

Time Series Analysis on Geospatial Data with Python

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Chapter 7 - Time Series Smoothing and Filtering

Smoothing a time series removes certain frequencies or components to gain insight into the underlying structure of the time series. For example, we want to remove noise to emphasize the signal in the time series before we begin our analysis. Removing noise improves the quality of our data and, in turn, the results of our analysis. Think of the famous saying "garbage in, garbage out."

Data smoothing is nothing more than averaging data points with their neighbors in a time series, resulting in a blur of sharp edges in our time series. Therefore, data smoothing is similar to filtering, where high frequencies are suppressed to extract low-frequency signals. In doing so, we generate a new smoothed data point for each data point in the time series.

To smooth our time series, we can choose between different approaches, which mainly differ in how the mean around a data point is calculated. The most commonly used approaches are:

- Moving Average
- Kernel Smoothing
- (Single, Double, Triple) Exponential Smoothing

Which approach we choose depends on the amount of noise and the components, such as trend and seasonality, in our time series.

Moving statistics

Moving or continuous statistics are computed by sliding a window of a given size over the original time series and aggregating the data for each window. This is also known as convolution over time index. The two important parameters of the convolution operation are the window size and the stride length. The former defines the number of time units taken as input to the aggregate function, while the latter defines the gap over the time index between each computation. For example, suppose a window size of k and a stride length l are used to compute the function f over a time series x_1, x_2, \dots, x_n having N observations. In this scenario, the moving statistic is obtained as $f(x_1, x_2, \dots, x_t)$, $f(x_{1+l}, x_{2+l}, \dots, x_{t+l})$ and so on. Note that each time the function is computed by shifting the time window to the right by l time units.

Moving Average

The Moving Average is the easiest approach we can use. Within a fixed-length Sliding Window, all data points are averaged with the same weighting.

The approach is well suited for data with little noise and for highlighting long-term trends. However, the Moving Average cannot capture seasonality and should therefore not be used for time series with complex seasonality and non-linearity. Furthermore, the approach cannot calculate values at the beginning and/or end of the time series, depending on whether a one-sided or two-sided Moving Average is calculated.

The Sliding Window is placed around a data point and the values within the window are averaged before the window is slid to the next data point. This is repeated until the time series is smoothed. The degree of smoothing is determined by the width of the Sliding Window. The wider the window, the stronger the smoothing.

Let's extract a time series from the GEE:

```
In [ ]: import ee
import matplotlib.pyplot as plt
import numpy as np
import pandas as pd
import geemap
```

```
In [ ]: ee.Authenticate()
ee.Initialize(project='my-project-1527255156007')
```

```
In [ ]: coordinates = np.array([ 23.5544698, 40.025684])
x = float(coordinates[0])
y = float(coordinates[1])
```

```
In [ ]: date_start = '2005-01-01'
date_end = '2010-01-01'
```

Let's get air temperature values from the ERA5 database:

```
In [ ]: location_point = ee.Geometry.Point(x, y)
gre= ee.ImageCollection("ECMWF/ERA5/DAILY").select('mean_2m_air_temperature').fi
```

```
In [ ]: data= gre.getRegion(location_point, 27830).getInfo()
data=pd.DataFrame(data,columns=data[0])
data = data.drop(0, axis=0)
```

Let's get a DataFrame and display our time series:

```
In [ ]: data['mean_2m_air_temperature']=data['mean_2m_air_temperature'].astype('float')
data['mean_2m_air_temperature']=data['mean_2m_air_temperature'].apply(lambda x:
data['date'] = pd.to_datetime(data['id'], format='%Y%m%d')
data.set_index("date", inplace=True)
data.head()
```

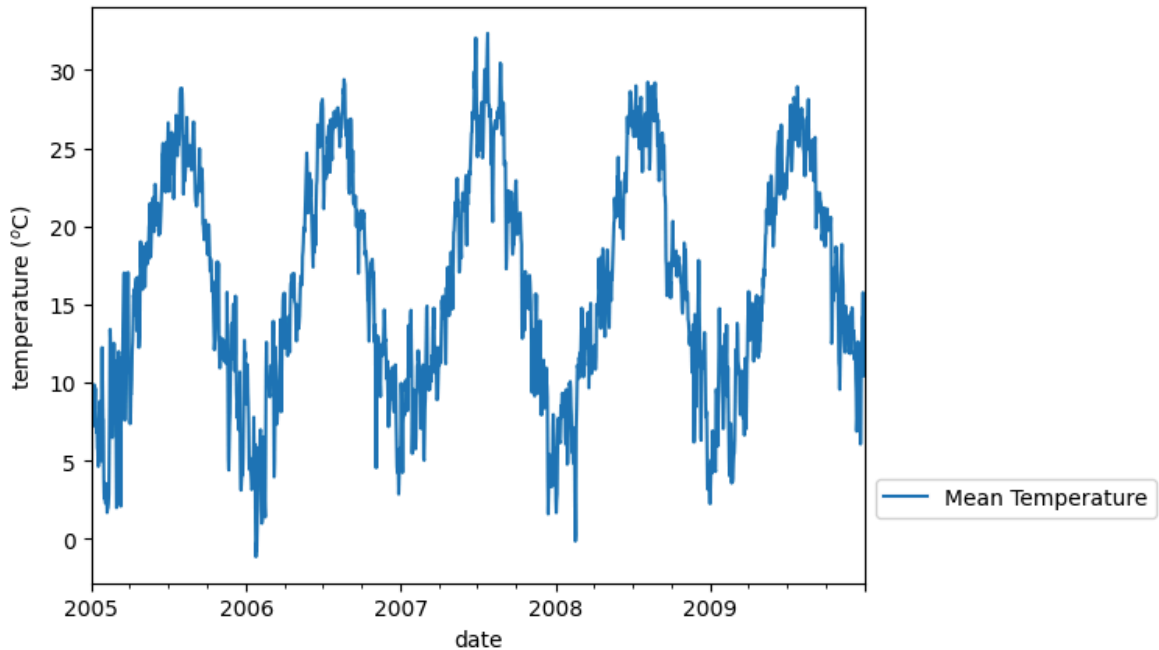
```
Out [ ]:      id longitude  latitude      time  mean_2m_air_temperature
date
2005-01-01  20050101  23.625108  40.125184  1104537600000          7.851562
2005-01-02  20050102  23.625108  40.125184  1104624000000          7.653076
2005-01-03  20050103  23.625108  40.125184  1104710400000          7.288391
2005-01-04  20050104  23.625108  40.125184  1104796800000          7.175964
2005-01-05  20050105  23.625108  40.125184  1104883200000          9.686920
```

```
In [ ]: data = data.drop(columns=['id', 'longitude', 'latitude', 'time'])
```

```
In [ ]: import matplotlib.pyplot as plt

data.mean_2m_air_temperature.plot(label='Mean Temperature')
plt.ylabel('temperature ($^oC$)')
plt.legend(loc='upper left', bbox_to_anchor=(1, 0.2))
```

```
Out [ ]: <matplotlib.legend.Legend at 0x7f72f625a590>
```



Let's apply the weekly and monthly moving average:

```
In [ ]: weekly_moving_average = data['mean_2m_air_temperature'].rolling(7).mean()
```

```
In [ ]: monthly_moving_average = data['mean_2m_air_temperature'].rolling(30).mean()
```

Let's use matplotlib to visualize the two transformations:

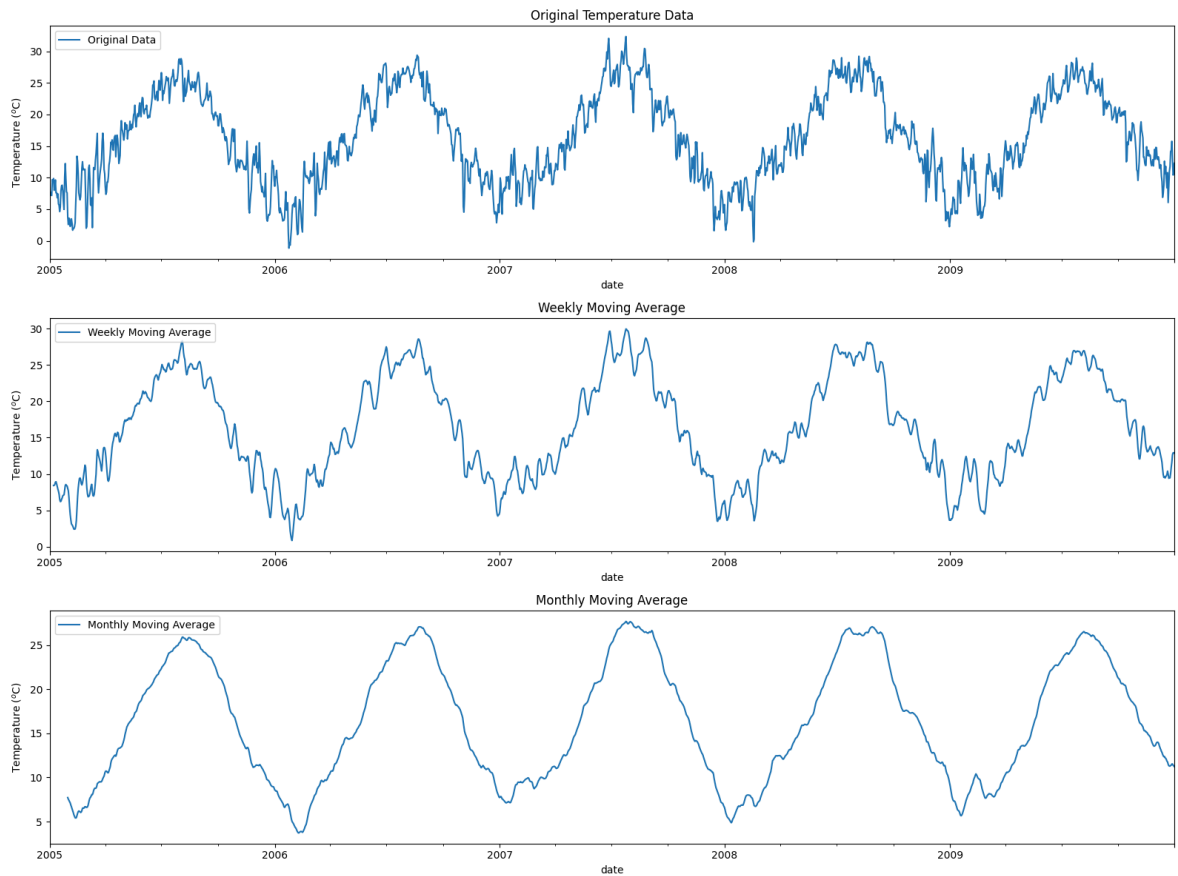
```
In [ ]: plt.figure(figsize=(16, 12))

plt.subplot(3, 1, 1)
data['mean_2m_air_temperature'].plot(label='Original Data')
plt.ylabel('Temperature ($^o$C)')
plt.legend(loc='upper left')
plt.title('Original Temperature Data')

plt.subplot(3, 1, 2)
weekly_moving_average.plot(label='Weekly Moving Average')
plt.ylabel('Temperature ($^o$C)')
plt.legend(loc='upper left')
plt.title('Weekly Moving Average')

plt.subplot(3, 1, 3)
monthly_moving_average.plot(label='Monthly Moving Average')
plt.ylabel('Temperature ($^o$C)')
plt.legend(loc='upper left')
plt.title('Monthly Moving Average')

plt.tight_layout()
plt.show()
```



Kernel Smoothing

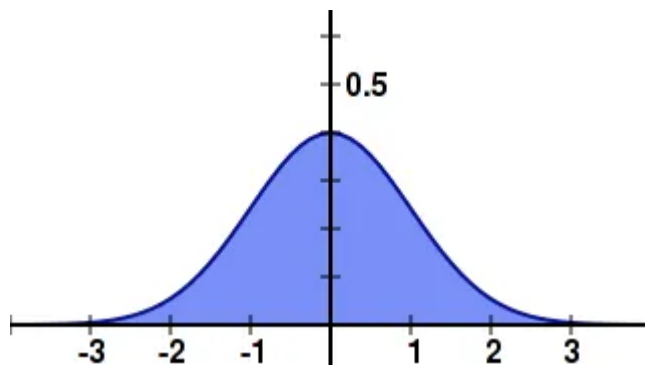
Kernel Smoothing is very similar to Moving Average. The only difference is that we use different weights for the average in Sliding Window. The weights depend on the format of the kernel function. Due to the similarity with Moving Average, the advantages and disadvantages are also similar.

The width of the Sliding Window can be defined based on the Full Width at Half Maximum (FWHM). This cuts off the tails of the kernel that have values less than half the maximum height of the curve.

Often, a Gaussian kernel is used, which represents a Gaussian distribution. This gives a higher weight to data points that are close to the data point around which we want to smooth the time series.

Gaussian Kernel

Kernels define the shape of the function used to average neighboring points. The Gaussian kernel has the shape of the Gaussian curve. The Gaussian curve has the following shape:



As seen in the Gaussian curve, points close to (around 0 on the curve above) will have higher weighting and points further away will have lower weighting.

```
In [ ]: from scipy.ndimage import gaussian_filter1d

def apply_gaussian_smoothing(data, sigma=1):

    smoothed_data = gaussian_filter1d(data, sigma=sigma)
    return smoothed_data

# Example usage (assuming 'data' is already defined)
data['smoothed_temperature'] = apply_gaussian_smoothing(data['mean_2m_air_temper
```

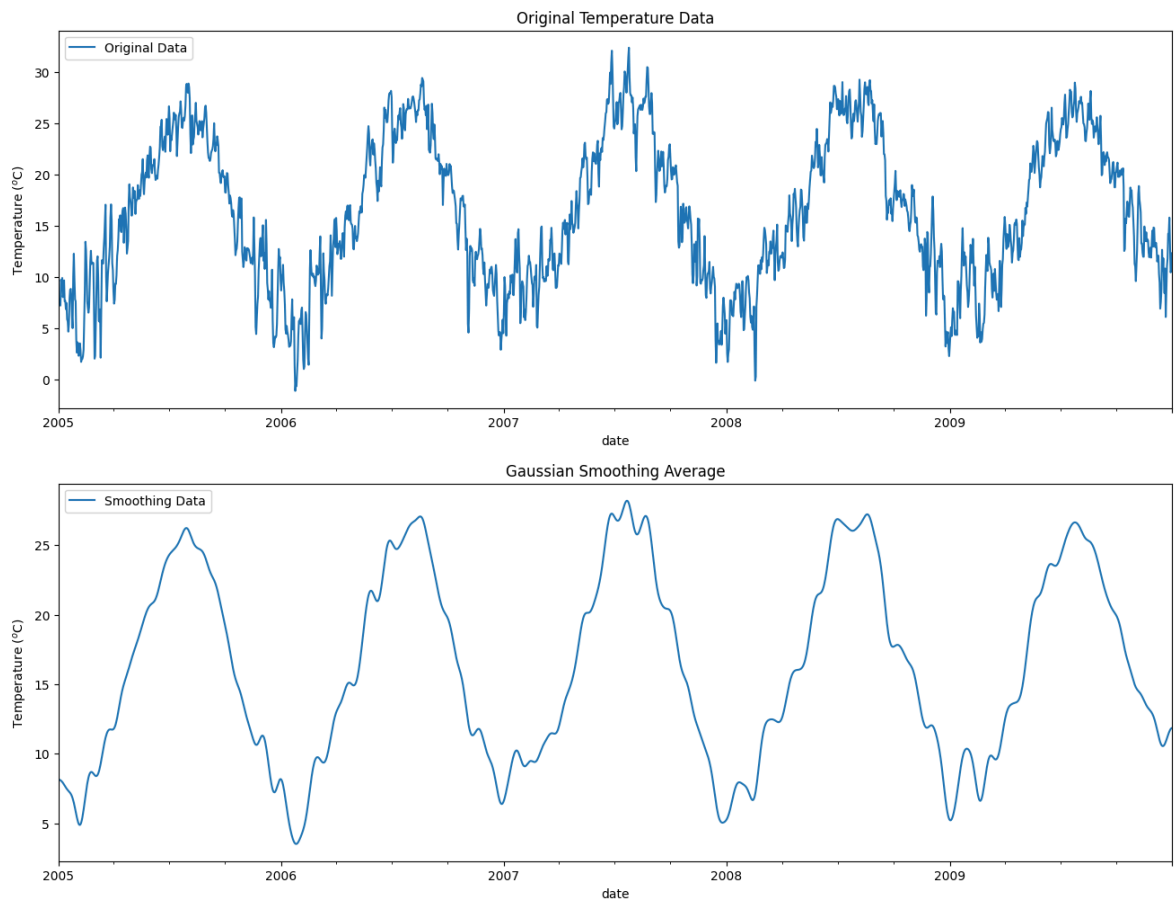
Let's plot the original data with the smoothed data:

```
In [ ]: plt.figure(figsize=(16, 12))

plt.subplot(2, 1, 1)
data['mean_2m_air_temperature'].plot(label='Original Data')
plt.ylabel('Temperature (^o$C)')
plt.legend(loc='upper left')
plt.title('Original Temperature Data')

plt.subplot(2, 1, 2)
data['smoothed_temperature'].plot(label='Smoothing Data')
plt.ylabel('Temperature (^o$C)')
plt.legend(loc='upper left')
plt.title('Gaussian Smoothing Average')
```

```
Out[ ]: Text(0.5, 1.0, 'Gaussian Smoothing Average')
```



Exponential Smoothing

Since Moving Average and Kernel Smoothing cannot capture complex non-linearity and cannot calculate values at the beginning and/or end of the time series, Exponential Smoothing was developed.

Here, all past observations are weighted based on an exponentially decreasing function. For this, no Sliding Window is used and more recent data points are given a higher weight than those further back in the past.

Similar to Moving Average and Kernel Smoothing, a challenging part of smoothing is choosing the right smoothing factors and model hyperparameters. This can be done manually or through optimization.

We can choose between three types, which differ in which components of the time series they can handle: Single, Double, and Triple Exponential Smoothing. Below, the three types are ordered by their complexity, starting with the simplest.

Simple Exponential Smoothing

Single exponential smoothing can be used for stationary time series that do not have a trend or seasonality.

Smoothing is controlled by a smoothing factor α . The smoothing factor can vary between 0 and 1 and controls the exponential decay of the weights. The higher the

smoothing factor, the lower the weight for past data points and therefore the lower the smoothing.

```
In [ ]: from google.colab import drive
drive.mount('/content/drive')
```

Mounted at /content/drive

```
In [ ]: import pandas as pd
import matplotlib.pyplot as plt
```

Let's use our global temperature history dataset:

Link to Dataset:

https://drive.google.com/file/d/10omy6A3pjEAbQzISjglvSkpiCpBpx3A_/view?usp=drive_link


```
In [ ]: path = '/content/drive/MyDrive/Datasets_TS/Global Temperature.csv'
```

```
In [ ]: df = pd.read_csv(path)
```

```
In [ ]: df.head()
```

```
Out [ ]:
```

| | Year | Month | Monthly Anomaly | Monthly Unc. | Annual Anomaly | Annual Unc. | Five-Year Anomaly | Five-Year Unc. | Ten-Year Anomaly | Ten Year Unc. |
|---|------|-------|-----------------|--------------|----------------|-------------|-------------------|----------------|------------------|---------------|
| 0 | 1850 | 1 | -0.801 | 0.482 | NaN | NaN | NaN | NaN | NaN | NaN |
| 1 | 1850 | 2 | -0.102 | 0.592 | NaN | NaN | NaN | NaN | NaN | NaN |
| 2 | 1850 | 3 | -0.119 | 0.819 | NaN | NaN | NaN | NaN | NaN | NaN |
| 3 | 1850 | 4 | -0.485 | 0.575 | NaN | NaN | NaN | NaN | NaN | NaN |
| 4 | 1850 | 5 | -0.351 | 0.549 | NaN | NaN | NaN | NaN | NaN | NaN |



```
In [ ]: df.rename(columns={'Month': 'Month'}, inplace=True)
```

```
In [ ]: df['Date'] = pd.to_datetime(df.Year.astype(str) + '/' + df.Month.astype(str) + '
```

```
In [ ]: df.set_index('Date', inplace=True)
```

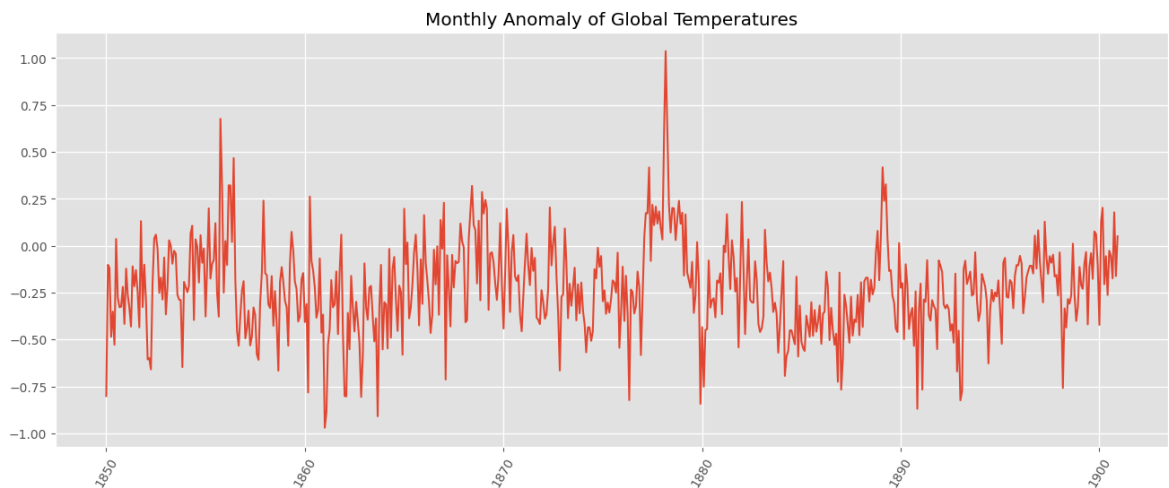
We will only select data up to the year 1900:

```
In [ ]: df_1900 = df[:'1900'].copy()
```

```
In [ ]: plt.figure(figsize=(16,6))
plt.style.use("ggplot")
plt.plot(df_1900.index, df_1900['Monthly Anomaly'])
plt.title('Monthly Anomaly of Global Temperatures')
```



```
plt.xticks(rotation=60)
plt.show()
```



```
In [ ]: from statsmodels.tsa.api import SimpleExpSmoothing
smoother = SimpleExpSmoothing(df_1900['Monthly Anomaly'])
smoothed_time_series = smoother.fit(smoothing_level=0.1, optimized=False).fitted
```

/usr/local/lib/python3.11/dist-packages/statsmodels/tsa/base/tsa_model.py:473: ValueWarning: No frequency information was provided, so inferred frequency MS will be used.

```
self._init_dates(dates, freq)
```

```
In [ ]: plt.figure(figsize=(16, 12))

plt.subplot(2, 1, 1)
df_1900['Monthly Anomaly'].plot(label='Original Data')
plt.ylabel('Temperature ( $^{\circ}$ C)')
plt.legend(loc='upper left')
plt.title('Original Temperature Data')

plt.subplot(2, 1, 2)
smoothed_time_series.plot(label='Smoothing Data')
plt.ylabel('Temperature ( $^{\circ}$ C)')
plt.legend(loc='upper left')
plt.title('Exponential Smoothing Average')
```

```
Out[ ]: Text(0.5, 1.0, 'Exponential Smoothing Average')
```



Double Exponential Smoothing

Double Exponential Smoothing extends Single Exponential Smoothing by repeating the smoothing. This allows the trend of a time series to be captured while the seasonality is not captured.

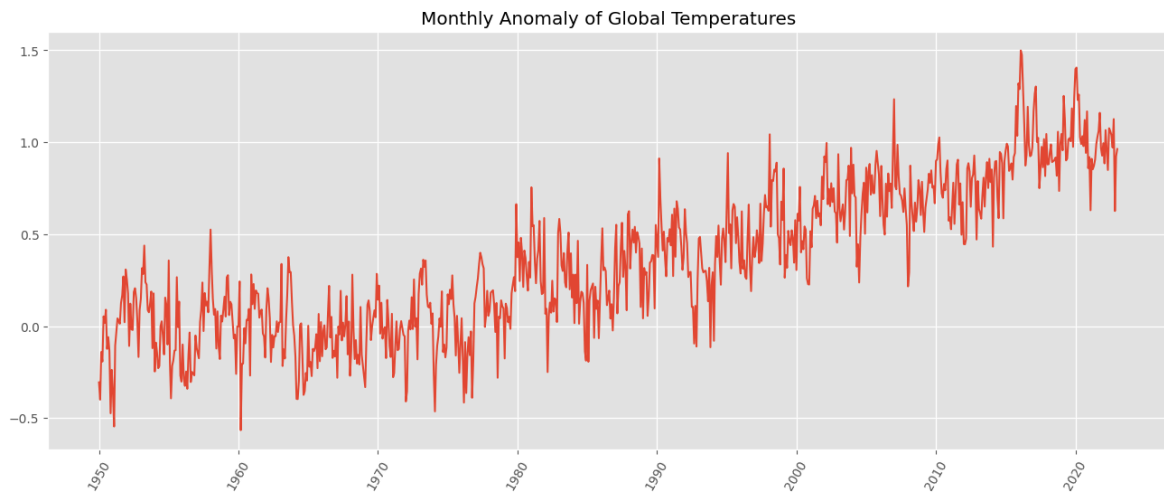
To achieve this, another smoothing factor β is added that controls the smoothing of the trend. Similar to α , β can range between 0 and 1 and controls the exponential decay of the weights.

Since the trend can be additive (i.e. a linear trend) or multiplicative (i.e. an exponential trend), smoothing and its implementation in Python differ slightly. Therefore, before we apply Double Exponential Smoothing, we need to identify what type of trend is present in the time series.

Let's now get the data from 1950 onwards and apply Holt smoothing:

```
In [ ]: df_1950 = df['1950:'].copy()
```

```
In [ ]: plt.figure(figsize=(16,6))
plt.style.use("ggplot")
plt.plot(df_1950.index, df_1950['Monthly Anomaly'])
plt.title('Monthly Anomaly of Global Temperatures')
plt.xticks(rotation=60)
plt.show()
```



```
In [ ]: from statsmodels.tsa.api import Holt
```

```
smoother = Holt(df_1950['Monthly Anomaly'])
smoothed_double_exp = smoother.fit(smoothing_level=0.2, smoothing_trend=0.02, op
```

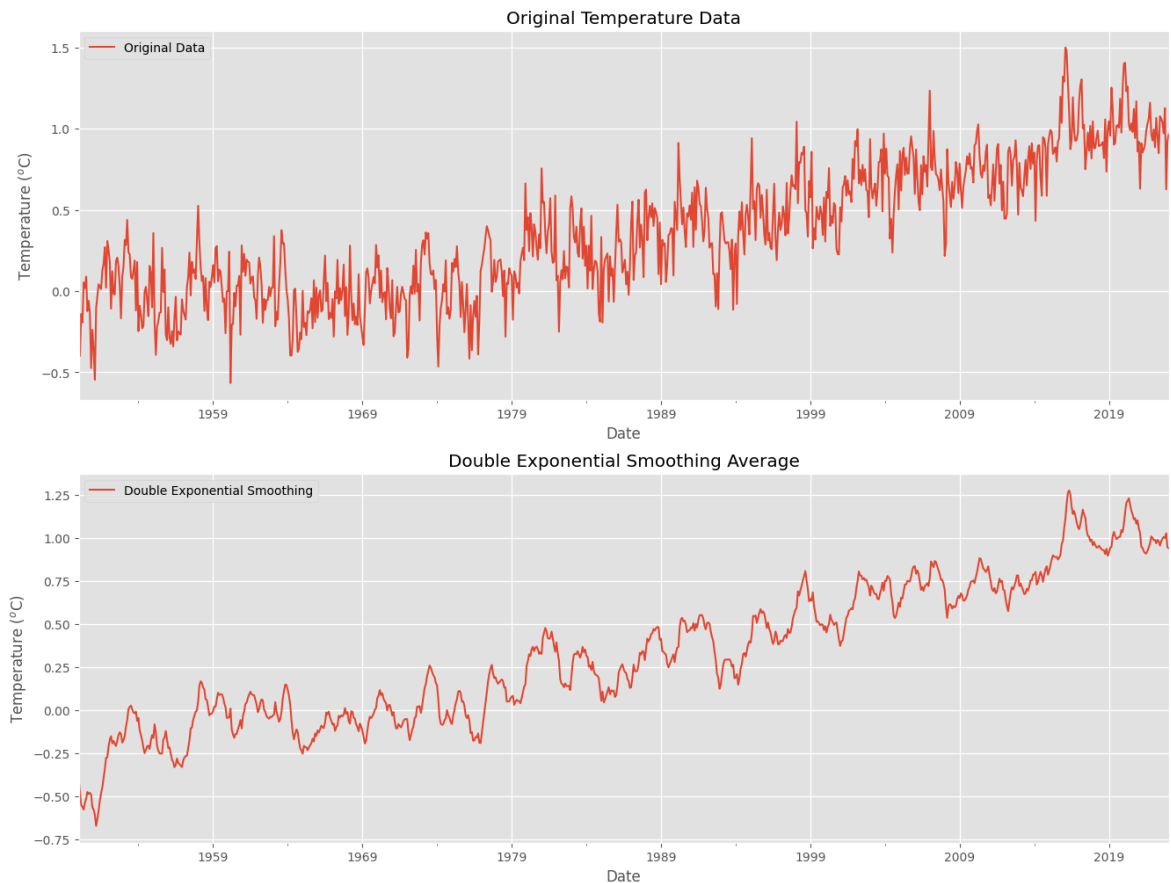
/usr/local/lib/python3.11/dist-packages/statsmodels/tsa/base/tsa_model.py:473: ValueWarning: No frequency information was provided, so inferred frequency MS will be used.

```
self._init_dates(dates, freq)
```

```
In [ ]: plt.figure(figsize=(16, 12))
```

```
plt.subplot(2, 1, 1)
df_1950['Monthly Anomaly'].plot(label='Original Data')
plt.ylabel('Temperature ($^oC$)')
plt.legend(loc='upper left')
plt.title('Original Temperature Data')

plt.subplot(2, 1, 2)
smoothed_double_exp.plot(label='Double Exponential Smoothing')
plt.ylabel('Temperature ($^oC$)')
plt.legend(loc='upper left')
plt.title('Double Exponential Smoothing Average')
plt.show()
```



Triple Exponential Smoothing

Triple Exponential Smoothing is the most sophisticated exponential smoothing method. The method can capture both the trend and seasonality of a time series. The approach is also called Holt-Winters Exponential Smoothing.

For this, another smoothing factor γ is added to capture seasonality. Similar to trend, seasonality can be additive or multiplicative.

```
In [ ]: from statsmodels.tsa.api import ExponentialSmoothing
smoother = ExponentialSmoothing(df_1950['Monthly Anomaly'])
smoothed_triple_exp = smoother.fit(smoothing_level=0.2, smoothing_trend=0.02, sm
```

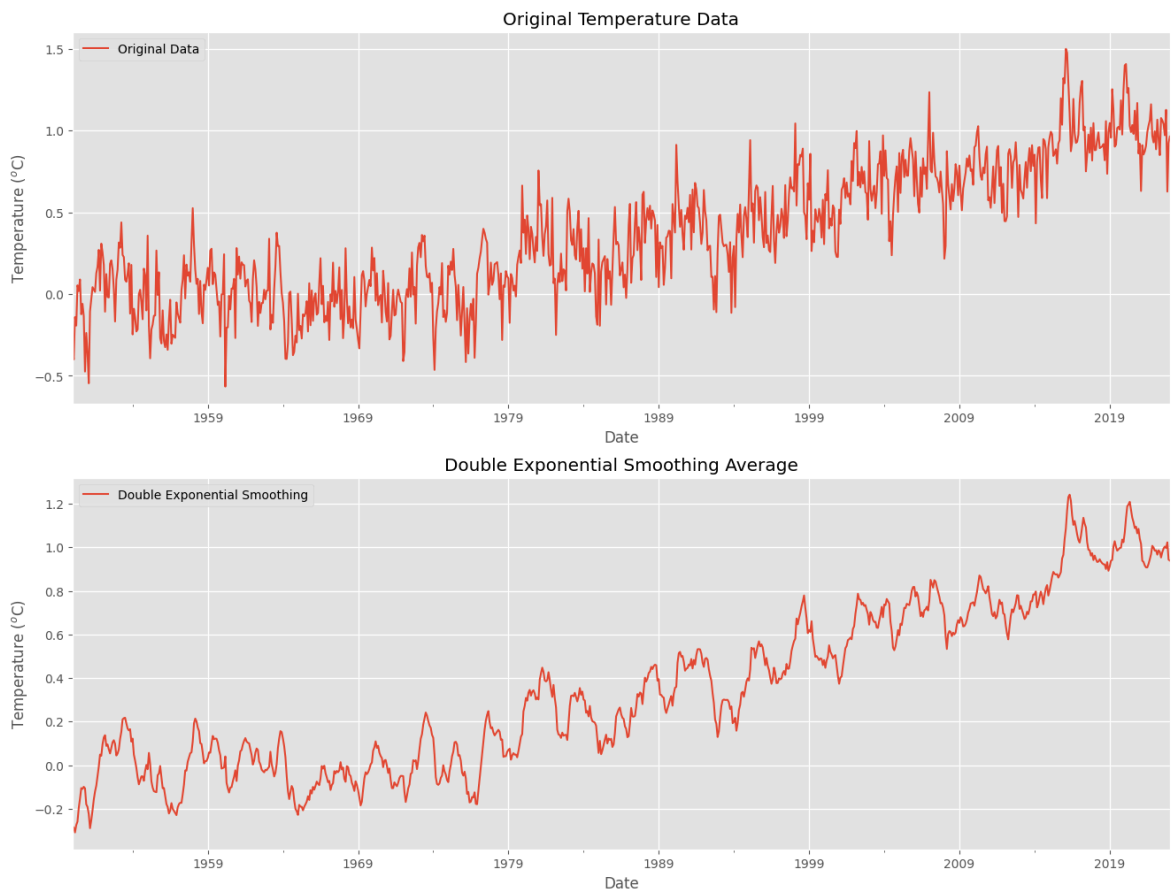
```
/usr/local/lib/python3.11/dist-packages/statsmodels/tsa/base/tsa_model.py:473: Va
lueWarning: No frequency information was provided, so inferred frequency MS will
be used.
    self._init_dates(dates, freq)
```

```
In [ ]: plt.figure(figsize=(16, 12))

plt.subplot(2, 1, 1)
df_1950['Monthly Anomaly'].plot(label='Original Data')
plt.ylabel('Temperature ($^{\circ}$C)')
plt.legend(loc='upper left')
plt.title('Original Temperature Data')

plt.subplot(2, 1, 2)
smoothed_triple_exp.plot(label='Double Exponential Smoothing')
plt.ylabel('Temperature ($^{\circ}$C)')
plt.legend(loc='upper left')
```

```
plt.title('Double Exponential Smoothing Average')
plt.show()
```



Convolutional Filters

Convolutional smoothing is a technique used to smooth time series data by applying a mathematical function within a sliding window. The following are the different types of windows used in convolutional smoothing:

- Constant/Unitary Window: Each point in the window has an equal weight.
- Hanning Window: Weights are calculated using a cosine function, giving more weight to points in the middle of the window.
- Hamming Window: Similar to the Hanning window, but with weight calculations adjusted to minimize disturbances.
- Bartlett Window: A triangle-shaped window, with weights decreasing linearly towards the center.
- Blackman Window: Uses cosine functions to enhance frequency component analysis.

```
In [ ]: !pip install tsmoothie
```

Collecting tsmoother

Downloading tsmoother-1.0.5-py3-none-any.whl.metadata (6.9 kB)

Requirement already satisfied: numpy in /usr/local/lib/python3.11/dist-packages (from tsmoother) (2.0.2)

Requirement already satisfied: scipy in /usr/local/lib/python3.11/dist-packages (from tsmoother) (1.15.3)

Collecting simdkalman (from tsmoother)

Downloading simdkalman-1.0.4-py2.py3-none-any.whl.metadata (1.2 kB)

Downloading tsmoother-1.0.5-py3-none-any.whl (22 kB)

Downloading simdkalman-1.0.4-py2.py3-none-any.whl (11 kB)

Installing collected packages: simdkalman, tsmoother

Successfully installed simdkalman-1.0.4 tsmoother-1.0.5

Let's apply our smoothing with convolutional kernels to the data from 1950 onwards:

```
In [ ]: from tsmoother.smoother import ConvolutionSmoother
```

```
In [ ]: Smoother = ConvolutionSmoother(window_len=20, window_type='ones')
```

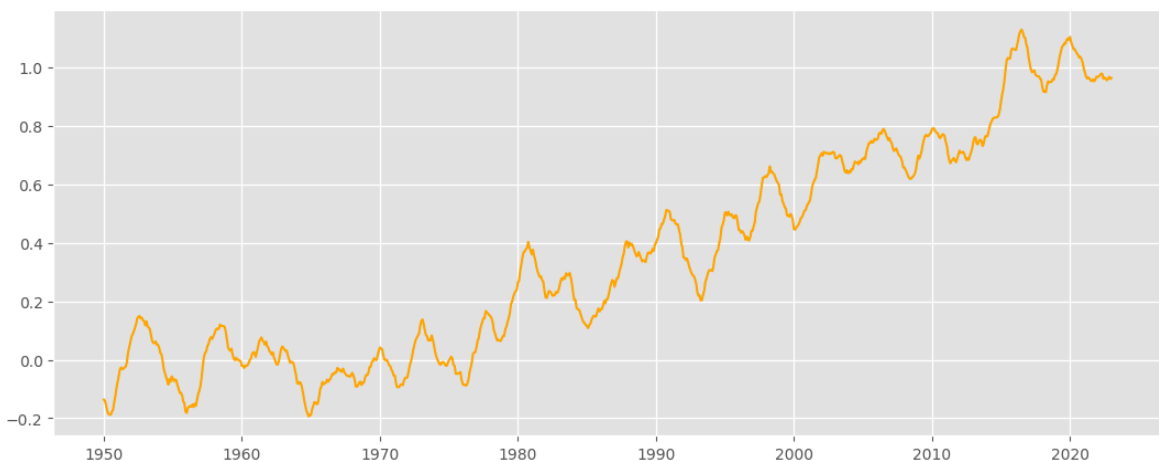
```
In [ ]: Smoother.smooth(df_1950['Monthly Anomaly'])
```

```
Out[ ]: <tsmoother.smoother.ConvolutionSmoother>
```

```
In [ ]: df_1950['Conv Smooth Monthly Anomaly'] = Smoother.smooth_data[0]
```

```
In [ ]: plt.figure(figsize=(13,5))
plt.plot(df_1950['Conv Smooth Monthly Anomaly'], c='orange')
```

```
Out[ ]: [<matplotlib.lines.Line2D at 0x7f72e2cfd6d0>]
```



Kalman Filter

Kalman filtering is a technique used to estimate how a data point in a series evolves over time, even when the measurements are noisy. It predicts the next state based on a model and then refines the prediction using actual measurements. This process consists of two main steps: predicting the state and then correcting it. By doing this, Kalman filtering reduces measurement error and makes estimates more accurate.

```
In [ ]: !pip install pykalman
```

Collecting pykalman

Downloading pykalman-0.10.1-py2.py3-none-any.whl.metadata (9.5 kB)

Requirement already satisfied: numpy<3 in /usr/local/lib/python3.11/dist-packages (from pykalman) (2.0.2)

Requirement already satisfied: packaging in /usr/local/lib/python3.11/dist-packages (from pykalman) (24.2)

Collecting scikit-base<0.13.0 (from pykalman)

Downloading scikit_base-0.12.2-py3-none-any.whl.metadata (8.8 kB)

Requirement already satisfied: scipy<2.0.0 in /usr/local/lib/python3.11/dist-packages (from pykalman) (1.15.3)

Downloading pykalman-0.10.1-py2.py3-none-any.whl (248 kB)

248.5/248.5 kB 4.8 MB/s eta 0:00:00

Downloading scikit_base-0.12.2-py3-none-any.whl (142 kB)

142.7/142.7 kB 11.4 MB/s eta 0:00:00

Installing collected packages: scikit-base, pykalman

Successfully installed pykalman-0.10.1 scikit-base-0.12.2

```
In [ ]: from pykalman import KalmanFilter
```

After installing the library and importing the function we can apply the Kalman Filter to our data:

```
In [ ]: data = df_1950['Monthly Anomaly'].values
```

```
In [ ]: # Initialize Kalman Filter
kf = KalmanFilter(transition_matrices=[1],
                  observation_matrices=[1],
                  initial_state_mean=data[0],
                  initial_state_covariance=1,
                  observation_covariance=1,
                  transition_covariance=0.01)

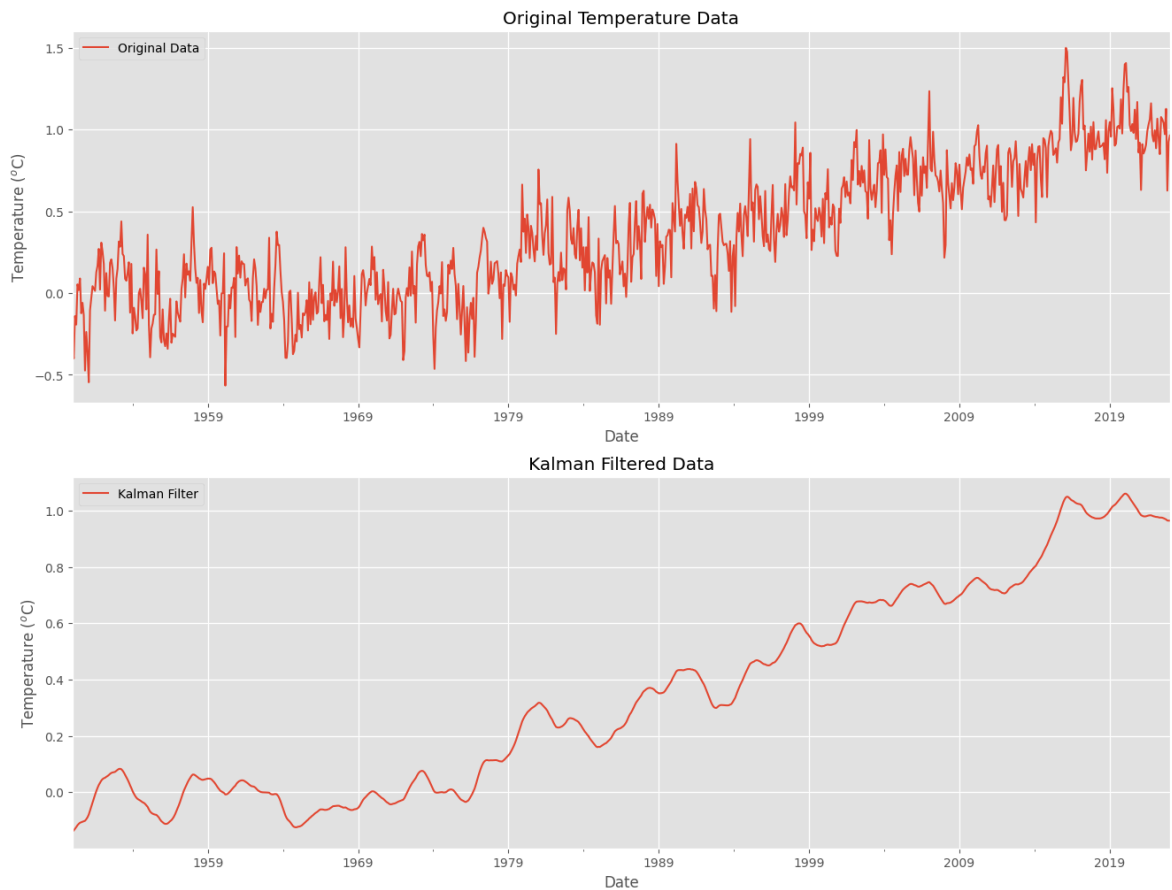
# Estimate the state sequence using the Kalman filter
kalman_filter, _ = kf.smooth(data)

# Add the Kalman smoothed data to the dataframe
df_1950['Kalman_filter'] = kalman_filter
```

```
In [ ]: plt.figure(figsize=(16, 12))

plt.subplot(2, 1, 1)
df_1950['Monthly Anomaly'].plot(label='Original Data')
plt.ylabel('Temperature ( $^{\circ}$ C)')
plt.legend(loc='upper left')
plt.title('Original Temperature Data')

plt.subplot(2, 1, 2)
df_1950['Kalman_filter'].plot(label='Kalman Filter')
plt.ylabel('Temperature ( $^{\circ}$ C)')
plt.legend(loc='upper left')
plt.title('Kalman Filtered Data')
plt.show()
```



Kalman Smoothing

Unlike Kalman filtering, which focuses on predicting and updating the current state using historical measurements, Kalman smoothing increases the accuracy of past state values. This approach is particularly beneficial in scenarios that require a comprehensive and accurate understanding of the entire data set. By effectively reducing the impact of noise and uncertainty, Kalman smoothing contributes to producing cleaner and more reliable data. The reverse approach in Kalman smoothing involves revisiting and recalculating previous data points using information from past and future data. This approach allows for rechecking previous estimates with additional information that was not available during the initial estimation or prediction.

Following are various components used in Kalman smoother that help define the pattern of the series:

- **Level:** This component assumes that the time series has a consistent level or mean over time, which helps filter out random noise.
- **Trend Level:** In addition to the average over time, this component helps capture whether the data is trending upward or downward over time.
- **Seasonal Level:** Helps capture repetitive patterns of averaging over time, which captures periodic fluctuations in the data.

- Seasonal Trend Level: This is a combination of level, trend and seasonality components
- Long Seasonal Level: Captures long-term patterns over multiple seasons, which helps capture the periodic behavior of data over long durations.

```
In [ ]: from tsmoother.smoother import KalmanSmoother
```

Let's apply Kalman smoothing here:

```
In [ ]: smoother = KalmanSmoother(component='level_trend', component_noise={'level':0.2, '
smoother.smooth(df_1950['Monthly Anomaly'])

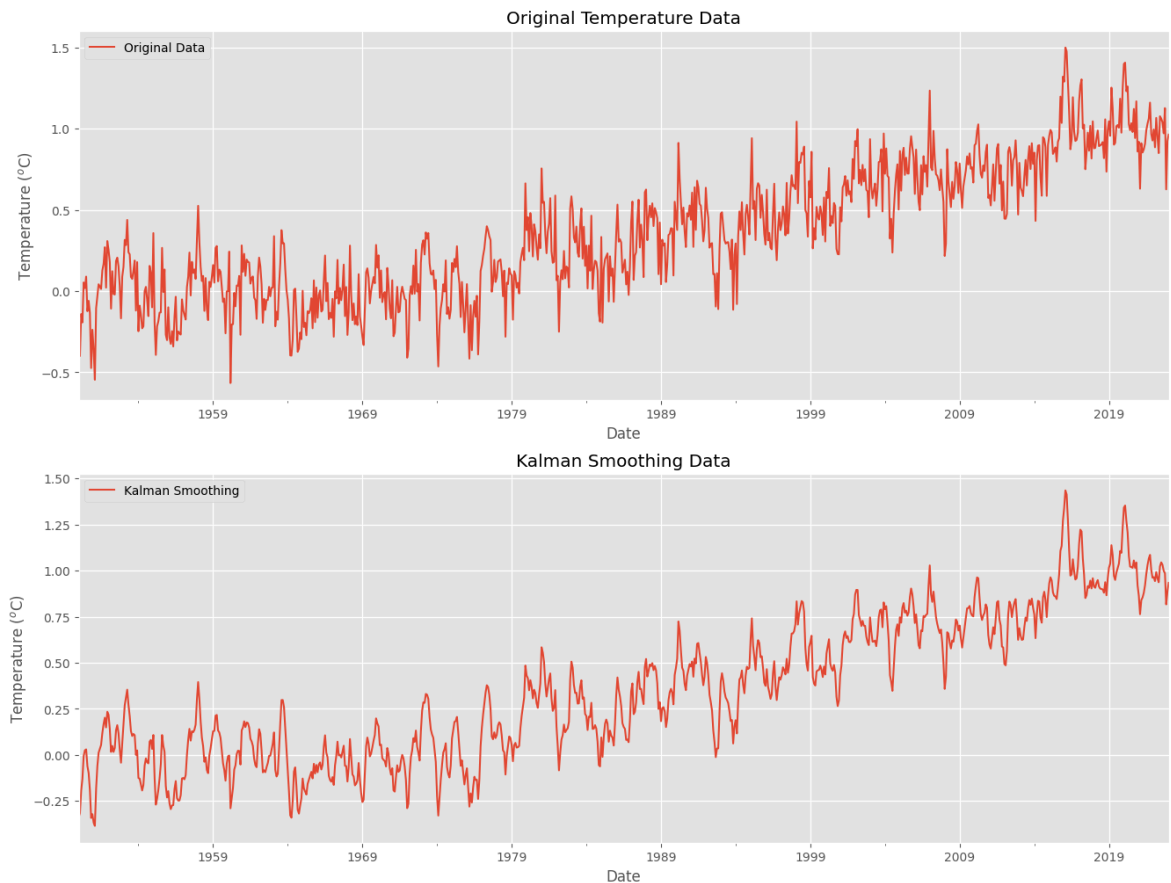
# generate intervals
low, up = smoother.get_intervals('kalman_interval')
```

```
In [ ]: df_1950['Kalman_smoothing'] = smoother.smooth_data[0]
```

```
In [ ]: plt.figure(figsize=(16, 12))

plt.subplot(2, 1, 1)
df_1950['Monthly Anomaly'].plot(label='Original Data')
plt.ylabel('Temperature ($^oC$)')
plt.legend(loc='upper left')
plt.title('Original Temperature Data')

plt.subplot(2, 1, 2)
df_1950['Kalman_smoothing'].plot(label='Kalman Smoothing')
plt.ylabel('Temperature ($^oC$)')
plt.legend(loc='upper left')
plt.title('Kalman Smoothing Data')
plt.show()
```



Hodrick–Prescott filter

The Hodrick-Prescott Filter (HP Filter) is a statistical technique used to decompose a time series into two components: the long-term trend and the short-term fluctuations. It is named after its creators, Robert Hodrick and Edward Prescott.

The idea behind the HP Filter is to find a smoothed trend function that minimizes the variance of the fluctuations with respect to the trend. This is achieved through a process of minimizing an objective function that takes into account both the smoothness of the trend and the goodness of fit of the fluctuations.

Once the time series is decomposed into trends and short-term fluctuations, analysts can analyze these components separately, better understanding the long-term patterns and cyclical variations of the series. This can be useful for identifying growth trends, economic cycles, turning points, and anomalies in the data.

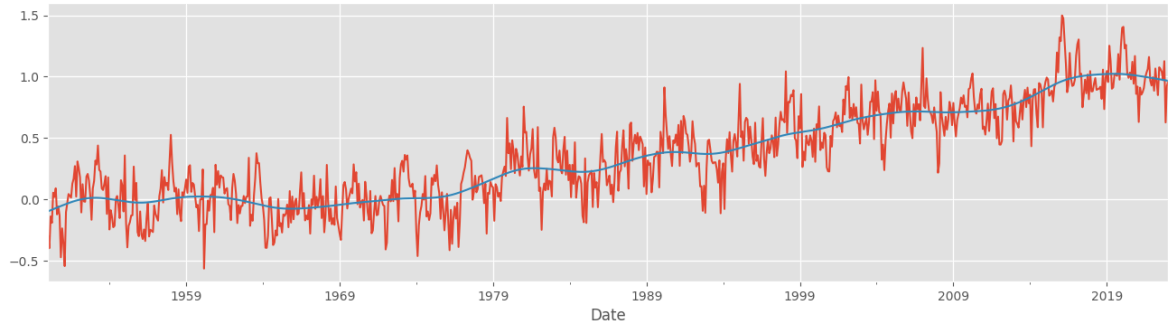
It is important to note that the HP Filter is not a perfect technique and has some limitations. The choice of the smoothing parameter can affect the results, and the interpretation of short-term fluctuations also requires caution, as they can be influenced by temporary factors or events not captured by the model.

```
In [ ]: import statsmodels.api as sm
```

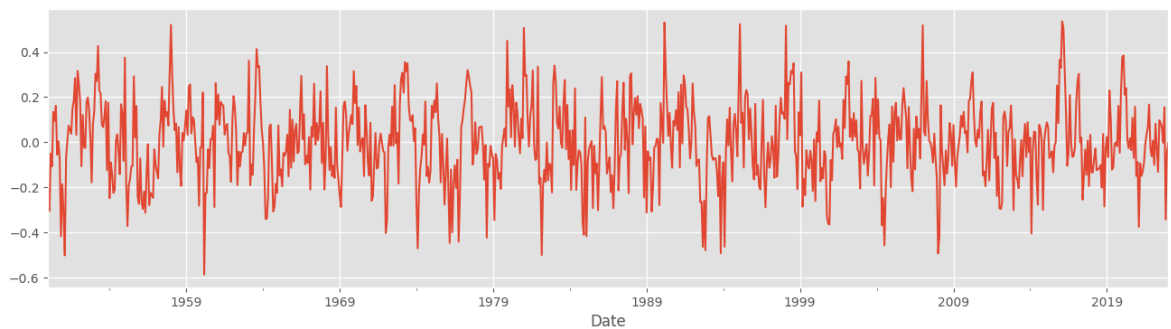
```
In [ ]: cicle, trend = sm.tsa.filters.hpfilter(df_1950['Monthly Anomaly'], 129600)
```

```
In [ ]: df_1950["Monthly Cicle Anomaly"] = cicle
df_1950["Monthly Trend Anomaly"] = trend
```

```
In [ ]: plt.figure(figsize=(16, 4))
df_1950["Monthly Anomaly"].plot()
df_1950["Monthly Trend Anomaly"].plot()
plt.show()
```

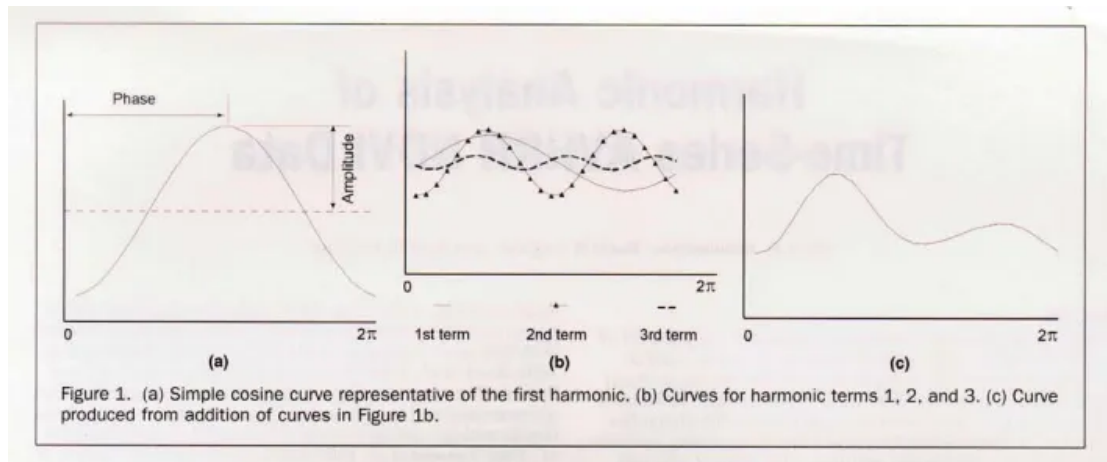


```
In [ ]: plt.figure(figsize=(16, 4))
df_1950["Monthly Cicle Anomaly"].plot()
plt.show()
```



Harmonic Models

Harmonic analysis of NDVI time series aims to characterize seasonal changes in the spectral behavior of targets by decomposing the time series into harmonic terms. Similar to principal component analysis, most of the variance in a dataset is contained in the first few terms (components). Over 90% of the variance in the original time series was captured in the additive and first two harmonic terms. The additive term and the phase and amplitude for the first two harmonic terms were extracted and used for further analysis.



The amplitude corresponds to half the value at which the function is maximized, and the phase is the displacement between the origin and the peak of the wave in the interval from 0 to 2π . Each harmonic term represents the number of cycles completed by a wave, in a given time interval, and is responsible for a percentage of the total variance of the original time series. Thus, the first harmonic has a period T equal to the total period, the second harmonic corresponds to half the period of the first harmonic $T/2$, the third harmonic to $T/3$ and so on.

First, we will obtain NDVI data from areas with soybeans, where in each campaign, the NDVI has a harmonic pattern according to the phenological cycle of the crop:

```
In [ ]: import ee
import matplotlib.pyplot as plt
import numpy as np
import pandas as pd
import geemap
import geopandas as gpd
import warnings
import datetime
warnings.filterwarnings('ignore')
```

Let's authenticate and connect to Drive to get our area of interest:

```
In [ ]: ee.Authenticate()
ee.Initialize(project='my-project-1527255156007')
```

```
In [ ]: from google.colab import drive
drive.mount('/content/drive')
```

Drive already mounted at /content/drive; to attempt to forcibly remount, call `drive.mount("/content/drive", force_remount=True)`.

Link to Dataset:

https://drive.google.com/drive/folders/1_zwxcE3YM6R4NaXfvoMVCKQaOzA6I_kR?usp=sharing

```
In [ ]: path_aoi_soja = '/content/drive/MyDrive/Datasets_TS/AOI_soja/AOI_SOJA.shp'
```

```
In [ ]: gdf_soja = gpd.read_file(path_aoi_soja)
```

Let's convert the GeoDataFrame into a FeatureCollection:

```
In [ ]: fc = geemap.geopandas_to_ee(gdf_soja)
```

We will get the average monthly NDVI data from 2017 to 2024:

```
In [ ]: S2_coll = ee.ImageCollection("COPERNICUS/S2_SR_HARMONIZED").filter(ee.Filter.lt(
```

```
In [ ]: def addNDVI(image):  
    ndvi = image.normalizedDifference(['B8', 'B4']).rename('NDVI')  
  
    return image.addBands(ndvi)  
  
S2_ndvi = S2_coll.map(addNDVI)
```

```
In [ ]: def meanNDVI(image):  
    image = ee.Image(image)  
    meanDict = image.reduceRegion(reducer = ee.Reducer.mean().setOutputs(['NDVI'  
        geometry = fc,  
        scale = image.projection().nominalScale().getInfo(),  
        maxPixels = 100000,  
        bestEffort = True);  
    return meanDict.get('NDVI').getInfo()
```

```
In [ ]: listOfImages_ndvi = S2_ndvi.select('NDVI').toList(S2_ndvi.size())  
  
ndvi_coll = []  
  
for i in range(listOfImages_ndvi.length().getInfo()):  
    image = ee.Image(listOfImages_ndvi.get(i-1))  
    temp_ndvi = meanNDVI(image)  
    ndvi_coll.append(temp_ndvi)
```

We can convert it to a DataFrame:

```
In [ ]: dates = np.array(S2_ndvi.aggregate_array("system:time_start").getInfo())  
day = [datetime.datetime.fromtimestamp(i/1000).strftime('%Y-%m-%d') for i in (da
```

```
In [ ]: ndvi_df = pd.DataFrame(ndvi_coll, index = day, columns = ['ndvi'])  
ndvi_df.index = pd.to_datetime(ndvi_df.index)  
ndvi_df.sort_index(ascending = True, inplace = True)  
  
ndvi_df.head(5)
```

Out[]: **ndvi**

2019-05-09 0.165736

2019-05-19 0.807025

2019-05-19 0.783828

2019-06-08 0.807190

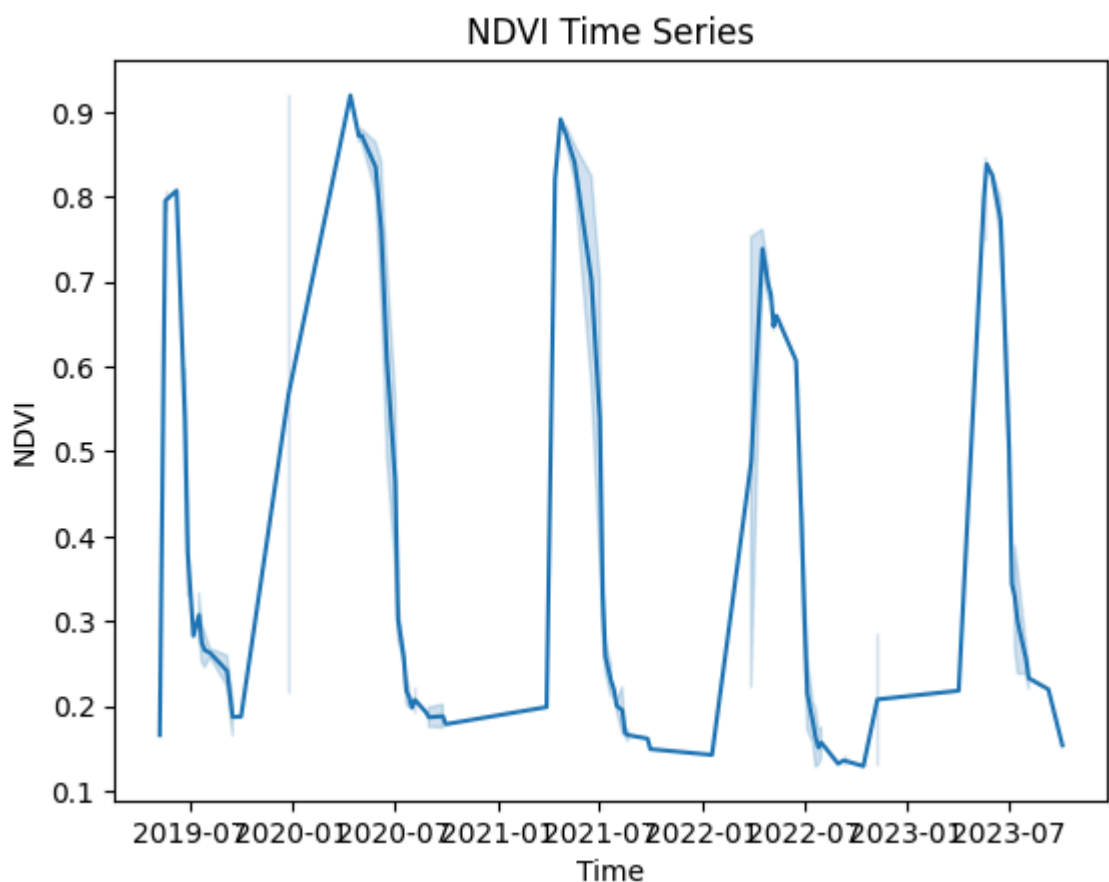
2019-06-23 0.596796

```
In [ ]: import seaborn as sns
import matplotlib.pyplot as plt

# Create the time series plot
sns.lineplot(data=ndvi_df, x=ndvi_df.index, y='ndvi')

# Set the title and axis labels
plt.title('NDVI Time Series')
plt.xlabel('Time')
plt.ylabel('NDVI')

# Display the plot
plt.show()
```



Let's then apply the harmonic transformation:

```
In [ ]: dependent = 'NDVI'
harmonics = 3
harmonicFrequencies = list(range(1, harmonics+1))
```

```
In [ ]: harmonicFrequencies
```

```
Out[ ]: [1, 2, 3]
```

```
In [ ]: def getNames (base, lst_freq) :  
        name_lst = []  
        for i in lst_freq:  
            name_lst.append(ee.String(base + str(i)))  
        return name_lst
```

```
In [ ]: cosNames = getNames('cos_', harmonicFrequencies);  
sinNames = getNames('sin_', harmonicFrequencies);  
independents = ee.List(['constant', 't']).cat(cosNames).cat(sinNames);
```

```
In [ ]: def addConstant (image) :  
        return image.addBands(ee.Image(1));
```

```
In [ ]: import math  
def addTime (image) :  
    date = ee.Date(image.get('system:time_start'));  
    years = date.difference(ee.Date('1970-01-01'), 'year');  
    timeRadians = ee.Image(years.multiply(2 * math.pi));  
    return image.addBands(timeRadians.rename('t').float());
```

```
In [ ]: def addHarmonics (image) :  
    frequencies = ee.Image.constant(harmonicFrequencies)  
    time = ee.Image(image).select('t')  
    cosines = time.multiply(frequencies).cos().rename(cosNames)  
    sines = time.multiply(frequencies).sin().rename(sinNames)  
    return image.addBands(cosines).addBands(sines)
```

We apply the functions created in our imageCollection:

```
In [ ]: harmonicNDVI = S2_ndvi.map(addConstant).map(addTime).map(addHarmonics);
```

```
In [ ]: harmonicTrend = harmonicNDVI.select(independents.add(dependent)).reduce(ee.Reduc
```

```
In [ ]: harmonicTrendCoefficients = harmonicTrend.select('coefficients').arrayProject([0
```

```
In [ ]: fittedHarmonic = harmonicNDVI.map(lambda image : image.addBands(image.select(ind
```

```
In [ ]: print(fittedHarmonic.getInfo())  
print(harmonicTrendCoefficients.getInfo())
```

{'type': 'ImageCollection', 'bands': [], 'version': 1743009715176097, 'id': 'COPERNICUS/S2_SR_HARMONIZED', 'properties': {'date_range': [1490659200000, 1647907200000], 'period': 0, 'system:visualization_0_min': '0.0', 'type_name': 'ImageCollection', 'keywords': ['copernicus', 'esa', 'eu', 'msi', 'reflectance', 'sentinel', 'sr'], 'system:visualization_0_bands': 'B4,B3,B2', 'thumb': 'https://mw1.google.com/ges/dd/images/COPERNICUS_S2_SR_thumb.png', 'description': '<p>Sentinel-2 is a wide-swath, high-resolution, multi-spectral imaging mission supporting Copernicus Land Monitoring studies, including the monitoring of vegetation, soil and water cover, as well as observation of inland waterways and coastal areas.</p><p>The Sentinel-2 L2 data are downloaded from scihub. They were computed by running sen2cor. WARNING: ESA did not produce L2 data for all L1 assets, and earlier L2 coverage is not global.</p><p>The assets contain 12 UINT16 spectral bands representing SR scaled by 10000 (unlike in L1 data, there is no B10). There are also several more L2-specific bands (see band list for details). See the Sentinel-2 User Handbook for details. In addition, three QA bands are present where one (QA60) is a bitmask band with cloud mask information. For more details, see the full explanation of how cloud masks are computed.</p><p>EE asset ids for Sentinel-2 L2 assets have the following format: COPERNICUS/S2_SR/20151128T002653_20151128T102149_T56MNN. Here the first numeric part represents the sensing date and time, the second numeric part represents the product generation date and time, and the final 6-character string is a unique granule identifier indicating its UTM grid reference (see MGRS).</p><p>Clouds can be removed by using COPERNICUS/S2_CLOUD_PROBABILITY. See this tutorial explaining how to apply the cloud mask.</p><p>For more details on Sentinel-2 radiometric resolution, see this page.</p><p>Provider: European Union/ESA/Copernicus</p><p>Revisit Interval
 5 days</p><p>Bands<table class="eecat"><tr><th scope="col">Name</th><th scope="col">Description</th></tr><tr><td>B1</td><td><p>Aerosols</p></td></tr><tr><td>B2</td><td><p>Blue</p></td></tr><tr><td>B3</td><td><p>Green</p></td></tr><tr><td>B4</td><td><p>Red</p></td></tr><tr><td>B5</td><td><p>Red Edge 1</p></td></tr><tr><td>B6</td><td><p>Red Edge 2</p></td></tr><tr><td>B7</td><td><p>Red Edge 3</p></td></tr><tr><td>B8</td><td><p>NIR</p></td></tr><tr><td>B8A</td><td><p>Red Edge 4</p></td></tr><tr><td>B9</td><td><p>Water vapor</p></td></tr><tr><td>B11</td><td><p>SWIR 1</p></td></tr><tr><td>B12</td><td><p>SWIR 2</p></td></tr><tr><td>AOT</td><td><p>Aerosol Optical Thickness</p></td></tr><tr><td>WVP</td><td><p>Water Vapor Pressure. The height the water would occupy if the vapor were condensed into liquid and spread evenly across the column.</p></td></tr><tr><td>SCL</td><td><p>Scene Classification Map (The "No Data" value of 0 is masked out)</p></td></tr><tr><td>TCI_R</td><td><p>True Color Image, Red channel</p></td></tr><tr><td>TCI_G</td><td><p>True Color Image, Green channel</p></td></tr><tr><td>TCI_B</td><td><p>True Color Image, Blue channel</p></td></tr><tr><td>MSK_CLDPRB</td><td><p>Cloud Probability Map (missing in some products)</p></td></tr><tr><td>MSK_SNOWPRB</td><td><p>Snow Probability Map (missing in some products)</p></td></tr><tr><td>QA10</td><td><p>Always empty</p></td></tr><tr><td>QA20</td><td><p>Always empty</p></td></tr><tr><td>QA60</td><td><p>Cloud mask</p></td></tr><tr><td colspan=100><p>Bitmask for QA60</p><p>Bit 10: Opaque clouds</p><p>0: No opaque clouds</p><p>1: Opaque clouds present</p><p>Bit 11: Cirrus clouds</p><p>0: No cirrus clouds</p><p>1: Cirrus clouds present</p></td></tr></table><p>Image Properties<table class="eecat"><tr><th scope="col">Name</th><th scope="col">Type</th><th scope="col">Description</th></tr><tr><td>AOT_RETRIEVAL_ACCURACY</td><td>DOUBLE</td><td><p>Accuracy of Aerosol Optical thickness model</p></td></tr><tr><td>CLOUDY_PIXEL_PERCENTAGE</td><td>DOUBLE</td><td><p>Granule-specific cloudy pixel percentage taken from the original metadata</p></td></tr><tr><td>CLOUD_CO

| | | |
|----------------------------------|--------|---|
| VERAGE_ASSESSMENT | DOUBLE | Cloudy pixel percentage for the whole archive that contains this granule. Taken from the original metadata |
| CLOUDY_SHADOW_PERCENTAGE | DOUBLE | Percentage of pixels classified as cloud shadow |
| DARK_FEATURES_PERCENTAGE | DOUBLE | Percentage of pixels classified as dark features or shadows |
| DATASTRIP_ID | STRING | Unique identifier of the datastrip Product Data Item (PDI) |
| DATATAKE_IDENTIFIER | STRING | Uniquely identifies a given Datatake. The ID contains the Sentinel-2 satellite, start date and time, absolute orbit number, and processing baseline. |
| DATATAKE_TYPE | STRING | MSI operation mode |
| DEGRADED_MSI_DATA_PERCENTAGE | DOUBLE | Percentage of degraded MSI and ancillary data |
| FORMAT_CORRECTNESS | STRING | Synthesis of the On-Line Quality Control (OLQC) checks performed at granule (Product_Syntax) and datastrip (Product_Syntax and DS_Consistency) levels |
| GENERAL_QUALITY | STRING | Synthesis of the OLQC checks performed at the datastrip level (Relative_Orbit_Number) |
| GENERATION_TIME | DOUBLE | Product generation time |
| GEOMETRIC_QUALITY | STRING | Synthesis of the OLQC checks performed at the datastrip level (Attitude_Quality_Indicator) |
| GRANULE_ID | STRING | Unique identifier of the granule PDI (PDI_ID) |
| HIGH_PROBA_CLOUDS_PERCENTAGE | DOUBLE | Percentage of pixels classified as high probability clouds |
| MEAN_INCIDENCE_AZIMUTH_ANGLE_B1 | DOUBLE | Mean value containing viewing incidence azimuth angle average for band B1 and for all detectors |
| MEAN_INCIDENCE_AZIMUTH_ANGLE_B2 | DOUBLE | Mean value containing viewing incidence azimuth angle average for band B2 and for all detectors |
| MEAN_INCIDENCE_AZIMUTH_ANGLE_B3 | DOUBLE | Mean value containing viewing incidence azimuth angle average for band B3 and for all detectors |
| MEAN_INCIDENCE_AZIMUTH_ANGLE_B4 | DOUBLE | Mean value containing viewing incidence azimuth angle average for band B4 and for all detectors |
| MEAN_INCIDENCE_AZIMUTH_ANGLE_B5 | DOUBLE | Mean value containing viewing incidence azimuth angle average for band B5 and for all detectors |
| MEAN_INCIDENCE_AZIMUTH_ANGLE_B6 | DOUBLE | Mean value containing viewing incidence azimuth angle average for band B6 and for all detectors |
| MEAN_INCIDENCE_AZIMUTH_ANGLE_B7 | DOUBLE | Mean value containing viewing incidence azimuth angle average for band B7 and for all detectors |
| MEAN_INCIDENCE_AZIMUTH_ANGLE_B8 | DOUBLE | Mean value containing viewing incidence azimuth angle average for band B8 and for all detectors |
| MEAN_INCIDENCE_AZIMUTH_ANGLE_B8A | DOUBLE | Mean value containing viewing incidence azimuth angle average for band B8a and for all detectors |
| MEAN_INCIDENCE_AZIMUTH_ANGLE_B9 | DOUBLE | Mean value containing viewing incidence azimuth angle average for band B9 and for all detectors |
| MEAN_INCIDENCE_AZIMUTH_ANGLE_B10 | DOUBLE | Mean value containing viewing incidence azimuth angle average for band B10 and for all detectors |
| MEAN_INCIDENCE_AZIMUTH_ANGLE_B11 | DOUBLE | Mean value containing viewing incidence azimuth angle average for band B11 and for all detectors |
| MEAN_INCIDENCE_AZIMUTH_ANGLE_B12 | DOUBLE | Mean value containing viewing incidence azimuth angle average for band B12 and for all detectors |
| MEAN_INCIDENCE_ZENITH_ANGLE_B1 | DOUBLE | Mean value containing viewing incidence zenith angle average for band B1 and for all detectors |
| MEAN_INCIDENCE_ZENITH_ANGLE_B2 | DOUBLE | Mean value containing viewing incidence zenith angle average for band B2 and for all detectors |
| MEAN_INCIDENCE_ZENITH_ANGLE_B3 | DOUBLE | Mean value containing viewing incidence zenith angle average for band B3 and for all detectors |
| MEAN_INCIDENCE_ZENITH_ANGLE_B4 | DOUBLE | Mean value containing viewing incidence zenith angle average for band B4 and for all detectors |
| MEAN_INCIDENCE_ZENITH_ANGLE_B5 | DOUBLE | Mean value containing |

viewing incidence zenith angle average for band B5 and for all detectors

| | | |
|--------------------------------------|--------|--|
| MEAN_INCIDENCE_ZENITH_ANGLE_B6 | DOUBLE | Mean value containing viewing incidence zenith angle average for band B6 and for all detectors |
| MEAN_INCIDENCE_ZENITH_ANGLE_B7 | DOUBLE | Mean value containing viewing incidence zenith angle average for band B7 and for all detectors |
| MEAN_INCIDENCE_ZENITH_ANGLE_B8 | DOUBLE | Mean value containing viewing incidence zenith angle average for band B8 and for all detectors |
| MEAN_INCIDENCE_ZENITH_ANGLE_B8A | DOUBLE | Mean value containing viewing incidence zenith angle average for band B8a and for all detectors |
| MEAN_INCIDENCE_ZENITH_ANGLE_B9 | DOUBLE | Mean value containing viewing incidence zenith angle average for band B9 and for all detectors |
| MEAN_INCIDENCE_ZENITH_ANGLE_B10 | DOUBLE | Mean value containing viewing incidence zenith angle average for band B10 and for all detectors |
| MEAN_INCIDENCE_ZENITH_ANGLE_B11 | DOUBLE | Mean value containing viewing incidence zenith angle average for band B11 and for all detectors |
| MEAN_INCIDENCE_ZENITH_ANGLE_B12 | DOUBLE | Mean value containing viewing incidence zenith angle average for band B12 and for all detectors |
| MEAN_SOLAR_AZIMUTH_ANGLE | DOUBLE | Mean value containing sun azimuth angle average for all bands and detectors |
| MEAN_SOLAR_ZENITH_ANGLE | DOUBLE | Mean value containing sun zenith angle average for all bands and detectors |
| MEDIUM_PROBA_CLOUDS_PERCENTAGE | DOUBLE | Percentage of pixels classified as medium probability clouds |
| MGRS_TILE | STRING | US-Military Grid Reference System (MGRS) tile |
| NODATA_PIXEL_PERCENTAGE | DOUBLE | Percentage of No Data pixels |
| NOT_VEGETATED_PERCENTAGE | DOUBLE | Percentage of pixels classified as non-vegetated |
| PROCESSING_BASELINE | STRING | Configuration baseline used at the time of the product generation in terms of processor software version and major Ground Image Processing Parameters (GIPP) version |
| PRODUCT_ID | STRING | The full id of the original Sentinel-2 product |
| RADIATIVE_TRANSFER_ACCURACY | DOUBLE | Accuracy of radiative transfer model |
| RADIOMETRIC_QUALITY | STRING | Based on the OLQC reports contained in the Datastrips/QI_DATA with RADIOMETRIC_QUALITY checklist name |
| REFLECTANCE_CONVERSION_CORRECTION | DOUBLE | Earth-Sun distance correction factor |
| SATURATED_DEFECTIVE_PIXEL_PERCENTAGE | DOUBLE | Percentage of saturated or defective pixels |
| SENSING_ORBIT_DIRECTION | STRING | Imaging orbit direction |
| SENSING_ORBIT_NUMBER | DOUBLE | Imaging orbit number |
| SENSOR_QUALITY | STRING | Synthesis of the OLQC checks performed at granule (Missing_Lines, Corrupted_ISP, and Sensing_Time) and datastrip (Degraded_SAD and Datation_Model) levels |
| SOLAR_IRRADIANCE_B1 | DOUBLE | Mean solar exoatmospheric irradiance for band B1 |
| SOLAR_IRRADIANCE_B2 | DOUBLE | Mean solar exoatmospheric irradiance for band B2 |
| SOLAR_IRRADIANCE_B3 | DOUBLE | Mean solar exoatmospheric irradiance for band B3 |
| SOLAR_IRRADIANCE_B4 | DOUBLE | Mean solar exoatmospheric irradiance for band B4 |
| SOLAR_IRRADIANCE_B5 | DOUBLE | Mean solar exoatmospheric irradiance for band B5 |
| SOLAR_IRRADIANCE_B6 | DOUBLE | Mean solar exoatmospheric irradiance for band B6 |
| SOLAR_IRRADIANCE_B7 | DOUBLE | Mean solar exoatmospheric irradiance for band B7 |
| SOLAR_IRRADIANCE_B8 | DOUBLE | Mean solar exoatmospheric irradiance for band B8 |
| SOLAR_IRRADIANCE_B8A | DOUBLE | Mean solar exoatmospheric irradiance for band B8a |
| SOLAR_IRRADIANCE_B9 | DOUBLE | Mean solar exoatmospheric irradiance for band B9 |
| SOLAR_IRRADIANCE_B10 | DOUBLE | Mean solar exoatmospheric irradiance for band B10 |
| SOLAR_IRRADIANCE_B11 | DOUBLE | Mean solar exoatmospheric irradiance for band B11 |

| | | |
|---|---------------------------------|--------|
| irradiance for band B11 | SOLAR_IRRADIANCE_B12 | DOUBLE |
| Mean solar exoatmospheric irradiance for band B12 | SNOW_ICE_PERCENTAGE | DOUBLE |
| Percentage of pixels classified as snow or ice | SPACECRAFT_NAME | STRING |
| Sentinel-2 spacecraft name: Sentinel-2A, Sentinel-2B | THIN_CIRRUS_PERCENTAGE | DOUBLE |
| Percentage of pixels classified as thin cirrus clouds | UNCLASSIFIED_PERCENTAGE | DOUBLE |
| Percentage of unclassified pixels | VEGETATION_PERCENTAGE | DOUBLE |
| Percentage of pixels classified as vegetation | WATER_PERCENTAGE | DOUBLE |
| Percentage of pixels classified as water | WATER_VAPOUR_RETRIEVAL_ACCURACY | DOUBLE |
| Declared accuracy of the Water Vapor model | | |

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The use of Sentinel data is governed by the http://scihub.copernicus.eu/twiki/pub/SciHubWebPortal/TermsConditions/Sentinel_Data_Terms_and_Conditions.pdf Copernicus Sentinel Data Terms and Conditions.

```

table.eecat {
  border: 1px solid black;
  border-collapse: collapse;
  font-size: 13px;
}
table.eecat td, tr, th {
  text-align: left;
  vertical-align: top;
  border: 1px solid gray;
  padding: 3px;
}
td.nobreak {
  white-space: nowrap;
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```

Then we can extract the harmonic time series as a DataFrame:

```

In [ ]: def fitted_harmonic_to_df(fitted_harmonic_coll):

    fitted_values_list = []
    dates_list = []

    for i in range(fitted_harmonic_coll.size().getInfo()):
        image = ee.Image(fitted_harmonic_coll.toList(fitted_harmonic_coll.size()).ge
        fitted_value = image.reduceRegion(
            reducer=ee.Reducer.first(),
            geometry=fc, # Assuming 'fc' is your region of interest
            scale=30,
            maxPixels=1e13
        ).get('fitted').getInfo()
        date = image.date().format('YYYY-MM-dd').getInfo()

        fitted_values_list.append(fitted_value)
        dates_list.append(date)

    df = pd.DataFrame({'fitted': fitted_values_list}, index=pd.to_datetime(dates_l
    return df

```

```
# Example usage:
fitted_df = fitted_harmonic_to_df(fittedHarmonic)
fitted_df
```

Out[]:

| | fitted |
|-------------------|---------------|
| 2019-05-09 | 0.370493 |
| 2019-05-19 | 0.345088 |
| 2019-05-19 | 0.345088 |
| 2019-06-08 | 0.261273 |
| 2019-06-23 | 0.197078 |
| ... | ... |
| 2023-08-01 | 0.124218 |
| 2023-08-06 | 0.123245 |
| 2023-08-06 | 0.123245 |
| 2023-09-10 | 0.114466 |
| 2023-10-05 | 0.107687 |

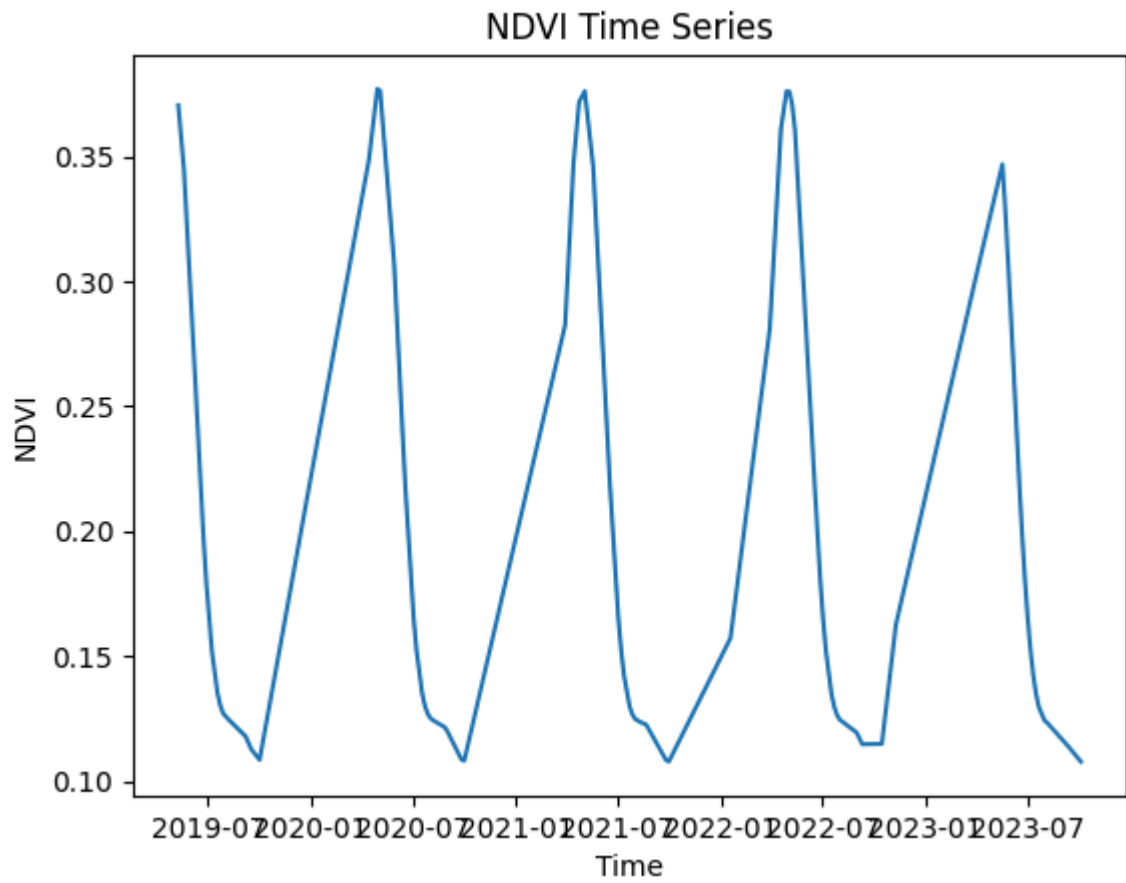
143 rows × 1 columns

Finally we use matplotlib to visualize:

```
In [ ]: sns.lineplot(data=fitted_df, x=fitted_df.index, y='fitted')

# Set the title and axis labels
plt.title('NDVI Time Series')
plt.xlabel('Time')
plt.ylabel('NDVI')

# Display the plot
plt.show()
```



Thank you! See you in the next Chapter!

References:

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https://docs.sunpy.org/en/stable/generated/gallery/time_series/timeseries_convolution_filter

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<https://dkko.me/posts/filtro-hp-python-statsmodels/>

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<https://analyticsindiamag.com/developers-corner/a-complete-guide-to-hodrick-prescott-filter-in-time-series-analysis/>

<https://medium.com/@shahalkp1/kalman-smoothing-using-tsmoothie-0175260464e5>

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