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Impact of the North Sea–Caspian pattern on meteorological drought and vegetation response over diverging environmental systems in western Eurasia

Qing He[1] | **Bolin Xu**[1] | **Bastien Dieppois**[2] | **Omer Yetemen**[3] | **Omer Lutfi Sen**[3] | **Julian Klaus**[4] | **Rémy Schoppach**[5] | **Ferat Çağlar**[3] | **Ping Yu Fan**[1] | **Liang Chen**[6] | **Luminita Danaila**[7] | **Nicolas Massei**[7] | **Kwok Pan Chun**[1,8]

[1]Department of Geography, Hong Kong Baptist University, Hong Kong SAR, China

[2]Centre for Agroecology, Water and Resilience, Coventry University, Coventry, UK

[3]Eurasia Institute of Earth Sciences, Istanbul Technical University, Istanbul, Turkey

[4]Department of Geography, University of Bonn, Bonn, Germany

[5]Catchment and Eco-hydrology Research Group, Department of Environmental Research and Innovation, Luxembourg Institute of Science and Technology, Esch-sur-Alzette, Luxembourg

[6]Key Laboratory of Regional Climate Environment for Temperate East Asia, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

[7]M2C Laboratory, The University of Rouen Normandy, Mont-Saint-Aignan, France

[8]Department of Geography and Environmental Management, University of the West of England, Bristol, UK

Correspondence
Kwok Pan Chun, Department of Geography and Enviromental Management, University of the West of England, Bristol, UK.
Email: kwok.chun@uwe.ac.uk

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Abstract

Emerging drought stress on vegetation over western Eurasia is linked to varying teleconnection patterns. The North Sea–Caspian Pattern (NCP) is a relatively less studied Eurasian teleconnection pattern, which has a role on drought conditions and the consequence of changing conditions on vegetation. Between 1981 and 2015, we found that the Standardized Precipitation Index (SPI) and the Normalized Difference Vegetation Index (NDVI) have different trend patterns over various parts of western Eurasia. Specifically, the vegetation greenness is linked with wetter conditions over Scandinavia, and vegetation cover decreases over a drying central Asia. However, western Russia and Franceare paradoxically becoming greener under drier conditions. Using the Budyko framework, such paradoxical patterns are found in energy-limited environmental systems, where vegetation growth is primarily promoted by warmer temperatures. While most studies focused on the impacts of the North Atlantic Oscillation (NAO), we test whether the NCP explains better the variability of meteorological drought and vegetation response over western Eurasia. We hypothesised that the positive phases of the NCP are correlated to high pressure anomalies over the North Sea, which can be associated with weakening onshore moisture advection, leading to warmer and dryness conditions. These conditions are driving vegetation greening, as western Eurasia is mainly energy limited. However, we show that as the climate is warming along with the teleconnection impacts, the future ecosystem over western Eurasia will be transferred from energy-limited to water-limited systems. This suggests that the observed vegetation greening over past three decades is unlikely to sustain in the future.

Significance statement

Meteorological droughts affect vegetation cover differently across western Eurasia depending on water and energy supply. Droughts hinder vegetation development in water-limited areas, but promote vegetation growth in energy-limited areas due to rising temperatures. The teleconnections that influence precipitation and temperature patterns are linked to these patterns of vegetation responses. The North Sea-Caspian Pattern (NCP) explains more variance between meteorological drought and vegetation response over western Eurasia than the North Atlantic Oscillation (NAO). The observed vegetation greening over the last three decades is unlikely to persist, given the effects of rising temperatures and NCP changes.

KEYWORDS
Budyko framework, drought conditions, Normalized Difference Vegetation Index (NDVI), North Sea–Caspian Pattern (NCP), Standardized Precipitation Index (SPI), Western Eurasia

1 | INTRODUCTION

Vegetation growth over western Eurasia has been linked with large-scale teleconnections, local hydrological conditions and temperature increase from the early 1980s (Gouveia et al., 2008; Olafsson & Rousta, 2021). Hydroclimate conditions over western Eurasia are shown to be modulated by several teleconnection patterns including the North Atlantic Oscillation (NAO; Deser et al., 2017; Iles & Hegerl, 2017; Tsanis & Tapoglou, 2019), Atlantic Oscillation (AO; Báez et al., 2014; D. Y. Lee et al., 2020), East Atlantic (EA; Ionita, 2014; Toreti et al., 2010; Tošić & Putniković, 2021; Ulbrich et al., 2012), El Nino Southern Oscillation (ENSO; R. W. Lee et al., 2019; Mezzina et al., 2020) and South Asian monsoon (SAM; Alpert et al., 2006). Despite that teleconnections between these different modes of climate variability and hydroclimate conditions are well-documented in previous studies (Lledó et al., 2020; Rousi et al., 2020; Rust et al., 2018), the impact of the North Sea–Caspian Pattern (NCP) remains largely unexplored. The NCP is an upper-level atmospheric teleconnection with centres of active variability over the North Sea and the Caspian Sea regions. These seas are regional water bodies, which affect the common locations of local pressure systems due to seasonal circulation variations driven by temperature gradients caused by differences of thermal capacity between land and water (Dippner et al., 2012; Sibley et al., 2015). To date, NCP effects on temperature and precipitation have been studied mainly for the East Mediterranean and its surrounding regions (Kutiel et al., 2002; Kutiel & Türkeş, 2005; Sezen & Partal, 2019). However, given that the NCP centres of action are farther north, it might strongly impact precipitation patterns, hence drought occurrence and vegetation conditions over the entire Eurasia (Brunetti & Kutiel, 2011; Çağlar et al., 2021).

In recent decades, western Eurasia has experienced several severe drought events, notably in 2002, 2003, 2015 and 2018, due to large-scale climate variability (Buras & Rammig, 2020; Ionita et al., 2017; Rimkus et al., 2017). These droughts strongly impacted agricultural activities and ecological services (Changnon, 2003; Murnane, 2004; Parmesan et al., 2000). Vegetation indices serve as a crucial ecohydrological indicator of terrestrial ecosystems and agriculture (Measho et al., 2019; Niu et al., 2019; Sawada, 2018). Detecting and monitoring the onset and early stage of droughts are therefore of critical significance for predicting the impacts on vegetation conditions and anticipate eco-environmental management actions on a regional scale (Bachmair et al., 2018; Sutanto et al., 2019).

Droughts are traditionally quantified by water availability indices, such as Standardized Precipitation Index (SPI) (Cancelliere et al., 2007; Livada & Assimakopoulos, 2007; McKee et al., 1993). Given the direct effects of droughts on vegetation, vegetation indices (van Hateren et al., 2021) have also been used as drought indicators (Buitink & Swank, 2020; Hu et al., 2019; Sepulcre-Canto et al., 2012; Di Wu et al., 2015). However, there are various factors, such as warming temperatures (Peng et al., 2011; X. Wang et al., 2017; G. Xu et al., 2014), increasing solar irradiation (Teuling, 2013), and increasing CO_2 fertilization (Lian et al., 2021), which may lead the vegetation to be less affected by the declining water availability. According to previous studies, the vegetation responses to drought conditions are divergent for different climate environments, and the similarity and differences in water and vegetation variability need to be further explored (Denissen et al., 2020; Peled et al., 2010; van van Hateren et al., 2021). To explore the long-term interactions among climate, regional hydrology and vegetation cover, which is related to the water-limited and energy-limited environment, the Budyko framework is applied (Abera et al., 2019; Li et al., 2013; D. Zhang et al., 2018).

In Section 2, we introduce the study area, data sources and methods. In Section 3, we examine the similarity and disparity in meteorological and vegetation variations over western Eurasia. Then, we test whether NCP can be a better contributor than NAO to explain changes in meteorological and vegetation conditions and describe the mechanisms associated with NCP teleconnections over various environmental systems. In Sections 4 and 5, we discuss their wider implications and summarize the main results.

2 | DATA AND METHODS

2.1 | Study area

The study is centred on western Eurasia (i.e., 10°W–70°E and 35°N–72°N; Figure 1). The western part of the study region has an oceanic/maritime climate with temperate summers and mild winters, whereas the central and eastern parts have a continental climate with hot summers and cold winters (Stampoulis & Anagnostou, 2012). Due to different climate zones of western Eurasia, water and vegetation are unevenly distributed. The total amount of precipitation ranges from 600 to 900 mm·year^{-1} over the western part to 500 mm·year^{-1} in the eastern part of western Eurasia (Mikolaskova, 2009). The main vegetation cover types vary from woody savannas and mixed forest in the high latitudes to croplands and grassland in the mid-latitudes (Figure 1).

2.2 | Data

2.2.1 | Normalized Difference Vegetation Index data

As a proxy of vegetation greenness, the Normalized Difference Vegetation Index (NDVI) is extracted from the National Oceanographic and Atmospheric Administration (NOAA) Global Inventory Monitoring and Modeling System (GIMMS), version number 3g.v1 (Cai et al., 2014; Pinzon & Tucker, 2014; Donghai Wu et al., 2014). This dataset provides bimonthly data (∼every 14 days), with a 1/12° resolution, between July 1981 and December 2015. In order to validate the GIMMS NDVI datasets, we use the monthly NDVI dataset from the Moderate Resolution Imaging Spectroradiometer (MODIS MOD13C2), which is available at 0.05° resolution (Fensholt & Proud, 2012; Solano et al., 2010). For comparison, the GIMMS NDVI data were made to be monthly by averaging the two values in each month. We found that both datasets are largely similar in terms of seasonal and interannual variations (Figure S1).

2.2.2 | Climate data

For hydroclimate variables (precipitation, potential evapotranspiration, temperature), we used the ERA5-Land data, which is derived from the fifth generation European Centre for Medium-Range Weather

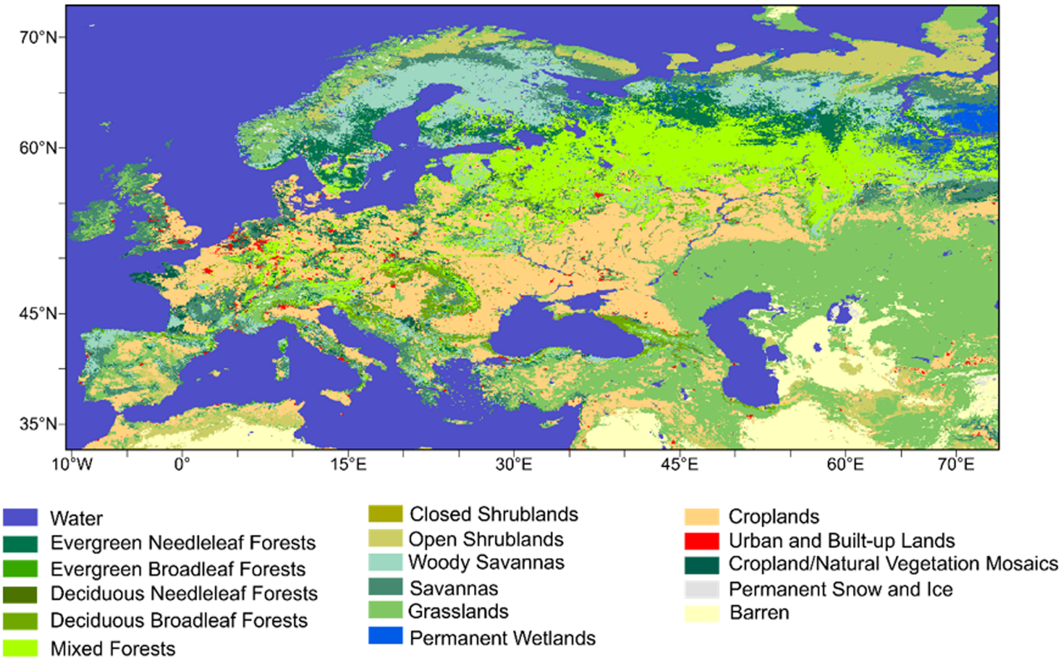

FIGURE 1 The land cover types over the western continental Eurasia between 10°W–70°E and 35°N–72°N

Forecasts (ECMWF) atmospheric reanalysis of the global climate, with a spatial resolution of 0.1° × 0.1° and monthly temporal resolution (Smith et al., 2021; Tarek et al., 2020). By using a higher spatial resolution (0.1° × 0.1°) than that of its driven climate reanalysis data (ERA5; 0.25° × 0.25°), ERA5-Land reanalysis datasets provide an improved representations of land surface processes (Muñoz, 2019).

To calculate the NAO and NCP indices, sea-level pressure (SLP) and 500 hPa geopotential height are derived from ERA5 datasets, with a spatial resolution of 0.25° × 0.25°. Here, the NAO index is calculated using the 1st principal component (PC) of SLP anomalies over the North Atlantic (90°W–20°E, 20°–80°N) (Hurrell, 1995; Hurrell & Deser, 2009). The NCP index is the difference in the 500-hPa level geopotential height between the North Sea (0°, 55°N; 10°E, 55°N) and northern Caspian Sea (50°E, 45°N; 60°E, 45°N) region (Kutiel et al., 2002; Sezen, 2017). Here, ERA5-Land and ERA5 data have been extracted between 1981 and 2015 for consistency with the NDVI datasets.

We provide a comparison of precipitation patterns between the ERA5 and observation data from the Climate Research Unit (CRU: https://crudata.uea.ac.uk/cru/data/hrg/) in Figure S2. Generally, the annual summer and winter precipitation trends derived from ERA5 are consistent with that from CRU, with drying trends over eastern part of western Eurasia and wetting trends over western part (Figure S2). However, the CRU precipitation variability could be lower over the eastern part of western Eurasia, as the CRU dataset has fewer station data than ERA5 in some regions (Harris et al., 2020). Since we focus on the mechanism explaining co-variations in the NCP and dry/wet conditions in western Eurasia, such potential shortcomings should be neglectable.

2.3 | Drought and vegetation indices

To quantify droughts and vegetation conditions, the SPI (McKee et al., 1993) and the NDVI are used. The SPI is calculated by assuming that precipitation is Gamma distributed (Chun, 2010). As the growing season generally ranges from April to September (total 6 months) over western Eurasia, we use a 6-month aggregated SPI (i.e., SPI-6) (van Hateren et al., 2021). Nevertheless, the 1- to 12-month SPI time series have very similar patterns with the 6-month SPI results (not shown). To identify drought conditions, the SPI-6 < -1 is selected (van Hateren et al., 2021). To allow for a fair comparison between SPI-6 and NDVI, the NDVI is also standardized (hereafter called NDVI anomalies). The NDVI value less than −1 is also characterized as a significant vegetation decline.

2.4 | Trend and the GLS regression

The Mann–Kendall (MK) test is used to quantify the significance of linear temporal trends nonparametrically (Kendall, 1975; Mann, 1945). Previous work argued that the results of the MK trend test could be misleading if serial correlations and outliers are ignored (Guo et al., 2018; Hamed, 2008; Hamed & Ramachandra Rao, 1998; Klaus et al., 2015; Sang et al., 2014). Thus, we use the modified MK test (Hamed & Ramachandra Rao, 1998) to examine trends of NDVI and hydroclimate variability. Trend intensity is estimated based on Thiel-Sen's slope, which is robust to outliers (Sen, 1968).

To explore the relationships between teleconnections and water and vegetation distributions, generalized least square (GLS) regressions are used, as in previous hydroclimate analysis (He et al., 2021; Klaus et al., 2015). The analytic GLS regressions can be written as

$$Y = \beta_0 + \beta_1 X, \tag{1}$$

where Y is the climate variables or vegetation index, and X is the NCP index value. β_0 and β_1 are regression coefficients.

To consider spatial autocorrelation and the problem of multiplicity of spatial trend and regression results, we used a global significance test based on false discovery rate (FDR) as recommended in previous studies (Wilks, 2006, 2016). After estimating the p values of trend and GLS regressions, the FDR test at $p = 0.05$ is used to control the expected proportion of locally significant tests that are actually true, i.e., not occurring by chance due to spatial autocorrelation and the problem of multiplicity. A local significance test is rejected if the local p value is no greater than:

$$P_{FDR} = \max_{j=1 \to k} \left\{ p_{local}(j) : p_{local}(j) \leq \alpha_{FDR} \left(\frac{j}{k} \right) \right\}, \tag{2}$$

where p_{local} (j) denotes the jth smallest (out of k) local p values, and the α_{FDR} is the chosen control level for the FDR (0.05 for this study).

2.5 | Budyko framework

The Budyko framework has been used to examine long-term interactions among climate, regional hydrology and vegetation cover (Abera et al., 2019; Li et al., 2013; D. Zhang et al., 2018). There are different types of Budyko framework (Budyko, 1974; Choudhury, 1999; Fu, 1981; H. Yang et al., 2008), which are summarized as follows:

$$\text{Budyko (1974)} \quad \frac{\mathrm{ET}}{P} = \left[\frac{\mathrm{PET}}{P} \tanh \left(\frac{\mathrm{PET}}{P} \right)^{-1} \left(1 - \exp \left(-\frac{\mathrm{PET}}{P} \right) \right) \right]^{0.5}, \tag{3}$$

$$\text{Fu (1981)} \quad \frac{ET}{P} = 1 + \frac{PET}{P} - \left[1 + \left(\frac{PET}{P} \right)^{\omega} \right]^{\frac{1}{\omega}}, \tag{4}$$

$$\text{Choudhury (1999); H.Yang et al. (2008)} \quad \frac{ET}{P} = \frac{1}{\left[1 + (P + PET)^{\omega} \right]^{1/\omega}}, \tag{5}$$

where ET, P and PET are land surface evapotranspiration, precipitation (water supply) and potential evapotranspiration (water demand), respectively, and ω is an empirical coefficient related to land patterns and characteristics.

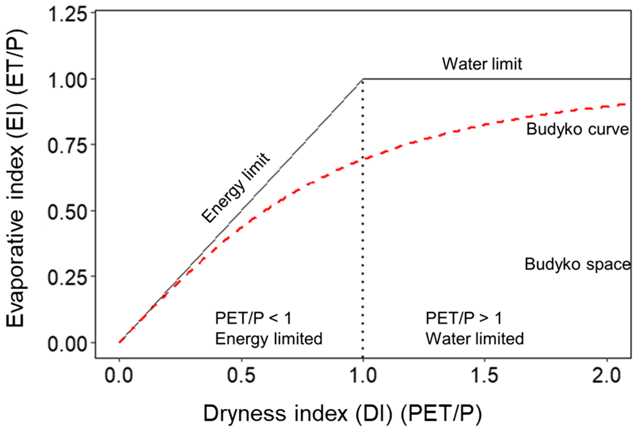

FIGURE 2 Budyko framework (Dryness Index against evaporative index). The solid lines indicate the energy limit and water limit boundaries. The red dashed line is the theoretical Budyko curve with a default ω value (i.e., 2.6; Creed et al., 2014)

Among these three equations (Equations 3–5), the one proposed by Fu (1981) is the most widely used. The Budyko space defines whether catchment state variations, processes and dynamics are water or energy limited based on precipitation (P), evapotranspiration (ET) and potential evapotranspiration (PET) (Berghuijs et al., 2020; Gentine et al., 2012; Sposito, 2017). In the Budyko space, a Dryness Index (DI) (i.e., PET/P) value lower than 1 indicates a humid, energy-limited environment, whereas a DI value higher than 1 indicates a dry, water-limited environment (Figure 2). The empirical coefficient ω is used to define and describe the relevant landscape characteristics, like climate and vegetation covers (Abera et al., 2019; C. Wang et al., 2016).

3 | RESULTS

3.1 | Impact of NAO and NCP on meteorological drought and vegetation

We examine the relationships between two teleconnection patterns (i.e., NAO and NCP) and regional drought conditions over western Eurasia (Figure 3). There are no significant relationships between the DI, EI and the NAO, whereas the NCP is positively related to the DI and EI over western Eurasia (Figure 3). This indicates that positive NCP phases may better contribute to drier conditions over the region than the NAO. Moreover, based on the Budyko space (Figure S3b), the positive phases of NCP contribute to increasing dryness, thus causing the region to become more water-limited.

The NCP has significant negative impacts on precipitation over most western Eurasia, but positive impacts over central Asia (Figure S4). Regarding the temperature, NCP shows a negative relationship over the whole Eurasia (Figure S4). Such negative relationship with NCP is found over most parts of western Eurasia for PET, ET and NDVI variations. Generally, the NCP has negative impacts on meteorological and vegetation conditions over the region.

To further investigate how NCP affects regional drying/wetting conditions related to moisture circulations, we examine the regressed vertically integrated moisture flux associated with NCP variations (Figure 4). Positive NCP phases appear to promote anti-cyclonic circulation over the North Sea (closely adjacent to the continental western Eurasia), but cyclonic circulation anomalies over the Caspian Sea (Figure 4). Such circulation patterns are associated with drier condition over most part of the study region, but wetter condition over Central Asia.

3.2 | Trends in meteorological and vegetation conditions

The mean SPI-6 values are positive and near to zero, suggesting that there is generally slightly humid air over most western Eurasia between 1981 and 2015 (Figure 5a). The mean state of NDVI shows dense vegetation cover (NDVI > 0.3) over most parts of western Eurasia and sparse vegetation canopy (NDVI < 0.3) over Central Asia (Figure 5c). Between 1981 and 2015, there are generally significant decreasing trends in SPI-6 over western Eurasia except for the Italian Peninsula, Scandinavia and the Balkans (increasing trends; Figure 5b).

Regarding trends in vegetation cover, regions with dense vegetation cover (NDVI > 0.3) show increasing trends, and regions with sparse vegetation cover (NDVI < 0.3) show decreasing trends (Figure 5d). Therefore, green regions are becoming greener, and regions where vegetation coverage was low are becoming even less green. Interestingly, trend patterns in vegetation cover are not strictly following precipitation trend patterns. For instance, in western Russia and France, we can observe drier conditions concurrent with greening trends (Figure 5b,d).

3.3 | Concomitance of meteorological drought and vegetation decline

To further explore the relationships between water deficits and vegetation growth, we examine the concurrence of meteorological drought and vegetation decline in Figure 6. On the basis of the SPI-6, we can identify five drought events that are particularly widespread (the area percentage is more than 50%; Figure S5): 1988, 1996, 2003, 2006 and 2010. Among these widespread drought events, the 1996 drought event appears as the most severe one, and therefore, it is selected to analyse whether the meteorological drought and vegetation decline are concurrent (Figure 6; see Figures S6–S9 for other events). In April, both the SPI-6 and NDVI anomalies indicate a deficit in the Scandinavia, Baltic regions and western Russia, while this is only detected in the northernmost regions of Scandinavia in May (Figure 6a,b). Similar results are found in northern France and England, but in August and September (Figure 6e,f). In June and July, meteorological drought and vegetation decline do not occur simultaneously in most western Europe (Figure 6c,d). Generally, vegetation decline prevails in April and May, but hardly appears from June to September.

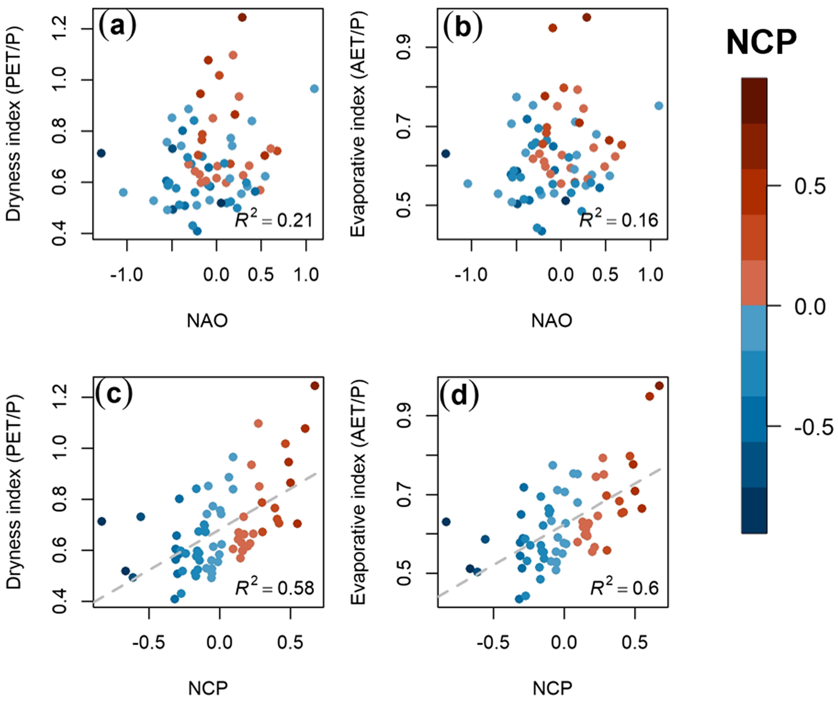

FIGURE 3 The NAO against DI (a) and EI (b) between 1981 and 2015. (c) and (d) are same as (a) and (b) but for NCP. Red and blue colours indicate the positive and negative phases of NAO/NCP, respectively. The colorbar indicates the NCP values

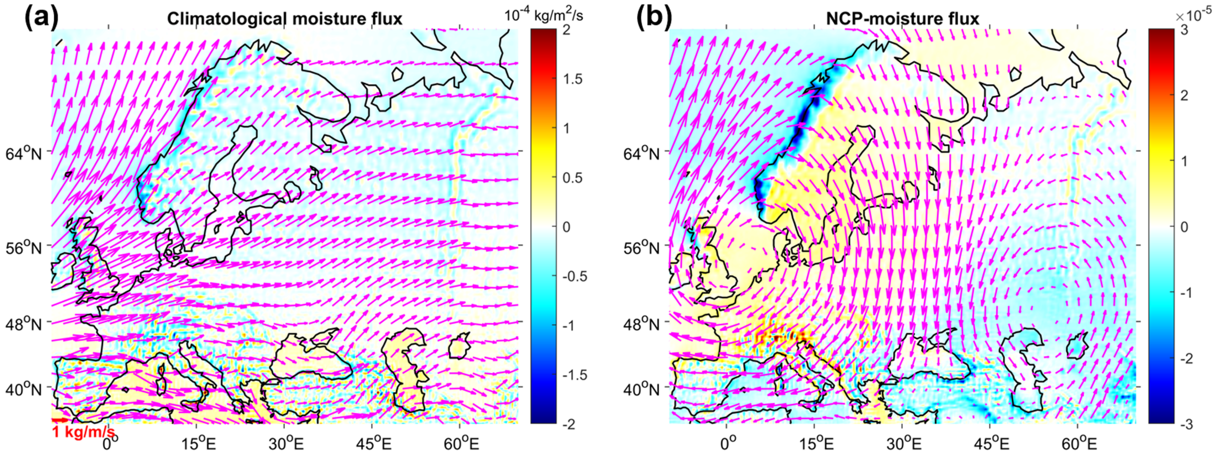

FIGURE 4 Vertically integrated moisture flux and divergence climatological state (a) and regressed map with NCP (b) between 1981 and 2015. For (a), the magenta arrows and shaded area are climatological moisture flux and moisture flux divergence, respectively. For (b), the arrows and shaded areas represent the regressed coefficients of moisture flux and regressed coefficients of moisture flux divergence, respectively. For regression map, only significant results at $p \leq 0.05$ according to the local significance test and to the FDR global significance test are shown (Wilks, 2006, 2016)

Based on the above results (Figure 6), western Russia and France tend to become drier, but greener (Figure 5b,d). Here, we found that these regions are generally energy limited (Figure 7), indicating that vegetation growth is mainly restricted by energy supply, and not by water supply (Gokmen et al., 2013; Parsons & Abrahams, 1994). Therefore, even though the region is drier, warmer temperatures promote vegetation growth. Scandinavia and Baltic regions are mainly water limited (Figure 7), and thus the vegetation is very responsive to water deficits, and the NDVI declines as soon as water deficits occur (Figure 6a). In addition, considering for the whole of western Eurasia, all dots representing EI and DI values are approaching the energy-limited line (i.e., the line of EI = DI) in the Budyko space (Figure S5), suggesting that the whole region can be regarded as an energy-limited environment. Moreover, higher NDVI values correspond to higher EI and DI (Figure S5a), further confirming that drying condition may promote vegetation greenness in the energy-limited environment.

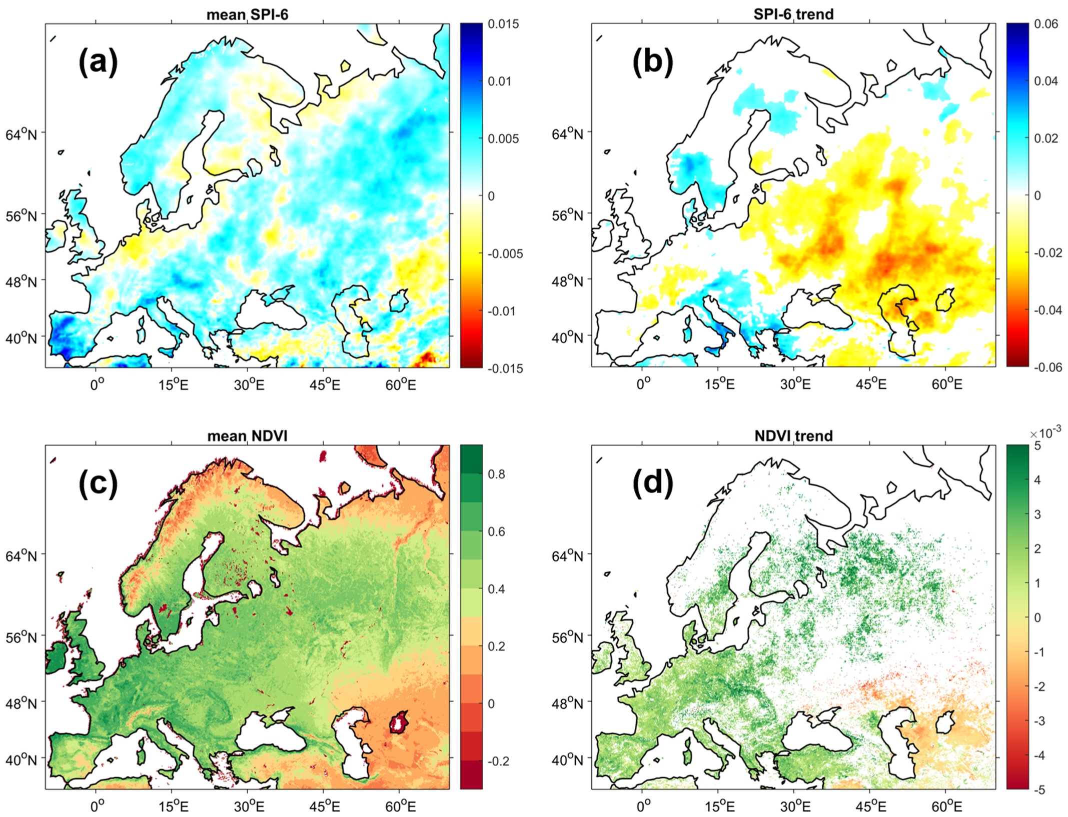

FIGURE 5 The mean state (a) and trend (b) of SPI-6 and NDVI (c and d) between 1981 and 2015 over western Eurasia. Trend maps only show results that are statistically significant at $p \leq 0.05$ according to the MK trend test, and to the FDR global significance test (Wilks, 2006, 2016). For trend maps, the colorbar refers to the slope value of trend analysis

4 | DISCUSSION

4.1 | The role of teleconnection patterns on vegetation during droughts

NAO has been broadly accepted as the major mode causing hydrological and climate variability over western Eurasia (Lledó et al., 2020; Tsonis et al., 2008; W. Zhang et al., 2019). However, here, we demonstrated that NCP is a much better indicator for regional environmental changes over this region. The positive phases of NCP are related to an anticyclonic anomaly centred over the North Sea, and a cyclonic anomaly is centred over the Caspian Sea region. NCP is indeed associated with moisture flux divergence, causing dryness over most parts of western Eurasia. Moreover, the positive phases of NCP are found to promote the drier continental airflow from northern Asia that affect the study region (Kutiel & Benaroch, 2002), contributing to the increased dryness. Such a negative relationship between NCP and winter precipitation has been previously reported over Turkey (Sezen, 2017). Sezen (2017), however, suggested that NCP is positively correlated with summer precipitation in some parts of Turkey. The difference of NCP impacts on precipitation could be related to seasonal variances. The negative relationships between NCP and precipitation in winter may be too strong to mask the positive relationship in summer. Therefore, we found that the NCP has negative impacts on total precipitation of the whole year in this study. The seasonal impacts of NCP on regional climate variability require further investigation in future research work. In addition, the NCP has significant impacts on temperature (Brunetti & Kutiel, 2011), which may also contribute to vegetation growth. In addition, future studies should also examine the potential contribution of other large-scale climate modes of variability.

4.2 | Similarity and disparity between drought conditions and vegetation patterns

Previous studies examined the relationship between droughts and vegetation growth in water- and energy-limited environments over Europe (Denissen et al., 2020; Peled et al., 2010; van Hateren et al., 2021). Peled et al. (2010) and van Hateren et al. (2021) found strong correlations between NDVI and drought indices in water-limited environments. We achieved similar results in our study: the meteorological droughts and vegetation decline occurred simultaneously over Scandinavia and Baltic regions, water-limited environments based on Budyko framework (Figure 5). However, the disparity in long-term variations in water quantity and vegetation density was not fully explained in previous studies. France and western Russia are getting drier during the past decades. Therefore, one might expect

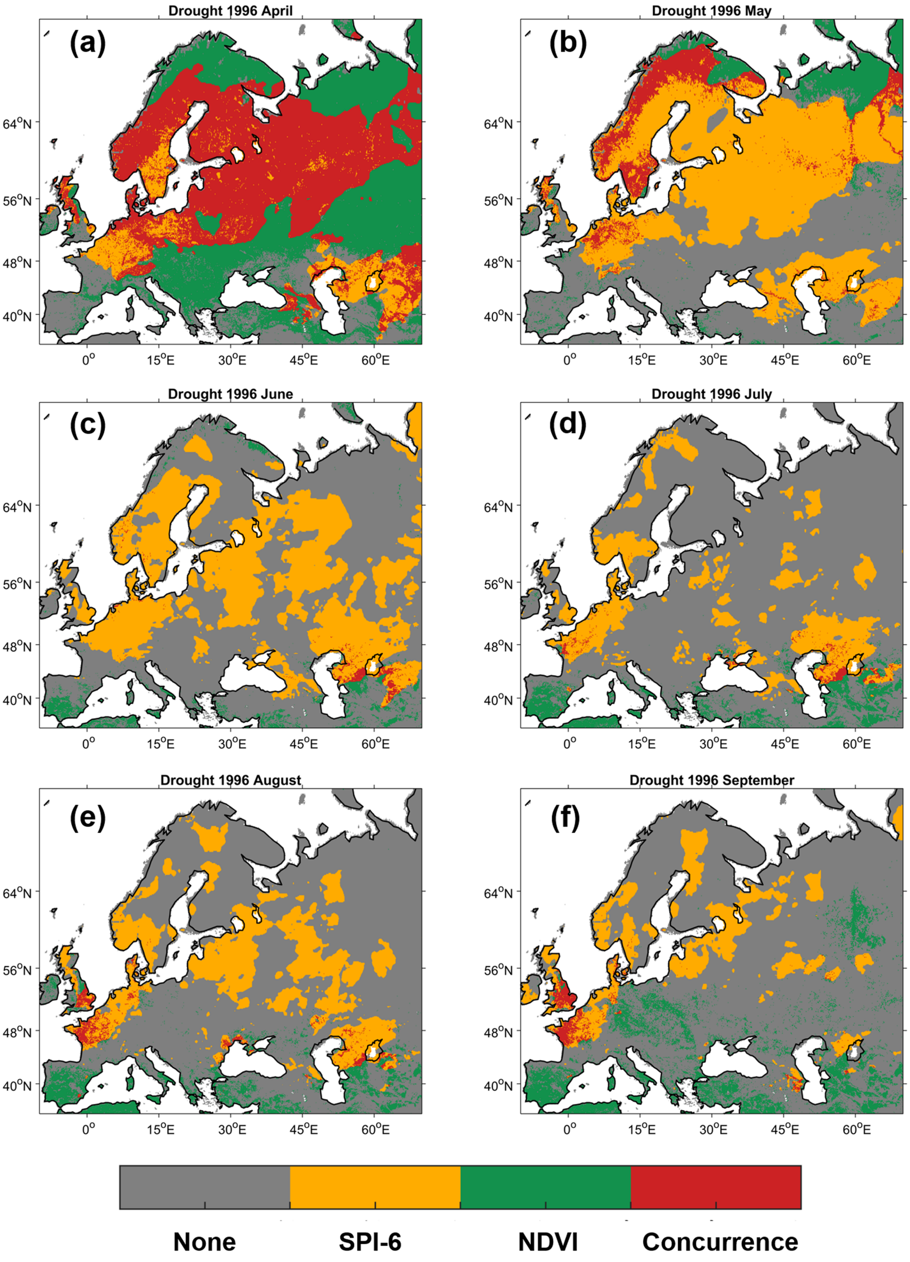

FIGURE 6 Concurrence of meteorological drought (SPI-6) and vegetation deficit (NDVI anomaly) during the 1996 growing season: April (a), May (b), June (c), July (d), August (e) and September (f). 'Concurrence' indicates a deficit for both SPI-6 and NDVI anomalies

vegetation to decline in response to such water deficits and thus NDVI values to decrease. However, this is not what we observed: NDVI values increased. France and western Russia are energy limited according to the Budyko framework (Figure 5), which explains why vegetation is greening instead of suffering from the lack of water. In an energy-limited region, warmer temperatures promote vegetation growth, which is hypothesised to be due to enhancing photosynthesis activity (Dusenge et al., 2019; L. Xu et al., 2013; D. Yang et al., 2021). However, if the precipitation deficits persist, we expect that vegetation growth will eventually be negatively affected. For instance, in 1996, the NDVI decreased in August and September over France after four months (April–July) of continuous precipitation deficits. The reason for the delayed vegetation responses might be due to large aquifer systems for water storage in this region (de Lavenne et al., 2021). Therefore, over France, the vegetation takes around four months before starting to decline after a precipitation deficit. Moreover, there are mostly croplands over France, and the irrigation for agriculture may also be the reason for the delayed vegetation responses (Foudi & Erdlenbruch, 2012; Sidibé et al., 2012).

4.3 | Future implication for vegetation

Between 1981 and 2015, most parts of western Eurasia are energy limited, and the vegetation growth is promoted by warmer temperatures via photosynthesis activity. However, as the climate is getting warmer, during the positive phase of NCP, we suggest here that the Eurasian ecosystem could reach a tipping point when warmer temperatures lead to a reduction in photosynthesis in the future (Moore et al., 2021; Slattery & Ort, 2019). In this case, many regions in Eurasia

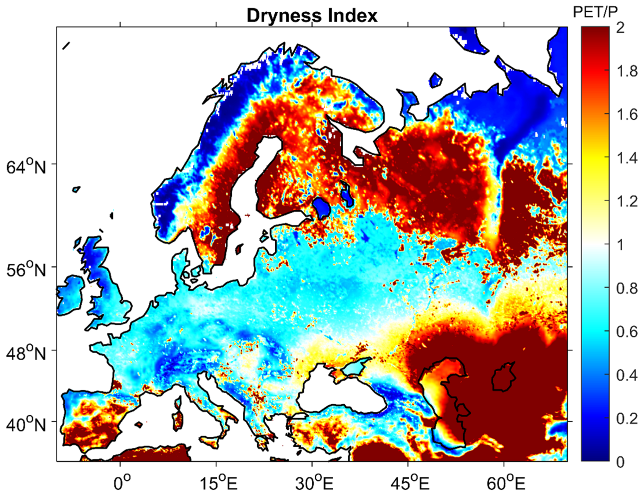

FIGURE 7 The Dryness Index pattern over WE between 1981 and 2015. Warm colours denote water-limited regions (i.e., DI > 1), and cool colours denote energy-limited regions (i.e., DI < 1)

will have a transition to water-limited ecosystems and be more sensitive to drought risk (Bhuiyan et al., 2017; Tello-Garca et al., 2020). Therefore, the greening trend of vegetation will be unlikely to be continued sustainably in the future. Similarly, Rajczak and Schär (2017) projected the decrease in precipitation in the future over central Europe and France, and the increased droughts negatively affect the forestry (Maracchi et al., 2005). However, based on the IPCC report (IPCC, 2021), both precipitation and temperature are increasing for the main part of our studied region under the global warming in the future, and such precipitation and temperature patterns can promote vegetation growth. Moreover, the climate impacts on vegetation can be quite different among regions related to the water-limited and energy-limited characteristics. Therefore, the future dynamic changes of vegetation in different regions need to be further studied.

5 | CONCLUSIONS

In this study, we aim at exploring the similarity and disparity between meteorological drought conditions and vegetation pattern, and the role of teleconnection patterns on vegetation during droughts across western Eurasia. Between 1981 and 2015, trends in the SPI-6 and NDVI indicate contrasting results across different regions of western Eurasia. Specifically, while in northern and southeastern regions, recent trends to wetter (drier) conditions are associated with an increase (decrease) in vegetation cover, other regions are paradoxically becoming greener while becoming drier. Such paradoxical patterns are found in energy-limited environmental systems based on the Budyko framework, where vegetation growth is primarily promoted by warmer temperature, enhancing photosynthesis activity. Moreover, the droughts and vegetation variability are suggested to be closely related to large-scale teleconnections. While previous studies have focused mostly on the impact of NAO, NCP, a relatively less studied teleconnections pattern, seems to explain better the variance of meteorological drought and vegetation response over western Eurasia.

The positive phases of NCP are demonstrated to contribute to the regional drying but greening trends over western Eurasia. Under the intensifying warming condition, due to the extra warmth brought by the positive phases of NCP, it will eventually lead the European ecosystem from energy limited to be water limited. As a result, the current trend of vegetation greening is unlikely to be sustained in the future. Overall, we demonstrate an approach for investigating and forecasting droughts and vegetation changes based on emerging eco-hydrological risk related to NCP which can be useful for regional land use and environment management.

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DATA AVAILABILITY STATEMENT

The NDVI data that support the findings of this study are available in the National Aeronautics and Space Administration (NASA) ARC ECOCAST (https://iridl.ldeo.columbia.edu/SOURCES/.NASA/.ARC/.ECOCAST/.GIMMS/.NDVI3g/.v1p0/index.html), and NASA Land Processes Distributed Active Archive Center (LP DAAC; https://e4ftl01.cr.usgs.gov/MOLT/MOD13C2.006/). The climate data that support the findings of this study are openly available in ERA5-Land monthly averaged data from 1981 to present at https://doi.org/10.24381/cds.68d2bb30, ERA5 monthly averaged data on single levels from 1979 to present at https://doi.org/10.24381/cds.f17050d7, the Climate Research Unit (CRU; https://crudata.uea.ac.uk/cru/data/hrg/).

ORCID

Qing He https://orcid.org/0000-0002-3401-5898
Bastien Dieppois https://orcid.org/0000-0001-7052-1483
Omer Yetemen https://orcid.org/0000-0003-1593-3519
Omer Lutfi Sen https://orcid.org/0000-0002-8186-8594
Julian Klaus https://orcid.org/0000-0002-6301-1634
Rémy Schoppach https://orcid.org/0000-0002-9500-7007
Ferat Çağlar https://orcid.org/0000-0002-2584-2883
Liang Chen https://orcid.org/0000-0003-3242-7124
Kwok Pan Chun https://orcid.org/0000-0001-9873-6240

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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