Analysis of NVDI variability in response to precipitation and air temperature in different regions of Iraq, using MODIS vegetation indices

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Abstract
Iraq, the land of two rivers, has a history that extends back millennia and is the subject of much archaeological research. However, little environmental research has been carried out, and as such relatively little is known about the interaction between Iraq's vegetation and climate. This research serves to fill this knowledge gap by investigating the relationship between the Normalized Difference Vegetation Index (NDVI) and two climatic factors (precipitation and air temperature) over the last decade. The precipitation and air temperature datasets are from the Water and Global Change Forcing Data ERA-Interim (WFDEI), and the NDVI dataset was extracted from the Moderate Resolution Imaging Spectroradiometer (MODIS) at 250 m spatial resolution and 16 day temporal resolution. Three different climatic regions in Iraq, Sulaymaniyah, Wasit, and Basrah, were selected for the period of 2001-2015. This is the first study to compare these regions in Iraq, and one of only a few investigating vegetation's relationship with multiple climatic factors, including precipitation and air temperature, particularly in a semi-arid region.

The interannual, intra-annual and seasonal variability for each region is analysed to compare the different responses of vegetation growth to climatic factors. Correlations between NDVI and climatic factors are also included. Plotting annual cycles of NDVI and precipitation reveals a coherent onset, fluctuation (peak and decline), with a time lag of 4 months for Sulaymaniyah and Wasit (while for the Basrah region, high temperatures and a short rainy season was observed). The correlation coefficients between NDVI and precipitation are relatively high, especially in Sulaymaniyah, and the largest positive correlation was (0.8635) with a time lag of 4 months. The phenological transition points range between 3 and 4 month time lag; this corresponds to the duration of maturity of the vegetation. However, when correlated with air temperature, NDVI experiences an inverse relationship, although not as strong as that of NDVI and precipitation; the highest negative correlation was observed in Wasit with a time lag of 2 months (-0.7562).

The results showed that there is a similarity between temporal patterns of NDVI and precipitation. This similarity is stronger than that of NDVI and air temperature, so it can be concluded that NDVI is a sensitive indicator of the inter-annual variability of precipitation and that precipitation constitutes the primary factor in germination while the air temperature acts with a lesser effect.

Keywords: WATCH Forcing Data ERA-Interim (WFDEI), NDVI, precipitation, air temperature, vegetation, inter-annual, intra-annual, seasonal variability, rainfall indicators, air temperature indicators.

1. Introduction

Vegetation is an important and sensitive component in the earth ecosystem: it affects both weather and climate and influences the energy, water, and carbon exchange between the atmosphere and land surface (Rousvel et al. 2013). In particular, vegetation influences atmospheric water vapour through the process of evapotranspiration, changing both humidity and temperature. Vegetation also impacts the albedo effect, generally reducing the amount of heat reflected back into the atmosphere. Furthermore, plants play an integral role in reducing the atmospheric concentration of carbon because they use carbon dioxide and energy for photosynthesis, which also partially mitigates against the impacts of human carbon emissions. Vegetation covers 20% of the Earth's surface, however, increasing levels of deforestation are adversely affecting climate by disrupting the processes described above (IPCC, 2014; Jones, 2013).

Since vegetation growth has such a considerable effect on the environment, it is a crucial aspect in the current climate change discussions (IPCC, 2014; Rousvel et al. 2013). The degree of vegetation response to climate change can be investigated through understanding the relationship between vegetation and climate change, which in turn provides helpful and important information on climate change adaptation (Hou et al. 2015). Researchers use remote sensing methods to monitor and quantify regional changes in vegetation, which are driven by both human actions and natural climate variation (Rousvel et al. 2013). Remote sensing techniques are particularly useful in not only assessing large areas but also obtaining information on geographical regions that otherwise are inaccessible, such as high-conflict areas.

Satellite-derived vegetation indices, such as the Normalized Difference Vegetation Index (NDVI), have been used in interactive biosphere and production efficiency models for a number of decades (Prince, 1991; Sellers et al. 1994) and researchers have investigated NDVI patterns across global and regional scales. For instance, Moulin et al. (1997) assessed vegetation dynamics on a continental scale; Wang et al. (2001) looked at the NDVI spatial patterns in the Central Great Plains in response to precipitation and temperature; Liu et al. (2003) extracted the NDVI index from the Advanced Very High Resolution Radiometer (AVHRR) sensors for China; and Hou et al. (2015) investigated the correlation between the interannual variations in the Growing-Season NDVI and climate variables in southwestern China. NDVI data has also been used in a range of applications incorporating time series analysis (Boyte et al. 2015): through time series analysis, the use of the NDVI data has been extended to highlight land surface climate interactions (Running et al. 2004), phenology (Lee et al., 2002; Lobo et al. 1997), landscape change (Kastens & Legates, 2002; Lambin, 1996), and vegetation potential (e.g., drought) (Martínez & Gilabert, 2009; Nicholson et al. 1990). NDVI time series data can also be used as climate/environmental proxies, such as precipitation and land surface temperature. For instance, NDVI indices are used to gauge drought and other weather impacts on agriculture (Dabrowska-Zielinska et al., 2002; Li et al. 2004), agricultural potential (Mkhabela et al. 2011) and vegetation in general (for example, Cuomo et al., 2001).

The Moderate Resolution Imaging Spectroradiometer (MODIS), located in the Terra and Aqua satellites, has a global NDVI product (MOD13Q1). NASA and the USGS state that MOD13Q1 products are reliable for vegetation change observations as long as there is minimal cloud interference (https://lpdaac.usgs.gov). Because Iraq is generally cloud-free for most of the year, this product is suitable for this research. Iraq presents an interesting study area because it is situated in the subtropical region, with highly seasonal precipitation in the north and a large temperature range in the south. The northern part of Iraq (i.e., Sulaymaniyah) is comprised mostly of mountains and intermontane plains, with high precipitation (up to 1200mm/year). Wasit (central Iraq) and Basrah (southern Iraq) are located in the alluvial plains of the Euphrates and Tigris rivers, where temperatures are generally higher and precipitation (100-200mm/year) is much lower (FAO, 2008). Therefore, vegetation growth/coverage will vary distinctly across the country dependent on local temperature and precipitation conditions. However, very little is known about the interaction between vegetation and climate in Iraq.

In the last few decades, Iraq's vegetation has changed dramatically because of natural environmental/climatic factors and human activities. Unfortunately, little vegetation data has been obtained from fieldwork due to the continuous conflict in Iraq. As such, remote sensing is the only viable method to assess the relationship between vegetation and climate. While there has been some research on vegetation and climate in Iraq (most research centres on water quality and pollution issues arising from the continued conflict), researchers concentrate on single variables and geographical areas, with little regional comparison (see Qader et al. 2015 and Section 5). Because Iraq's environment is fragile, it is more prone to the effects of climate change. Therefore, understanding Iraq's climate and vegetation is important in order to plan and implement mitigation strategies. Using multiple datasets and comparing across different environments provides policymakers with better and more nuanced information on vegetation-climate dynamics, enabling them to implement different strategies as needed across Iraq.

As such, the aim of this paper is to explore the relationship between NDVI and two climatic factors (precipitation and air temperature) in three different climatic locations across Iraq (Sulaymaniyah, Wasit and Basrah). This is the first attempt to compare climatically different areas in Iraq to better understand vegetation's relationship with the two climatic indicators, precipitation and air temperature, and to determine which of these is more dominant in semi-arid to arid environments. The results here can be potentially applied to other semi-arid regions due to its broad coverage of the areas and climate variables.

In the next section, the study areas are described. This is followed by a discussion on the datasets and methods used. Section 4 details the results of the analyses, and is followed by Section 5, which further discusses the results and their implications. Section 6 concludes.

2. The Study Areas: Environment and climate of Iraq

The three study areas are Sulaymaniyah in the north, Wasit in the centre and Basrah in the south of Iraq. These regions extend between latitude 34.548-36.528 N and longitude 46.349-44.506 E, latitude 29.166-31.297 N and longitude 46.543-48.568 E, latitude 31.297-33.506 N and longitude 46.564-44.482 E, respectively. They cover an area of approximately 122 × 110 km^2, 115 × 114 km^2, and 75 × 120 km^2, respectively. Iraq shares borders with Iran (east), Turkey (north), and Syria, Jordan and the Kingdom of Saudi Arabia (west); the Arabian Gulf is to the south (see Figure 1).

Most of Iraq is covered by the expansive Mesopotamian alluvial plain, created by the Tigris and Euphrates rivers. The south and southwest is mainly desert, and the northern area (Kurdistan) is mountainous, with small intermontane plains. Iraq has two main agro-zones: the rain-fed north and the irrigated central and southern parts (FAO, 2003). Grasses and open woodlands characterise the northern highlands, while the rest of the country is characterised by open scrubland. Wheat and barley are grown in the winter and harvested in late spring, while sorghum, corn, millet and rice are grown in the summer and harvested in August/September (FAO, 2003; Schnepf, 2004).

Iraq, generally, has a subtropical continental climate, but the north's climate is more Mediterranean (FAO, 2008; Jaradat, 2002). The average annual precipitation is about 216 mm a year for the whole country (FAO, 2008, 2011), but precipitation rates vary considerably depending on topography. The climatic variability (differences in precipitation and temperature) is affected by four factors: the nature of topographical features (particularly in the northern mountains of Iraq), the vegetation characteristics, the edaphic conditions, and natural climatic variability.

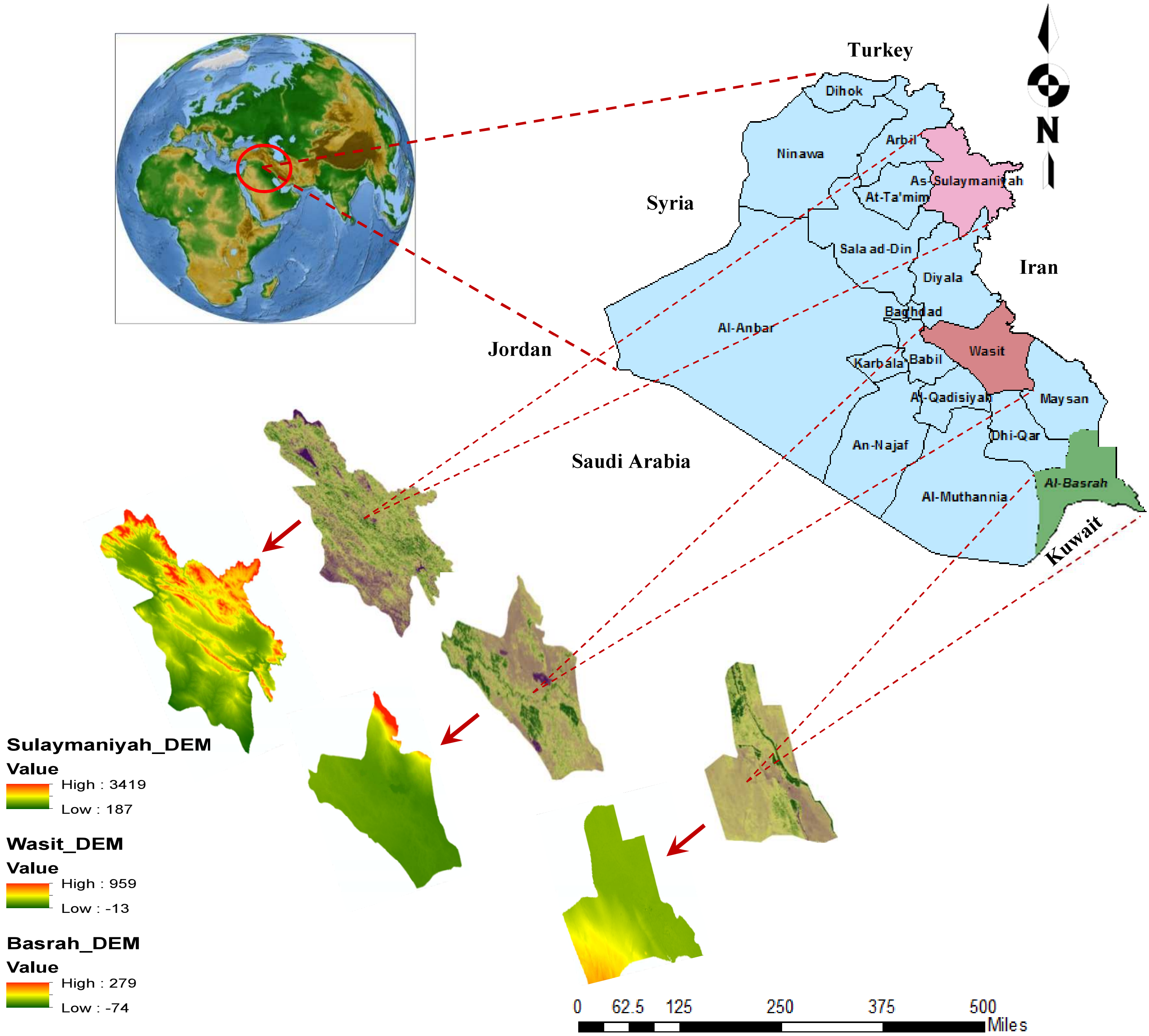


Figure 1: Location of the study area and test sites with NDVI and Digital Elevation Model (DEM) images.

Sulaymaniyah, Wasit and Basrah were chosen because they differ considerably in terms of climate and topography, with different temperatures, precipitation levels and NDVIs. As such, they provide an interesting comparative study.

Sulaymaniyah is located in Iraqi Kurdistan and is one of the largest cities in the country. It is situated in the Shahrizor plain, bounded by the Zagros Mountains and the Binzird, Baranan and Qara Daghs in Iraqi Kurdistan. The climate is Mediterranean, characterised by cooler summer temperatures (as compared with the rest of Iraq) and wetter winters. Average temperatures range from 0°C to 39°C (but higher temperatures have been recorded). Precipitation, as a mixture of rain and snow, occurs mainly between November and April and can reach over 1200mm per year (FAO, 2008). Irrigation is not needed for grain crops.

Wasit, located southwest of Sulaymaniyah, towards the centre of Iraq, has agricultural and industrial potential, however agriculture has been adversely impacted by increasing water salinity, lack of modern agricultural infrastructure, conflict in the region and migration from rural areas (FAO, 2011; IAU, 2009). The climate is subtropical continental, with hot, dry summers and somewhat cooler winters. The average temperatures range from 38° C (August high, but temperatures can go higher) to 12° C (January low), with the rainy season between December and February (average rainfall is less than 200mm/year).

Basrah, located in the south, is very arid, with insufficient precipitation to sustain any substantial vegetation. Summer temperatures can exceed 50° C, and precipitation levels are less than 100mm/year (FAO, 2008). Winter temperatures are milder, with an average high of 20°C and occasional minimums below 0°C. Because Basrah is located near the Persian Gulf, humidity levels can exceed 90% (Kottek et al. 2006).

3. Datasets and methods

3.1 Datasets

Some of the datasets listed below have been used in other climate studies (e.g. Najmadin et al., 2017; Agha and Sarlak, 2016), however, this is the first study to use these datasets together in Iraq. We used a number of datasets in order to ensure the robustness of both the data and the analyses. Additionally, we examined different aspects of the data, namely interannual and intra-annual/seasonal variability, in order to gain a more sophisticated understanding of the relationship between NDVI, precipitation and air temperatures in the different climatic regions in Iraq.

3.1.1 Satellite Observation Data / Normalized Difference Vegetation Index (NDVI) Dataset

The monthly mean NDVI dataset from the Moderate Resolution Imaging Spectroradiometer (MODIS) was downloaded from NASA's Land Processes Distributed Active Archive Center (LP DAAC) (https://lpdaac.usgs.gov/data-access). MODIS is part of the NASA Earth Observing System (EOS) with 250m spatial resolution. MODIS-data covers the period February 2000 (composite 045) until 2016. Each original MODIS (.hdf) file from the Distributed Active Archive Center (DAAC) contains the best NDVI value of a certain period, and so is called a composite.

Composite periods vary, depending on the product there are16-day composites, 8-day composites, and monthly composites. In this study, the MODIS Terra MOD13Q1 product from 2001 to 2015 was used because these years had complete datasets. This dataset contains 16-day composites of the Red, Near-Infrared (NIR), Mid-Infrared (MIR), and NDVI. The data was downloaded from the USGS's MRTWeb interface. The 15-year timespan for vegetation indices was chosen primarily because of the dynamic nature of Iraq's vegetation, which changes annually due to natural and human factors.

NDVI is calculated based on differences between wavelengths from reflected surfaces. The most important wavelengths to identify vegetation are the visible band (VIS) and near-infrared (NIR), for which the reflectance from vegetation is distinctly different (strong for NIR and weak for VIS) (Bannari et al. 1995). This difference is exploited by the NDVI index, generally calculated as follows (Mennis, 2001):

$$\mathrm{NDVI} = \frac{\text{NIR reflectance} - \text{VIS reflectance}}{\text{NIR reflectance} + \text{VIS reflectance}} \tag{1}$$

Because NDVI data is the key vegetation indicator, its data availability period is used to define the study period (2001–2015), however temperature data is only available until 2013. Therefore, the study period for precipitation is 15 years (corresponding to the NDVI period) but the study period for temperature is from 2001–2013 (13 years).

3.1.2 Meteorological Forcing Data

Various meteorological datasets have been used in this study, covering the period of 2001–2015. The main dataset used is the Water and Global Change (WATCH) Forcing Data ERA-Interim (WFDEI) (including precipitation, bias corrected with Global Precipitation Climatology Centre's GPCCv5 and GPCCv6 and air temperature (2m instantaneous air temperature)). This dataset was chosen because there is a high correlation between this dataset and in-situ observations in Iraq as shown in Section 3.2.1.

The data cover the period 1979–2012 (Weedon et al. 2014) and thus it needs to be extended by the Climatic Research Unit (CRU) data (Harris et al. 2014, see Section 3.1.3). The spatial coverage of WFDEI is 0.5° x 0.5° global land (including Antarctica) and is available online through ftp://rfdata:forceDATA@ftp.iiasa.ac.at. Other precipitation and air temperature datasets for the period of 2001–2012 covering the study areas were collected from the Centre for Ecology and Hydrology (CEH), which provides records of eight meteorological variables at 3-hourly time steps, and as daily averages (precipitation (Rainf), air temperature (Tair), instantaneous surface pressure (PSurf), 2m instantaneous specific humidity (Qair), long-wave downwards surface radiation flux (LWdown), short-wave downwards surface radiation flux (SWdown), snowfall rate (Snowf), and 10m instantaneous wind speed (Wind)).

3.1.3 Tropical Rainfall Measuring Mission (TRMM), Climatic Research Unit (CRU), and Global Precipitation Climatology Centre (GPCC) datasets

A number of other climate datasets were also used in this study for validation purposes (see Section 3.2.1), including the data from TRMM, CRU and GPCC. TRMM is a dataset used to study precipitation for a range of climate/meteorological purposes as discussed in Huffman et al. (2007). The 3B43 dataset is the monthly version of the dataset (available online http://mirador.gsfc.nasa.gov/), and covers the latitude band between 50° N to 50° S, using 'best estimates' from global sources, including infrared data and rain gauge analyses (more information is available on NASA's GES DISC website: https://disc.gsfc.nasa.gov). The TRMM dataset was used at a spatial resolution of 0.25° and with a monthly temporal resolution, to validate the other datasets over the period 1998–2015 (Huffman et al. 2010).

Climatic Research Unit (CRU) datasets for precipitation and air temperature (available online https://crudata.uea.ac.uk/cru/data/hrg) have a spatial resolution of 0.5° and a monthly temporal resolution over the periods 1901–2015 for precipitation and 1901-2013 for air temperature (Harris et al., 2014). The TRMM data was standardised at 0.5 degrees as described in Section 3.2.1.

Global Precipitation Climatology Centre (GPCC, part of the National Meteorological Service of Germany, DWD) datasets consist of the analyses of global monthly precipitation data, based on rain gauge data collected from about 67,200 stations, with available resolutions of 2.5°, 10°, 0.5° and 0.25° (Schneider et al. 2014). Gridded datasets of GPCC are available online at: http://gpcc.dwd.de/. The 0.5° Full Data Reanalysis product used here is available for the period 1950–2001.

In addition, some observational precipitation data over the short period 1997-2008 were used, obtained from the meteorological centre in Baghdad, Iraq (The Ministry of Planning / Central Statistical Organization / Directorate of Environmental Statistics for 2008 in Iraq (CSO, 2008)). These data were used alongside WFDEI, TRMM, CRU and GPCC datasets. All the datasets used are described in Table1:

Table 1: A summary of the climate datasets used in the study

No.	Dataset	Spatial Resolution	Temporal Resolution	Variables availability		Period
				Precipitation	Temperature	
1	Meteorological Forcing Data: Water and Global Change (WATCH) Forcing Data ERA-Interim (WFDEI)	0.5°	Daily	☑	☑	1979–2012
2	Tropical Rainfall Measuring Mission (TRMM)	0.25°	Monthly	☑	☐	1998–2015
3	Climatic Research Unit (CRU)	0.5°	Monthly	☑	☑	1901–2015 (Precip.) 1901–2013 (Temp.)
4	Global Precipitation Climatology Centre (GPCC)	0.5°	Monthly	☑	☑	1950–2001
5	Observations	-	Yearly	☑	☐	1997–2008

Note: 'Period' indicates the time period for which the data is available. The data analysis periods are different as explained in Sections 3.1 and 3.2.

3.2 Methods

3.2.1 Extraction of the WFDEI and NDVI Data

The WFDEI and NDVI data were extracted for Sulaymaniyah, Wasit and Basrah. Grid data were extracted because individual rain gauge data has issues related to missing data and variable density of distribution of stations. Statistical analysis was performed for four types of precipitation datasets (WFDEI, CRU, GPCC and TRMM) and three types of air temperature datasets (WFDEI, CRU and GPCC) in order to test the validity of the WFDEI data.

The four rainfall datasets for the study areas, GPCC, CRU and WFDEI at a resolution of 0.5° and TRMM at a resolution of 0.25° (resampled to the resolution of 0.5°) were compared with the observed datasets from the meteorological centre in Baghdad (Iraq) for the period 1997–2008 (CSO, 2008). Additionally, we calculated the monthly and yearly values to match the temporal resolution. These data were processed and analysed using customised Matlab scripts and a trend analysis was implemented to track climate changes during this period.

We also conducted an initial comparative study in order to identify the relationship between the four types of datasets (GPCC, CRU, TRMM, and WFDEI) and the observations, to further test the validity of using the WFDEI dataset for Iraq. Using observations as a reference, we computed the correlation coefficient (r) over the study areas for the common period between datasets (1998–2001). This analysis indicated that the WFDEI dataset had the highest correlation coefficient with the observed data over all regions for the same period (as shown in Table 2).

Table 2: Correlation coefficient (r) of the observations for the yearly time series (1998–2001) of four gridded datasets against observations

Gridded datasets against observations	Correlation coefficient (r)		
	Sulaymaniyah	**Wasit**	**Basrah**
GPCC	0.9728	0.4288	0.9818
CRU	0.9678	0.7556	0.8483
TRMM	0.9834	0.7555	0.9380
WFDEI	0.9903	0.8463	0.9964

3.2 Calculations for the precipitation and air temperature indicators

Eleven precipitation and air temperature indicators were calculated. We selected these indicators based on studies by Gessner et al. (2013) and Zoungrana et al. (2014) for precipitation and Marszeleweski and Skowron (2006) for air temperature.

Precipitation and air temperature indicators were computed on Excel. First, monthly rainfall data were listed in an Excel column. Then computations were listed in the next column and consisted of the calculated figures. With the figures of Time lag0, Time Lag1, Time Lag2, Time Lag3, Time Lag4, and Time Lag5, these calculated figures are the sum of the adjacent cell and the cell above; and the figures for Time Lag-1, Time Lag-2, Time Lag-3, Time Lag-4, and Time Lag-5, are the sum of the adjacent cell and the cell below (Table 3).

We selected these indicators because of their good correlations with vegetation temporal dynamics. The periods 2001–2015 and 2001–2013 were used to compute the monthly cumulated precipitation and air temperature, respectively.

Table 3: Indicators characterising precipitation and air temperature variability in the study areas

No.	Indicators	Description
1	Tim Lag (0): Amount 1 month	Precipitation / air temperature of concurrent
2	Tim Lag (1): Cumulated 2 months	Sum of precipitation / air temperature of current and previous 1 month
3	Tim Lag (2): Cumulated 3 months	Sum of precipitation / air temperature of current and previous 2 months
4	Tim Lag (3): Cumulated 4 months	Sum of precipitation / air temperature of current and previous 3 months
5	Tim Lag (4): Cumulated 5 months	Sum of precipitation / air temperature of current and previous 4 months
6	Tim Lag (5): Cumulated 6 months	Sum of precipitation / air temperature of current and previous 5 months
7	Tim Lag (-1): Cumulated 2 months	Sum of precipitation / air temperature of current and earlier 1 month
8	Tim Lag (-2): Cumulated 3 months	Sum of precipitation / air temperature of current and earlier 2 months
9	Tim Lag (-3): Cumulated 4 months	Sum of precipitation / air temperature of current and earlier 3 months
10	Tim Lag (-4): Cumulated 5 months	Sum of precipitation / air temperature of current and earlier 4 months
11	Tim Lag (-5): Cumulated 6 months	Sum of precipitation / air temperature of current and earlier 5 months

3.3 Formatting WFDEI and NDVI Data

After extraction, the NDVI, precipitation, and air temperature (WFDEI) scales were standardised, in order to compare them on a common scale (0.5°). The following equation was used to standardise the data (Rousvel et al. 2013):

$$Std(x) = \frac{x_{i-}\overline{x}}{\sigma_x} \quad (2)$$

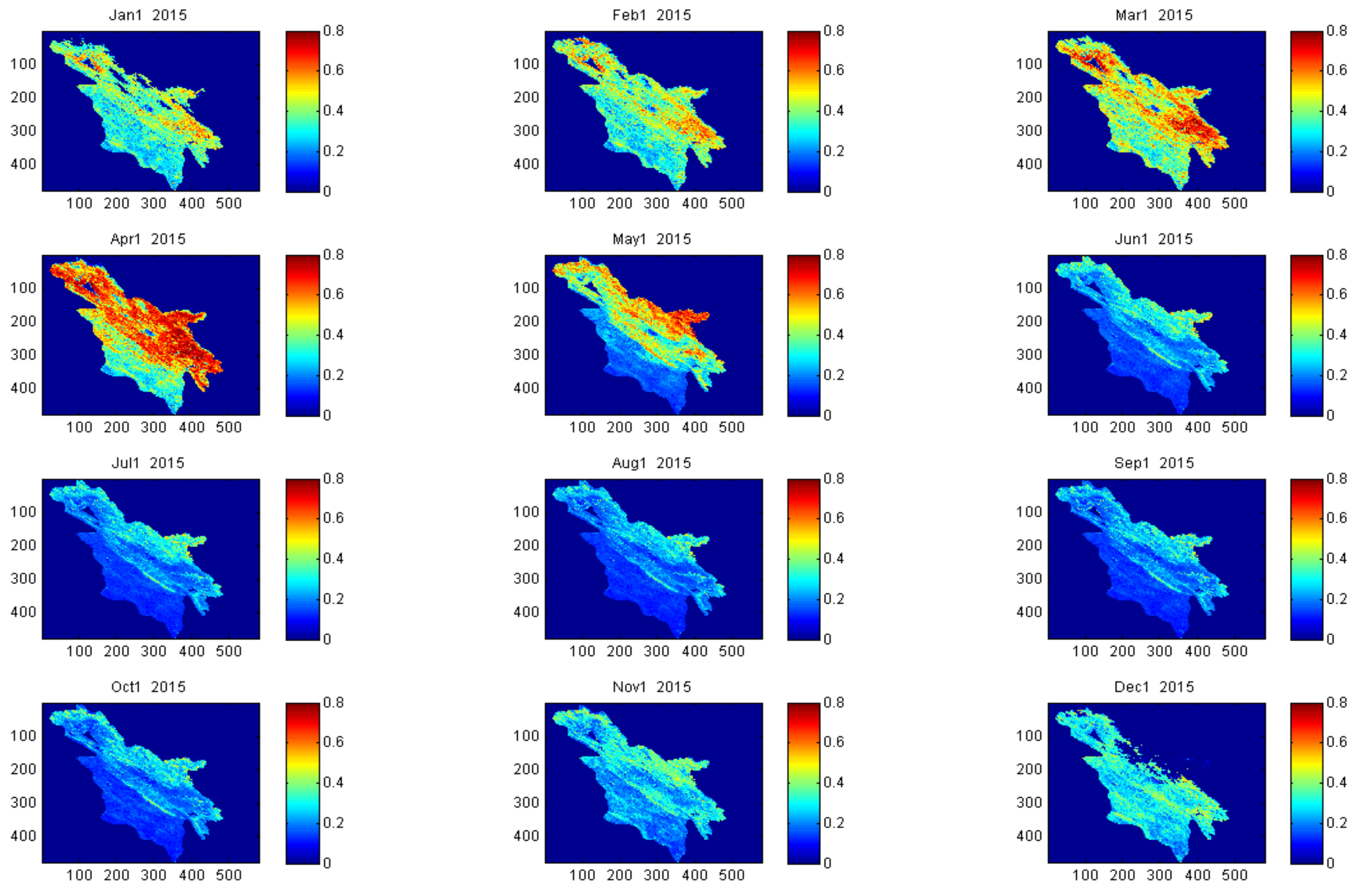
where x represents the NDVI, precipitation or temperature under investigation, $\overline{x}$ represents the mean and σ_x the standard deviation of the NDVI, precipitation or temperature over the observation period. To standardise the grids for the NDVI and WFDEI data, we used ordinary kriging and inverse distance weighting (IDW) interpolation methods provided by the Arc Map software toolbox (Childs, 2004). For inter-annual variability, the standardised values across the entire study period were analysed against each other. For intra-annual and seasonal variability, the average standardised values for each month were analysed against each other. Climatic seasons were then identified and analysed individually. The correlation between the absolute values was calculated and plotted across a range of monthly time-lags, ranging from -5 to +5.

4. Results

4.1 Spatial NDVI Patterns and quality assessment

The monthly NDVI data covers 15 years from 2001 to 2015 and is represented in Figure 2 with the year 2015 (there is not enough space to show all the years). Because MODIS is an optical/IR satellite, it cannot retrieve information when conditions are cloudy. Thus, the dataset contains some missing values that need spatial and temporal interpolation. We used the Time-Series Generator (TiSeG) software developed by Colditz et al. (2008), firstly to assess the quality of the MODIS product and secondly to correct invalid data and fill gaps by linear interpolation. We used the setting of UI5-CS (Perfect-Intermediate, no Cloud, and no Shadow), as it gave the best results. We found that the data were of good quality and suitable for our analysis.

(a)


Jan1 2015
Feb1 2015
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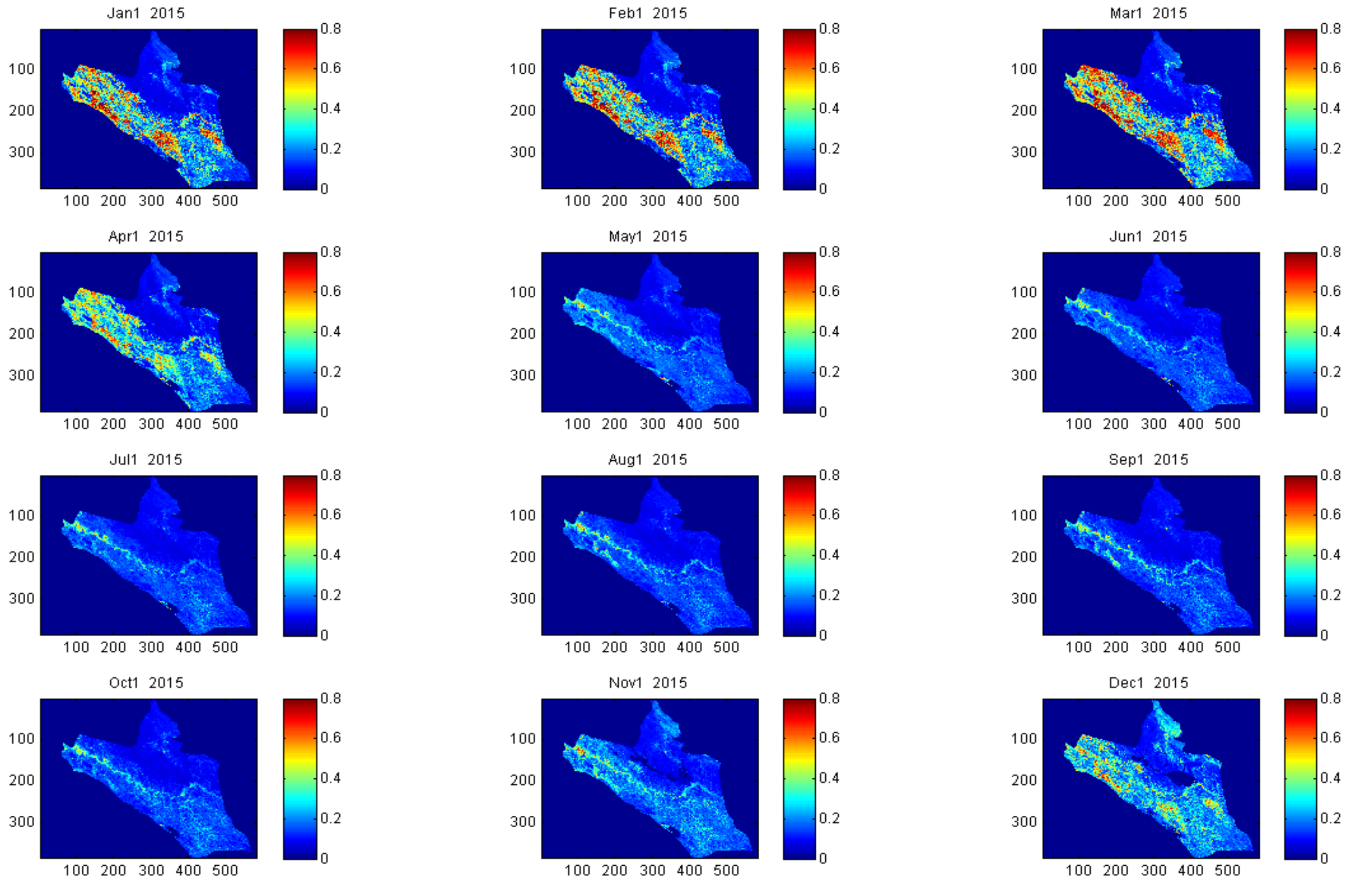
(b)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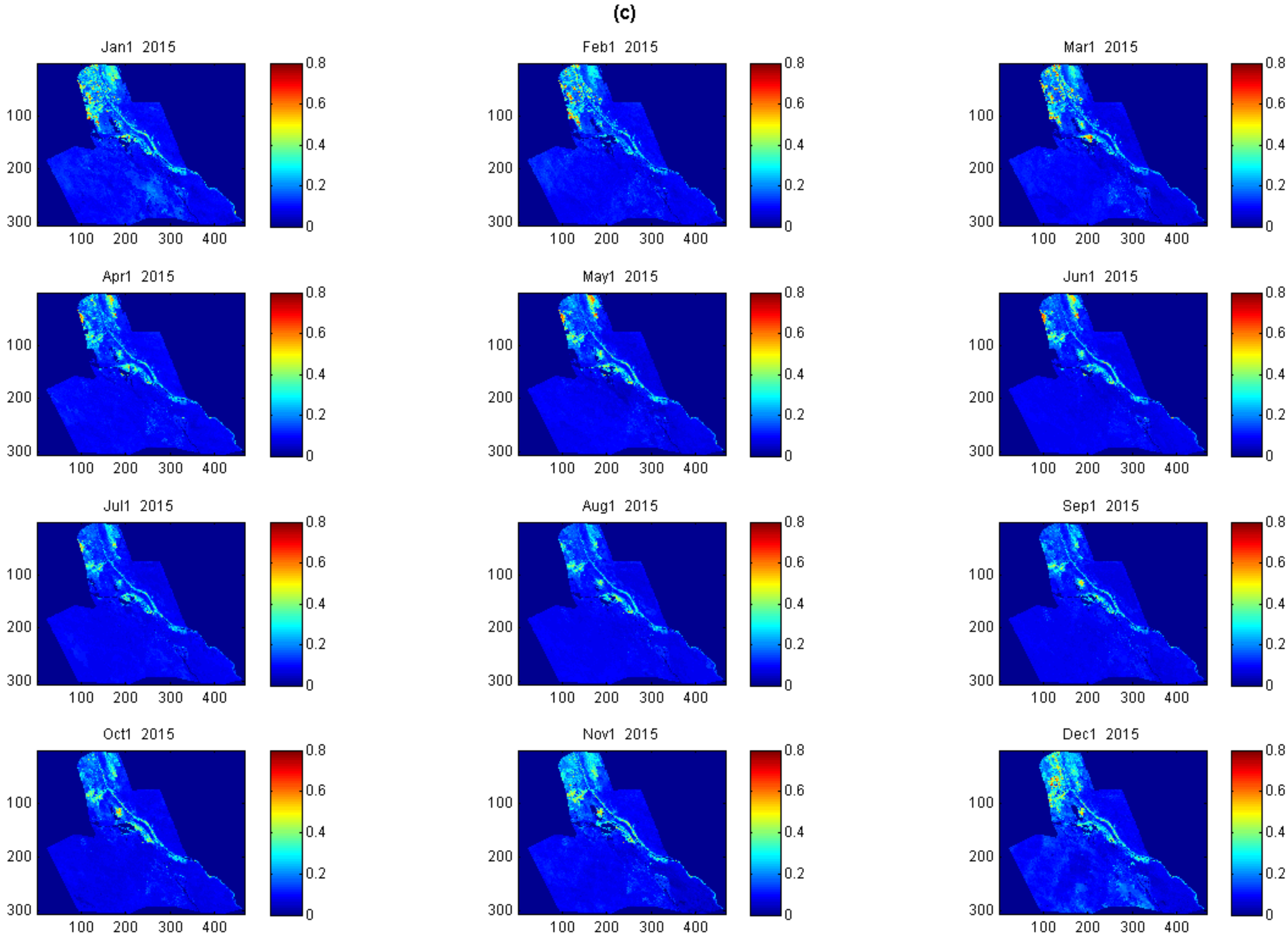

Figure 2: NDVI for 2015 with 250 m spatial resolution for the three regions, (a) Sulaymaniyah in the north, (b) Wasit in central Iraq, and (c) Basrah in the south.

One anomaly stands out: vegetation density in northeast Sulaymaniyah is higher compared to southern Sulaymaniyah. This is because of longer sun exposure in the south. As mentioned previously, Sulaymaniyah is located between the Zagros Mountains in the northeast and its foothills to the southwest. The southern foothills are more exposed to the sun, resulting in an increase of soil temperature and therefore in soil evaporation, which leads in turn to a decrease in available moisture for vegetation growth. Rainfall in Iraq generally occurs in March, April and May, so there is limited winter vegetation growth from November to February. This results in peak NDVI values in April and May.

4.2 Precipitation

4.2.1 Analysis of interannual variability

We studied the interannual variability of NDVI and precipitation for each region during the period 2001–2015 in order to examine their relationship. The result is illustrated in Figure 3, showing the temporal plots for the three regions.

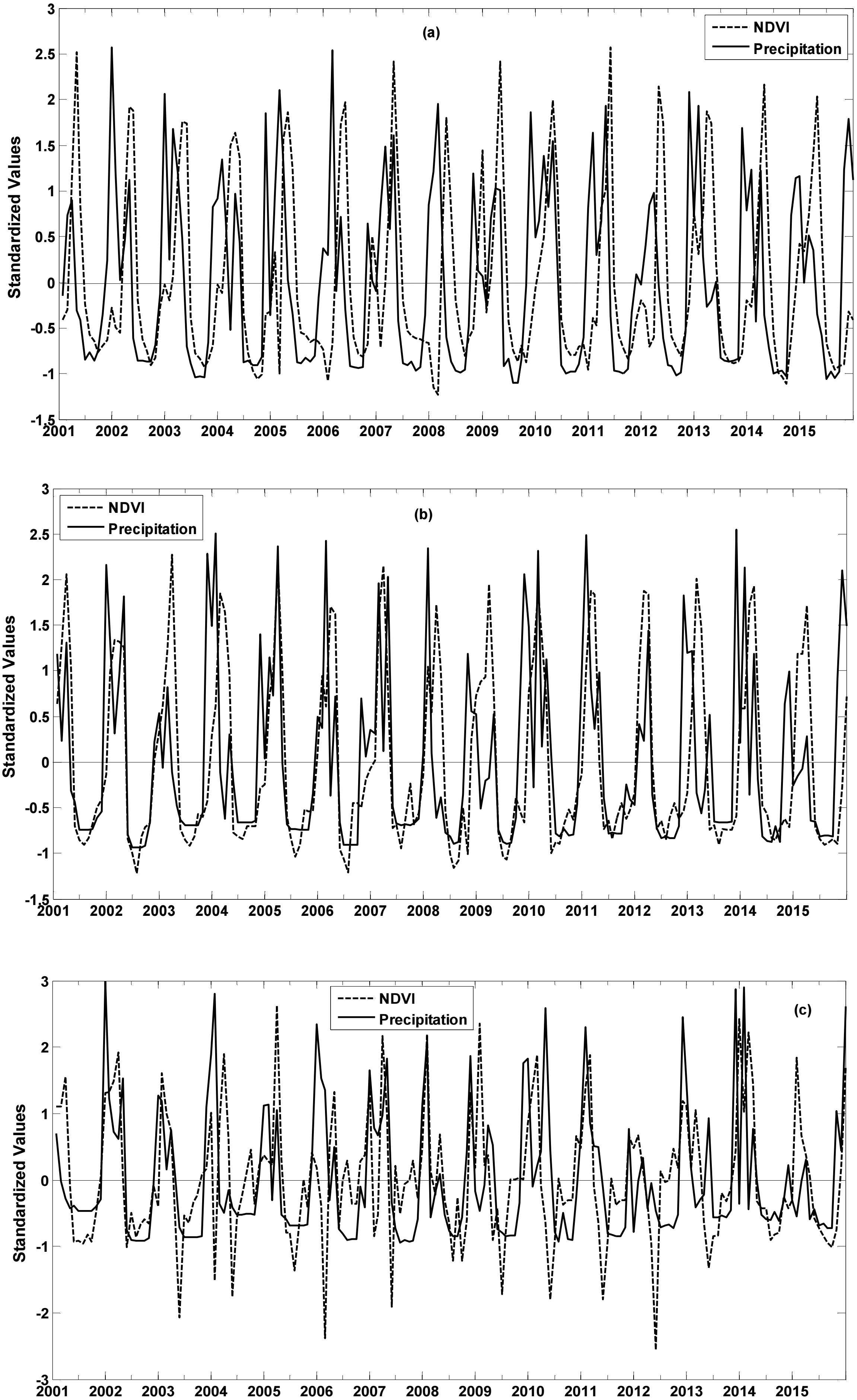

Figure 3: Interannual variability of monthly averages of the NDVI (dashed line) and precipitation (solid line) for the period 2001–2015 for each region. (a) Sulaymaniyah, (b) Wasit, and (c) Basrah.

Sulaymaniyah and Wasit have bimodal annual cycles for both NDVI and precipitation. The NDVI and precipitation in Figure 3 are correlated with coefficients of 0.8635 and 0.6274 for Sulaymaniyah and Wasit (at Time lag 4), respectively, and 0.4190 for Basrah (at Time lag 3).

The variance in correlation is mainly related to precipitation: there is a very strong linear relationship between NDVI and rainfall in Sulaymaniyah and slightly less in Wasit, in particular with a four-month time lag. This indicates that the vegetation does not respond directly to precipitation, but rather to increased soil moisture resulting from cumulative precipitation events. However, different types of vegetation have different growth rates. For instance, there are variations between deciduous and evergreen vegetation, which can affect correlations. In this study, since we relied on the density of vegetation in general, rather than classifications of vegetation types, the contrast in correlation here is mainly related to vegetation responding to increased soil moisture. It should also be noted different types of soils have differing moisture holding capacities, and that combined with evaporation rates will also impact soil moisture (see Discussion, Section 5).

In addition, these regions are generally characterised by high NDVI values and a moderate vegetation cover, and this trend increases with distance to the north. The correlation magnitude of NDVI and precipitation is higher in Northern Iraq (Sulaymaniyah) than central Iraq (Wasit). The response time (between adjacent maxima) of the NDVI to precipitation varies from one to three months in both regions.

Basrah, on the other hand, is characterised by a dry sub-humid climate. A unimodal annual pattern for both NDVI and precipitation can be observed for most of the study period. Although there is a correlation between NDVI and precipitation in Basrah, in particular with a three-month time lag, the correlation is low compared to the other regions because of low rainfall. We also observed that in 2004, 2006 and 2009, the two parameters sometimes reversed, giving negative correlations: the NDVI decreased, precipitation increased, and they peaked at the same time. This might be due to a decrease in land surface temperature in autumn, with commensurate plant die-off. Additionally, there is high interannual climate variability within Iraq, as well as spatial variability, which can lead to changes within the thermal state.

The response time between NDVI and precipitation is around four to six months. Notably, throughout the study period, both datasets exhibited high variance.

4.2.2 Analysis of intra-annual seasonal variability

We investigated intra-annual and seasonal variability to better understand the relationship between NDVI and precipitation. Figure 4 displays the intra-annual variability of the yearly averages of NDVI and precipitation for the 15-year period (2001–2015) in Sulaymaniyah, Wasit and Basrah. For NDVI and precipitation, the figure shows a bimodal seasonal cycle in Sulaymaniyah and Wasit and a semi-unimodal seasonal cycle in Basrah.

In Figures 4a and 4b, two mean peaks occur in both Sulaymaniyah and Wasit. The two peaks in Sulaymaniyah are in FMAMJ (February, March, April, May, June) and in SOND (September, October, November, December). The peaks in Wasit are in JFMA (January, February, March, April) and in SOND. The first part of the curve in Figures 4a and 4b picks up the dominant agriculture signal in these regions: the main agricultural growth ('greeness') starts in December/January and ends in June/July in Iraq. However, there is a second growing season between September and December: in some parts of central Iraq, we observed a growing season from September to March/April (i.e., an earlier start and end to the agricultural season). Furthermore, the two rainy seasons are characterised by a high precipitation variability followed by increased vegetation growth, especially in Sulaymaniyah. As such, because there is such intra-annual variability between the regions, analysing the NDVI and precipitation year-to-year changes of the February to June and September to December periods in Sulaymaniyah, and January to May and September to December periods in Wasit is useful.

In Sulaymaniyah and Wasit, the distribution of NDVI and precipitation is relatively constant from June until September. The highest NDVI values occur in April and March respectively, with a four-month lag time due to vegetation responding to soil moisture rather than directly to individual precipitation events, as discussed above. It is important to note that from September until December precipitation increases in both of these regions. NDVI responds to this increased precipitation during the FMAMJ growing season in Sulaymaniyah and the JFMA growing season in Wasit.

In Basrah (Figure 4), the distribution of NDVI and precipitation is almost constant from October through April. Two growing seasons can be observed: the first one between February and April and the second one between September and December. Precipitation also increases from September until December in this region. NDVI responds to this increased precipitation during the JFMA growing season. Then we note fluctuations in rainfall between January and April, which impacts the NDVI, with falls then peaks in March.

In Figure 4a, the NDVI peaks in April, with precipitation in February, while in Figures 4b and 4c these are shifted forward by one month; NDVI peaks in March with precipitation in January. On closer inspection, NDVI is generally a lagging indicator of precipitation. This lag in peaks throughout the year suggests that the inter-annual causal relationship asserted in the previous section is also valid at an intra-annual timescale. As such, the specific season's variability will be analysed over the study period.

Figure 5 shows the seasonal variability of monthly averages of NDVI and precipitation for the 2001–2015 period for the three regions: FMAMJ (February, March, April, May, June) for Sulaymaniyah (Figure 5g), SOND (September, October, November, December) for all regions (Figures 5 a, c, and e), JFMA (January, February, March, April) for all regions (Figure 5b, d, and f), and JASO (July, August, September, October) for Basrah (Figure 5h).

Figures 5a, c and e display the close NDVI response to precipitation in all the regions during the SOND growing season. This correlation is both in trend and in magnitude. Although Figure 5g displays an even closer correlation in Sulaymaniyah during the FMAMJ season, this may be due to the increased magnitude and frequency of precipitation. In Figures 5b, d and f, this correlation reverses during the JFMA season for all the regions.

Based on these observations, we conclude that NDVI responds well to precipitation for the FMAMJ seasonal variation in Sulaymaniyah and the SOND seasonal variation in Basrah, where the trend and the magnitude are almost identical. A good response for NDVI can also be observed in Wasit through JFMA and SOND seasonal variability. However, we also observe an opposing trend between NDVI and precipitation in most years through the JFMA seasonal variability in Sulaymaniyah. This may be due to precipitation falling as snow (see Discussion, Section 5).

Basrah also has an opposing trend between NDVI and precipitation observed through the JFMA (as shown in Figure 5f) seasonal variability, for the years of 2004, 2005, 2006, 2009, 2010, 2011, 2013 and 2015. The reasons behind this are far more complex. These negative correlations signal the differences in climate patterns and human activities: negative correlations in the JFMA seasons (precipitation) for Sulaymaniyah may be due to lack of soil moisture (increased snow) and for Basrah, they may be also due to lack of soil moisture, combined with increased use of irrigation and conflict. This is discussed in more detail in the discussion (Section 5).

Additionally, we analysed the JASO (July, August, September, October) season for Basrah (Figure 5h). Although we can see the NDVI response to precipitation, the response is not strong. This is due to lack of precipitation in July and August, which results in low vegetation growth.

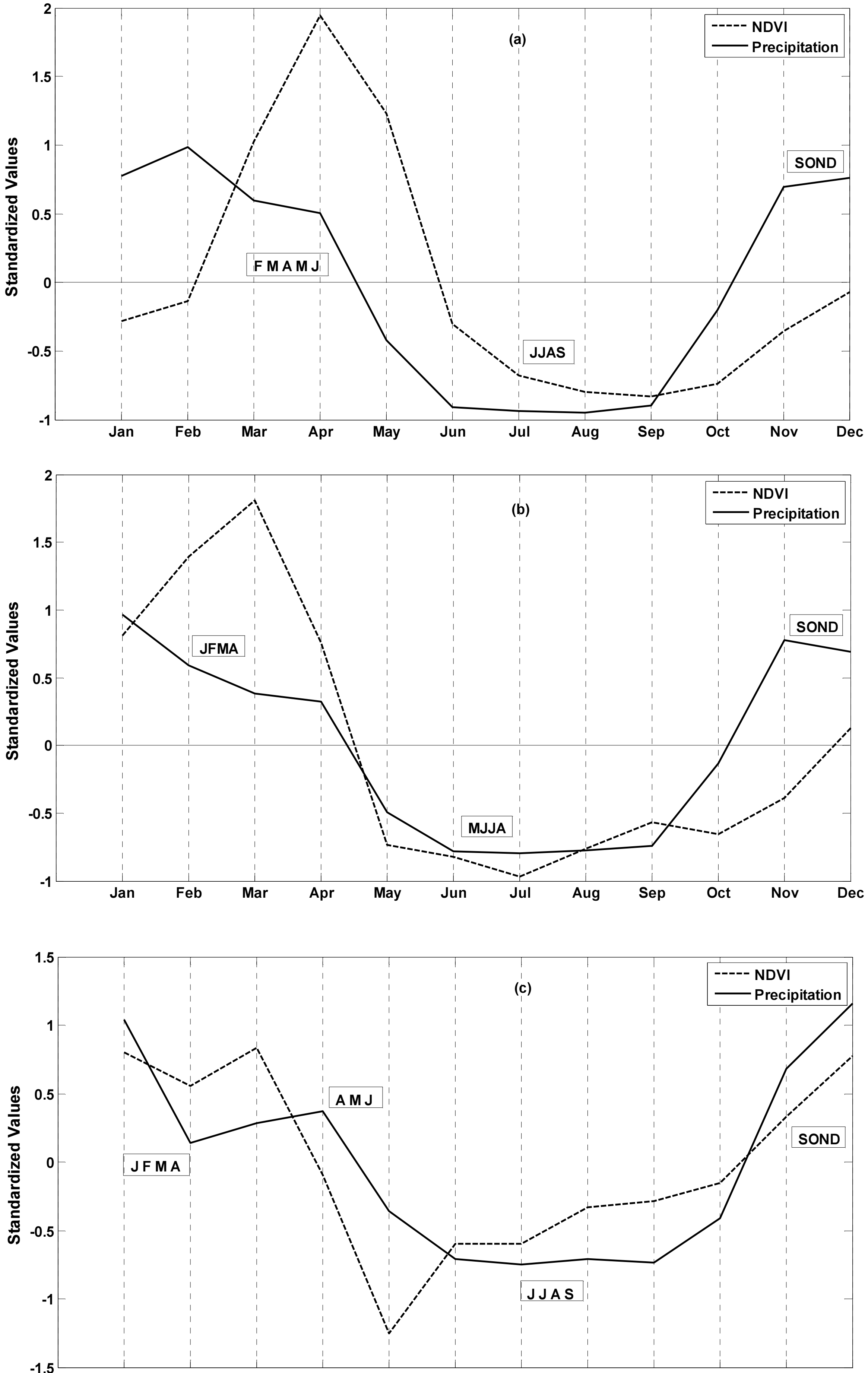

Figure 4: Intra-annual variability of yearly averages of NDVI (dashed line) and precipitation (solid line) for the period 2000–2015 for each region. (a) Sulaymaniyah, (b) Wasit, and (c) Basrah.

NDVI presents a clear response to precipitation in the FMAMJ and the SOND seasons in Sulaymaniyah and Wasit. However, this response is more pronounced in the FMAMJ season. One reason is that precipitation is higher and more regular throughout this season. Additionally, the NDVI and precipitation magnitude are slightly greater in the FMAMJ season. The maximum values are nearly constant, and the distribution is concentrated around the mean value for the SOND season.

That vegetation responds to precipitation is more evident in the seasonal variability than in the interannual variability, and the response for the FMAMJ season is much stronger than the SOND season in Sulaymaniyah. The opposite can be seen in Wasit. The results show that these regions differ noticeably in their response to precipitation variability. Overall, NDVI demonstrates a clear response to precipitation (or lack thereof).

To sum up, and for the purposes of this study, interpretation of these results helps to determine the efficiency at which rainfall is used by vegetation (the role of human activities is beyond the scope of this paper). Long and intense rainfall, as occurs in the FMAMJ season in Sulaymaniyah, is favourable to vegetation growth, while a short rainy season combined with a long dry season, as in Basrah, is unfavourable. Essentially, this highlights the role of precipitation in soil moisture availability. Sulaymaniyah illustrates the strongest results, where there is a very correlated and immediate response of NDVI to the precipitation variability. This is also somewhat true in Wasit. In Basrah, the relationship is less clear. This may have to do with additional factors (discussed further in Section 5). We also see in the JFMA season in Sulaymaniyah, that there are some negative correlations between precipitation and vegetation. This can be explained by snow falling as precipitation, so while there is increased precipitation, vegetation growth is hindered by the frozen ground (causing a lack of soil moisture).

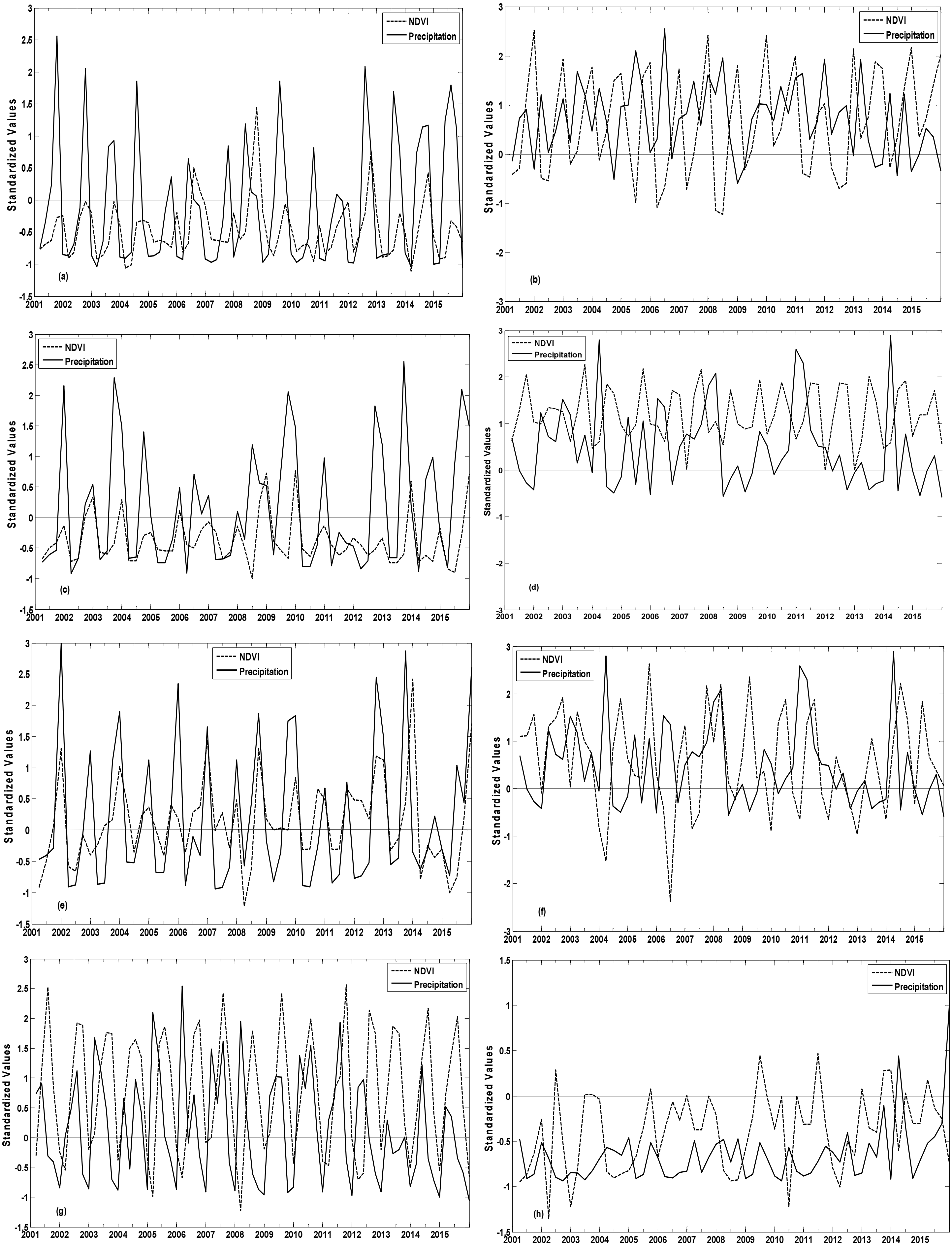

Figure 5: Seasonal variability of the monthly averages of NDVI (dashed line) and precipitation (solid line) for the period 2001–2015 across the regions. (a) SOND Sulaymaniyah, (b) JFMA Sulaymaniyah, (c) SOND Wasit, (d) JFMA Wasit, (e) SOND Basrah, (f) JFMA Basrah, (g) FMAMJ Sulaymaniyah, and (h) JASO Basrah.

4.3 Air Temperature

4.3.1 Analysis of Interannual variability

The relationship between NDVI and air temperature was investigated by studying the interannual variability for each region during the period 2001–2013. The results are illustrated in Figure 6, which shows the temporal plots for the three regions.

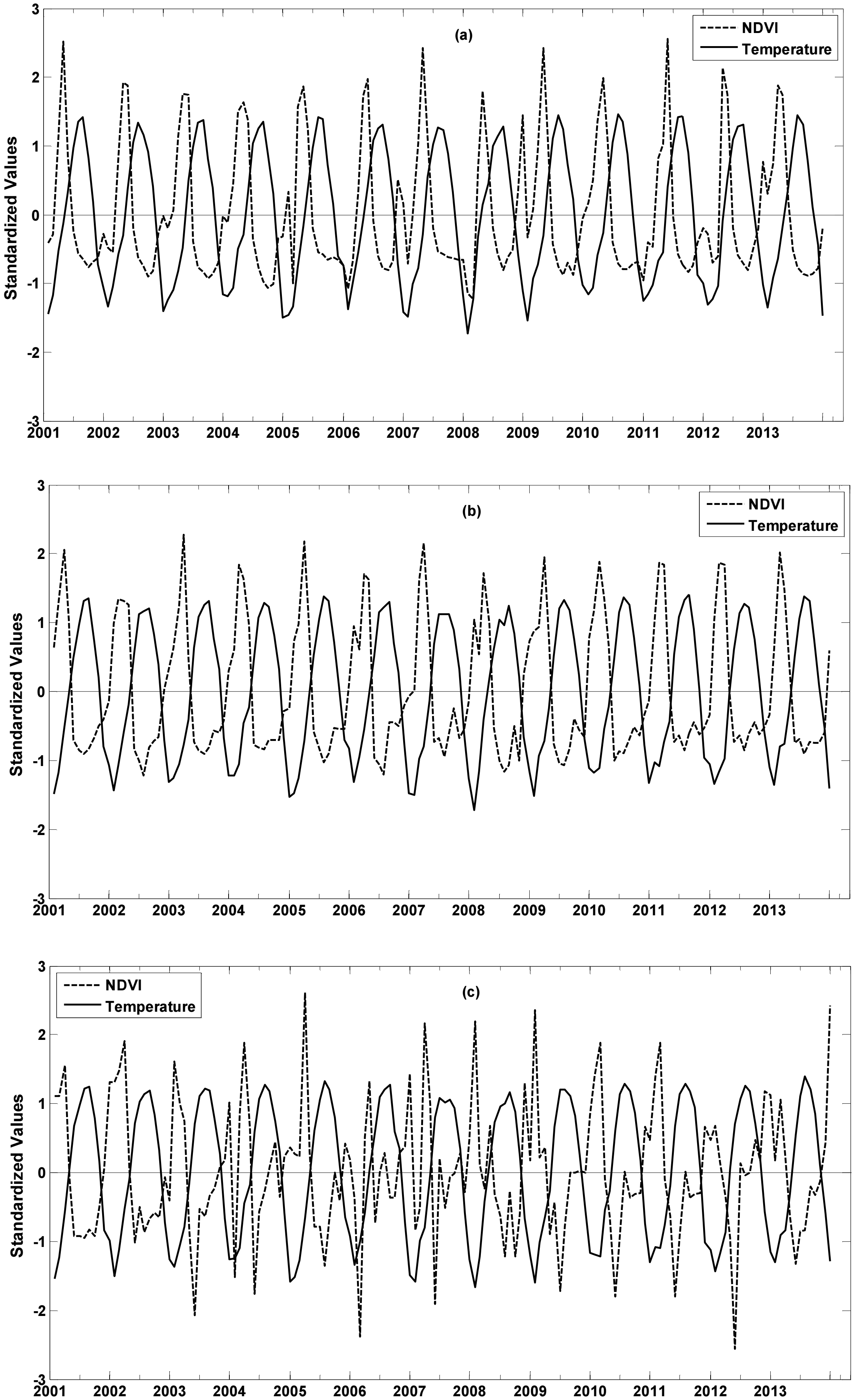

Figure 6: Interannual variability of monthly averages of Normalized Difference Vegetation Index (NDVI) (dashed line) and air temperature (solid line) for the period 2001–2013 over each region. (a) Sulaymaniyah, (b) Wasit, and (c) Basrah.

Sulaymaniyah is characterised by relatively cooler summers and wetter winters. During winter, there can also be a significant amount of snow. Figure 6a displays a unimodal annual cycle between NDVI and air temperature. The variables demonstrate opposite trends with a 3–4 month time lag. Additionally, there is a difference between the minimum and maximum of the two variables, which is seen in all regions (although this is most distinct in Basrah). Standardised NDVI peaks at about 2.5 with a minimum below −1.1, while maximum temperature peaks at 1.3 with a minimum around −1.3. This suggests that NDVI is more variable than air temperature, particularly at positive standardised values.

Figure 6b presents Wasit, characterised by a subtropical climate, with a bimodal pattern for both air temperature and NDVI. The two parameters in Wasit have a strong negative correlation. The time lag between the sequential maxima of NDVI and air temperature is five to six months. NDVI reaches its peak at 2.3, with a minimum below -1.6, while temperature peaks at 1.4 and a minimum around -1.8. The NDVI and air temperature distribution for Basrah is characteristic of a hot desert climate, but the climate resembles that of Wasit. This is particularly evident in the air temperature pattern of Figure 6c. This region has bimodal annual cycles for both NDVI and air temperature, again with a negative correlation between the two variables.

There are some plausible explanations for the similarities between the NDVI pattern and air temperature in Wasit and Basrah over the whole period.

Firstly, growth conditions, such as temperature and humidity, are similar in both Wasit and Basrah. Secondly, there is a similarity in soil type and moisture content, which can be attributed to the alluviation patterns and microclimates of the Tigris and Euphrates rivers. Entisols are the dominant soil type in the middle and south of Iraq (Brady & Weil, 2000). Entisols are young, underdeveloped soils that are common in high erosion and deposition areas (see Section 5), such as the Iraqi alluvial plain. Additionally, the increasing salinisation of soils (due to both anthropogenic and natural factors) also hinders any development of deep soils, which are characterised by well-developed horizons. The problems are compounded by erosion. Relatively well-developed soils (such as Mollisols and Vertisols) are limited to areas in the eastern part of northern Iraq (i.e., Sulaymaniyah), where there is more precipitation and increasing variation in vegetation.

Thirdly, the characteristic NDVI signatures for both Wasit and Basrah are similar. Dense vegetation canopies typically have NDVI values between 0.3 and 0.6, while clouds, snow, oceans and other surface waters are 0 or less, and areas denuded of vegetation tend to be around 0.1 or less (Brady & Weil, 2000).

NDVI and air temperature are negatively correlated in Wasit and Basrah (except for a few unusual years in Basrah, perhaps because it is such an extreme environment). Meanwhile, the correlation between these variables in Sulaymaniyah is shifted by a time lag. This difference may be due to the difference in crops that are cultivated: mainly winter crops are grown in Sulaymaniyah, a mixture of winter and summer crops are grown in Wasit and summer, drought-resistant crops are grown in Basrah.

4.3.2 Analysis of Intra-Annual and seasonal variability

Intra-annual and seasonal variability was studied in order to examine the relationship between air temperature and the NDVI. The intra-annual variability of the yearly averages of the NDVI and air temperatures for the period of 2001–2013 for the three regions is given in Figure 7. As was found from the inter-annual variability, the NDVI and air temperature intra-annual variability presents a bimodal seasonal cycle in all regions. The NDVI and air temperature is almost constant from June to August in Sulaymaniyah and from May to September in Wasit and Basrah (temperatures start to rise earlier in the south). In Wasit, the temperatures are slightly lower than in Basrah.

Figure 7a (Sulaymaniyah) shows a small increase in vegetation in January, with a higher increase following in February and March. This is a period of significant growth due to low but increasing air temperature progressing towards the summer months. In addition to increasing NDVI in agricultural areas, this growth also reflects areas of other vegetation (i.e., open oak woodland that covers about 80 percent of Sulaymaniyah and its surrounding region). A sharp decline in NDVI starts from April and the decline is greatest during the summer due to increasing air temperatures. Arable land is bare because winter crops, such as wheat and barley, have been harvested. The NDVI increases again in October, due to decreasing air temperature and increasing precipitation. This occurs across much Iraq as is shown in Figures 7b and 7c.

Wasit is characterised by average temperatures ranging from 38° C (August high, but temperatures can be higher) to 12° C (January low), with the rainy season between December and February (average rainfall is less than 200mm/year). Agriculture depends on run-off irrigation, especially in winter. Figure 7b shows that NDVI increases in spring, peaking in March, after which there is a rapid decline. This corresponds to air temperature that significantly increases in April and continues through July and August. Temperature peaks in summer correlates with low NDVI. The dominant agricultural crops in this region are winter crops, wheat and barley. Some fields are left in fallow during the summer to enable the soil to regain nutrients.

Figure 7c represents Basrah, which is characterised by high temperatures in summer, which can exceed 50° C, and very low precipitation (less than 100mm per year). There is a long hot season, and the agriculture relies on mechanical irrigation using water from rivers and wells. NDVI remains relatively high from November through until March, corresponding with lower air temperatures. A sharp and significant decline in NDVI begins after March, with a minimum in May. This decline then reverses slowly because of the presence of summer crops, but there is also an increase in air temperature (from May until August, where the air temperatures reach the maximum values during June, July, and August). After the temperatures begin to drop between August and December, the NDVI increases more rapidly due to the growth of grasses and evergreen date palms across the region. The air temperature has a strong negative impact on the vegetation in this region, as with Basrah.

While previous studies classify NDVI into different vegetation classes (Rousvel et al. 2013), this is not necessary for Iraq due to the general uniformity of vegetation types within the given regions. Vegetation cover in Sulaymaniyah is dominated by open woodland, Wasit is dominated by wheat and barley, and date palms dominate in Basrah.

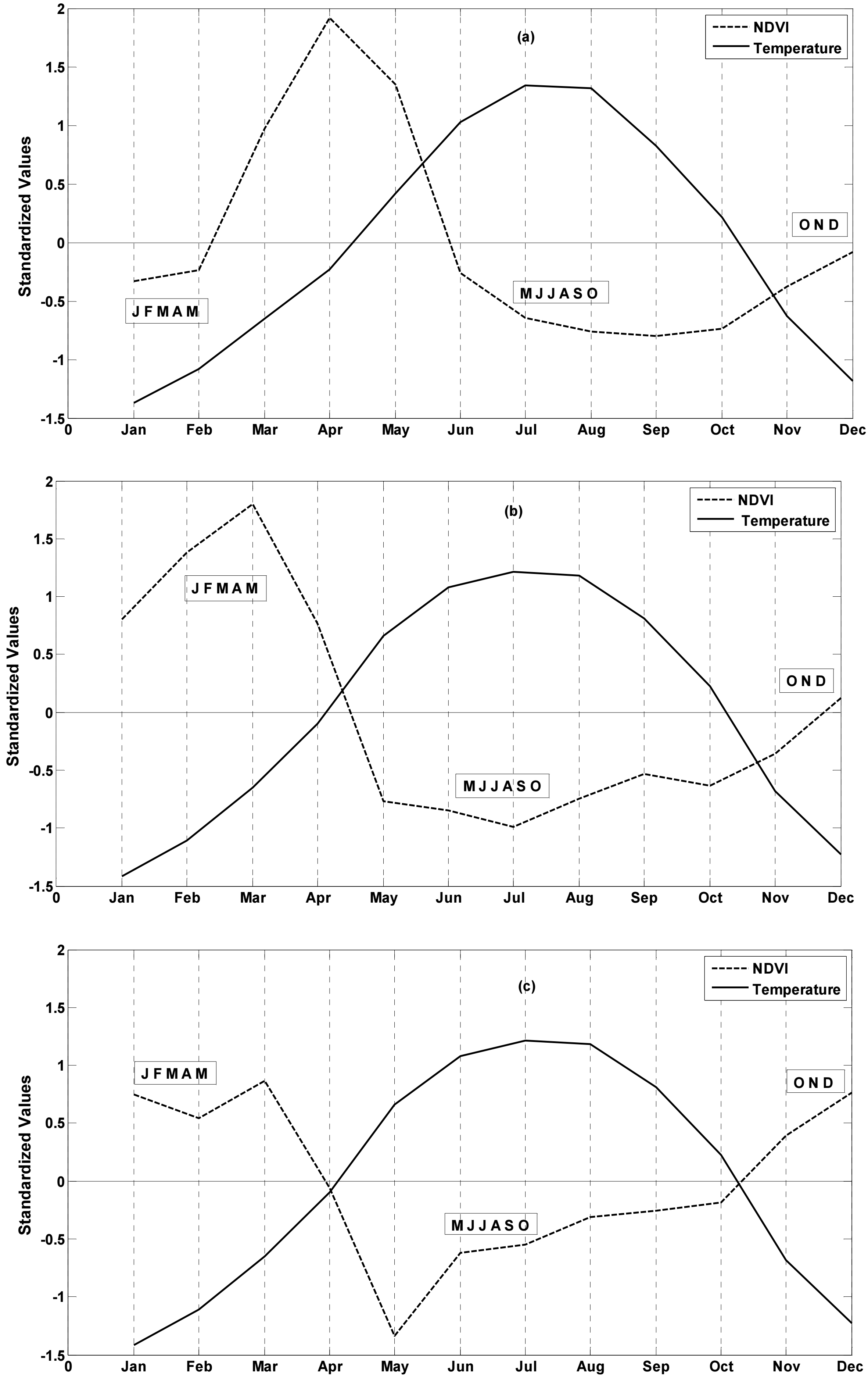

Figure 7: Intra-annual variability of yearly averages of Normalized Difference Vegetation Index (NDVI) (dashed line) and air temperature (solid line) for the period 2001–2013 over each region. (a) Sulaymaniyah, (b) Wasit, and (c) Basrah.

The Interannual variability in Sulaymnaiyah (Figure 6a) suggests a lagged negative correlation between NDVI and air temperature. However, the intra-annual variability of the JFMAM season (Figure 8a) shows that there is a strong positive correlation. Meanwhile, in Wasit and Basrah, the intra-annual variability of JFMAM season (Figures 8c and 8e) is negatively correlated. In addition, there are specific years, for example 2005, 2007, and 2009 as shown in Figure 6a (Sulaymaniyah) and 2004, 2006, and 2008 as shown in Figure 6c (Basrah), that show positive correlations between NDVI and air temperature. This may be due to the types of vegetation growing in those years, which were more suitable for the temperatures.

The interannual variability of Wasit and Basrah (Figures 6b and 6c) is fairly consistent, although there are exceptions. The inconsistencies in the correlation between NDVI and air temperature may be due to the high temperatures that characterise this region, as mentioned previously. This leads to a decrease in the relative humidity and therefore high vapour pressure deficit, which depends mainly on the temperatures and relative humidity: if the temperature decreases, then the amount of water vapor which the air can hold decreases, thus saturation vapor pressure decreases. This, in turn, leads to an increase in relative humidity, which, in turn, affects vegetation growth.

In contrast to the JFMAM season, the intra-annual variability between NDVI and air temperature in Sulaymaniyah (Figure 8b) shows a negative correlation in the OND season and unlike the interannual variability, there is no lag in this correlation. Again, the correlation in Wasit and Basrah in the OND season is negative, consistent with the JFMAM season and intra-annual variability. It is worth mentioning that the difference in the correlation for seasonal variability in the north, and middle and south of Iraq for the same season, such as the JFMAM season, can be attributed to the different soil types in these areas. In Wasit and Basrah, the soils are very poorly developed due to high temperatures, lack of moisture and erosion. Salinisation, which results from irrigation and high temperatures (irrigation deposits more salts into the soils, and the high heat evaporates the moisture, leaving a higher concentration of salts), is also a major issue in these areas, inhibiting plant growth. In the north of Iraq, despite the high air temperatures, the main soil types, Mollisols and Vertisols, are more deeply developed and are able to retain moisture better.

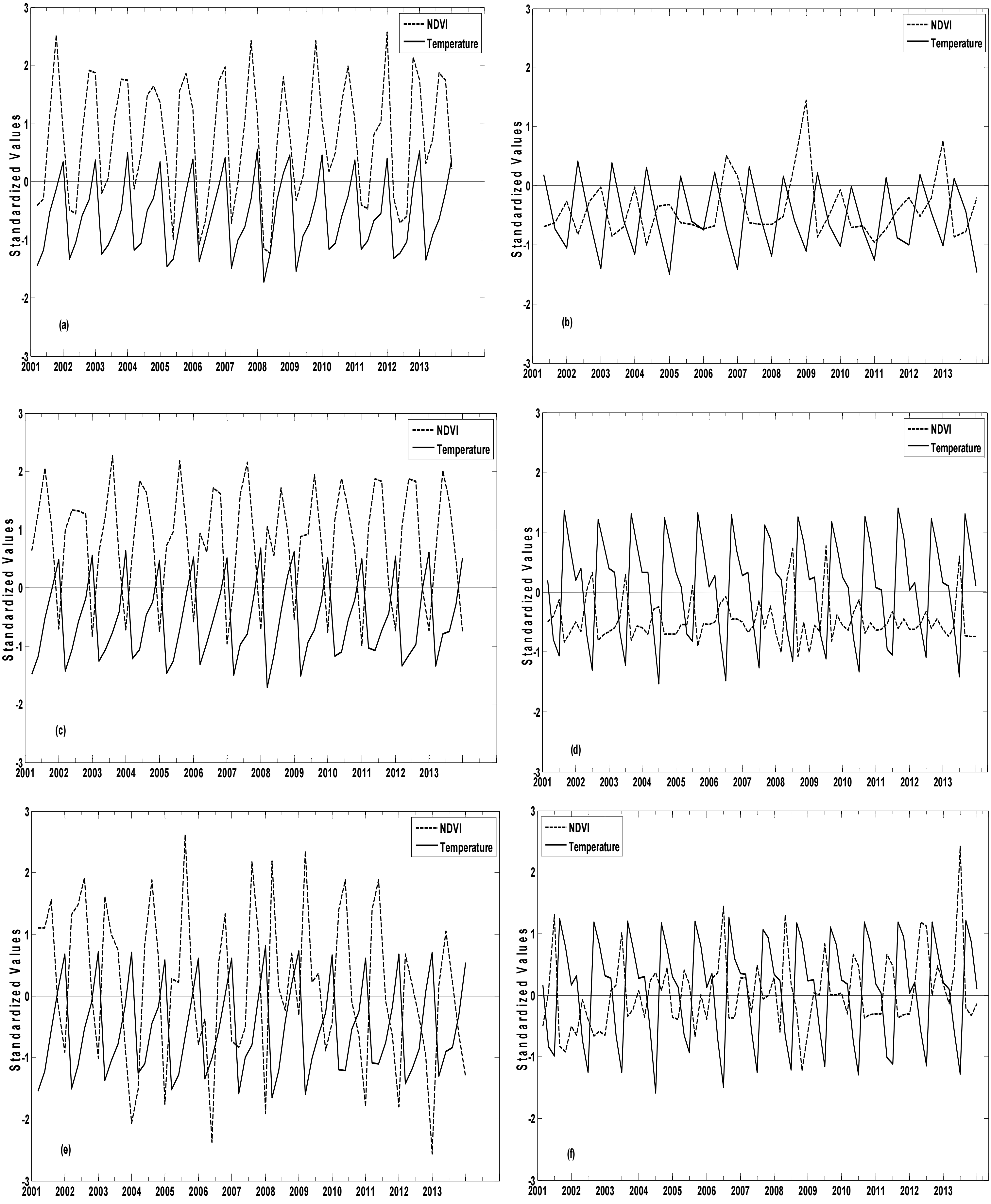

Figure 8: Seasonal variability of the monthly averages of NDVI and air temperature for the period 2001–2013 across regions. (a) JFMAM Sulaymaniyah, (b) OND Sulaymaniyah, (c) JFMAM Wasit, (d) OND Wasit, (e) JFMAM Basrah, and (f) OND Basrah.

4.4 Correlation between precipitation and air temperature with monthly NDVI

The linear correlation coefficient between monthly NDVI and precipitation and air temperature was calculated for each region. It was evaluated for concurrent monthly NDVI and precipitation and air temperature data and for different time lags between -5 and 5 months, as suggested by Gessner et al. (2013) and Marszeleweski and Skowron (2006).

Figures 9 and 10 show the values of the correlation coefficient for precipitation and air temperature, respectively. The period 2001–2015 was used to compute the monthly-cumulated precipitation.

Figure 9 shows that the highest correlation is with a four-month time lag of NDVI to precipitation in Sulaymaniyah and Wasit, while in Basrah, the highest correlation occurs with a three-month time lag. Sulaymaniyah contains the highest correlations between NDVI and precipitation from a 0 to five-month time lag. The high correlations found in these time lags are related to the fact that vegetation responds to soil moisture, which has accumulated through cycles of precipitation events. The phenological transition points range between three- and four-month time lag for all regions, corresponding to the length of time it take for plants to mature (Rousvel et al. 2013).

However, in Sulaymaniyah there is also a sharp drop in correlation with time lag -1. As seen in the intra-annual results for precipitation and vegetation in Section 4.2.2, there are years when there is a negative correlation between precipitation and vegetation (high precipitation, low vegetation) in the JFMA season. We conclude that this is the result of precipitation falling as snow, which would add no real moisture to soils until the spring melt, thus hindering vegetation growth. The same reason may account for this drop in correlation at the time lag -1.

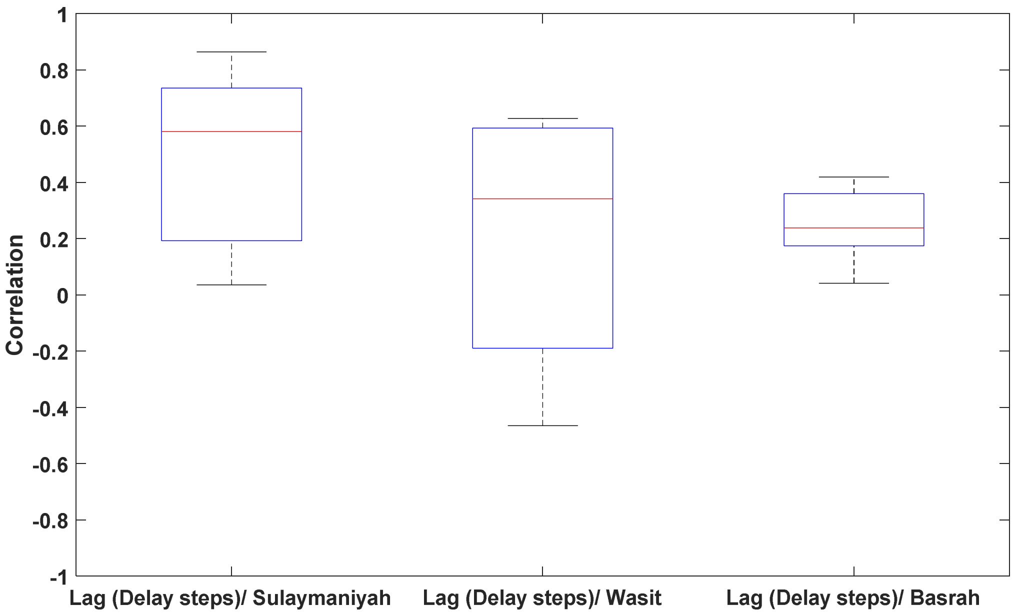

Figure 9: Correlation between monthly NDVI and precipitation in various intervals for the three climatic regions. The correlations are for in the concurrent month (0), one month earlier (−1), two month earlier (−2), three months earlier (−3), four months earlier (−4), the four months earlier (−5), the previous month (1), the two previous months (2), the three previous months (3), the three previous months (4), and the three previous months (5).

To study the relationship between air temperature and vegetation temporal dynamics, the same time lags were used, shown in Figure 10. The period of 2001–2013 was used to calculate the monthly-cumulated air temperatures. As opposed to precipitation, a relatively weak negative correlation was observed between air temperature and NDVI for all regions. The weak impact of air temperature on NDVI can be explained by the higher levels of precipitation, particularly in Sulaymaniyah and Wasit. The increased cloud coverage during these periods reduces air temperatures and solar radiation levels, thus slowing down photosynthesis and subsequently hindering vegetation growth. Air temperature is not the only parameter affecting vegetation; there are other, more important, factors such as an adequate supply of water and nutrients, as well as sunlight.

While the phenological transition points of correlation between precipitation and NDVI align with crop maturity duration for all regions, this is not the case with air temperature, where the points are only aligned in Sulaymaniyah and Wasit. This suggests that NDVI is partially driven by lower air temperatures in these regions. It may be the case that in Basrah, because the temperature is high all year round, there is never a low enough temperature to trigger the same processes.

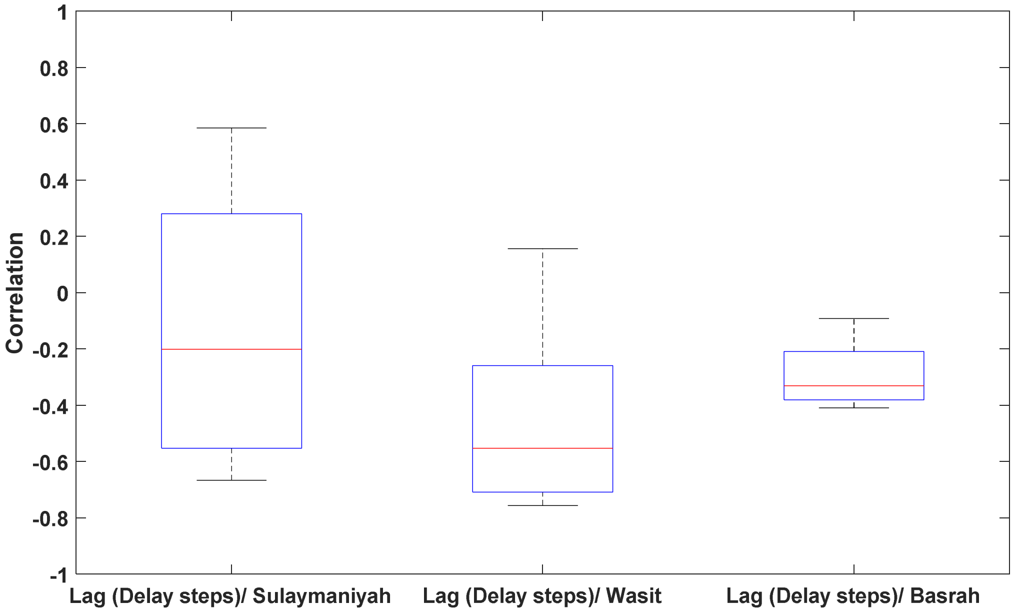

Figure 10: Correlation between monthly NDVI and air temperature in various intervals for the three climatic regions. The correlations are for in the concurrent month (0), one month earlier (−1), two month earlier (−2), three months earlier (−3), four months earlier (−4), the four months earlier (−5), the previous month (1), the two previous months (2), the three previous months (3), the three previous months (4), and the three previous months (5).

5. Discussion

Previous research suggests that vegetation is very sensitive to climatic components (for example, Matthews, 1982, Roerink et al. 2003, Djamali et al. 2010) and its growth is influenced by climatic factors such as precipitation and temperature (Prasad et al. 2008; Suzuki et al. 2006; Wang et al. 2003). Our results from the analyses of NVDI variability in response to precipitation and air temperature using interannual, intra-annual, and seasonal variability in different regions of Iraq captured the important climatic parameters governing vegetation vigour. We also found that other, external, factors sometimes skewed our results.

First, we analysed the interannual variation in order to better understand the relationship between precipitation and NDVI. We found that the similarities between NDVI and precipitation (in trend and amplitude) in Sulaymaniyah and Wasit point towards a causal relationship between precipitation and vegetation (Figures 3a and 3b). Throughout, NDVI shows a clear response to the cycle of precipitation, except in Basrah, where there is a weak correlation between NDVI and precipitation (Figure 3c). This, we found, could be explained through the seasonal/intra-annual results, where there were a number of negative correlations between precipitation and vegetation.

We then examined the intra-annual and seasonal variation in order to further assess the relationship between precipitation and NDVI and found that these regions differ noticeably in their response to precipitation variability. Overall, NDVI demonstrates a clear response to precipitation in Sulaymaniyah (but see below) and to a lesser degree in Wasit. In Basrah, the NDVI distribution pattern presents an opposite trend to the precipitation except for some years during the period. Soil type, and the volatility and fragility of the environment may play a role here, as well as external factors such as war and other conflicts impacting on agriculture and irrigation infrastructure.

Soil moisture impacts vegetation growth. The more fully developed soils are (such as those found in Sulaymaniyah), the better they are able to retain moisture. The mollisols of Sulaymaniyah and its surrounding regions are deeply developed and are clay rich, with additions of alluvial silts and fine sands (Marsh and Altaweel, 2018 In Press). The clays help to retain water and indeed could lead to oversaturated soils, but the use of the plough helps to increase drainage. Although summer temperatures can be high in the north, leading to higher rates of evaporation, this is countered by the water retention in the underlying silty clay sediments (observed through field trenches: Marsh and Altaweel, 2018 In Press).

In the alluvial plain (Wasit and Basrah regions), entisols are the dominant soil type. These soils are young and underdeveloped (i.e., they only have an A horizon), and their development is impacted by erosion and/or rapid rates of deposition of sediments. However, in alluvial environments, soils can be high in nutrients (due to annual river flooding) and thus are areas of high agricultural potential. In the south of Iraq, though, the high temperatures lead to high evaporation rates. To mitigate against this (and the lack of rainfall in the summer months), drought tolerant crops are planted, and irrigation is used extensively. Irrigation in turn leads to issues of increased salinisation of soils, which inhibits vegetation growth. Because of these factors, there is less soil moisture availability in Basrah, so it would be expected that in drought years, vegetation and precipitation should be positively correlated. However, there are exceptions (where the relationship with precipitation is negative). This is likely reflecting in the increased use of irrigation, which increases (short term) soil moisture content and promotes vegetation growth.

In years where precipitation is high and NDVI is low, there is a far different reason: conflict (war and terrorism). In 2003, the invasion of Iraq was followed by the Battle of Basrah. In 2004, the NDVI is drastically lower, likely as a consequence of this conflict and resultant lack of infrastructure (i.e., irrigation systems were put out of use).

These anomalies aside, however, the interpretation of these results helps to determine the efficiency at which rainfall is used by vegetation. Long and intense rainfall, as occurs in season FMAMJ in Sulaymaniyah, is favourable to vegetation growth, while a short rainfall season and long dry season, as in Basrah, is unfavourable, especially given the fragility of the environment and external factors such as conflict and extensive use of irrigation.

Variations in rainfall in all of the regions clearly influence the vegetation growth and vigour (NDVI). With respect to the NDVI response to rainfall, several studies report that vegetation does not immediately respond to rainfall, rather it is affected by soil moisture built up over time (cumulative rainfall) (Davenport & Nicholson, 1993; Prasad et al. 2008; Wang et al. 2003). We find similar results in Iraq. Figure 4a shows that the maximum peak for NDVI occurs in Sulaymaniyah in April, which picks up the dominant agriculture signal in this region. The agricultural 'greenness' increase starts in December /January and ends in June/July in Iraq. This peak in NDVI is a result of the accumulation of rainfall for the winter months (December, January, and February). In Figures 4b and 4c, the peaks are shifted forward by one month: NDVI peaks in March. This is also the result of the accumulation of rainfall for the winter months. We also see that for the JFMA season in Sulaymaniyah (Figure 5b), which represents part of the rainy season, there are years during which precipitation is negatively correlated with vegetation. In this case, snow as precipitation in the highlands may skew the correlation (when it is snowing, the ground freezes due to low temperatures, and thus soil moisture will not increase until the spring melt). So, for years of heavy snow, regrowth of vegetation may start slightly later in the year.

Generally speaking, the results clearly suggest that the NDVI gives a marked response to precipitation in the FMAMJ season and the SOND season in Sulaymaniyah and Wasit. However, in the FMAMJ season, the response is stronger. This could be due to the fact that there is higher and more regular precipitation. Additionally, the NDVI and precipitation magnitudes are slightly greater in the FMAMJ season for Sulaymaniyah and the maximum values are nearly constant, and the distribution is concentrated around the mean value for the SOND season for Sulaymaniyah and Wasit.

Vegetation response to rainfall is stronger in seasonal variability analyses than in the interannual variability analyses. The response for the FMAMJ season is much better than for the SOND season in Sulaymaniyah. The opposite can be seen in Wasit, where the response for the SOND season is much better than the FMAMJ season.

The importance of looking at different regions across Iraq, and at different scales (i.e., interannual and intra-annual) is highlighted by the study. The results indicate that these regions' responses differ markedly from each other in terms of precipitation variability.

We also examined interannual variability of air temperature and the NDVI in order to understand the relationship between the two. We found that, in general, the relationship between vegetation and air temperature is not as strong as that of vegetation and precipitation. This is because air temperature is not the primary factor that affects vegetation growth, which is more influenced by an adequate supply of water, nutrients, and sunlight. Generally, the presence of moisture in the soil from irrigation increases the appropriate conditions for vegetation growth, which, on the one hand, encourages the increase of vegetation and on the other hand, the presence of moisture leads to a decline in soil temperature. (It should be noted that arid conditions and irrigation can also lead to an increase in soil salinisation, which could negate the effects of soil moisture.) Precipitation constitutes the primary factor in germination, whereas the air temperature only assists with a weaker effect than that of precipitation.

Finally, the linear correlation coefficients between monthly NDVI and precipitation and air temperature were calculated for each region, for concurrent monthly NDVI and precipitation and air temperature data and for different time lags between -5 and 5 months. On the one hand, we found that the highest correlation is with a 4-month time lag of NDVI to precipitation in Sulaymaniyah and Wasit, while in Basrah the highest correlation occurs with a 3-month time lag. On the other hand, a relatively weak negative correlation was observed between air temperature and NDVI for all regions. The weak impact of air temperature on NDVI is explained by the presence of precipitation, particularly in Sulaymaniyah and Wasit, which can negate or mitigate against the impact of air temperature. Air temperature, additionally, is driven more by natural climate cycles (such as the NAO: Agha and Sarlak, 2016) than environmental change. While the phenological transition points of correlation between precipitation and NDVI align with crop maturity duration for all regions, this is not the case with air temperature, where the points are only aligned in Sulaymaniyah and Wasit. This suggests that NDVI is partially driven by lower air temperatures in these regions.

The relationship between NDVI and precipitation is stronger than for air temperature, especially in Sulaymaniyah and to a lesser extent, Wasit. This may be because Sulaymaniyah is located in northern Iraq, with higher levels of precipitation and more temperate temperatures, so slight changes in temperature should not significantly affect vegetation growth. Furthermore, the structure of hydrological system of northern Iraq leads to more productive vegetation growth: there is more available water in the aquifers, and the spring melt leads to the flooding of the alluvial plains, adding more nutrients to the soils as well as increasing soil moisture content. As for the positive correlation with air temperature and the negative correlation with precipitation with the NDVI in specific years across regions, this may be related to the increase in cloud cover and precipitation causing reduced air temperatures and solar radiation, which subsequently weakens photosynthesis, hindering vegetation growth.

As mentioned in the Introduction, there has been little research in Iraq in terms of vegetation and environmental/climate studies (see Jaradat 2002). Most of the work that has been carried out relates to palaeoclimate studies (tracking changing seasonality in Iraq: Marsh et al., 2018), research into the effects of the conflicts on agriculture (FAO 2013; FAO 2016; Jaradat 2002), or studies that are limited in scope.

Qader et al. (2015), for instance, assessed and mapped the spatial variation in key land surface phenology (LSP) parameters in relation to elevation across Iraq over the last decade. Fadhil (2011) investigated the use of NDVI to detect drought impacts in the Kurdish region of Iraq. Agha and Sarlak (2016) used precipitation and temperature data, however the data was derived only from Iraqi meteorological stations and subjected to different statistical analyses (Mann–Kendall and Spearman's Rho test and Kendall and Sen's T tests) in contrast to the ones used in this study, and no comparisons were made with satellite data. Najmadin et al. (2017), in their study of the Lesser Zab (northern Iraq) rainfall runoff model, used TRMM data and precipitation data, but unlike the current study, did not compare these with other available datasets, particularly the NDVI. Slightly further afield, Hashemi (2011) used the NDVI response to cumulative monthly rainfall in the Azerbaijan province of Iran and found that multivariate regression analysis was better than simple linear regression. Other research is also available (e.g., Azooz & Talal, 2015, Amanollahi et al. 2012), however, the data and interpretations have not been peer reviewed and thus are not considered here.

There has also been researched carried out in semi-arid to arid environments similar to Iraq, however they use different methods and concentrate primarily on soil erosion and land use. Examples include catchment analysis and GIS analysis, using topographical (i.e., elevation data) to quantify vegetation and soil/sediment runoff (Canton et al., 2011) and development of soil erosion models in arid environments using STREAM soil erosion models (Ciampolini et al., 2012).

There is some limited research into the predictability of the NDVI dataset in semi-arid regions. Martiny et al. (2010) examined the predictability of the NDVI dataset compared to other proxies including datasets from the Niño3.4 sea surface temperature index, and indices based on surface temperatures and atmospheric variables from the National Center for Environmental Prediction (NCEP). Similarly to our study, the authors looked at three regions with differing precipitation regimes and topography and found that the correlation between their proxy datasets and NDVI were high, and that the proxy data provided good predictability of vegetation cover in the region. The difference in the Martiny study and ours here is the use of rainfall as a variable. Rainfall data is difficult to gather in many parts of Africa (similarly to Iraq), and the authors argue that the NDVI can stand in as a predictor for rainfall patterns in the region. Moreover, in an earlier paper, Martiny et al. (2007) argue that it is the 'structure' of the precipitation regime that affects the correlations between rain data and the NDVI. However, we would argue that the addition of precipitation data adds nuanced interpretation to the NDVI data, and that there are additional factors at play that impact the correlations. An example is the negative correlation between rain and vegetation that is seen in Basrah in certain years. The NDVI may be picking up a vegetation signal, however, as discussed above, irrigation, rather than precipitation, may be the driver of this vegetation growth. Precipitation data, therefore, is necessary, where possible, in order to tease out details that could be important in fragile environments such as these.

Another study, also conducted in Africa (Tunisia) by Amri et al. (2011), develops the VAI (vegetation anomaly index) model, based on NDVI data to measure the persistence of drought in the region and its impact on three vegetation types (pasture land, agricultural fields and non-irrigated olive groves). While they found that the VAI is a good predictor for drought persistence, we argue that precipitation data is needed in order to confirm that the the lack of vegetation in certain periods is caused by a lack of precipitation or due to other reasons. Furthermore, the effect of irrigation (necessary for agriculture in many semi-arid regions) is not accounted for in the VAI model.

6. Concluding comments

In this study, we compared two variables (precipitation and air temperature) and found that there are correlations between the NDVI and climatic regimes, and that external factors can skew these correlations. In addition, we used a combination of datasets in order to improve the robustness of the data and analyses and looked at both the interannual and intra-annual/seasonal variation in order to gain an enhanced understanding of the relationship between vegetation and climate across different environments in Iraq. We found that in highland regions (such as Sulaymaniyah), precipitation as snow affected the results and as such type of precipitation must be taken into consideration when studying the correlations between precipitation and vegetation.

Additionally, we found that the relationship between precipitation and the NDVI in Basrah is much more complicated, with both negative and positive correlations. This shows that while precipitation is a primary driver in vegetation growth, other factors can also have significant impacts. These factors include temperature extremes, fragility of the environment, and human activities including the use of irrigation (leading to salinisation of soils) and especially the impacts of conflict, which affect infrastructure and agricultural output, which in turn, impacts the NDVI for that time period.

There are now different avenues of future research that can be pursued. Firstly, we can take these results to modify existing phenological models, adding precipitation as a variable. Secondly, we can look with more detail into the relationship between precipitation and the NDVI in Basrah, particularly in relation to other external factors, which can skew correlations. This work could also be applied to other regions of high conflict and fragile environments, such as Syria. Thirdly, we can see the need to initiate phenology network stations across Iraq, in order to adequately cover the highly diverse environments. This would include a simple and effective means to input, report and utilise ground-based phenological observations for a variety of ecological, climatic and agricultural applications. Such a network can also capitalise on a wide variety of remote-sensing products and meteorological data already available from different governmental departments in Iraq.

Fourthly, since precipitation and temperature in Iraq are driven by different mechanisms, more research needs to be undertaken to further quantify how the relationship between vegetation, temperature and precipitation works in Iraq (and other semi-arid to arid environments). This could be done through looking at different classifications of vegetation in the region, combined with a closer analysis of soil types and water availability.

This combination of analyses (both used in this study and suggested for future research) is especially useful for semi-arid to arid locations that not only are naturally fragile but also prone to environmental degradation due to human activities. Understanding vegetation-climate-human dynamics may help NGOs and governments to better plan mitigation strategies within these areas, and to implement strategies that are finetuned to the specific needs of the locales.

7. References

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