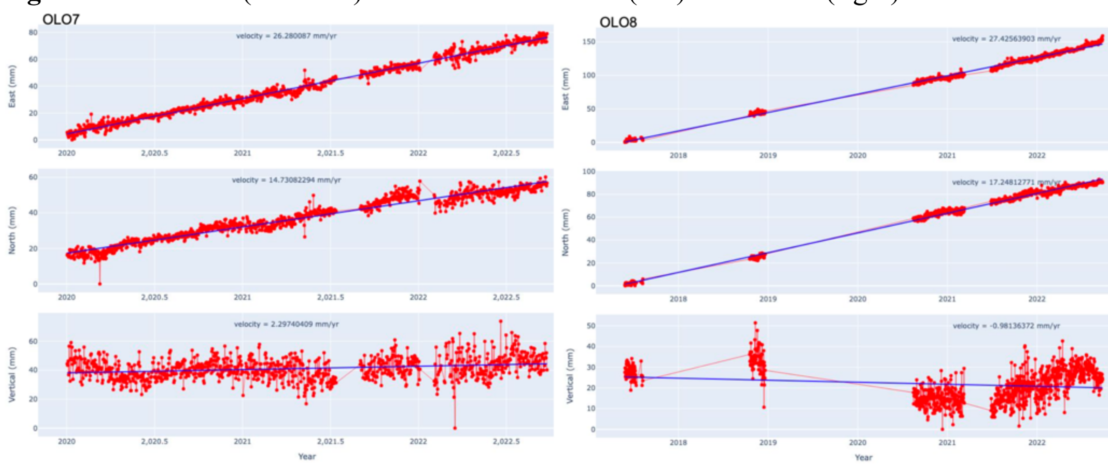

Figure 8. The fitted (blue line) time series for OLO7 (left) and OLO8 (right) sites

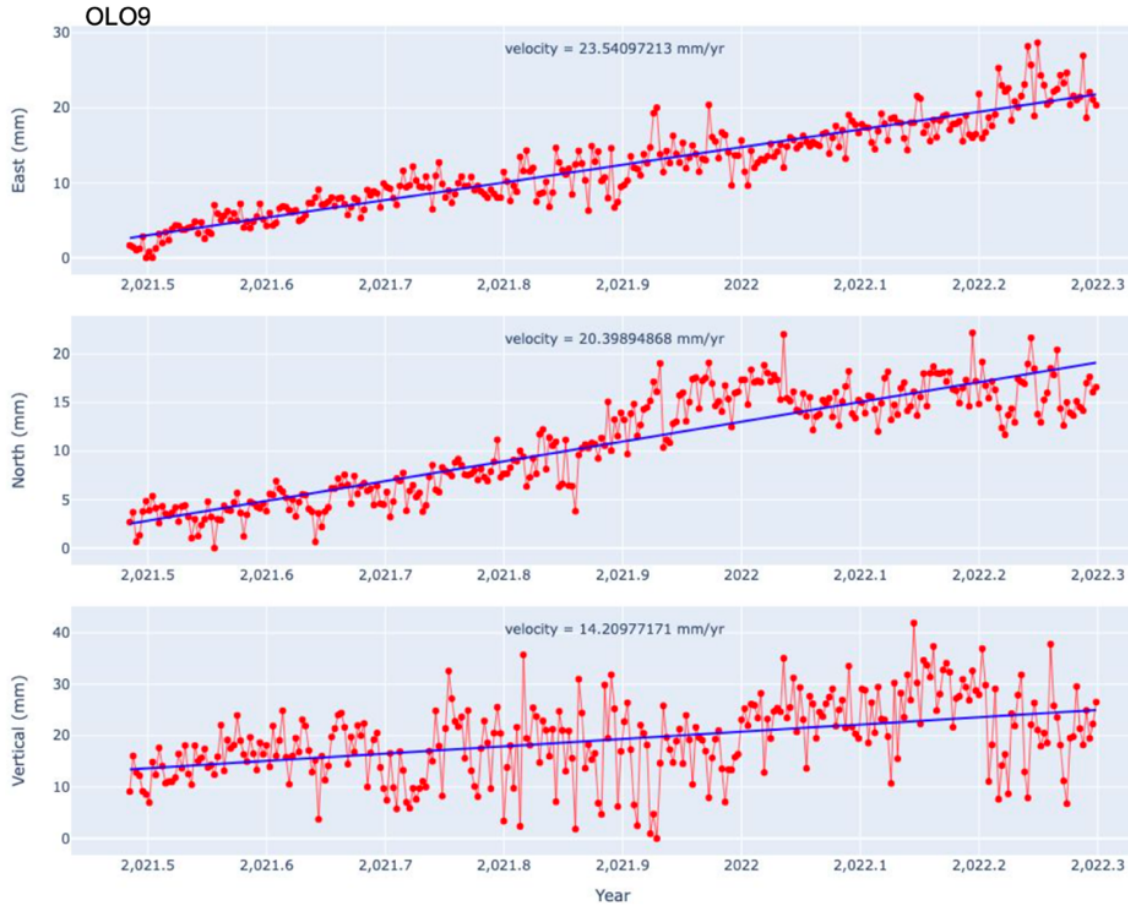

Figure 9. The fitted (blue line) time series for OLO9 site

The computed velocities from time series were analyzed and plotted to quantify the tectonic motion at global scale. To filter the volcanic deformation from the tectonic motion, I used a local reference frame by fixing one single GNSS site, OLO5, a stable and outside the influence of volcanic activity located 19 km north of the volcano (Figure 1). Table 1 shows horizontal velocities in global scale and relative to a local OLO5 for the timeframe of June 2016 to July 2022 respectively, and their respective plots (Figure 10).

Table 1. GNSS velocity solutions in the ITRF14 reference frame. V_E, V_N, V_U are the velocities in the East, North, and Up directions respectively. σ_E, σ_N, σ_U are the 1 sigma uncertainties on each component of the velocity, $corr_{EN}$ is the correlation.

Site Name	Lon degree	lat degree	V_E mm/yr	σ_E mm/yr	V_N mm/yr	σ_N mm/yr	$corr_{EN}$	V_U mm/yr	σ_U mm/yr
OLO1	35.950	-2.734	27.06	0.4	17.44	0.2	0.002	-2.7 6	1.0
OLO3	35.871	-2.754	25.66	0.2	18.68	0.2	0.010	-3.79	1.2
OLO5	35.889	-2.634	25.65	0.2	18.04	0.2	0.004	-2.11	1.3
OLO6	35.906	-2.709	25.85	0.4	18.77	0.3	0.003	-2.85	1.5
OLO7	35.913	-2.796	26.28	0.6	14.73	0.9	0.007	2.30	3.0
OLO8	35.947	-2.785	27.43	0.4	17.25	0.3	0.004	-0.98	1.6
OLO9	35.870	-2.752	23.54	0.2	20.40	0.2	0.007	14.21	1.0

GNSS velocity solutions in the local OLO5 reference frame. V_E, V_N, V_U are the velocities in the East, North, and Up directions respectively. σ_E, σ_N, σ_U are the 1 sigma uncertainties on each component of the velocity, $corr_{EN}$ is the correlation.

Site Name	Lon degree	lat degree	V_E mm/yr	σ_E mm/yr	V_N mm/yr	σ_N mm/yr	$corr_{EN}$	V_U mm/yr	σ_U mm/yr
OLO1	35.950	-2.734	1.13	0.4	-0.51	0.2	0.001	-2.76	1.0
OLO3	35.871	-2.754	-0.45	0.2	0.36	0.2	0.007	-2.76	1.2
OLO6	35.906	-2.709	-0.16	0.4	1.31	0.3	0.001	-2.85	1.5
OLO7	35.913	-2.796	0.77	0.6	-4.32	0.9	0.001	2.30	3.0
OLO8	35.947	-2.785	1.84	0.4	0.44	0.3	0.001	-0.98	1.6
OLO9	35.870	-2.752	-0.45	0.2	0.36	0.2	0.007	14.21	1.0

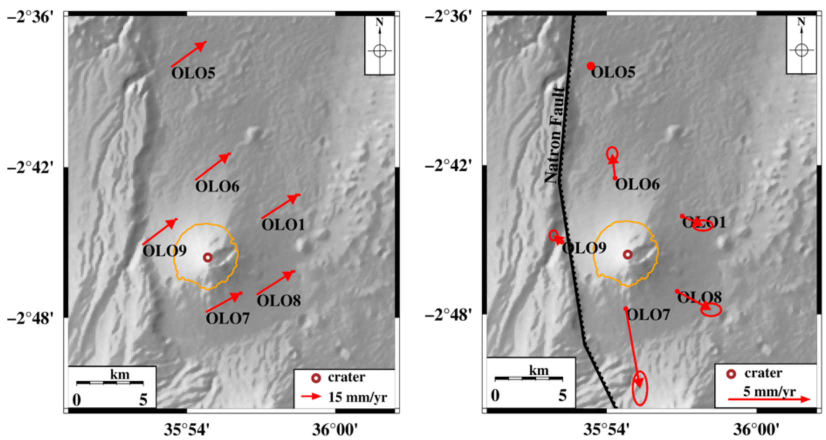

Figure 10. The horizontal velocities with respect to Nubian plate (left) and with respect to local reference site OLO5 (right) at 95% uncertainties.

The estimated velocities show the motion of the area consistent to the African plate (figure 10 left)). The velocities relative to a local site, OLO5 suggests that the active volcano (Ol Doinyo Lengai), currently is inflating (Figure 10 right).

3.2 Spatial and temporal features

3.2.1 GNSS spatial and temporal patterns

Here I present both GNSS spatial and temporal signatures for five stations estimated using singular value decomposition (SVD) technique and compare with temperature and precipitation to understand the most variable affecting the particular GNSS site. Due to the data gaps in GNSS sites, only five stations with two common years of observations from Jan. 2020 to Dec. 2021 were used to estimate the SVD components for the five sites. The GNSS spatial features for east, north and up/vertical components are shown in Figure 11 while the corresponding temporal variation in Figure 12 and Figure 13. The sum of their cumulative singular value decomposition shown in Figure 14.

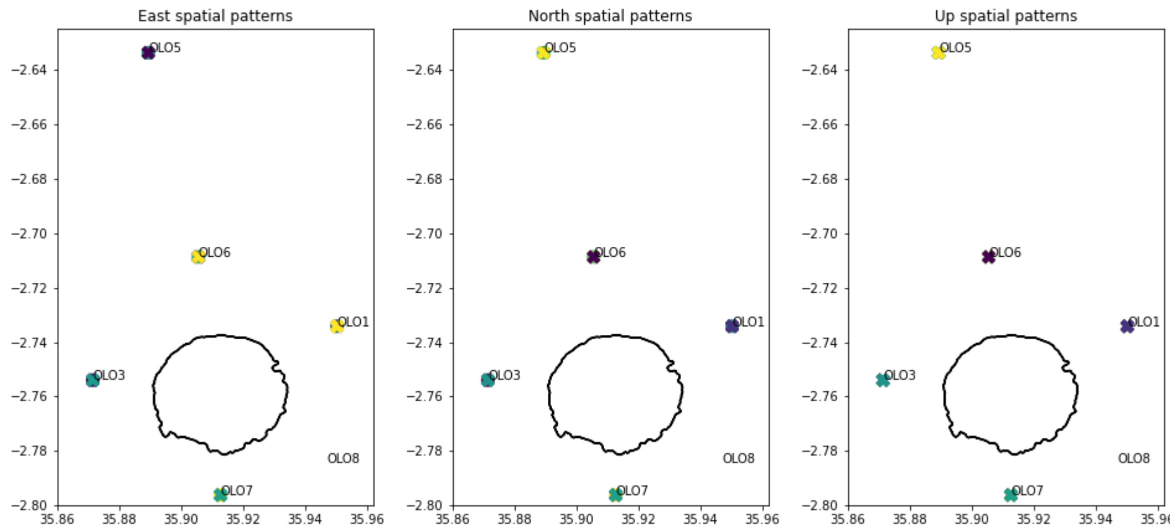

Figure 11: Spatial patterns for GNSS components from Jan. 2020 to Dec. 2021.

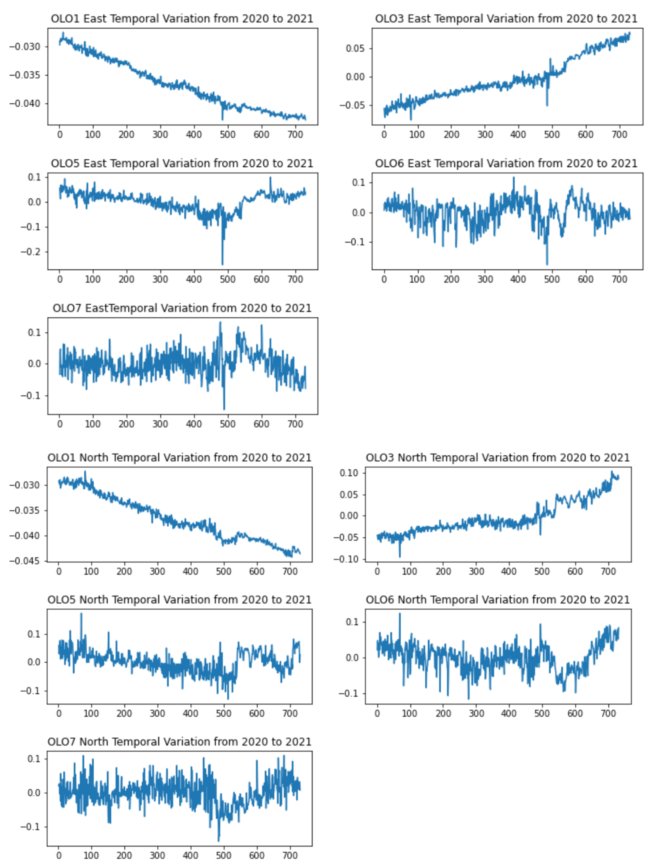

Figure 12: GNSS East temporal component (left panel) and North temporal component (right panel)

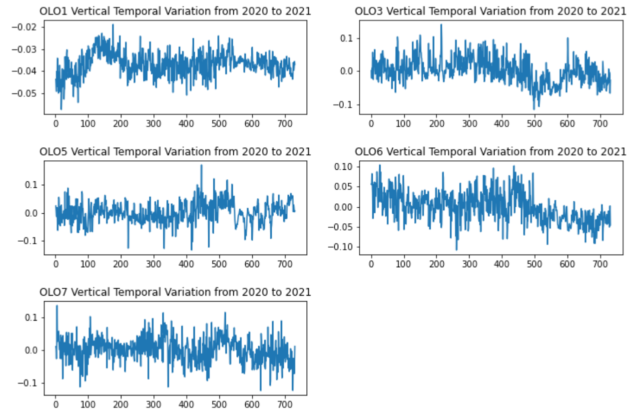

Figure 13: GNSS Up/Vertical temporal component

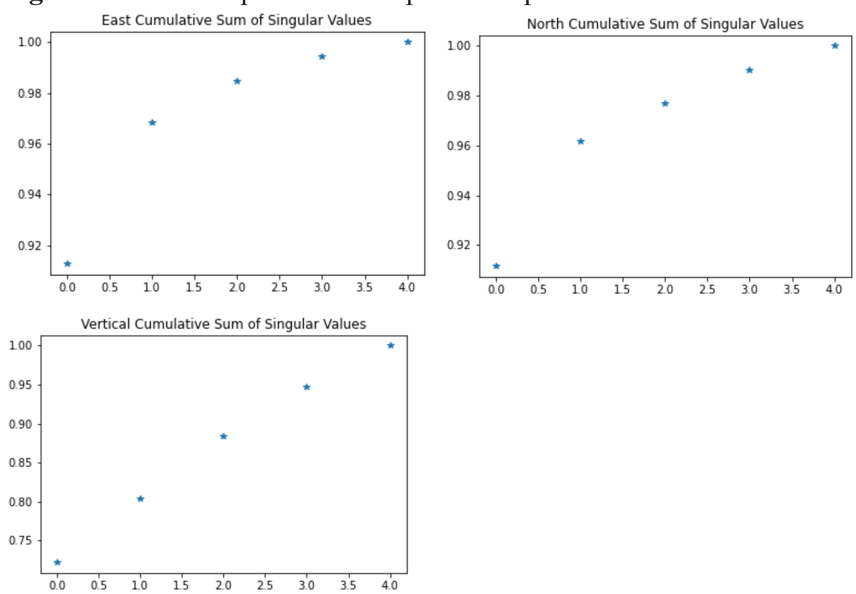

Figure 14: Cumulative SVD for GNSS Components

3.2.2 Spatial and temporal features for Temperature and Precipitation

Singular value decomposition (SVD) was used to estimate the spatial (Figure 15, 16) and temporal patterns (Figure 17) for temperature and precipitation variables to investigate their influence on daily GNSS positions.

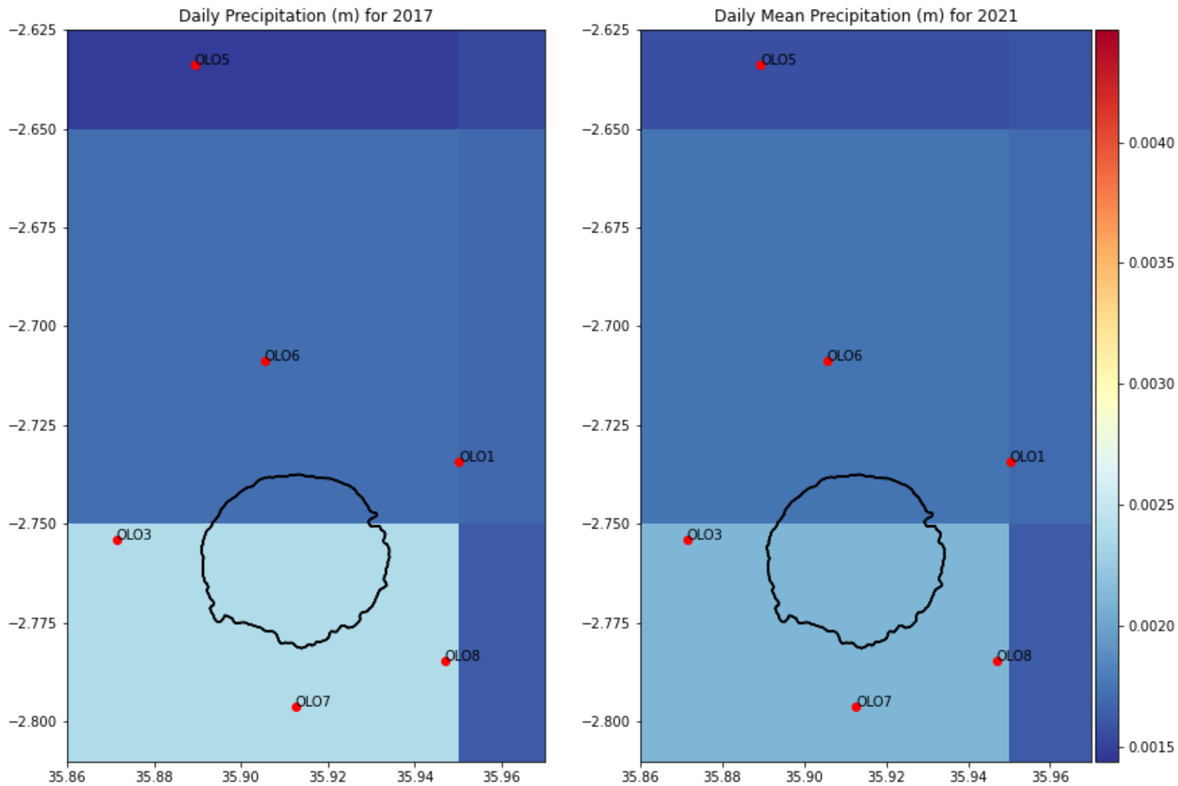

Figure 15: Spatial patterns for precipitation from 2017 to 2021. Red circles are GNSS sites, black line is the boundary of the volcano.

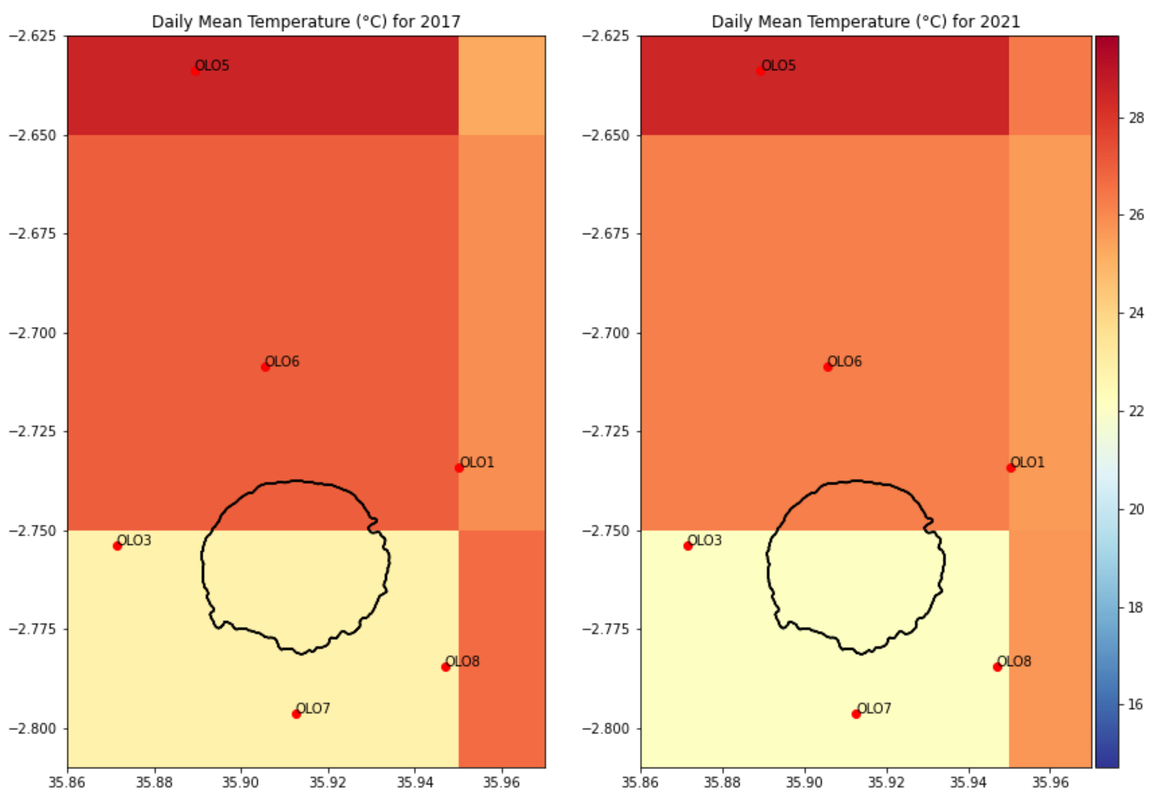

Figure 16: Spatial patterns for temperature from 2017 to 2021. Red circles are GNSS sites, black line is the boundary of the volcano.

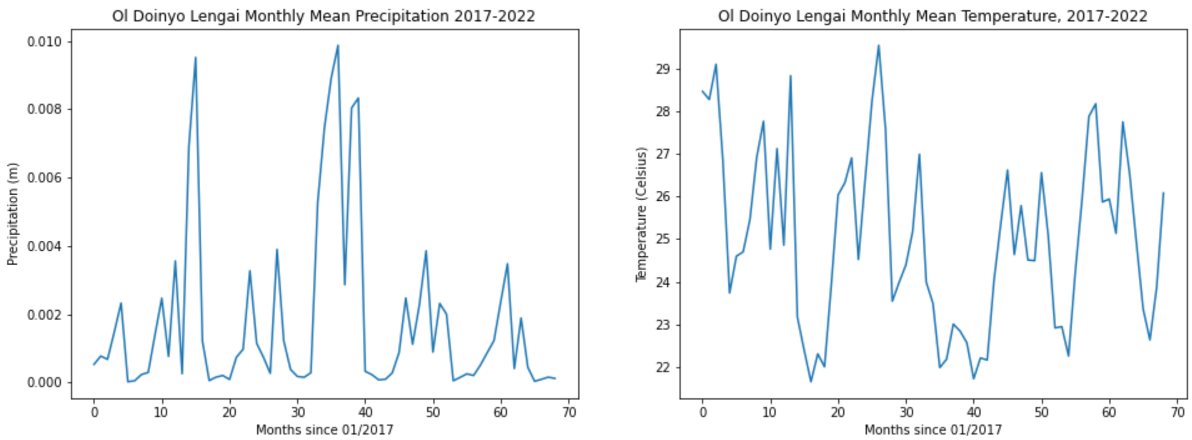

Figure 17: Temporal patterns for precipitation (right) and temperature (left)for from 2017 to 2021.

I also present the first four spatial features for precipitation and temperature (Figure 18) and the corresponding temporal variation (Figure 19) and the sum of their cumulative singular value decomposition to assess for their correlation with GNSS components.

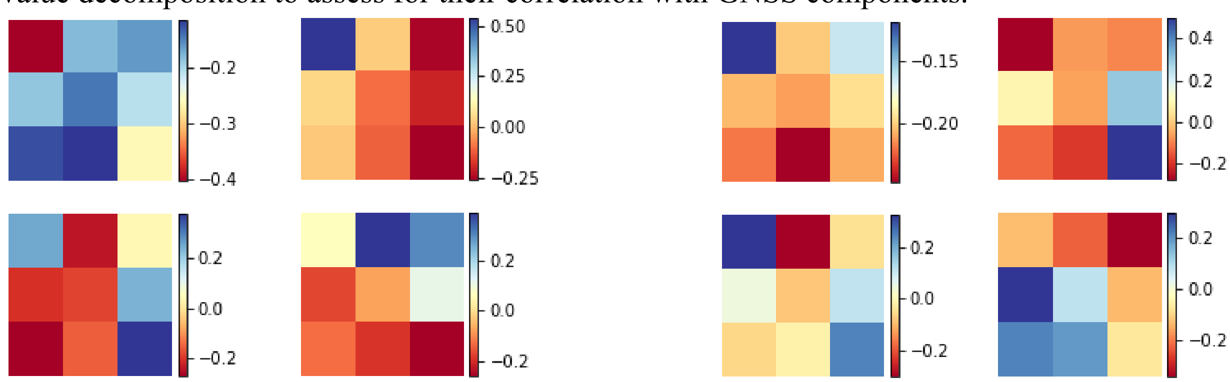

Figure 18: The first four spatial features for precipitation (right) and temperature (left)

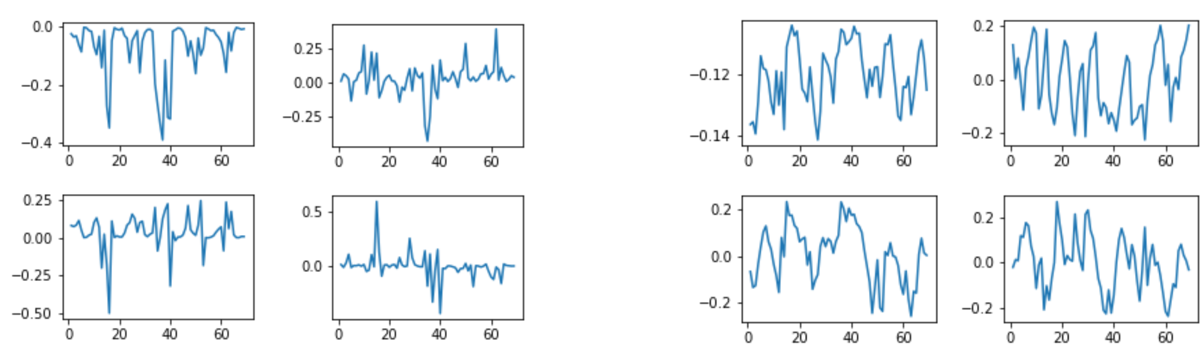

Figure 19: The first four temporal features for precipitation (right) and temperature (left)

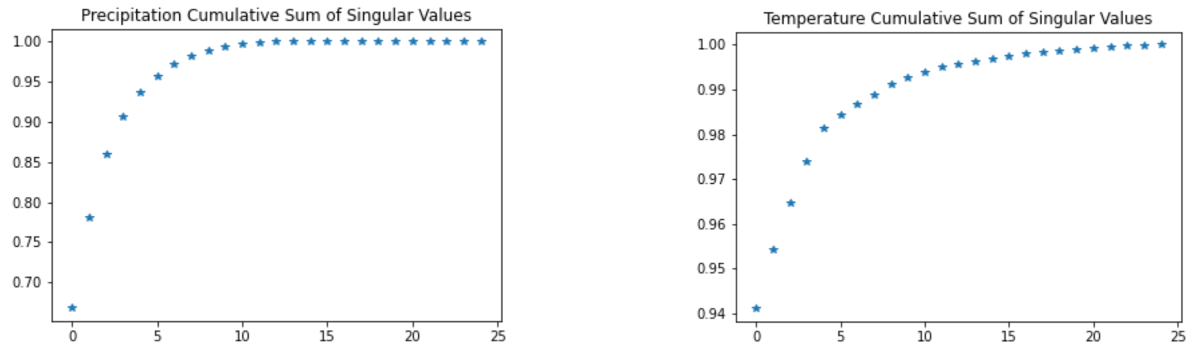

Figure 20. Cumulative SVD for Precipitation (left) and Temperature (right) at the volcano

4. Discussion

There is a temporal correlation between precipitation and temperature (Figure 17). I found a strong coefficient of correlation for the third component between precipitation and temperature (Spearman's correlation coefficient = -0.449 and Pearson' correlation coefficient = -0.399). The GNSS east component for OLO1, OLO3, OLO5 and OLO7 is sensitive to temperature while OLO6 is sensitive to precipitation. Both sites, the GNSS north component, are sensitive to temperature variable while the vertical component for all sites is affected by precipitation. The five GNSS components for east and north contribute about 97% while the vertical about 70% to the SVD as shown in the figure of the cumulative sums (Figure 13). For the precipitation and temperature, the four components contribute about 75% and 95 % respectively to the SVD as shown in the figure of the cumulative sums (Figure 18). Generally, temperature is the most variable affecting the daily GNSS position. This is probably due to lack of rainfall. The area experiences longer periods of drought.

5. Conclusion

This study suggests that the daily GNSS positions are correlated with climatic variables. Both Temperature and precipitation show a significant correlation with the daily GNSS position and can impact the trend of surface deformation. Model corrections for each particular variable is needed to account for their effects during processing. This will enhance the accuracy in interpreting the geodynamic process and characterize the mechanism of an ongoing deformation such as plate movements, uplift or subsidence due to magma source activity which are important parameters for seismic hazard assessment.

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Notes from Geo Data Science with Python class, 2022 by Prof Susanna Werth

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https://cds.climate.copernicus.eu/cdsapp#!/yourrequests?tab=form

https://github.com/chianhenglee/GPS_timeseries_auto_fitting