Remote Sensing of Vegetation Chlorophyll Content for Climate Modelling

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by

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Abstract

In the coming decades, there is prediction for an increasing greenhouse gases by unlimited degree Celsius. Thus, affecting many natural systems including the functioning of terrestrial key ecosystem within the biosphere. To understand such effects of exchange between the systems, the establishment of the relationship between the state of natural vegetation (productivity) and associated climate anomaly would be an advantage. In this study, the possibility of estimating the different phenological variables using MERIS MTCI time- series data, its relation with temperature anomaly and comparing with a process model, PnET for a period of 3 years in the UK was investigated. The spring and autumn anomalies were detected for 2003, 2004 and 2005 by taking the difference of the three years against the Long- Term Average (1961- 1990). Therefore, eight positive and two negative anomalies were identified in different years. The natural vegetation phenology variables (i.e.., start, end, length of the growing season and net productivity) were estimated for the "needle- leaved evergreen forest" and "mosaic of forest with either Shrub land or grassland" in these anomaly zones using MTCI. On the other hand, using the PnET model, the productivity of these two vegetation types was derived and comparison was made between the two output and their relationship with the anomaly during the study period.

The results showed that the "needle- leaved evergreen forest" does exhibit a low integrated MTCI value ranging from 20- 80 (unit less) and the magnitude vary with different years. The year 2005 was recorded to have the maximum MTCI value than in 2004 and in 2003 in conjunction with the anomaly. This suggests that there is an earlier onset of greenness in the spring and a delayed end of the season, thus a higher MTCI value in 2005 and 2004 than in 2003. Such relationship reveals that the spring and autumn anomalies of 2004 and 2005 are responsible for such a result. Moreover, the model output (NPP foliage) was also showing a strong positive relationship with the temperature anomaly in these two years, thus supporting the findings. Even the model derived NPP foliage and the integrated MTCI also show similar positive relationship, statistically (r^2 = 0.65). All these results showed similar observations that in 2004 and 2005, a higher net primary productivity was observed (in both Integrated MTCI and PnET Model) within "needle- leaved evergreen forest", for which the earlier start of onset of greenness and delayed end of season during the spring and autumn anomaly but with varying magnitude.

In conclusion, short- term temperature anomaly was found to have a positive relationship with the vegetation productivity as similar with those of long- term studies. Further, investigation within the "mosaic of forest with either Shrub land or grassland" was also carried out to see any different responses by different vegetation types. But, the result was not that much significant. However, there is a need for improvement (in the model parameter, phenology detection technique) for better accuracy and validate with the ground data.

Key Words: Vegetation Phenology, Productivity, Temperature Anomaly, MTCI, PnET model.

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Thirdly, I would like to wish a very happy and success to all my GEM 2007 classmates in their profession and personal life in the future. Hope we all can meet some other day (maybe through reliable Remotely Sensed Medium). Finally, I would like to express my gratitude to my loving parents and others for their encouragement and caring through the calls. Similarly, my heartfelt appreciation goes to my dear lady Anandini for her understanding, patience and above all, for her love.

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1. Introduction

1.1. Background and significance

Changes in Greenhouse gases (GHGs), aerosols (atmospheric concentrations), land cover, solar radiation does affect the nature of the climate system, resulting in increases in global mean temperature, climate variability and extreme events (IPCC 2007). It has been observed since 1850 that eleven of the last twelve years (1995- 2006) were among the 12 warmest years in context to the global surface temperatures recorded in IPCC 2007 report. Numerous short and long term changes in the aspects of climate is being observed at the different scales from continental, regional and ocean basin scales. It has been observed that the average temperature increases by 0.74 °C (0.56 to 0.92°C) in 1906- 2005 against the corresponding trend of 0.6 °C (0.4 to 0.8°C) in 1901-2000. And moreover, the linear warming trend over the 50 years from 1956 to 2005 is nearly twice than the 100 years from 1906 to 2005 (IPCC, 2007). On a global scale, there is an unequivocal distribution of the temperature trend particularly at higher northern latitudes and attained almost double the global average rate in the Arctic region in the past 100 years. Even the average temperature of the global ocean has increased from at least 3000 m depths since 1961. There is also a decreased observation in snow and ice extent in both the hemispheres which is also consistent with warming. A drastic change being observed in the precipitation pattern globally from 1900- 2005, with increased significantly in eastern parts of North and South America, northern Europe and northern and central Asia whereas precipitation declined in the Sahel, the Mediterranean, southern Africa and parts of southern Asia.

There is a discernible impact on physical and biological systems due to the changes in regional and global climate anomalies (particularly temperature and precipitation amounts). The other events such as earlier spring planting of agricultural crops and alterations in disturbances of forests due to fires and pests are also observed. The aspects related to human health concerning heat related mortality and dynamics of infectious disease vectors are the other effects of regional climate changes on human environments (IPCC 2007). In fact, many natural systems are being altered particularly in terrestrial ecosystems due to increase in temperature and changes in precipitation amount. There is a strong inter linkage between the chemical cycles, physical climate and the terrestrial biosphere. Hence, the prediction and analysis of climatic, environmental and ecological changes in the earth system is an extremely challenging task (IPCC, 2007).

One major component of terrestrial ecosystem, likely to be influenced by dynamic climatic anomalies is on patterns of terrestrial vegetation growth, timing of growing season, vigor and composition of the vegetation because of its spatial and temporal patterns being closely linked with climate in the form of energy, matter and heat exchange (IPCC 2007). There is a very high confidence in the terrestrial biological systems such as earlier timing of spring events (leaf- unfolding) and shifting of plant species towards the extreme hemispheres/ poles. Globally, vegetation covers almost 75% of the terrestrial surface. So, its characteristics, structure and functioning as a major carbon sink is an important theme to modeling ecosystem and energy cycles within our climate system such as global carbon cycle (Dixon et al., 1994). The quantification and monitoring of biophysical and biochemical characteristics of terrestrial vegetation is a prerequisite for the ecological studies (Asner, 1998). So, in order to reduce uncertainty in the global carbon cycle with changing climate thus, require repeatable and consistent measurement of the long-term monitoring of the global terrestrial productivity (Running et al., 2004) in which satellite remote sensing measurements are a prerequisite tool for addressing the impacts of pollution and climate change (Zhao et al., 2005). Because much more information is known about inter- annual variation in global climate (IPCC 2007) than about inter- annual variation in global Net Primary Productivity (NPP) (Turner et al., 2006). Therefore, these variations in NPP and its interactions with global climates have been regarded as one of the major focuses of ecosystem study in the past 3 decades (Hicke et al., 2002).

1.2. Vegetation phenology and factors affecting phenology

Of the terrestrial vegetation which reflects the impacts of the local to regional scale of climate change on vegetation is establish on the scaling of the different life stages of the vegetation or its phenology. It refers to the seasonal natural/ biological events such as the dates of the start of growth and the initiation of major developmental phases such as budding or flowering and senescence. Monitoring and understanding vegetation phenology are crucial because leaf phenology is a key driving factor in the annual vegetation carbon uptake (Baldocchi et al., 2001) which accounted for biotic processes such as NPP, thus quantifying carbon (forest) and water (atmosphere) exchange and its response to climate change. The vegetation phenological variables can be observed in different time scales for understanding its dynamics. Generally, vegetation communities follow seasonally driven phenologies in short term scale and typically end up in annual cycles. The vegetation phenological variables (for example, start of growing season, length of growing season) may respond quite differently on annual basis. The well established factors which controlled the vegetation phenological episodes are summarized as climatic variables/ fluctuations (for example, temperature and precipitation) and anthropogenic processes (for example, groundwater extraction) (Elmore et al., 2003). But annual phenological events may shift in longer time series due to inter- annual to decadal climate changes and large- scale human disturbance using either remote sensors (Myneni et al., 1997; Potter et al., 2003) or *in situ* stations (Sparks et al., 2000) in the UK. Thus, where temperature is the limiting factor to the vegetation growth, the inter- annual to long term phenological events are highly influenced by the mean temperature dynamics in the northern temperate regions (Zhou et al., 2001, Zhang et al., 2004). Similarly, the changing pattern of the precipitation amount is equally highly influencing the vegetation phenology in the areas such as those of the tropics (Zhang et al., 2006). In the Amazonian Rainforests, a seasonal swings in green leaf area of about 25% with the seasonal cycle timed to the seasonality of solar radiation in a manner - net leaf flushing (early to mid dry season) and net leaf abscission (the cloudy wet season) (Huete et al., 2006; Myneni et al., 2007). As Chen et al., (2005) highlighted temperature to be the most important controlling factor for vegetation phenology than the precipitation and photoperiod.

1.2.1. Vegetation productivity and factors affecting productivity

The phenological events of the leaf/ canopy have the capacity to affect the terrestrial vegetation in the form of vegetation productivity. For instance, more carbon gets sequestered via net primary productivity production of terrestrial vegetation and the amount of carbon released by soil respiration, which determines the annual flux between the atmosphere and land biosphere. This difference of the flux is the result of the enhanced productivity/ lengthening of the growing seasons which alter the global carbon cycle (Zhou et al., 2001). The different factors responsible for the vegetation productivity (NPP) that are subject to changes are due to response to human activities (e.g., land-use), climate change and environmental factors such as episodic events (e.g., El Nino' (ENSO), large- scale atmospheric perturbations from volcanic eruptions, fire). However, as a key component of the terrestrial carbon cycle and ecosystem process, terrestrial NPP has uniquely integrated with climatic, ecological and human- induced factors, its alteration greatly affects on the global carbon cycle (Nemani et al., 2003). Thus, accurate estimation of the vegetation productivity is a key input for Earth system models that are concerned with the water fluxes and global carbon cycle (Running and Nemani, 1991) as an indicator of ecosystem functions.

1.2.2. Linkage between phenology and productivity

Annual NPP is determined by the spatial distribution of vegetation and its photosynthetic activity (phenology) throughout the year. Generally the response of vegetation to the climate dynamism is evident across different spatial/temporal scales viz., climatic factors such as temperature, radiation and precipitation restricts complex limitations to plant growth in different regions (Churkina et al., 1998; Nemani et al., 2003). The link between the terrestrial vegetation phenology and its productivity is witnessed by its spatial relationships and shifts at different rates. For instance, onset of growing season, end of the growing season and length of the growing season appears to be of special interest for computation of the net primary productivity (White et al., 1999). The process involving changes in the rates of photosynthesis and decomposition in the short- term is found at local scale whereas at a regional to global scale in the long- term (decade to thousands of years) such activities and vegetation distribution might lead to annual variation of the NPP via terrestrial carbon sink.

1.2.3. Measurements of vegetation phenology and productivity

Traditionally, vegetation phenology was derived directly from ***in situ*** observations based on native plant phenological data and indirectly from climate data driven-phenological models based on cloned (genetically identical) plant data using interpolation techniques. However, extrapolations from such limited number of *in situ* sites and interpolations from the global and continental scales may result in inadequate representation and loss of information and provide a limited scope for such studies of vegetation responses using climate anomalies at ecosystem level (Zhang *et al*., 2006). Another method which is more appropriate for studying land vegetation in different spatial and temporal observation is derived from **satellite remote sensing**. Thus, a combination of remote sensing technology and *in- situ* data provides a potential tool for studying the impacts of climate change on terrestrial vegetation phenology and productivity on an ecosystem level because of its repetitive, synoptic view from the space and due to interaction of solar radiation with the plant canopy.

1.2.3.1. Remote Sensing of vegetation phenology and productivity

The traditional coarse spatial resolution data Advanced Very High Resolution Radiometer (AVHRR) derived Normalized Difference Vegetation Index (NDVI) with 1 km moderate spatial resolution onboard the National Oceanic and Atmospheric Administration (NOAA) series- 7, 9, 11 and 14 satellite provided the ever long term global temporal for vegetation and for identifying phenological events in vegetation communities (Tucker et al., 2005). Different techniques have been developed for measurement of phenological dates of plants using satellite-derived data such as NDVI and other Vegetation Indices (Reed et al., 1994; Zhou et al., 2001). Because NDVI seemed to be more suited for studies related to plant's photosynthetic capacity (e.g., fPAR). A major scientific achievement by Myneni et al., (1997) addresses the phenological advancement (leaf onset) over a decade (1981-1991) in the northern latitudes using AVHRR derived composite NDVI in relation with warmer air temperature. According to Zhou et al., (2001), the only source for accessing the seasonal- to decadal- scale dynamics in terrestrial vegetation globally is obtained from AVHRR derived NDVI. Recently, the study conducted by using a combination of the climatic data and Moderate Resolution Imaging Spectroradiometer (MODIS) data could precisely detect the different phenological stages of the vegetation (Zhang et al., 2004). In particular, the MODIS at spatial resolutions viz., 250 m, 500 m and 1 km globally have provided a new era of data products for monitoring globally ecosystem dynamics with substantially improved geometric, atmospherically corrected and radiometric properties over the AVHRR data.

In general, the direct estimation of the vegetation productivity on broad spatial scales cannot be considered and recently, remote sensing technology has been recognized as an appropriate tool for monitoring land vegetation at better spatial and temporal scales. However, satellite data derived from AVHRR, SeaWiFS, VEGETATION and MODIS now had increasingly used to draw the NPP of vegetation at 1 km spatial resolution (Turner et al., 2006). Because 20% of energy in the visible range (0.5- 0.7 µm) while 60 % in the near infrared (0.7- 1.3 µm) of the spectrum gets reflected by the green vegetation and the differential reflectance between these two bands depicted a sensitive indicator of green vegetation. Using the maximum value compositing technique, the state of the vegetation productivity (start, senescence and length of growing season) is best represented by the maximum NDVI in the compositing period (Holben, 1986). On a global scale, the primary source of remotely based gross primary productivity is derived from the MODIS product MOD17 (8- day) having 1 km spatial resolution based on the fraction of photosynthetically active radiation (fPAR) (Running et al., 2004). The NDVI due to its strong sensitivity to vegetation characteristics such as the amount of photosynthetically active radiation and LAI have been used for more than two decades for describing vegetation productivity. Previously, the interannual NPP was depicted using long- term climatic records and a fixed global vegetation map.

To infer the vegetation productivity, at a regional to local scale, the foliar biochemical content such as chlorophyll content and nitrogen concentration can be estimated using narrow visible/ near visible wavebands using remotely sensing data (Curran et al., 1997). The levels of chlorophyll content and nitrogen act as an indicator of plant productivity, stress and nutrients availability (Curran, 1989) because the energy absorbed by the vegetation can only be transferred to the dark reaction of the photosynthesis by the chlorophyll. Therefore, for an operational estimation of the vegetation productivity based on remotely sensed data, an accurate remote estimation of chlorophyll content is necessary. There are a wide number of the spectral indices computed from the visible and red edge spectral regions, successfully used to measure chlorophyll content from leaf optical properties (Zarco-Tejada et al., 2001). But, they are not appropriate at the canopy level due to the strong spectral signature influenced by soil background and the variations of Leaf Area Index (LAI) at different vegetation growth stages. Moreover, some of them display low relationships with vegetation pigments.

1.2.4. Model (use of RS and other features as inputs/ factors)

Traditionally ecological studies have focused on in situ observations of specific species derived from individual sites, which need to address across regional to global scales for providing the broader insight of the entire earth system. So, in order to extrapolate the *in- situ* observations and linked up with remote sensing technology method for the estimation of the real time monitoring of the physical processes such as terrestrial vegetation productivity more precisely, a number of the ecological and climatic models based productivity models are developed. Therefore, models are a fundamental tool which serves as an important input for designing future satellite- sensor missions. At the regional or global scales, a number of the ecological models for vegetation productivity/ NPP are developed using the remotely sensed data as inputs (e.g., AVHRR derived NDVI) and provide reference values for validation of the model outputs, at the desired temporal scales (Turner et al., 2006). The Carnegie Ames Stanford Approach model (CASA) based on light use efficiency (LUE) (Malmstron et al., 1997), Photosynthetic and Evapotransiration model (PnET) (Aber and Federer, 1992), Biome BioGeochemical Cycles (BIOME- BGC) (Running and Hunt, 1993) and Physiological Principles in Predicting Growth (3-PG) (Landsberg and Waring, 1997) are some of the well- established ecological based models. These physically- based resulting models can then be inverted against multispectral measurements of surface reflectance using ANNs (Artificial Neural Networks) and LUTs (Look- up Tables) methods to retrieve models' driving parameters (i.e., biophysical properties of the reflecting surfaces).

1.3. Research problem statement

Following the background, a scientific investigation to understand the dynamism of the climate change with reference to the terrestrial ecosystem will be carried out using remotely sensed data. There is a need for understanding the effect of climate change on ecosystem at a regional to global scale. Changes in vegetation productivity and carbon dynamics are very hard to estimate and predict directly in different scales from local to global estimates. As mentioned earlier, most of these studies concerning the phenological variables and productivity with respect to climatic variables are concerned using only those data averaged over a long period of usually a decade or two (Piao et al., 2006, Maignan et al., 2008). Such data/ studies hampered the uncertainties associated with extreme climatic events such as seasonal temperature anomalies due to the averaging over a long period of time (Reed et al., 2003). On the other hand, the outstanding warm autumn is recorded in Europe in 2006 and the year 2005 being the warmest year on record according to IPCC Report, 2007. In context to this, there is a need to understand and establish a relationship between the short term period with pronounced climatic anomalies (temperature) with the state of vegetation (productivity) at ecosystem level and compare the results using the long-term average data. Keeping view of the above shortcomings in the quality of the data, this scientific study will investigate and quantify the vegetation productivity (NPP) of the UK sites using time series MERIS MTCI and the Photosynthetic and Evapotransiration model (PnET) (Aber and Federer, 1992) as an alternative and better technique.

1.4. Research Objective

1.4.1. General objective

The overall main objective of this research is to understand the effects of climate varaibles on vegetation and its responses on short term changes through chlorophyll/ productivity estimation using MERIS MTCI.

1.4.2. Specific objective

To achieve the main general objective of the study, the following specfic parts will be investigated for a peer scientific research:

- To estimate productivity using chlorophyll content measures from MTCI time series.
- To compare MTCI derived productivity with the output derived from vegetation growth model (PnET developed by Aber and Federer, 1992).
- To quantify the effect of meteorological variables on vegetation productivity using statistical regression.

1.5 Research Questions

- Is it possible to estimate vegetation productivity using composite MTCI time series?
- Is there a difference between the productivity derived using time series composite MTCI and PnET model for different natural vegetation type such as needle- leaved coniferous?
- Can the influence on vegetation productivity by climate varaiables be quantified using statistical regression?

1.6. Research Hypothesis

Hypothesis 1

Estimating vegetation productivity using composite MTCI time series.

H_0: Vegetation productivity using composite MTCI time series cannot be predicted.

H_1: Vegetation productivity can be predicted using composite MTCI time series.

Hypothesis 2

Comparing composite MTCI derived productivity with the output derived from PnET model.

H_0: There is no difference between the productivity using MTCI time series and PnET model.

H_1: Composite MTCI time series productivity vary with PnET model output.

Hypothesis 3

Determining the effect of temperature variables on vegetation productivity using statistical regression.

H_0: There is no effect on vegetation productivity by temperature variables using statistical regression.

H_1: Vegetation productivity is affected by temperature variables using statistical regression.

1.7. Research approach

The annual time series of MERIS MTCI (8 days composite- 1 Km spatial resolution data) 2003- 2006 will be used for extracting phenological variables (for example, start of growing season, duration of growing season and end of growing season) of vegetation. Time integrated MTCI over the growing season will be used to estimate *surrogate* of vegetation productivity. On the contrary, spatial version of PnET model (Photosynthetic and Evapo-transpiration), a dynamic; process-based forest growth model will be used for producing vegetation productivity in the form of NPP of 1 km as output on regional basis, defined by a spatial grid of values. The parameters such as annual temperature, annual precipitation, soil, elevation, satellite derived NDVI and land cover data will be used as potential inputs in this PnET model. The productivity output from the PnET model and MTCI will be compared for checking whether the MTCI output is either valid or not and explore the reason if any mismatch result is observed. From the above observation, analyzing and developing a relationship between climatic variables and MTCI derived productivity will be carried out and thus, through statistical regression, this relationship will be captured. From this relationship, the surrogating/ indicator productivity output from composite MTCI will be regressed against annual temperature and annual precipitation (3 years). Therefore, the key aim is to capture the short term climatic anomalies and to see the nature of the relationship (for example, whether dependent on the vegetation type and their spatial distribution).

2. Materials and Methods

2.1. Study area

For conducting this study, the terrestrial natural vegetation types of United Kingdom will be focused on as shown in figure 1. This region was chosen based on climate data as the year 2006 was recorded to be the warmest mean temperature in the whole of Europe from 1659 – 2008 using Long Term Average data (http://badc.nerc.ac.uk/browse/badc/ukmo-cet/data/monthly/max). The average monthly maximum temperature in spring season was recorded to 25.6 ºC in July, 2006 (against 19.5 ºC in 1983) and 20.9 ºC was recorded as the average monthly maximum temperature for autumn season in September 2006 (against 16.6 ºC in 1729) (http://badc.nerc.ac.uk/browse/badc/ukmo-cet/data/monthly/max).

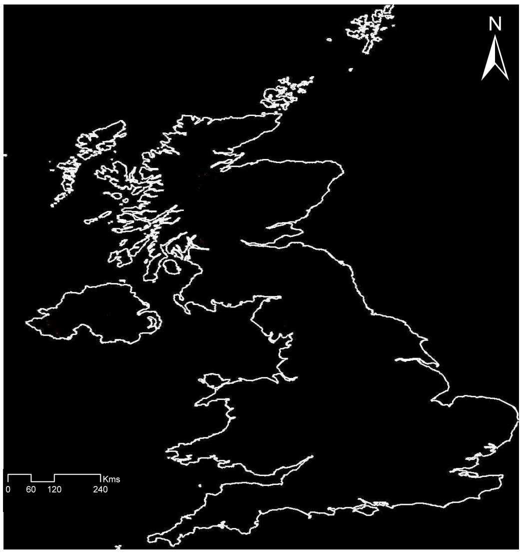


Fig.1. Study area (United Kingdom)

2.2. Data Description

For the analysis of the phenological behavior of terrestrial natural vegetation, a combination of the climatic parameters and other physical variables such as elevation and soil condition were considered. Apart from these, the remotely sensed data either captured by satellite sensor or aerial flight has become one of the pre- requisite for such studies. The product such as NDVI and other VI's has been used by the researcher for detecting the different phenological dates of the different vegetation types. Moreover, such indices were profoundly used to relate with the woody biomass and vegetation productivity. However, a quick saturation in the NDVI values has been observed in estimating and prediction of the biomass. Thus for this study, estimation of vegetation phenological variables and productivity, the MERIS Terrestrial Chlorophyll Index (MTCI) was used.

The state of vegetation and NPP can be indicated using the MERIS Terrestrial Chlorophyll Index (MTCI) (Dash and Curran, 2004) time series analysis. These phenology variables as derieved using MTCI, can then be linked up with the meterological variables collected from climate. Moreover, a strong positive correlation between temperature and MTCI was seen (Almond et al., 2007).

2.2.1. MERIS Terrestrial Chlorophyll Index (MTCI)

For this study, European regional MTCI data were downloaded from the NERC Observation Data Centre, UK website (www.neodc.rl.ac.uk). It has 1 km spatial resolution The MTCI data are processed and archived by European Space Agency (ESA) in different levels viz., Level 2 and 3; depicting the amount of processing that the original data has undergone and the accuracy of the product. Therefore, Level 3 data was chosen as it was presumed to be more accurate. The composite data was produced by combining individual passes (or swathes) of data into single composite products. The composite is usually organized by using large sample size of the data (http://l3-server.infoterra.co.uk/L3webPages/resources.html).

The MTCI data was derived using MEdium Resolution Imaging Spectrometer (MERIS) sensor. It is an advanced optical sensor, one of the payload components of the European Space Agency's (ESA) environmental research satellite Envisat, launched in March 2002. It contains 15 spectral bands which are designed to acquire data at variable bandwidth of 2.5*nm* to 20*nm* over the spectral range of 390*nm*–1040*nm*. This makes MERIS a potentially valuable sensor for monitoring of terrestrial vegetation from regional to global scales (Rast et al. 1999). In the standard band setting, MERIS has five discontinuous wavebands in red and infrared wavelengths with band centres at 665, 681.25, 708.75, 753.75 and 760.625 nm. MTCI is defined as the ratio of the difference in reflectance between band 10 (753.75 nm) and 9 (708.75 nm) and the difference in reflectance between band 9 and 8 (681.25 nm) of the MERIS standard band setting (Dash and Curran, 2004) as

$$MTCI = (\rho_{Band10} - \rho_{Band9}) / (\rho_{Band9} + (\rho_{Band8})$$

$$= (\rho_{753.75} - \rho_{708.75}) / (\rho_{708.75} + \rho_{681.25})$$

The MTCI has the advantage of being easy to calculate from MERIS data recorded at the standard band setting and being sensitive to a wide range of vegetation chlorophyll contents (Dash and Curran, 2004). MTCI composites can be used to derive terrestrial vegetation chlorophyll content in space and time, which can be used to estimate vegetation state and its productivity (Curran et al., 2007) and to finally generate a 'global productivity map'.

2.2.2. GlobCover Land Cover map

The GlobCover land Cover Map was downloaded from ESA GCAT website (www.esa.int/due/ionia/globcover). This global product was used in this study keeping view of the standardization requirement for easy comparison of results across regions.

This GlobCover product was created using time- series ENVISAT's Medium Resolution Imaging Spectrometer (MERIS) between December 2004 and June 2006. It was based on Level 1B Full Resolution mosaics of 300 m spatial resolution. GlobCover is a product on a 5º X 5º in a Geographic projection and the data has been re-sampled on a path- oriented grid with pixels being calibrated to Top Of Atmosphere (TOA) radiance.

The GlobCover map was created using various automatic and regionally- tuned classification schemes. The approach had the advantage of making the product more accurate than any other such as Global Land Cover Map (GLC 2000) due to local expert knowledge. It has 22 classes grouped together and labeled into a global legend system supported by UN Land Cover Classification System (LCCS) with reference from other sources such as the GLC 2000, the Corine Land Cover map and the National Land Cover Database.

2.2.3. Shuttle Radar Topography Mission Digital Elevation Model (DEM)

The Digital Elevation Model (DEM) data acquired by Shuttle Radar Topography Mission (SRTM) with 3 arc-second resolution (90 meter) of UK region were downloaded from the Global Land Cover Facility- ES Data Interface website (glcf.umiacs.umd.edu/data/srtm). The data is available in both an unedited and an edited format. For this study, the second generation edited SRTM DTED Level 2 product was used for its quality assurance (correction of spikes and wells, filling of small voids, flattening of water bodies).

The DEM data was derived using X- band and C- band (λ = 5.6 cm) radar data from a single- pass, across- track Interferometric Synthetic Aperture Radar (IFSAR). There are two data capture resolutions where 1 arc second (30 m) original data were available for United States locations and 3 arc- second (90 m) for global scenario (Smith and Sandwell, 2003).

2.2.4. UKCIP gridded data- Monthly Max, Min and Mean Temperature

The monthly gridded maximum, minimum, mean temperature (2003- 2005) and Long- Term Average (1961-1990) data having 5 km * 5 km spatial resolution were downloaded from Met Office, UK Climate Impacts Programme (UKCIP), (http://www.metoffice.gov.uk/research/hadleycentre/obsdata/ukcip/index.html). This data have been created in geographical information system (GIS) with combined multiple regression (topographic and geographic variables) and inverse- distant weighted interpolation process (local variations) using 540 weather stations. However, the impacts of a changing station network cannot be entirely removed, especially in topographical variable areas.

The gridded datasets of climatic variables such as monthly mean temperature, maximum temperature and minimum temperature are in an increasing demand for the ecological, climate change scenario and verification of climate modeling (Perry and Hollis, 2005).

2.2.5. UKCIP gridded data- Annual Precipitation

The monthly gridded precipitation (2003- 2005) and Long- Term Average (1961- 1990) data having 5 km * 5 km spatial resolution were downloaded from Met Office, UK Climate Impacts Programme (UKCIP), (http://www.metoffice.gov.uk/research/hadleycentre/obsdata/ukcip/index.html). This data have been created in geographical information system (GIS) similar to the temperature using approximately 4400 weather stations across UK.

2.2.6. Photosynthetically Active radiation (PAR)

Chlorophyll present in photosynthetic cells of plants and algae harvested radiation in the visible region of the solar spectrum ranging from 0.4 – 0.7 μm wavelength (Larcher, 2003). The vegetation used this visible range for enhancing photosynthesis process referred to as photosynthetically active radiation (PAR). According to Howell et al., (1983) PAR is related to global solar radiation (H) and it exists a relationship between clearness index K_T derived from daily extraterrestrial radiation (H_o) and relative sunshine S. Thus, this relationship leads to have a relationship between 'PAR clearness index' and S.

Thus, for estimating the PAR data of the United Kingdom using the above algorithm, the monthly total sunshine hour data for 26 weather stations viz., Armagh, Bradford, Cambridge, Oxford, Greenwich, Tiree, Durham and Lerwick located across the United Kingdom were downloaded from the UK Met Office website (http://www.metoffice.gov.uk/climate/uk/stationdata) for 2003, 2004 and 2005 respectively. But, only 15 stations were having the monthly total sunshine hour data and the rest sites were closed after 2000. These data were measured using an automatic Kipp & Zonen sensor and a Campbell Stokes recorder (Met Office).

2.2.7. Soil Water holding capacity

Soil data for estimating soil water holding capacity of UK were obtained from the International Soil Reference and Information Centre (ISRIC) and World Inventory of Soil Emission Potentials (WISE) derived global soil properties dataset website (http://www.isric.org/UK/About+Soils/Soil+data/Geographic+data/Global/WISE5by5minutes.htm) having a 5 by 5 arc- minutes global grid (spatial resolution). The data was created based on the soil distribution of FAO-UNESCO Soil Map of the World and global ISRIC- WISE soil profile database (1:5 million scale). This dataset consists of nineteen soil variables (viz., soil drainage class, organic carbon content, C/N ratio, water pH and available water capacity) required for crop growth simulation- modeling and analysis of global environmental change (Batjes, 2006).

2.3. Photosynthetic and Evapotranspiration model (PnET)

Photosynthetic and Evapotranspiration model (PnET) is a simple, lumped-parameter, monthly time- step model of carbon and water balances of forests built on two principal relationships: 1) maximum photosynthetic rate is a function of foliar nitrogen concentration, and 2) stomatal conductance is a function of photosynthetic rate. The model has been validated against field data from 10 well-studied temperate and boreal forest ecosystems for supporting the central hypothesis that aggregations of climatic and biological data do not cause a significant loss of information to long-term mean ecosystem responses (Aber and Federer, 1992). This PnET approach which combined a high resolution GIS with statistical models can provide a regional to continental wide estimates of forest NPP and terrestrial carbon flux (Ollinger et al., 1998; Aber et al., 1995). The important input parameters include digital elevation model (DEM), land use or land cover map, mean monthly climatic variables (temperature and precipitation), soil water holding capacity and PAR.

There are three versions of the PnET model based on the type of study and uses similar input variables and identical algorithms wherever possible. The first version PnET- Day works on a daily time step model of forest canopy carbon balance using point/ site data. Initially developed for validating the photosynthetic algorithms derived from the model against daily carbon flux data in Harvard Forest, MA, USA. The second version PnET-II is a monthly step model, an improved version of the original PnET model (Aber and Federer, 1992) which incorporates the photosynthesis routines from PnET- Day with respiration process (including soil respiration), allocation and a full water balance system. The latest version PnET- CN encompasses litter production and decomposition routines with Nitrogen cycling to all processes including mineralization, nitrification and nitrate leaching. The effect of CO2 and troposphere ozone has also been incorporated in PnET- CN, which interacts with N deposition, land- use history and other factors.

For this study, the PnET-II version which works in grid format using the vegetation variables in a .SIT file with climatic variables (.CLM file) was used for the estimation of the vegetation productivity of the United Kingdom.

2.4. Data analysis and Modeling Framework

The data analysis and modeling was analyzed according to the flowchart as shown below in figure 2 and the PnET model as shown in figure 3.

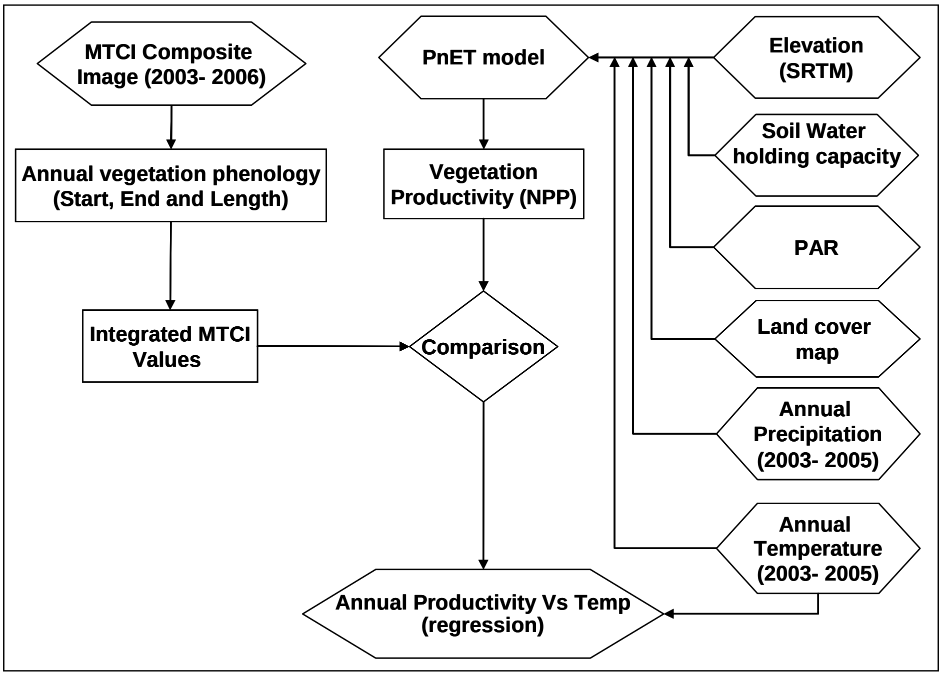


Fig. 2: A Paradigm of the analysis

PAR Model

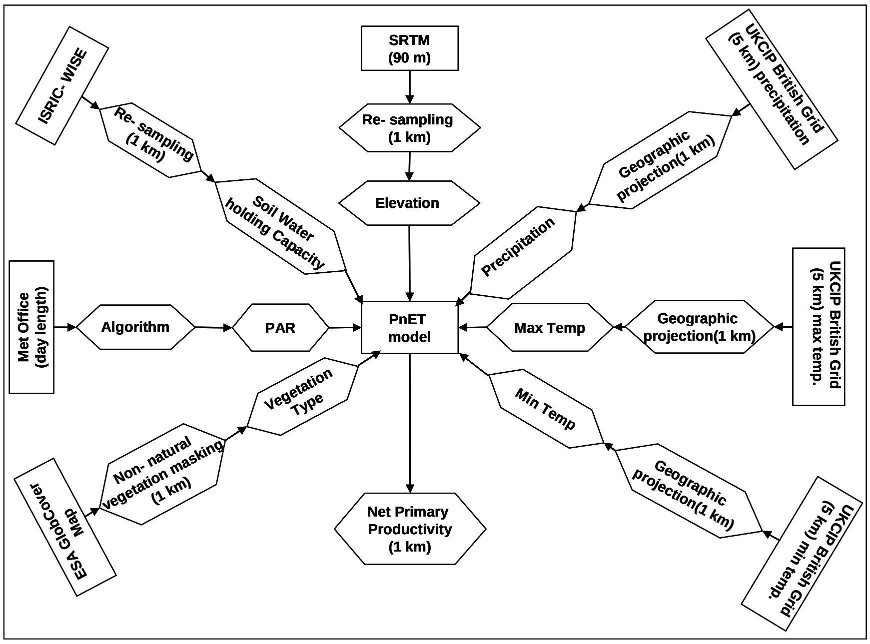


Fig. 3: PnET model analysis

2.5. Data Pre- processing

2.5.1. MTCI data Pre- processing

MTCI data required a number of processing before it could be used to extract the different phenological variables and estimate productivity of the terrestrial vegetation.
Layer stacking of the eight day composites to annual images (that is, from January to December) from 2003- 2005 was done and then masked to United Kingdom region for this study. The stacked MTCI data were then processed for cloud or gap removal followed by smoothing of the data using Fourier transformation technique.

The resultant stacked MTCI datasets were eventually used for the extraction of the maximum MTCI and minimum MTCI. Different phenological variables of each of the vegetation classes were then estimated as ‘start of the growing season’, ‘end of the growing season’, ‘length of the growing season’. The estimated length of the growing season was further used to develop the integrated MTCI values for each of the vegetation classes.

2.5.2. GlobCover Land Cover Map data Pre- processing

The processing of this dataset involves the extraction of the study area and separation of the map into Natural and Semi- natural Terrestrial vegetation (woody/ Trees, shrub and herbaceous) and non- natural vegetation classes (cultivated areas, urban areas, artificial surfaces and inland waters bodies). Amongst the 22 land cover global classes, only 9 natural and semi- natural terrestrial vegetation classes were found in UK as needle- leaved evergreen forest, broad- leaved deciduous forest, mosaic of forest with either Shrub land or grassland, mosaic of grassland with either forest or shrub land, herbaceous vegetation , Shrub land, Mixed Broad- leaved needle forest, grassland and sparse vegetation. Out of these, mosaic of forest with either shrub land or grassland and Grassland occupy the larger area respectively.

2.5.3. SRTM DEM data Pre- processing

The SRTM DEM data was also geo- referenced to Geographic Projection using Cubic Convolution re- sampling technique with 1 Km pixel size to line up with the other datasets, for using as an input in the PnET model.

2.5.4. Annual Monthly Temperature data Pre- processing

These dataset were first geo- referenced to the British National Grid co-ordinates to line up with the other datasets. For using these variables as an input in the PnET model, the maximum and minimum temperature datasets from 2003- 2005 were geo- referenced to Geographic Projection using Cubic Convolution re- sampling technique with 1 Km pixel size. In order to know the trend of the annual temperature in view of the anomaly, the geo- referencing of mean temperature (2003- 2005) into Geographic Projection with 1 Km pixel size was carried out and the difference of the mean temperature (2003, 2004 and 2005) and Long Term Average (1961- 1990) was calculated as shown in the figure 3.

2.5.5. Annual Monthly Precipitation data Pre- processing

These dataset are first geo- referenced to the British National Grid co-ordinates and later geo- referenced to Geographic Projection using Cubic Convolution re- sampling technique at 1 Km spatial resolution to line up with the other datasets and to be used as an input for PnET model.

2.6.6. PAR

For estimating the PAR data of the UK, the following calculations were done using a program written in MATLAB.

Determination of H_0 and N_0

H_o (the daily extraterrestrial radiation) is evaluated from the equation (Iqbal, 1983):

$H_o = (24/\pi)\, I_{sc}\, E_0\, \{(\pi/180)\, \omega_s\, (\sin\delta \sin Ø) + (\cos\delta \cos Ø \sin\omega_s)\}$, (1)

where I_{sc} = solar constant in energy unit = 4921 kJ/m^2/h = 1367 W/m^2; E_0 = eccentricity correction factor of the Earth's orbit; δ = the solar declination; ω_s = sunrise hour angle; and Ø = geographical latitude.

According to Spencer (1971):

$E_0 = 1.000110 + 0.034221 \cos\Gamma + 0.000128 \sin\Gamma + 0.000719 \cos 2\Gamma + 0.000077 \sin 2\Gamma$, (2)

where Γ = day angle (radian) and is defined by:

$\Gamma = 2\pi (d_n - 1)/365$, (3)

where d_n = the day number of the year.

Solar declination is evaluated according to Spencer (1971) by:

$\delta = 0.006918 - 0.399912 \cos\Gamma + 0.070257 \sin\Gamma - 0.006758 \cos 2\Gamma + 0.000907 \sin 2\Gamma - 0.002697 \cos 3\Gamma + 0.00148 \sin 3\Gamma)\,(180/\pi)$. (4)

The sunrise hour angle, ω_s, is evaluated using:

$\omega_s = \cos^{-1}(-\tan Ø \tan\delta)$. (5)

The daylength, $N0$ (= 2 ω_s) when expressed in hours as follows:

$N_0 = 2/15 \cos^{-1}(-\tan Ø \tan\delta)$. (6)

Thus, using the monthly total sunshine hour data for 15 weather stations across the UK for 2003, 2004 and 2005 respectively and using the above algorithm, the PAR data were estimated and these values at the locations were interpolated using the Kriging method (ordinary) at 1 km pixel size. Further, the estimated monthly PAR raster layers were layer stacked for 2003, 2004 and 2005 accordingly.

2.6.7. Soil Water holding capacity

The soil available water capacity data of the UK were extracted from the global soil map and re- projected to Geographic projection at 1 km spatial resolution for further analysis.

2.6. Data Analysis Methods

2.6.1. Detection of Temperature Anomaly zones in the UK region

The temperature anomaly zones of the UK region were derived using the monthly mean temperatures of 2003, 2004 and 2005 against the Long Term Average (LTA) resulting from the pre- processing done as described in the section 2. 4. 1. as summarized in the Figure 6. This was done for all the pixel for each month in a year and the calculation was performed using an equation in the form of band math written in ENVI as:

Temperature Anomaly = *float* (b1) – *float* (b2)

Where b1 = the mean temperature value of a pixel in 2003, 2004 and 2005 and b2 = the LTA value.

The above band math was applied starting to mean temperature data with the year 2003 then 2004 and 2005. And to get the anomaly value for pixels of the year 2003, the mean temperature 2003 layer stack was taken to be band 1 and the LTA as the band 2 and similarly for 2004 and 2005.

In order to adjust with the errors that are associated from the above procedure, the removal of those pixels having a zero value was done using a band math written in ENVI as:
Valid pixel = (B1 >0) and (B2 >0) and (B3> 0)
Where B1, B2 and B3 are pixel values for 2003, 2004 and 2005 respectively.

This result in masking of pixels which had all the values greater than 0 to be assigned a value of 1 and the rest which do not meet this criterion were assigned a value of 0. Then, this mask were multiplied with the temperature anomaly values, ensuring that only the validated anomaly values were used in deriving the desired anomaly zones.

Finally, to extract the anomaly zones from the mean temperature images, setting of the temperature threshold above and below a range was developed. For positive anomaly, it was set to +1.5 to +3.0 ºC and negative as -1.5 to -3.0 ºC in all the images of 2003, 2004 and 2005.

The anomaly zones were extracted from the mean temperatures of 2003, 2004 and 2005 respectively using the above threshold for the spring season (March, April and May) and autumn season (September, October and November).

2.6.2. Estimation of vegetation phenology variables in the anomaly zones using MTCI time series data

There are a several methodological approaches which present the vegetation phenological parameters quantitatively using remotely sensed data since the nineties. However, these methods can be grouped into three broad categories viz., threshold- based methods, inflection point methods and trend derivative methods (Reed et al., 2003).

Threshold based method uses either a pre- defined or relative reference value for extracting the start and end of the growing season. For instance, White (1997) used an NDVI value of 0.5 as the threshold value for defining the different phenological variables derived from AVHRR NDVI value. This method is effective only with less number of vegetation types as the threshold value will vary depending on the vegetation cover type (Reed, 1994).

Curve derivative phenology method use to identify points where the data exhibit a rapid increase between original vegetation temporal signal data and a derivative curve data (Reed et al., 2003). For instance, the different phenological variables are estimated using a backward – looking or delayed moving average (DMA) curve derivative method (Reed et al., 1994). The most critical part in this method is the selection of a moving average time interval where a lesser sensitive trend detector is being observed with large time intervals and vice- versa (Reed et al., 1994).

Inflection point phenology method seeks detection of points with maximum curvature in a time series NDVI data (Zhang et al., 2003). Thus, the points with the maximal curvatures signify occurring of the different

phenological phases. In this method, the start of the growing season is defined as the point where the derivative of the NDVI time series changes from a null to a positive value and the point where the derivative of the NDVI time series changes from a negative to a null is defined as end of the growing season (Reed et al., 2003). The ability to discriminate multiple growing seasons amongst the land cover types with multiple growth seasons e.g., crops (Reed et al., 2003), makes this method an advantage over the other mentioned approaches.

For this study, the inflection point phenology method was implemented. Initially, masking of the non- natural vegetation classes were employed in the GlobCover map covering UK region and this layer was used to extract the dominant natural vegetation classes from the raw time- series MTCI signatures. As raw MTCI time- series were contaminated with data processing errors (unidentified cloud shadows and geo- location errors). So, each time series required a process of “gap- filling” and smoothening, before the different phenological variables could be estimated.

Although the composited data is largely cloud free (Holben, 1986), but are associated with noise as a result of compositing and re- sampling disturbances leading to sinusoidal waveform time series data. For the smoothening of the raw data, different techniques are used; to name a few includes Median filters (VanDjik et al., 1987), splines and weighted least- square approach (White et al., 1997) and recently Discrete Fourier Transformation (DFT) (Jakubauskas et al., 2001). Whatever smoothening technique is employed, the signal should retain its temporal nuances and sustain representative of the condition of the vegetation state. During the process of transformation in the DFT approach, there is no creation or lost of information in the temporal profile and the original temporal data can be recovered from the knowledge of the Fourier transform and vice- versa (Geerken et al., 2005).

The DFT decomposes a time- dependent periodic signal into a series of constituent sinusoidal functions, each defined by a unique amplitude and phase value (Jakubauskas et al., 2001). These individual sinusoidal and their frequencies are then amalgamated inversely giving a complex waveform, thus removing the associated noise and retaining the smoothed temporal data.

The first two harmonics of the Fourier transformation usually accounts for 50- 90 % of the data variability (Geerken et al., 2005). In this case, vegetation growth cycle in the MTCI temporal series. Inverse Fourier transformation using the first two harmonics alone has been used successfully using NDVI profile for crop type identification (Jakubauskas et al., 2001), different agro- ecological zones and broad land cover types (Greeken et al., 2005). The vegetation phenology related information exists within the first five harmonics with higher order harmonics dominated by noise (Greeken et al., 2005). Therefore, in this study, Inverse Fourier Transformation was applied on the first five harmonics in ArcGIS to produce smoothed spatial coverage MTCI time series data for the vegetation classes in the anomaly zones. Thus, the implementation of the Fourier transformation and its inverse was done using a program written in ArcGIS software.

From the resulting smoothed MTCI time series data, a number of phenological variables (Table 1) were estimated for the dominant vegetation classes in the anomaly zones using the point inflection phenology method.

Table 1: Seasonal MTCI variables and their phenological interpretation (adapted from Reed et al., 1994).

Phenology Variable	Phenological interpretation
Start of growing season	Beginning of measurable photosynthesis
End of growing season	Cessation of measurable photosynthesis
Length of growing season	Duration of photosynthetic activity
Maximum MTCI	Maximum measurable level of photosynthetic activity
Time- integrated MTCI	Net primary production

For implementing the point inflection method using a program written in ArcGIS software the start of growing season was defined as the point where the rate of change of MTCI values changes from negative to positive value and stays positive consistently and when the rate of change in MTCI values changes in MTCI values changes from negative to zero or positive value in the smoothed time series MTCI data (Fig. 4).
The length of growing season was calculated by subtracting the start of growing season from the end of the growing season. The peak point of MTCI time series was taken as the maximum MTCI value. And the net primary productivity was estimated as an integration of the individual MTCI time series that fall within the interval of growing season i.e., the area under the MTCI time series curve (Reed et al., 1994).

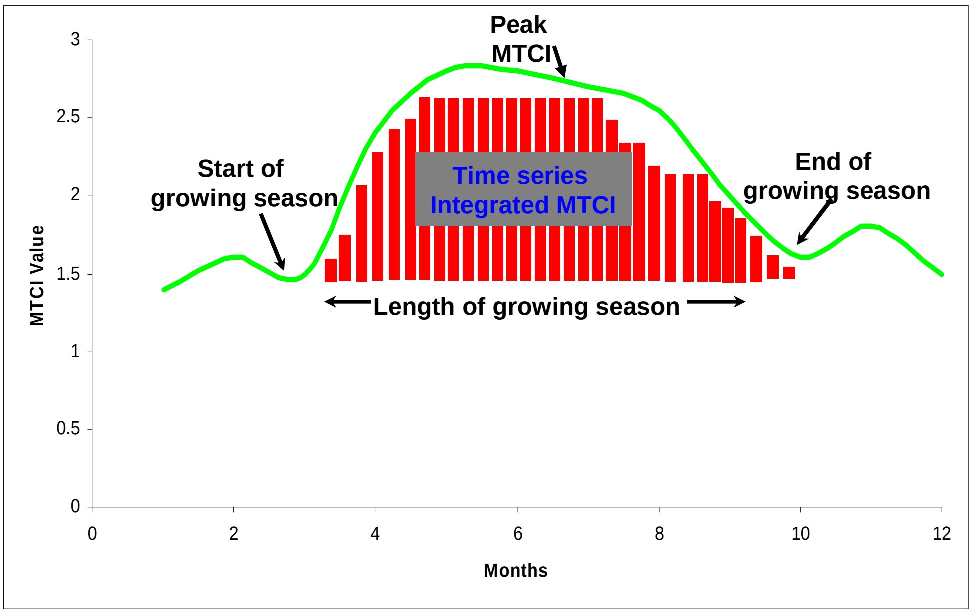


Fig. 4: Phenological variables in a MTCI time- series curve

2.6.3. Extraction of natural vegetation cover of the UK

In order to use this dataset as an input for the PnET model for NPP estimation, the non- natural vegetated classes were masked and being geo- referenced to Geographic Projection with 1 km pixel size (spatial resolution). According to the GlobCover Map, 2004, UK is dominated by 9 natural and semi- natural vegetation types (Fig. 5).

The needle- leaved evergreen forest are found in the upper Scotland and passing through the midlands and southern England whereas the mosaic of forest, shrub land and grassland being the dominant type occupy mostly Scotland, some in central, periphery and north and south east parts of Wales, Northern Ireland and England respectively. The mosaic of grassland forest and shrub land are found in parts of central and western parts of

Scotland whereas Herbaceous vegetation are found in small parts of central Scotland and western part of Northern Ireland. Grassland are mostly occurred in Wales, western parts of England and Northern Ireland and few patches in the upper extreme parts of Scotland (North- east). Other vegetation classes such as mixed broad- leaved needle forests are found in southern parts of England and central parts of Scotland. Even the broad- leaved deciduous forests are found in few in the western parts of Scotland towards the seashore.

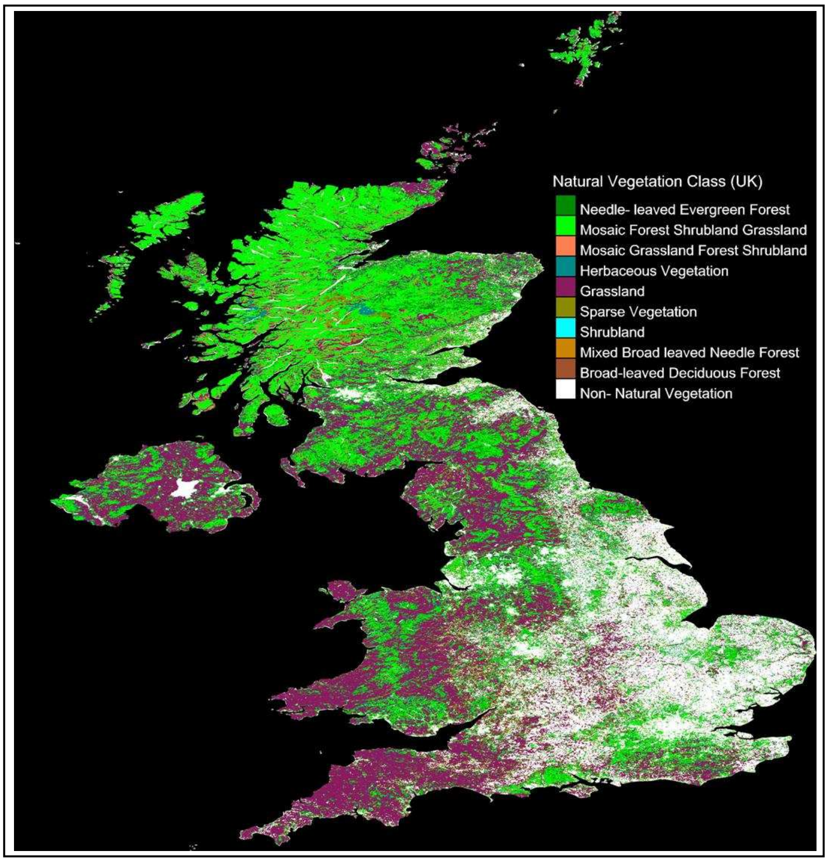


Fig. 5: Terrestrial vegetation map of UK (Source: GlobCover Map, ESA, 2004)

2.6.4. Estimation of Net Primary Productivity using PnET model.

For regional application in the natural vegetation productivity of the UK, PnET- II version was run in conjunction with a 1 km resolution GIS, thus calculate the water, carbon balances of forest including foliar, wood and root productivity. For each cell, elevation (from DEM) and vegetation type (from GlobCover map) were read as Pnetveg.LST file (see Table 2) which accounts for water balance, allocation and respiration terms to the photosynthetic routines of PnET- DAY version. To relate these physical parameters with the prevalent climatic variables, in a grid run format, the climate file (.CLM) with minimum, maximum temperature, PAR, soil water holding capacity and precipitation were calculated as a function of latitude, longitude and elevation. The different variables in this climate file (.CLM) are-

1. A line with number of pixels, number of rows, number of cols, number of years to run, the workd "Read", "Readi", "Calc" or "Calci".

2. The first pixel consists of 13 lines:
Latitude, longitude, elevation (meters), type of vegetation, soil water holding capacity (cm) and 13 characters or less identification of the pixel. This is followed by 12 lines depicting:
The monthly information for year (as an average data), day of year, Tmax (ºC), Tmin (ºC), Radiation in PAR (Photosynthetically Active Radiation), precipitation (cm). The next pixels will be on the next 13 lines and so on.

The vegetation type file is linked to the Pnetveg.LST file.

Table 2: PnETveg dataset

4	
Needle- leaved	SF
Grassland	PINE
Red Oak- Red Maple	RORM
Northern Hardwoods	NHWDS

The model was running using the Real climate from 2003 to 2005 as the “actual first year” and “actual last year”. For each run, the run model was set from first year to model as “< Real climate from” to last year to model. For example, using 2003 climate file, the model could run for a minimum of 3 years with the specifications as “Real Climate from = 2003”, “Real Climate to = 2005”, “Run model from = 2001” and “Run model to = 2003” in the Site/ Run variable icon. And this gives the NPP output for 2003 and so on for 2004 and 2005.

The output is in the form of tables with different NPP components as NPP Foliage, NPP Wood and NPP Root for each corresponding location and vegetation type. At the final stage, approximately 2000 point locations are produced with corresponding NPP components due to the model output limitations.

2.6.5. Comparison of vegetation productivity derived from PnET model and the time-series integrated MTCI values

To determine the relationships of the vegetation productivity output derived from PnET model and the time- series integrated MTCI values, the regression analysis was carried out.

2.6.6. Analysing the influence of Temperature anomalies on vegetation phenology

To understand the relationship between the temperature anomalies and vegetation phenological variables across the UK, the regression analysis was carried out. During the analysis, comparison was made with the monthly average maximum Temperatures and the PnET model NPP output for 2003, 2004 and 2005. Similarly, the monthly average maximum temperature was compared with MTCI derived different phenological variables (e.g., start of growing season, end of growing season and integrated MTCI values) for “needle- leaved evergreen forest” for 2003, 2004 and 2005.

3. Results

3.1. Temperature anomaly zones in the UK region

According to the pattern of the temperature anomaly as depicted by monthly mean temperature of 2003, 2004 and 2005 against the Long Term Average (LTA) which is described in chapter 2, eight positive and two negative anomaly zones was detected in the UK region (Fig. 6). A positive anomaly was defined in this study when the mean temperature was observed between +1.5 to + 3.0 ºC (orange to dark red color) and when the mean temperature was observed below -1.5 ºC and reaching up to -3.0 ºC (indicated as dark green to dark blue) was defined as a negative anomaly. However, four such positive anomalies were detected during the spring season (March and April- 2003, April- 2004 and March- 2005) and another four in the autumn season (November- 2003, November- 2004, September and October- 2005) respectively. We also observed two negative anomalies during the autumn season (October- 2003) and (October- 2004) in the study area.

The first positive spring season anomaly was detected in the Scotland, North, Midlands and South- West parts of the England in March, 2003 and second in the Scotland, North and Midlands of England in April, 2003. We also observed spring anomalies in the Upper Scotland, Midlands and East parts of England in April, 2004 and in Northern Ireland, Scotland and North England in March, 2005 respectively. With regards to autumn season anomalies, initially a positive anomaly was detected in parts of Scotland and East England in November, 2003 and another in small portions of Scotland and Northern Ireland in November, 2004. Similarly, two such positive anomalies were detected in small portion of Midlands of England in September, 2005 and whole of England and Wales in October of 2005 respectively. All these positive spring anomaly ranges with a mean temperature of +1.5 ºC to + 3.0 ºC. However, two negative autumn anomalies were observed in the whole of UK in October, 2003 and in Northern Ireland parts of UK in October, 2004 respectively with an observed mean temperature below -1.5 ºC to -2.0 ºC.

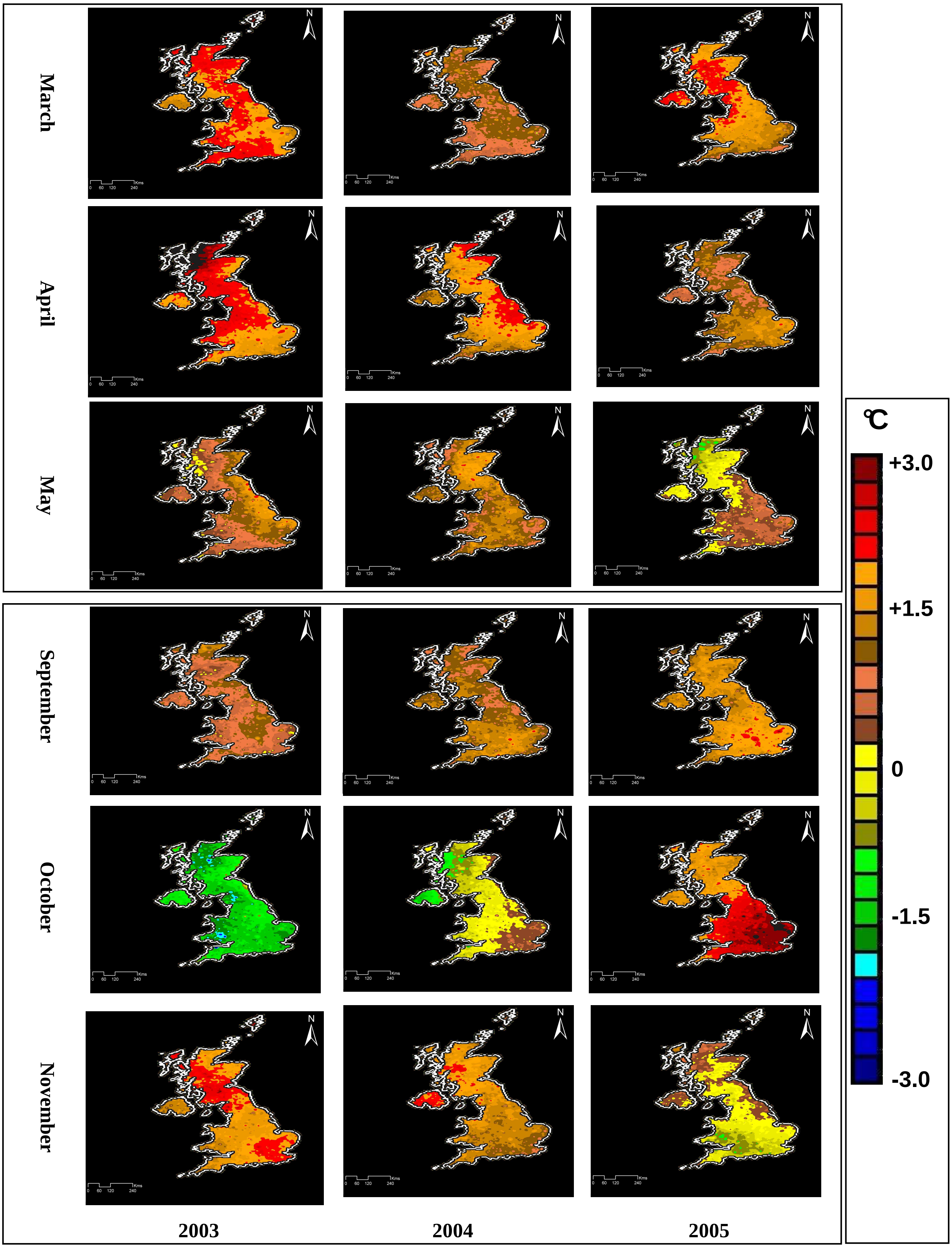


Fig. 6: Temperature anomalies in the United Kingdom for selected months in 2003, 2004 and 2005.

3.2. Temperature pattern across the UK

To know the profile of the temperature parameters across the United Kingdom, four different locations from south- north extension (50º to 58º latitude), monthly average maximum, minimum, mean and Long Term Average Temperatures were extracted from 1 km * 1 km plot size where different terrestrial vegetation types are found.

The monthly average maximum temperature during spring season was observed to be highest with 16 ºC in May, 2004 in North England than in 2003, 2005 and LTA (as shown in figure 7- d) where “mixed broad- leaved needle forest” was found. However, in the autumn season the monthly average maximum temperature (positive anomaly) was observed with 18 ºC in September, 2003 as the highest within the same location.

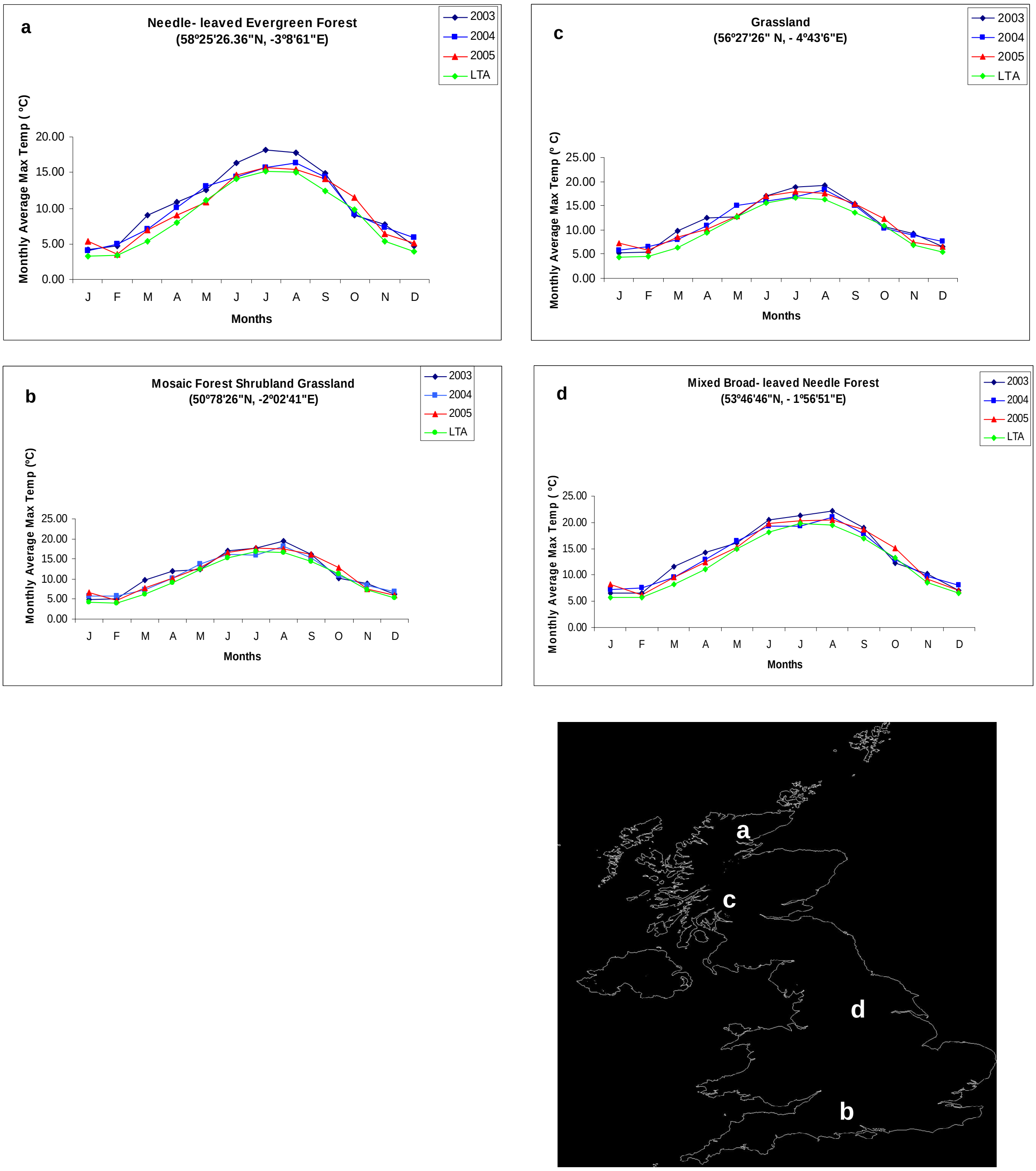


Fig.7: Monthly Average Maximum temperature pattern in 2003, 2004, 2005 and LTA across UK and plot location

From the figure 8- d, the monthly average minimum temperature during spring season was observed to be highest with 6 ºC in May, 2004 in North England than in 2003, 2005 and LTA where “mixed broad- leaved needle forest” was found. And during the autumn season the highest monthly average minimum temperature (positive anomaly) was observed with 10 ºC in September, 2005.

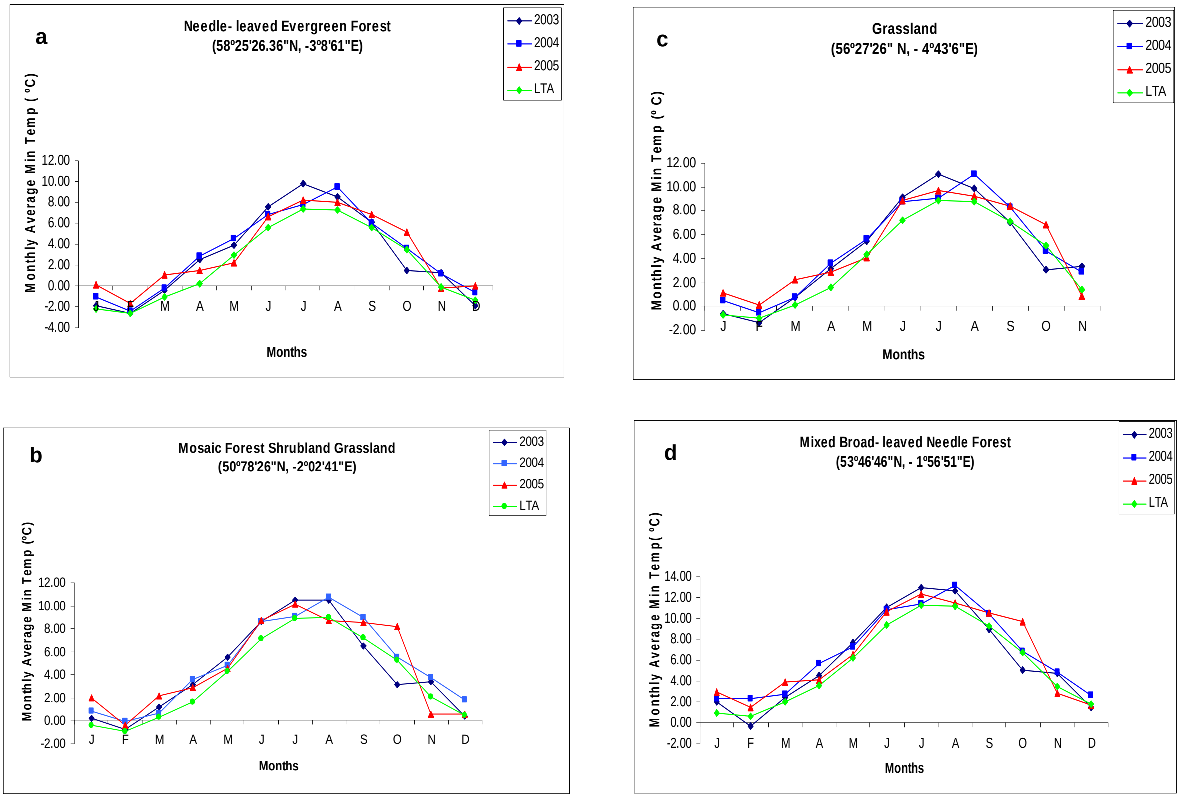


Fig.8: Monthly Average Minimum temperature pattern in 2003, 2004, 2005 and LTA across UK

The monthly average mean temperature during spring season was observed to be highest with 13 ºC in May, 2004 in North England than in 2003, 2005 and LTA (as shown in figure 9- d) where “mixed broad- leaved needle forest” was found. On the other hand, in the autumn season the highest monthly average mean temperature (positive anomaly) was observed with 15 ºC in September, 2005 within the same geographical location and vegetation type.

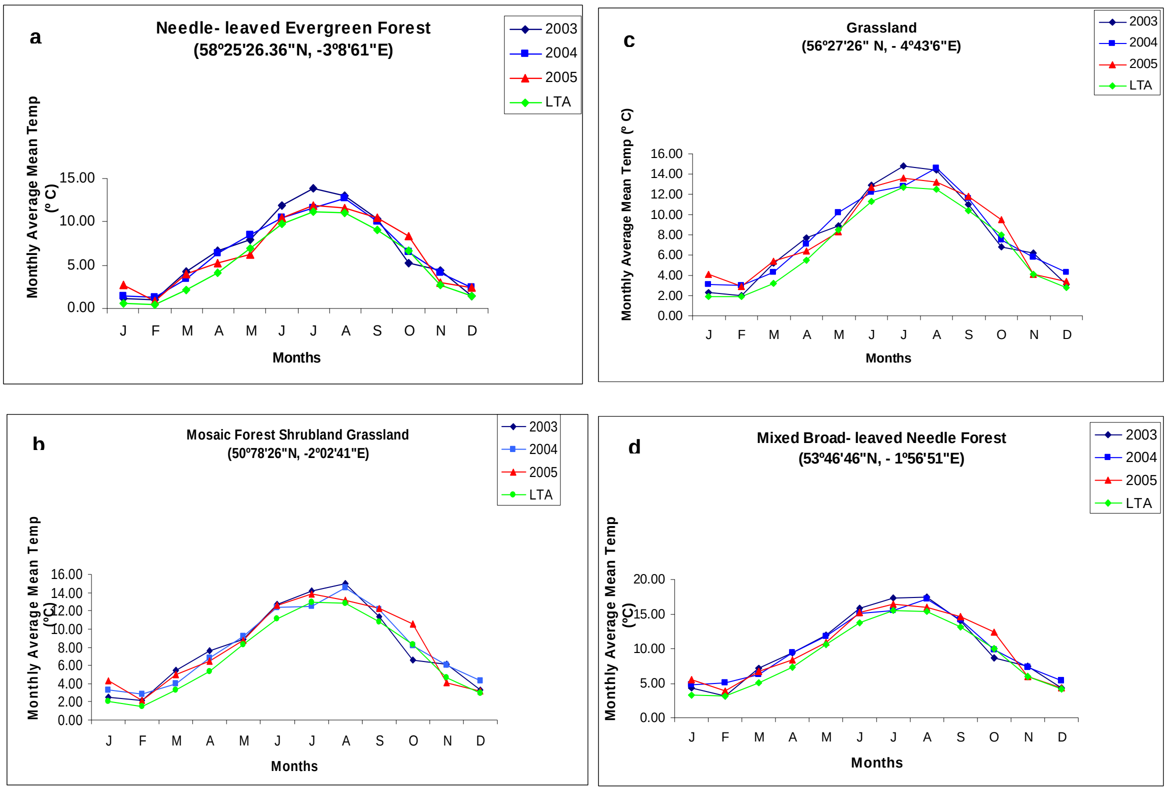


Fig.9: Monthly Average Mean temperature pattern in 2003, 2004, 2005 and LTA across UK

This was evident from the above figures and observations that the different temperature parameters such as monthly average maximum, minimum and mean temperatures were all above the LTA observations since 1946-1999 across the United Kingdom. The highest monthly average maximum, minimum and mean temperatures were observed within “mixed broad- leaved needle forest” class in the North England with 16 ºC in May, 2004; 6 ºC in May, 2004 and 13 ºC in May, 2004 respectively during spring season. Whereas, during autumn season, the highest monthly average maximum, minimum and mean temperatures were observed with 18 ºC in September, 2003; 10 ºC in September, 2005 and 15 ºC in September, 2005 respectively. All these parameters showed a higher pronounced temperature towards the northern parts of UK (i.e., north- east England, North England and Scotland) or in higher latitudes in 2003, 2004 and 2005.

3.3. Vegetation phenology variables in the anomaly zones derived from time- series MTCI

Out of 9 natural and semi- natural terrestrial vegetation classes that are found in UK, the class "mosaic of forest with either shrub land or grassland" is found to be most abundant followed by classes "grassland" and "needle- leaved evergreen forest". But for this particular study, the class "needle- leaved evergreen forest" has been focused. The different phenological and productivity variables to be estimated were: start of growing season, end of growing season, interval of growing season and integrated MTCI values.

3.3.1. Start of growing season

The start of growing season of the different vegetation types in the UK ranges from 1- 30 weeks (i.e., January – July) as shown in figure 10. The start of growing season for class "needle- leaved evergreen forest" was pre- dominantly seen with 1-3 weeks earlier in East Scotland (dark red color) than the other parts of UK in 2003 and 2004 but very few in 2005. Otherwise, this class start its greenness by mid- March (yellow color) later in 2004 and very lately by end of May (Chartreuse and green color) in 2005. The other classes "mosaic of forest with either shrub land or grassland", "grassland" and "herbaceous vegetation" also initiate its growth 1-3 weeks (dark red color) earlier in few places of the country (South- east England, North England and Northern Ireland) in 2003, 2004 and 2005. Most of the "mosaic of forest with either shrub land or grassland" and "grassland' classes start its greening up from early February (red color) earlier in Wales, South- West, West and North of England, Lower Scotland and most parts of Northern Ireland in 2003. In contrast, these vegetation types pronounced lately by mid- March (orange color) in 2004 and later in early April (yellow color) in 2005. Between February and March every year, all the non- natural vegetation classes such as cropland start its onset (orange color) in the whole country.

It was interesting to know that most of the vegetation classes occurring in the Scotland and North England onset its greenness by mid- April to end- May (Chartreuse color) in all the years. And around 59º N latitude, some of the vegetation types "grassland" start its greening up lately till mid-August (blue color). Thus, the spatial distribution of greening up of the different vegetation towards northward from February to early July reveals that the vegetation phenology is strongly dependent on latitude.

Overall, the start of the growing season of the different vegetation type across the UK was found to have a similar pattern between early February till mid- May (red to green color) in 2003, 2004 and 2005. But, it was observed that the MTCI raw data was missing in 2005 (black color) mostly in the Northern Ireland, South and Midland parts of the United Kingdom.

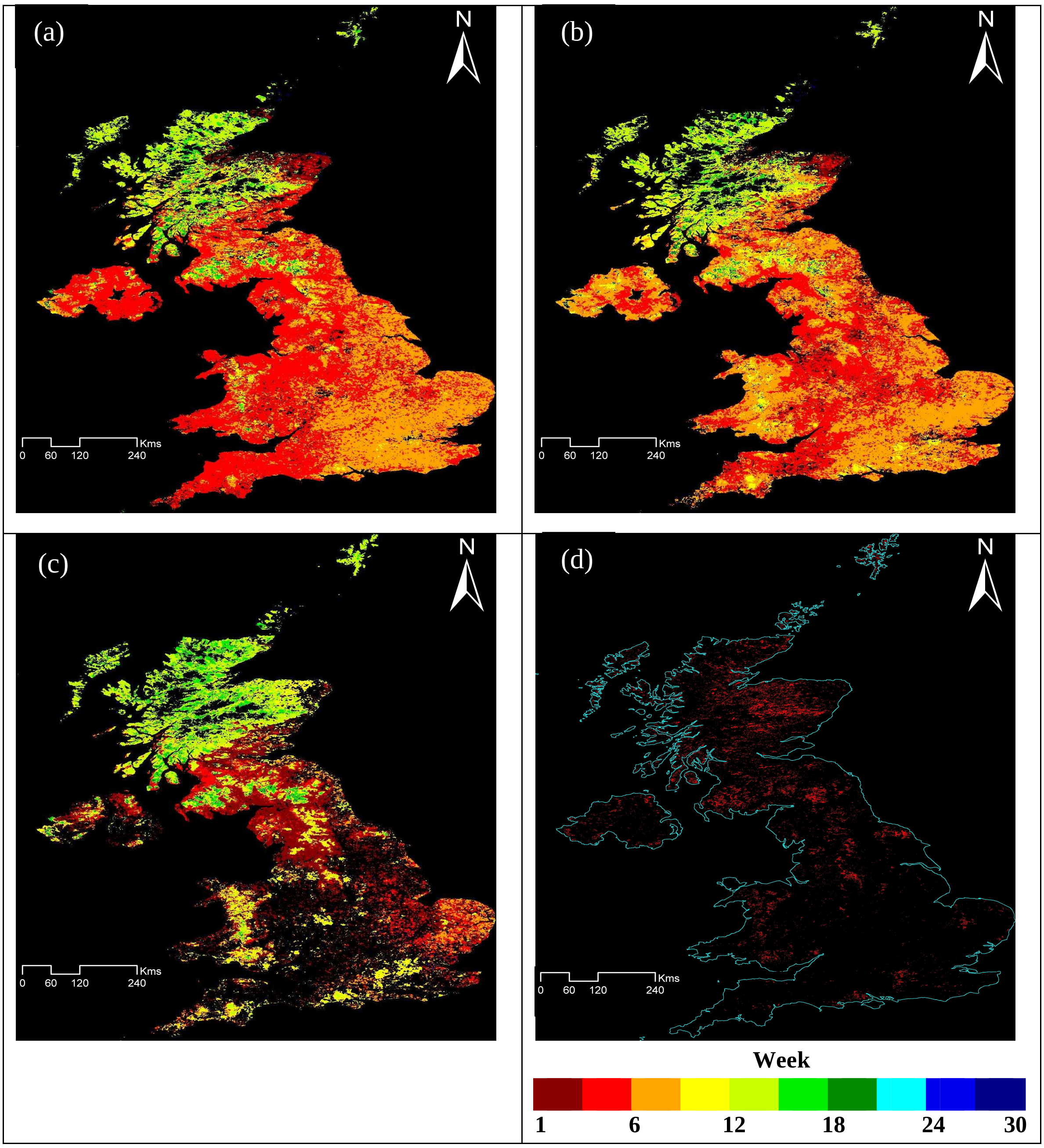


Fig. 10: Start of growing season of different natural vegetation of UK: (a) 2003, (b) 2004 and (c) 2005 (d) Needle- leaved Evergreen Forest (red color)

3.3.2. End of growing season

The end of growing season of the different vegetation type of UK ranges from 25- 52 weeks (i.e., early July - December) of the year (Figure 11). The dormancy onset for class "grassland" was observed in early July (dark red) earlier in few places of South- West and West England in 2003, 2004 and 2005. The classes "mosaic of forest with either shrub land or grassland" and "grassland" initiates its dormancy by late July (red color) earlier in 2003 than in 2004 and 2005. But, a late end of growing season within the same classes was observed in the higher latitudes by late August (orange color) to mid- October in different years (dark green color). The “needle- leaved evergreen forest” does exhibit a relatively late end of the season in autumn but differ according to the locations across the country. In the south part of UK, this forest ends its growth a relatively earlier than the north. It can be referred that “needle- leaved evergreen forest” ends its growth by mid- October in 2003, followed by mid- December in 2004 and mid- November in 2005 respectively. Comparatively, towards the north (Scotland and adjacent areas) the end of growing season for this forest was late till end of December in 2004 and more in 2005 than in 2003. However, the non- natural vegetation class such as cropland ends its growth in October (green color) in 2003 followed by November- December (blue to dark blue color) in 2004 and 2005. In the Northern Ireland, the end of growing season for both “mosaic of forest with either shrub land or grassland” and “grassland” was later in 2004 and 2005 (blue color) than in 2003. Further, most of the vegetation classes begin its dormancy onset earlier by mid- August to mid October in the southern part of UK in 2003 except in 2004 and 2005. Hence, the dormancy of most of vegetation classes begins later till December in the higher latitude.

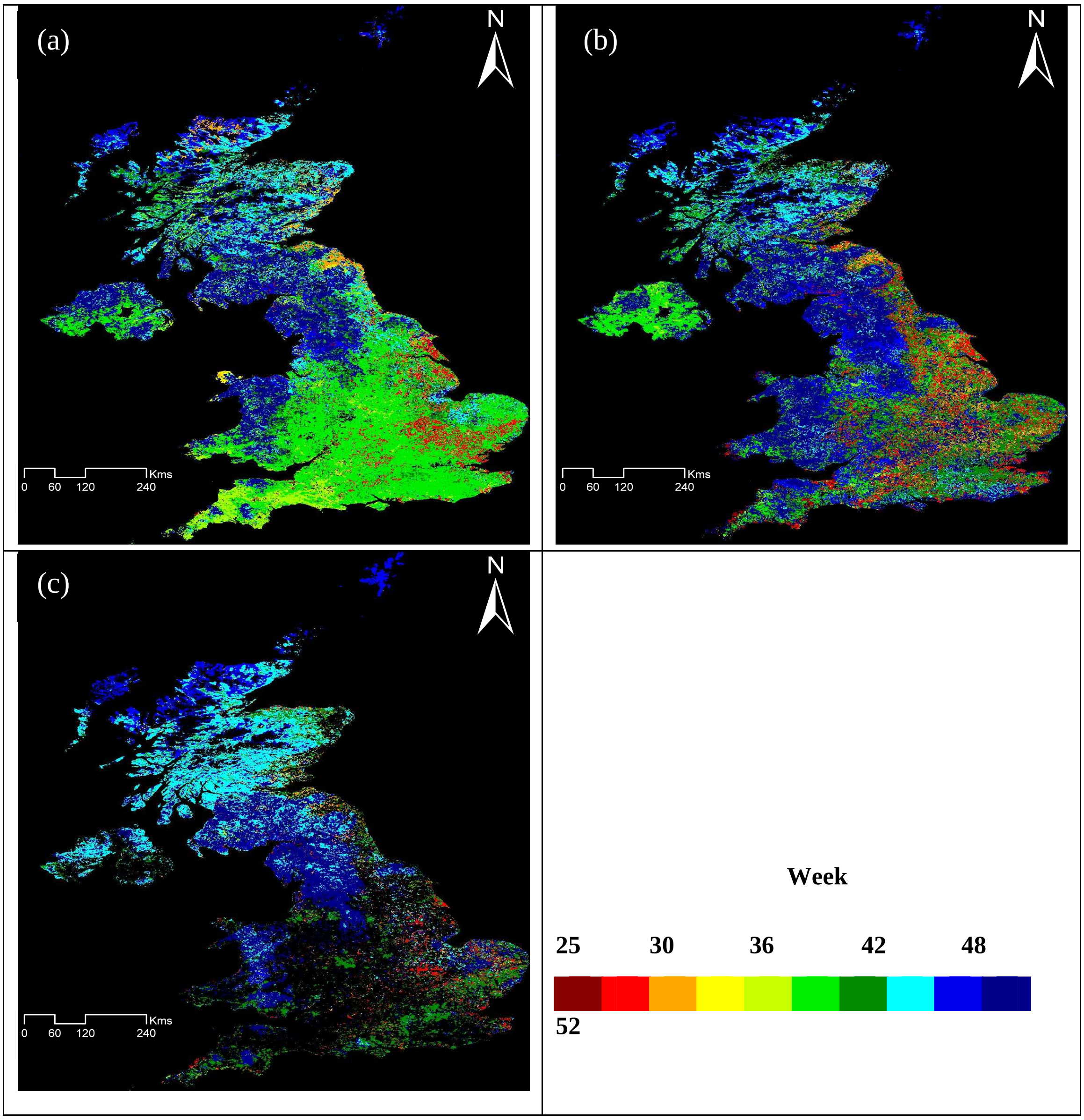


Fig. 11: End of growing season of different natural vegetation of UK: (a) 2003, (b) 2004 and (c) 2005.

3.3.3. Length of growing season

The length of growing season of the different vegetation type ranges from 16- 52 weeks across UK as shown in Fig. 12. A short length of growing season was observed within the class “grassland” in small area with 16- 18 weeks in Wales (dark red color) than the rest part of UK in 2003. Similar short length of growing season, reaching up to 25- 27 weeks (dark orange color) was also observed in the “mosaic of forest with either shrub land or grassland” towards the northern latitude in Scotland in 2003, 2004 and 2005. In few areas around extreme South- West England, similar short length of growing season was also observed within “grassland” class in 2004. The class “mosaic of forest with either shrub land or grassland” occupying the Midlands and North- East England have a short length of growing season (19- 24 weeks- orange color). The classes ‘mosaic of forest shrub land and grassland”, “needle- leaved evergreen forest” and “grassland” have a comparatively longer length of growing season with 28- 33 weeks (yellow color) in 2003 than 2004 and 2005 in the southern parts of England. On the other hand, these classes with 28- 33 weeks (yellow color) are found more in 2005 in major parts of Scotland. A major portion of South and Midlands of England, Northern Ireland and North of Scotland have a comparatively longer length of growing season amongst the “mosaic of forest with either shrub land or grassland”, “grassland” and “needle- leaved evergreen forest” with 34- 36 weeks (chartreuse color) in 2003 than 2004 and 2005 respectively.

The “mosaic of forest with either shrub land or grassland” and “grassland” classes between Wales and South England and East England have a longer length of growth with 37- 42 weeks (green color) in 2003 and 2004. Moreover, a longer length of 43- 45 weeks (cyan color) was observed within the “grassland” in the Wales and Northern Ireland in 2005. Similar length was observed in “mosaic of forest with either shrub land or grassland” in East Scotland in 2003 and in North England in 2005. As the start of growing season of most of the vegetation type was similar in 2003, 2004 and 2005 but different with the end of growing season, thus resulting to a different length of growing season between the three. Thus, as expected, a longer length of growing season was observed in 2004 and 2005 than in 2003 in most parts of the country.

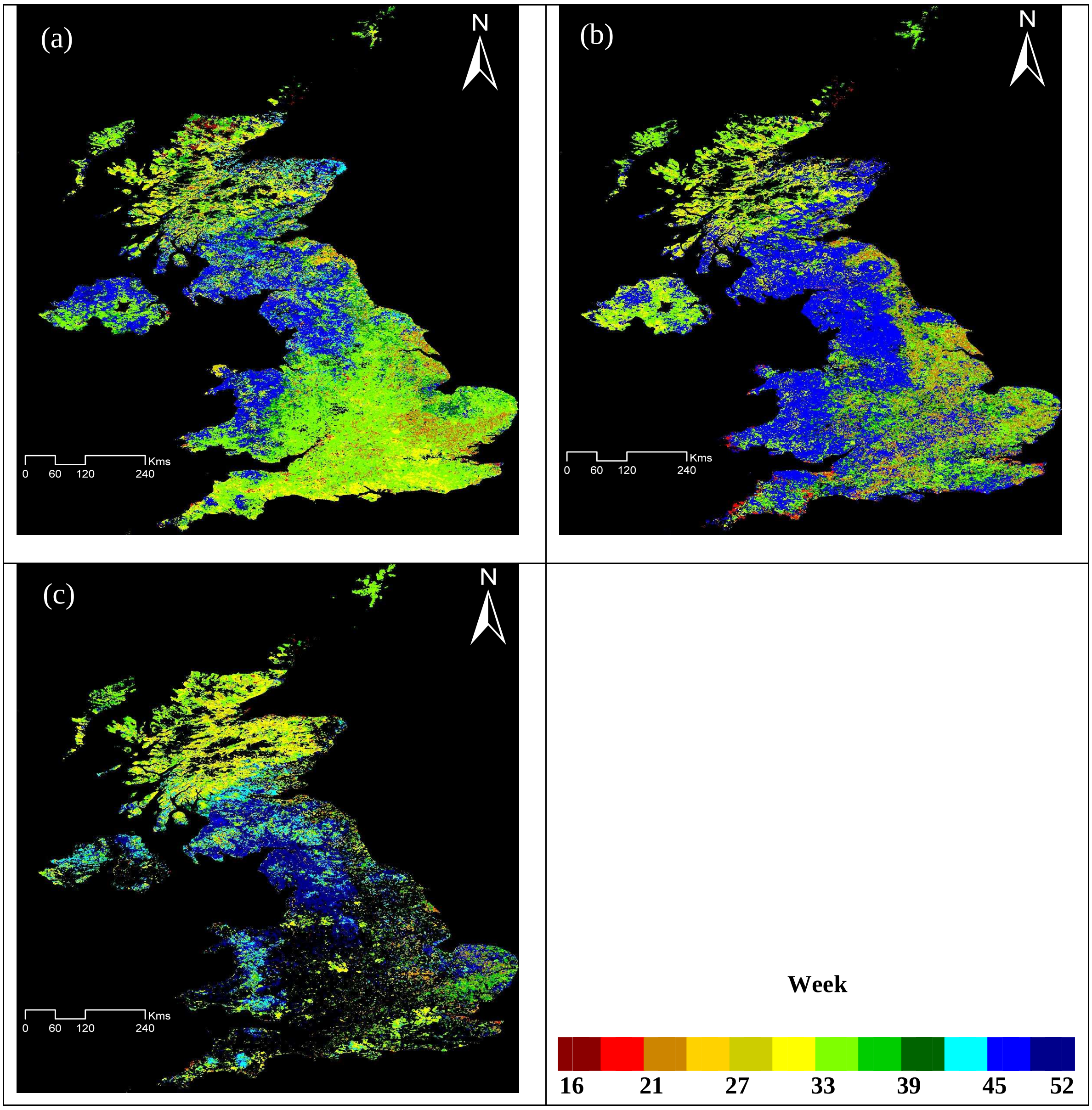


Fig. 12: Length of growing season of different natural vegetation of UK: (a) 2003, (b) 2004 and (c) 2005.

3.3.4. Integrated MTCI composite value

The integrated time- series MTCI values is an indicator for net primary productivity of the vegetation that falls within the length of growing season (i.e., the area under the MTCI time- series curve). Or, in other words, the integration or summation of all the MTCI layers that falls between the start and end of the growing seasons (i.e., length of the growing season). According to the figure 13, the integrated MTCI values ranges from 20 to 210. The “needle- leaved evergreen forest” and “mosaic of forest with either shrub land or grassland” has the minimum values approximately 20 to 40 (dark red) in East- Scotland in 2003, 2004 and 2005, thus representing a short length of growing season. The “mosaic of forest with either shrub land or grassland” and “herbaceous” in the South England has the integrated MTCI values of 40- 60 (red color) in 2003 but these classes reached up to 80 value in 2004 (orange color). This was because of the longer length of growing season in 2004 than in 2003 as a result of late dormancy in 2004 (**refer section: End of growing season**). Similarly, a higher value of 60- 80 was observed in Scotland within the “mosaic of forest with either shrub land or grassland” and “needle- leaved evergreen forest” in 2003, 2004 and 2005. Moreover, within the same vegetation types in most parts of UK have a higher value of 80- 100 MTCI Values (yellow color). But, the “grassland” occupying Wales, North England and Northern Ireland have 100- 120 MTCI values (chartreuse color). Very few vegetation classes reached up to 210 MTCI Values (blue color). Overall, the integrated MTCI Values of the different vegetation type was found to attained 80- 120 as the highest value across the UK for 2003, 2004 and 2005. But, a highest value reaching up to 140 (green color) was found within the “mixed broad- leaved needle forest”, “needle- leaved evergreen forest” in 2005 than in 2003 and 2004 respectively.

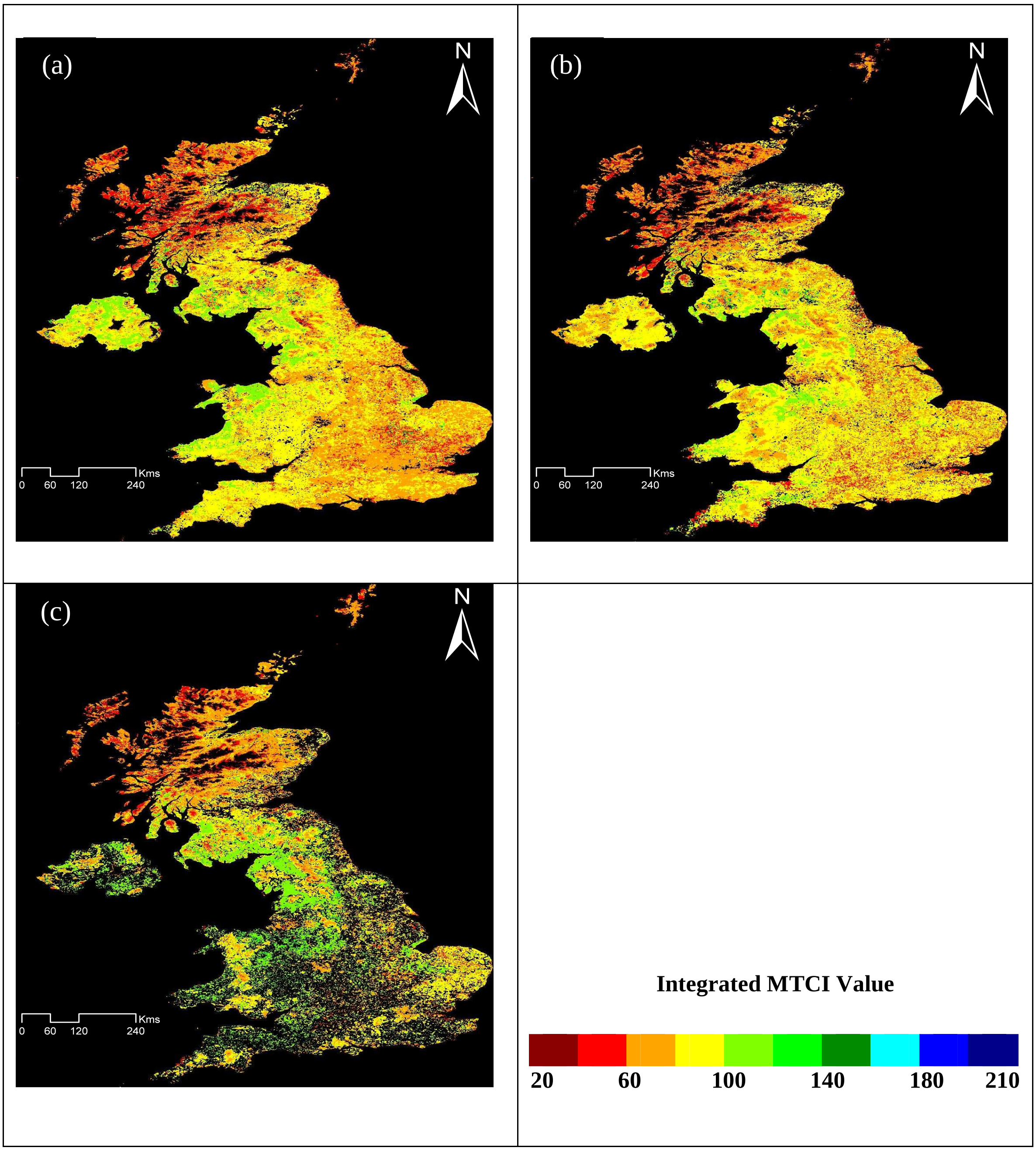


Fig. 13: Integrated MTCI composite of different natural vegetation of UK: (a) 2003, (b) 2004 and (c) 2005.

3.4. Vegetation phenology variables within the different vegetation types

For analysing the different phenological variables of different vegetation types, ten plot of 1 km * 1 km size which are representative pixels of (1) Needle- leaved evergreen forest (2) Mosaic of forest with either shrub land or grassland (3) Grassland (4) Mixed Broad- leaved Needle forest and (5) Broad- leaved deciduous forest were selected from different geographical locations across the United Kingdom.

3.4.1. Start of Growing Season

From the figure 14 as shown below, it was evident that the different forest type reveals different start of growing season (in weeks) in different year at different geographical locations (plot of 1 km * 1 km). For example, "needle- leaved evergreen forest" onset its greenness by end March earlier in 2005 (second plot) than in 2003 and 2004 (month of April) and similar pattern was seen with the "grassland". However, "broad- leaved deciduous forest" appears to start the growth 1- 2 weeks earlier in 2003, 2004 and 2005 in 1 sample plot as compare to the "needle- leaved evergreen forest", whereas the second plot shows a similar trend with the "needle- leaved evergreen forest". The other vegetation classes such as "mosaic of forest with either shrub land or grassland" and "mixed broad- leaved needle forest" exhibit an earlier start of greenness in 2005 by mid- February than in 2003 and 2004 (till March). Overall, the start of the growing season was earlier in 2005 than in 2003 and 2004 irrespective of the vegetation types.

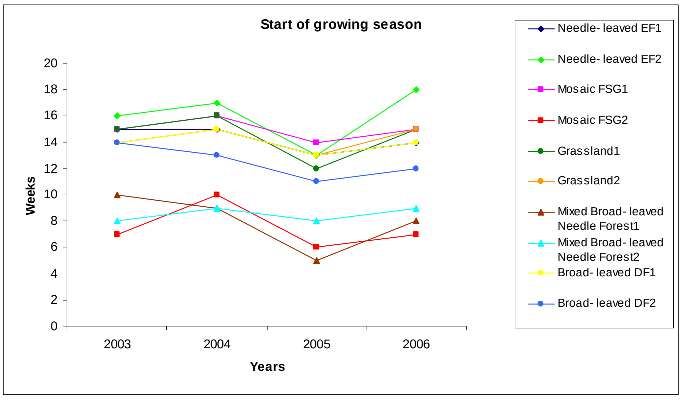


Fig. 14: Start of growing season of different natural vegetation of UK

3.4.2. End of Growing Season

Taking the end of the growing season on the other hand, (figure 15) shows that the dormant onset was late in 2005 than in 2003 and 2004 irrespective of the vegetation types. The “needle- leaved evergreen forest” lasts its growth by end- November later in 2005 than in 2003 and 2004 (early November) whereas the “broad- leaved deciduous forest” lasts by end of December later in 2005 than the preceding years in mid- November. Similar trend was also seen with “grassland” and “mosaic of forest with either shrub land or grassland” but it was observed that “mixed broad- leaved needle forest” has almost equal end of growing season in 2003, 2004 and 2005 around mid- November.

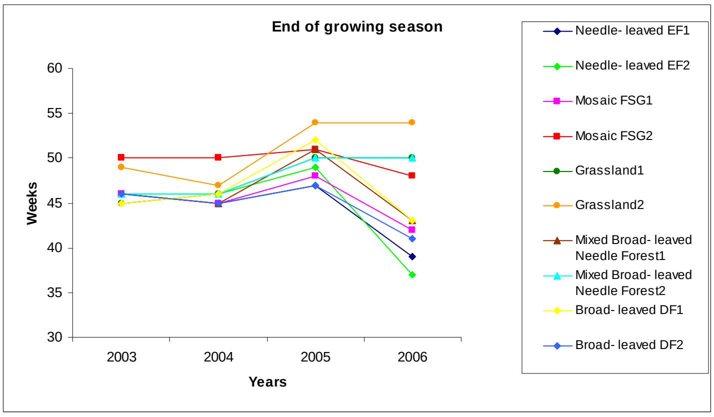


Fig. 15: End of growing season of different natural vegetation of UK

3.4.3. Length of Growing Season

On the basis of the different start and end of the growing season (in terms of weeks) of the different vegetation types, a similar pattern in the length of growing season was seen amongst different years (figure 16). The “needle- leaved evergreen forest” has a short interval of growing season (35 weeks) as compare to the “broad- leaved deciduous forest” and “mosaic of forest with either shrub land or grassland” (38 weeks). The “grassland” has a relatively longer interval of growing season reaching up to 40 weeks. Similar pattern of longer interval of growing season was also seen with the case of the “mixed broad- leaved needle forest” (40- 45 weeks). Due to the different end of the growing season between 2003, 2004 and 2005, as a result the length of growing season was more reaching up to 46 weeks in 2005 than in 2003 and 2004 respectively.

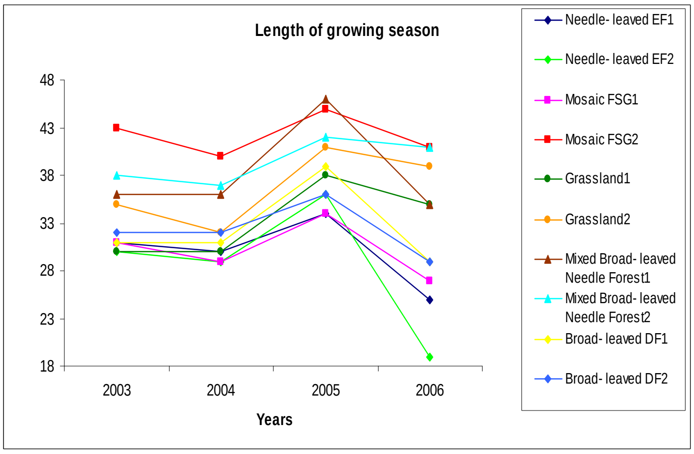


Fig. 16: Length of growing season of different natural vegetation of UK

3.4.4. Integrated MTCI Composite Value

According to the figure 17 as below, the "needle- leaved evergreen forest" varies with an integrated MTCI value of approximately 80 from 2003 to 2005 (first plot). In the second plot, it varies from 76- 94 from 2003 to 2005. However, the "mosaic of forest with either shrub land or grassland" varies with a higher integrated value of 82- 85 (2003 to 2005) in the first plot and 78- 98 in the second plot from 2003 to 2005. The "grassland" produces the MTCI value ranging from 75- 99 (2003- 2005) in the first plot while a lower value of 63- 58 (2003 to 2005) in the second plot. The lower MTCI Values of 70- 65 (2003 to 2005) and 58- 70 (2003 to 2005) are found in the "mixed broad- leaved needle forest" respectively. The "broad- leaved deciduous forest" produces a comparative lower integrated MTCI Values of 45- 68 (2003- 2005) and 59- 65 (2003 to 2005) in the two plots. Thus, irrespective of the vegetation types, a higher integrated MTCI values were observed in 2005 than in 2004 and 2003 (lowest range) was observed as a result of longer length of growing season in 2005.

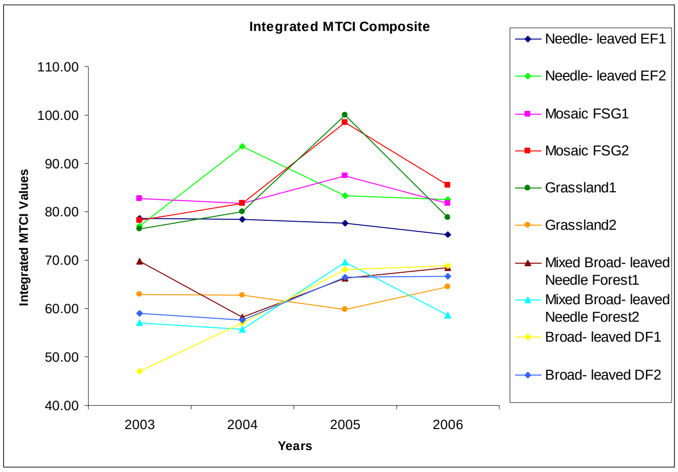


Fig. 17: Integrated MTCI composite of different natural vegetation of UK

3.5. Comparison of vegetation productivity derived from PnET model and the time- series integrated MTCI values

The predicted annual foliage net primary production for “needle- leaved evergreen forest” in the UK region ranged from 43- 639 g/m^2/yr for the three years. But, the model could predict up to 671 g/m^2/yr annual NPP foliage for “mosaic of forest with either shrub land or grassland”. The relationships between the vegetation productivity derived from PnET model and the time- series integrated MTCI Values were assessed by performing correlation analyses on temporal scales. From the figure 18 as shown below, the correlation between the monthly NPP foliage derived from PnET model and the time- series integrated MTCI values of the “needle- leaved evergreen forest” was significant (r^2 = 0.65) in 2003. But in 2004 and 2005, this relationship was fairly weak (r^2 = 0.22) and (r^2 = 0.07) respectively. Hence, a strong positive relationship between the NPP foliar derived from PnET model and the time- series integrated MTCI values was observed for only 2003. But this significant relationship does exist only with the NPP Foliar whose value is less than 54 g/m^2.yr., and becomes saturated with the integrated MTCI values once the PnET NPP Foliar exceeds this value. The calculated integrated MTCI Values ranged from 60 to 114 on an average. However, a weak positive relationship was also observed between the NPP Total derived from PnET model (i.e., sum of foliar and wood) and the time- series integrated MTCI in 2003, 2004 and 2005 respectively.

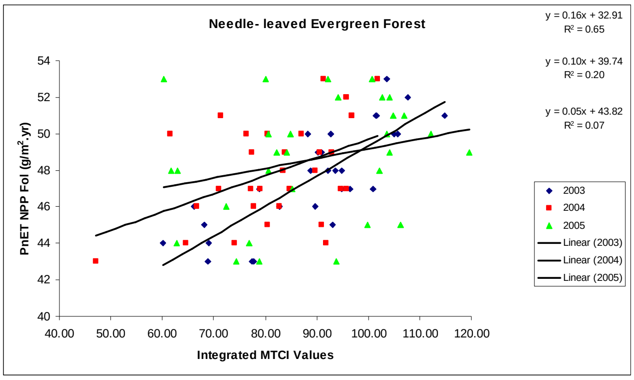


Fig. 18: Relationship between PnET model derived NPP Foliage with Integrated MTCI Values for 2003, 2004 and 2005.

3.6. Analysing the influence of Temperature anomalies on vegetation phenology

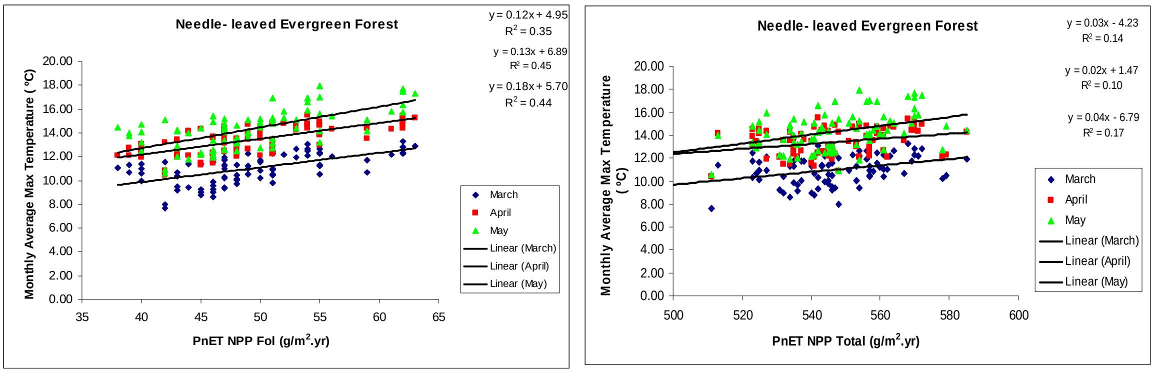
For the analysis of the influence of the temperature parameters on the forest phenological variables, approximately 50 samples (representative pixels) of “needle- leaved evergreen forest” were plotted based on correlation analyses against the Monthly Average Maximum Temperature for 2003, 2004 and 2005.

3.6.1. PnET model

Using the PnET model, the net primary productivity (foliage, wood and total) of different forest types e.g., “needle- leaved evergreen forest” was estimated. Thus, the phenological parameters derived from PnET model were statistically examined with the Monthly Average Maximum Temperature as shown below:

3.6.1.1. Spring season:

From the figure 19 as shown below, the correlation between the net primary productivity (i.e. foliage NPP) of the "needle- leaved evergreen forest" and positive spring Monthly Average Maximum Temperatures of 2003 was significant (r^2 = 0.45) in April and (r^2 = 0.44) in May respectively. On the other hand, a very weak correlation was also observed between the Total NPP of the "needle- leaved evergreen forest" and the spring anomalies with r^2 = 0.17. This suggests that in 2003, the warmer temperature (in case of anomaly) does correspond with the NPP (foliage only) within "needle- leaved evergreen forest". Thus, a significant positive relationship between the PnET NPP Foliage and monthly average maximum temperature variable was seen in spring season for the "needle- leaved evergreen forest".



(a) (b)

Fig. 19: Relationship of Monthly Average Maximum Temperature (spring) with Needle- leaved evergreen forest NPP for 2003 (a) PnET NPP Foliage (b) PnET NPP Total

The correlation between the net primary productivity (i.e. foliage NPP) of the "needle- leaved evergreen forest" and positive spring Monthly Average Maximum Temperatures was weak (r^2 = 0.27) in the month of May as shown in Figure 20. Similarly, a weak correlation was also observed between the Total NPP of the "needle- leaved evergreen forest" and the spring anomalies with r^2 = 0.02 in the month of March. Therefore, in 2004 the warmer temperature (in case of anomaly) does not correspond with the NPP (both foliage and total) in the case of "needle- leaved evergreen forest". Hence, a weak positive relationship between the net primary productivity (PnET model) and temperature variable was seen in spring season for the "needle- leaved evergreen forest".

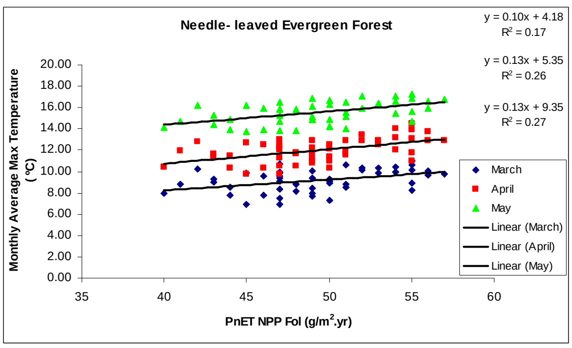


Fig. 20: Relationship of Monthly Average Maximum Temperature (spring) with Needle- leaved evergreen forest NPP for 2004 (PnET NPP Foliage)

From the figure 21 as shown below, the correlation between the net primary productivity (i.e. foliage NPP) of the "needle- leaved evergreen forest" and positive spring Monthly Average Maximum Temperatures was strong (r^2 = 0.67) in April and (r^2 = 0.72) in May respectively. Using the PnET NPP Total, a weak correlation was observed between the spring anomalies with r^2 = 0.22 (in April). This suggests that in 2005, the warmer temperature (in case of anomaly) does correspond with the NPP (foliage only) in the case of "needle- leaved evergreen forest". Hence, a strong positive relationship between the net primary productivity (PnET NPP Foliage) and temperature variable was seen in spring season for the "needle- leaved evergreen forest".

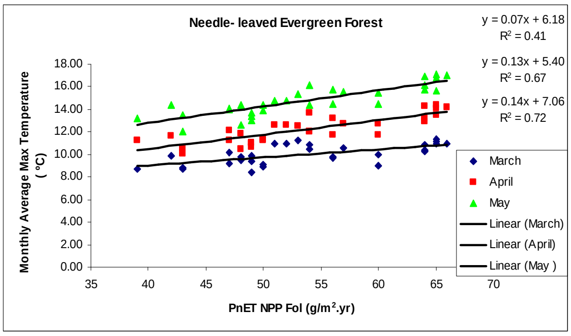


Fig. 21: Relationship of Monthly Average Maximum Temperature (spring) with Needle- leaved evergreen forest NPP for 2005 (PnET NPP Foliage)

3.6.1.2. Autumn season:

From the figure 22 as shown below, the correlation between the net primary productivity (i.e. foliage NPP) of the "needle- leaved evergreen forest" and positive autumn Monthly Average Maximum Temperatures (i.e., Sept, Oct and Nov) was strong (r^2 = 0.52, r^2 = 0.48 and r^2 = 0.37) respectively. But, a weak correlation was observed between the Total NPP of the "needle- leaved evergreen forest" and the autumn anomalies with r^2 = 0.23 in the month of September. This suggests that in 2003, the warmer temperature (in case of anomaly) does correspond with the NPP (only foliage) in the case of "needle- leaved evergreen forest". Hence, a strong positive relationship between the net primary productivity (PnET NPP Foliar) and monthly average maximum temperature variable was seen in autumn season for the "needle- leaved evergreen forest".

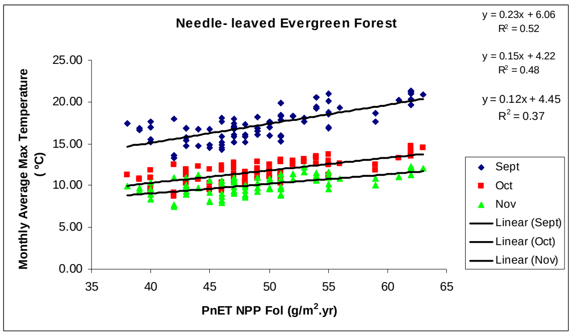


Fig. 22: Relationship of Monthly Average Maximum Temperature (autumn) with Needle- leaved evergreen forest NPP for 2003 (PnET NPP Foliage)

The correlation between the net primary productivity (i.e. foliage NPP) of the “needle- leaved evergreen forest” and positive spring Monthly Average Maximum Temperatures was strong (r^2 = 0.39) in September and (r^2 = 0.42) in October respectively (figure 23). On the other hand, a weak correlation was observed between the Total NPP of the “needle- leaved evergreen forest” and the autumn anomalies with r^2 = 0.09 in the month of September. Thus in 2004, the warmer temperature (in case of anomaly) does correspond with the NPP foliage only in the case of “needle- leaved evergreen forest”. Hence, a significant positive relationship between the net primary productivity (PnET Foliage) and temperature variable was observed in autumn season for the “needle- leaved evergreen forest”.

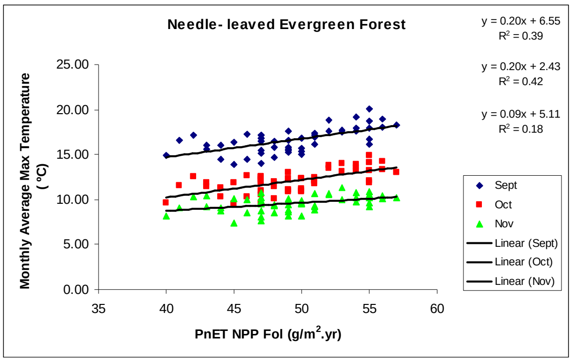
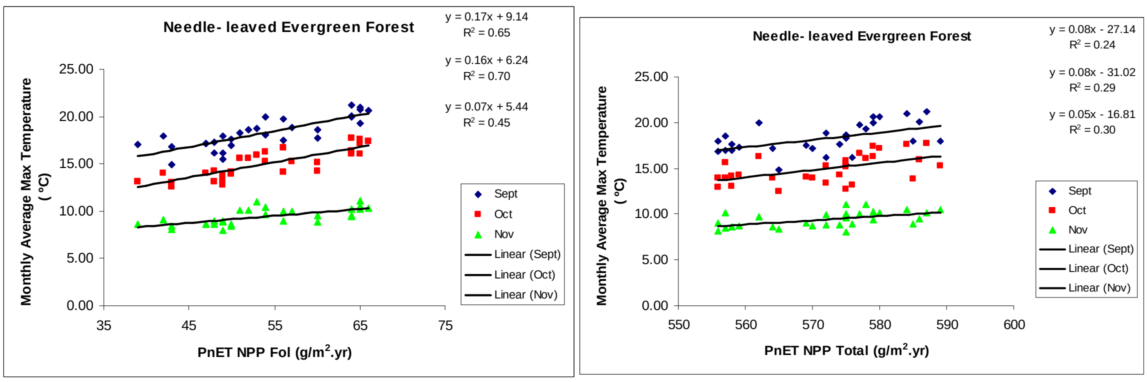


Fig. 23: Relationship of Monthly Average Maximum Temperature (autumn) with Needle- leaved evergreen forest NPP for 2004 (PnET NPP Foliage)

From the figure 24 as shown below, the correlation between the net primary productivity (i.e. foliage NPP) of the “needle- leaved evergreen forest” and positive autumn Monthly Average Maximum Temperatures was significant (r^2 = 0.65) in September and (r^2 = 0.70) in October respectively. But, a weak correlation was also observed between the Total NPP of the “needle- leaved evergreen forest” and the autumn anomalies with (r^2 = 0.30) in November. This suggests that in 2005, the warmer temperature (in case of anomaly) do correspond with the NPP (both foliage and total) in the case of “needle- leaved evergreen forest”. Hence, a strong positive relationship between the net primary productivity (PnET Foliage) and temperature variable was seen in autumn season for the “needle- leaved evergreen forest”.



(a) (b)

Fig. 24: Relationship of Monthly Average Maximum Temperature with Needle- leaved evergreen forest NPP for 2005 (a) PnET NPP Foliage (b) PnET NPP Total

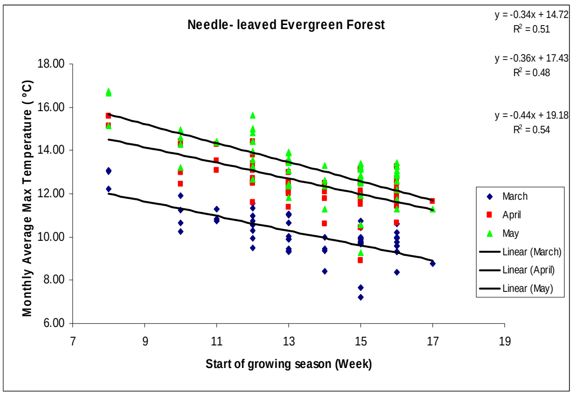
3.6.2. Time- series MTCI composite

Using the time- series MTCI composite, the different phenological variables of “needle- leaved evergreen forest” (start, end, length and Integrated MTCI Values) were statistically examined with the Monthly Average Maximum Temperature as shown below:

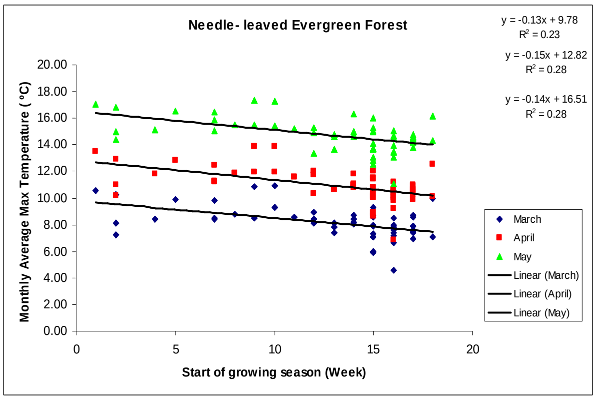
3.6.2.1. Spring season:

3.6.2.1.1. Start of growing season

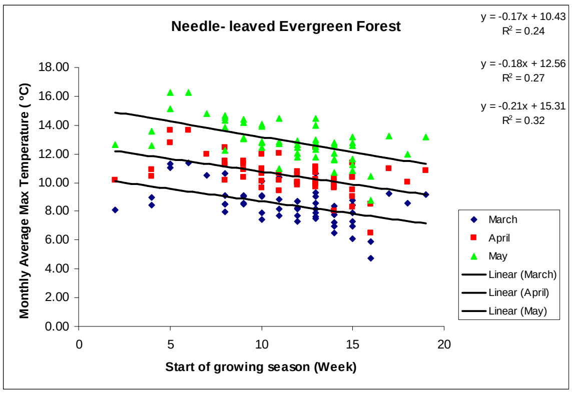
From the figure 25 (a) as shown below, the correlation between the “greenness onset” of the “needle- leaved evergreen forest” and positive spring Monthly Average Maximum Temperature of 2003 was strong (r^2 = 0.51) in March and (r^2 = 0.54) in May respectively. But, a weak relationship was observed in 2004 with (r^2 = 0.28) in April- May and (r^2 = 0.32) in May, 2005 (figure- (b) and (c)). This shows that in 2003, the warmer temperature (12- 17 ºC) favors an earlier start of growing season of the needle- leaved species in spring by end- February (within 8 weeks) in the anomaly zones as described in section 3.2. But, most of the needle species initiate its greenness after mid- March. However in 2004, the process of greenness was even earlier by January. It was worth to describe that most of the needle- leaved species in the UK, starts its greenness between mid- February and mid- April in 2005 on the basis of the temperature extremes. Hence, a strong negative relationship between greenness onset and Monthly Average Maximum Temperature was observed in spring season within the “needle- leaved evergreen forest” in 2003 but a weak negative relationship was witnessed in 2004 and 2005.



(a)



(b)

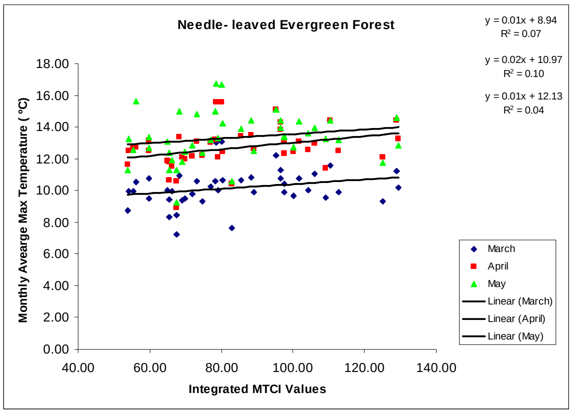


(c)

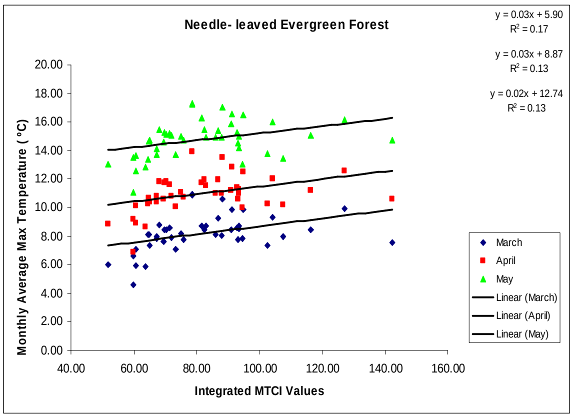
Fig. 25: Relationship of spring monthly average maximum temperature with start of growing season in Needle- leaved evergreen forest (a) 2003 (b) 2004 and (c) 2005.

3.6.2.1.2. Integrated MTCI values

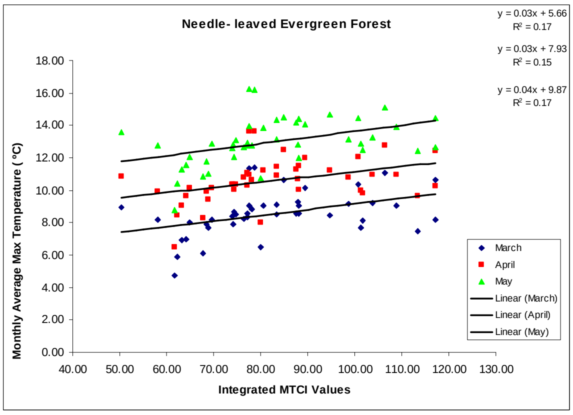
According to the figure 26 as shown below, the correlation between the integrated MTCI values of the "needle- leaved evergreen forest" and positive spring Monthly Average Maximum Temperature was insignificant (r^2 = 0.10) in April 2003, (r^2 = 0.17) in March 2004 and (r^2 = 0.17) in March and May, 2005 respectively. This suggests that as the temperature increases (between 8- 14 ºC) in spring season of 2003 to 2005, a higher integrated MTCI value was observed in the range of 60- 100 for the "needle- leaved evergreen forest". Therefore, a weak positive relationship between the integrated MTCI values and monthly average maximum temperature was seen in spring season in the case of the "needle- leaved evergreen forest" irrespective of the years.



(a)



(b)



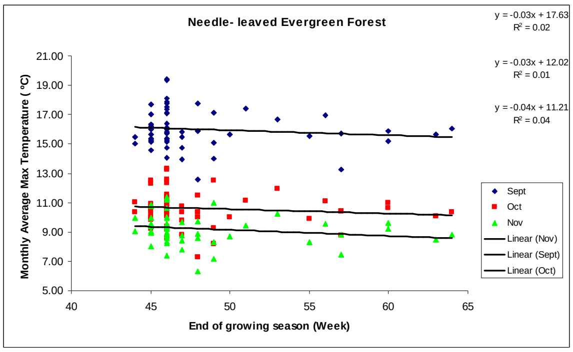
(c)

Fig. 26: Relationship of Temperature with integrated MTCI values in spring season in Needle- leaved evergreen forest (a) 2003 (b) 2004 (c) 2005

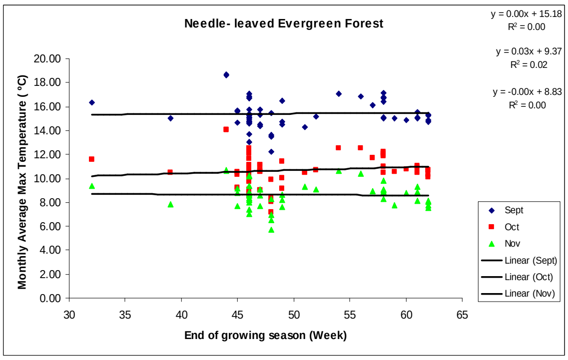
3.6.2.2. Autumn season:

3.6.2.2.1. End of growing season

The correlation between the end of growing season of the "needle- leaved evergreen forest" and positive autumn Monthly Average Maximum Temperature was insignificant (r^2 = 0.04) in November, 2003 (Figure 27). Similar weak relationship was also observed in October, 2004 with (r^2 = 0.02) and in 2005. This suggests that the higher temperature of autumn 2003 does not fit well with the dormancy season and hence an earlier end of growing season of "needle- leaved evergreen forest" was observed in 2003 by late November as compare to 2005 (mid- October to mid- November). According to figure 26 (b), it was known that even at higher temperature, the "needle- leaved evergreen forest" sets its dormancy from mid- November to mid- December in 2004. Hence, it can be drawn that the length of the growing season was expected to be longer in 2004 than in 2003 and 2005 due to late end of growing season. Overall, a weak positive relationship between end of growing season and autumn season Monthly Average Maximum Temperature was observed in all the three years within the "needle- leaved evergreen forest".



(a)



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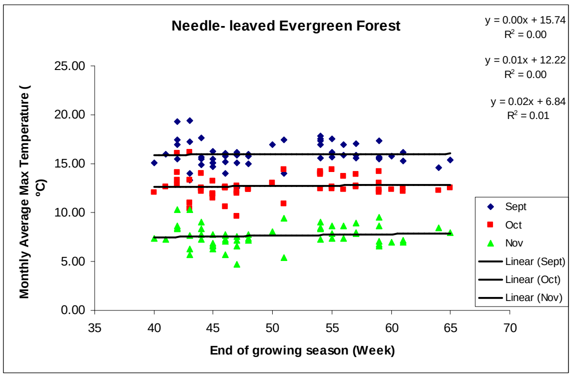
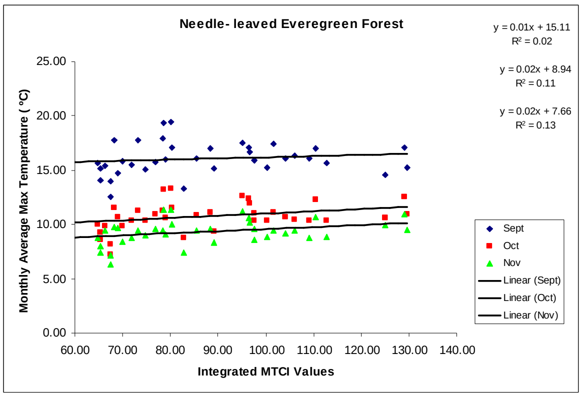


(c)

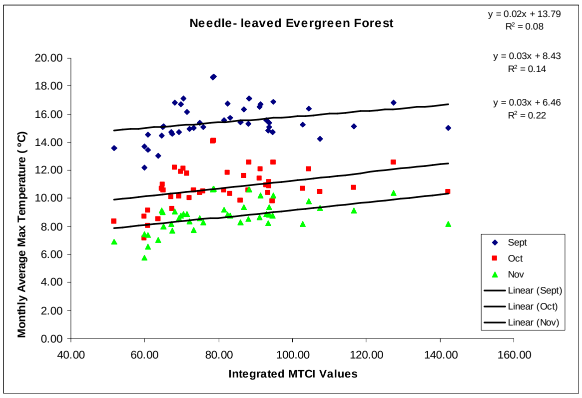
Fig. 27: Relationship of autumn monthly average maximum temperature with start of growing season in Needle- leaved evergreen forest (a) 2003 (b) 2004 and (c) 2005.

3.6.2.2.2. Integrated MTCI values

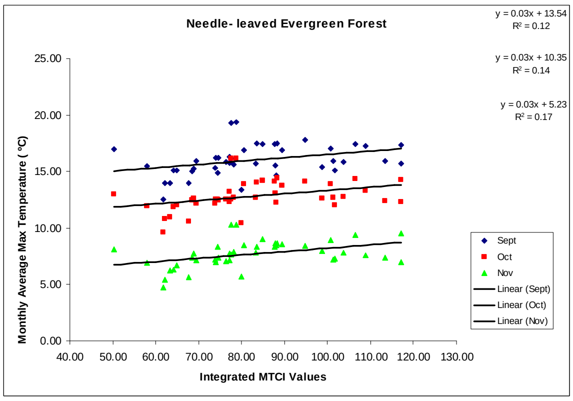
The correlation between the integrated MTCI values of the "needle- leaved evergreen forest" and positive autumn Monthly Average Maximum Temperature was relatively stronger with (r^2 = 0.22) in November, 2004 (figure 28). Otherwise, a weak positive relationship was seen during the autumn season of 2003 and 2005. This was evident with the monthly average maximum temperature between 7- 9 ºC in November, 2004 (figure 28- (b)). The integrated MTCI Values with 60- 100 range was observed to be common between the three years at 6- 16 ºC monthly average maximum temperature. Hence, a relatively stronger positive relationship between the integrated MTCI values and autumn season monthly average maximum temperature was observed in 2004 with the "needle- leaved evergreen forest".



(a)



(b)



(c)

Fig. 28: Relationship of Temperature with integrated MTCI values in autumn season in Needle- leaved evergreen forest (a) 2003 (b) 2004 (c) 2005

4. Discussion

4.1. Temperature Anomaly Zones from the Meterological data

This study presents that the interpolated map for monthly mean temperature of 2003, 2004, 2005 and Long-Term Average using the 450 weather stations was able to detect the anomalies across the United Kingdom. Accordingly, eight positive and two negative anomaly zones were identified in 2003, 2004 and 2005 (Fig 6). However, four such positive anomalies were detected during the spring season and another four in the autumn season with +1.5 to + 3.0 ºC in 2003, 2004 and 2005. In this study, two negative anomalies during the autumn season with -1.5 ºC to -2.0 ºC in 2003 and 2004. The first positive spring season anomaly was detected in the whole of UK in March and second in April 2003. The other two spring anomalies were identified in April, 2004 and March, 2005. With regards to the autumn season, positive anomalies were observed in November, 2003 and November, 2004. The remaining two positive autumn anomalies were identified in September and October, 2005. In the case of the negative anomalies, the month of October in 2003 and 2004 were identified.

However, when the monthly average temperature variables (maximum, minimum and mean) of 2003, 2004 and 2005 were compared with the Long- Term Average (1946- 1999) the results showed that they all were well above the LTA observations both in spring and autumn seasons (Fig 7; Fig 8 and Fig 9). Furthermore, a higher prominent temperature was observed in the higher latitudes (towards North England and Scotland) in the duration of the study period. This finding can be related to the observations made by the Met Office and Perry and Hollis, 2005) confirming that using the Long – Term Average Temperatures could detect both the spring and fall anomalies within the country and such anomaly zones can be easily detected. Therefore, the different temperature variables derived from the weather stations offer an important source for deriving the anomalies for various investigations including the vegetation- climate seasonal relationships.

4.2. Impacts of Temperature Anomalies on Vegetation Phenological Variables

The impact of the temperature anomalies on vegetation phenological variables is discussed separately as spring and autumn anomalies within the "needle- leaved evergreen forest".

4.2.1. The Impacts of Spring Anomalies on Vegetation Phenological Variables

4.2.1.1. PnET Model

The predictions of the net primary productivity for "needle- leaved evergreen forest' using the PnET model was almost similar for the three years in the range of 43- 639 $g/m^2/yr$. but the impact caused by the spring anomaly was different. The predicted annual foliage net primary production for "needle- leaved evergreen forest" in the UK region was fairly in agreement with the result as described by Ollinger et al., (1998). It was reported that such predictions are highest within the broad- leaved deciduous species than the "needle-leaved evergreen forest" as a result of higher photosynthetic activity. Regarding the relationship with the spring anomaly, the model output predictions of the NPP foliage was in agreement with the change in the temperature pattern. It was observed that the relationship was significant meaning that as the mean monthly temperature increases; relatively small increase in the NPP yield was also observed due to positive relationship. Or, in other words, an increase in both the maximum and minimum temperatures results to extension of the length of growing season, thus an increase in NPP was expected (Aber and Federer, 1992).

This causal relationship between the model predicted vegetation productivity- climate was even stronger in 2005 than in 2003 and in 2004 respectively. Hence, all these results support the findings of this study for detecting the relationship between the model predicted NPP and the spring Temperature anomaly.

4.2.1.2. Integrated MTCI Composite

The phenological variables for "needle- leaved evergreen forest" in the spring season anomaly resulted in an early onset of growing season. In general, the start of the greenness within the natural vegetation types in UK ranges from 1- 30 weeks (i.e., January to July). Depending on the location of the anomaly zone and year, this advancement of the greenness was varied in terms of weeks (i.e., 1- 20 weeks). In the spring anomaly zone in the higher latitude (Scotland) the onset of growing season of few "needle- leaved evergreen forest" advanced by mid- January in 2003 and 2004 than in 2005. Otherwise, this forest starts its greenness by mid- March later in 2004 and end of May in 2005 in other parts of the UK. This suggests that the occurrence of the spring anomaly in 2003 might be responsible for the advancement in earlier spring. Additionally, in 2005, this forest initiate its greenness earlier (end March) than in 2003 and 2004. This may be in conjunction with the positive spring anomaly which was observed in March, 2005. However, a little bit earlier spring was also observed in 2003 than in 2004 (in April) in different locations. Thus, an earlier spring (start) was seen in 2005 than in 2004 and 2003 respectively (figure 14).Moreover, a relatively strong and inverse relationship was observed between the spring anomaly temperature and the onset of greenness in 2003 and 2005.

The above results can be related to various assumptions and findings while dealing with this type of vegetation. One such reason for the variability in the start of greenness could have been due to vegetation classification scheme adopted in this study, as the classification was based on broad physical characteristics forming a particular class. A detailed land cover map, giving the distribution of the species (e.g., *Abies* spp., *Pinus* spp.) may allow for a finer estimation of phenology within this type of forest (Guyon et al., 2006). The second reason could be due to the reflectance from the understorey vegetation because of low Leaf Area Index in the needle- leaved species, a mixed signal could have occurred. Due to the relatively low seasonal variations in photosynthetic biomass within the coniferous forest when compared with deciduous forest, the varying incident angle of zenithal sun – linked with slope could be another reason. Keeping the note in context for the estimation of the growing season for coniferous forest, a reasonable ground- truth data are required to determine fair indicator on remote sensing data.

The location of the anomaly zones could be another reason for such a variation in the start within the same forest. It has been strongly observed that the location in terms of latitudinal gradient play a major role the way the vegetation type responds to warming. For example, an estimated variation of 2 Julian days per 1º latitude was observed on an average in Europe for responses to warming in different vegetation types (Zhang et al., 2004). This was due to the greenness onset moving towards northward and spreading of dormancy in the southwards direction. Since, the anomalies were in different locations; this factor could contribute to the variation in the spring greenness within the same vegetation type. For instance, due to the latitudinal gradient across the country, a relatively earlier onset of greenness (say early February) of the needle- leaved evergreen forest was observed in the south parts of UK, followed by mid- April onset of greenness in the North of England and finally in the end- May (parts of Scotland and adjoining).

Due to the spring anomaly occurrence in the study area and relatively earlier onset of greenness, seemed to have a longer length of the growing season in the coniferous forest type. But this forest has a relatively short length of growing season as compare to the other vegetation types. Thus, the lengthening of the growing season was a direct consequence of the early onset of greenness due to the spring anomaly. Regarding the different years, as a result of the different end of the growing seasons between 2003, 2004 and 2005, a longer length of growth was seen in 2005 by 3- 4 weeks than in 2003 and 2004 respectively. These results were in line with the studies, where the spring anomaly causes a longer length of growing season by varying magnitude of 2- 16 Julian days depending on the species and location (Menzel, 2000; Menzel et al., 1999; Zhang et al., 2006). This observation can be supported with the higher influence of the high monthly average temperature in spring season from the other season (Chmielewski and Rotzer, 2001). However, the retrieval of the onset of greenness was more difficult in forest dominated by needle- leaved evergreen forest than the broad- leaved species due to the presence of the photosynthetic needle- leaves throughout the year (Delbart et al., 2005).

Regarding the Integrated MTCI composite values, it ranges from 20- 210 unit less across the different vegetation types. The “needle- leaved evergreen forest” does exhibit a fairly low integrated MTCI value range across the UK. This was due to the short length of entire growth as compare to other vegetation types. Because of the strong and inverse relationship between the earlier springs (start) and the spring monthly average maximum temperature in 2005, the earlier spring (start) and associated longer growing season promote greater net primary productivity in 2005 than in 2004 and 2003 respectively (Almond et al., 2007). Additionally, the higher latitudes (North England and Scotland) tend to have later springs (onset of greenness) with shorter growing season and lower net primary productivity than the lower latitude (West and Midlands).

The results of this study stress on the responses of the “needle- leaved evergreen forest” to the spring anomaly temperature is within the range of the results found using the long- term climatic parameters for the influence of the global warming on terrestrial vegetation phenology and productivity (Myneni et al., 1997, Zhang et al., 2004 and Chen et al., 2005). These studies highlighted that in the higher latitudes, the climatic parameter (especially temperature) has influenced the phenological pattern of the natural vegetation with an advancement of the onset of greenness by 4- 9 Julian days (Myneni et al., 1997) using satellite data and in- situ observations on species- level in the UK region (Sparks et al., 2000). It was reported that spring and the onset of summer plant species will expect a progressive earlier in the UK due to warmer temperature (Sparks et al., 2000). The emergence of early European climate could be as a result of the North Atlantic Oscillation which enhances the atmospheric temperature, could be responsible for an early start of onset of greenness in the UK region. Regarding the net primary productivity, the findings using the Integrated MTCI composite was in line with those of the result using the radar dataset within the evergreen forest (Kimball et al., 2004). It was reported that the annual productivity and distribution of the evergreen forest in the higher latitude are controlled by the start (onset of greenness) and length of growing season. For example, earlier start and associated longer growing season promote greater productivity within the natural vegetation, while the delayed start and associated shorter growing seasons promote the opposite response. Moreover, this delayed start (spring) was observed in the higher latitude with the associated shorter length (growth), thus producing a lower net primary productivity than the lower sites. But, a 20 day shift in spring greenness can induced change in the productivity by 30% irrespective of the vegetation type (Botta, 1999).

For this particular study, short- term data were used and the results were being in line even using the long- term climatic and remotely sensed data.

4.2.2. The Impacts of Autumn Anomalies on Vegetation Phenological Variables

4.2.2.1. PnET Model

As described earlier, the net primary productivity for “needle- leaved evergreen forest’ as predicted by the PnET model was almost similar in 2003, 2004 and 2005 respectively. However, the influenced due to the autumn anomaly was quite different in all the years. Keeping view of the agreement that the model could predict a lower NPP within the “needle- leaved evergreen forest’ when compared to the board- leaved Deciduous Forest, the relationship with the autumn anomaly, was in a good agreement with the change in the temperature pattern. It was interesting to highlight that even during the autumn season; the relationship was very strongly correlated due to an increase in the autumn temperature. It could be summarized in the way that due to the autumn anomaly, the end of the growing season was extended far beyond the expectation within the ‘needle- leaved evergreen forest”, thus a relatively increase in the NPP yield was observed (Aber and Federer, 1992). Further, this relationship between the model predicted vegetation productivity and the autumn anomaly was even stronger in 2005 than the preceding years and even more than of spring anomaly. In general, the predictions of the increasing NPP and growing season length from higher to lower latitude was not fairly observed during this study.

4.2.2.2. Integrated MTCI Composite

During the autumn season anomaly, the phenological variables for “needle- leaved evergreen forest” resulted in different end of growing season across the country. On the basis of the location of the anomaly zone and year, this phenomenon of the end of season was varied in terms of weeks. In the autumn anomaly zone in the higher latitude (Scotland and adjoining areas) the end of growing season of most of the coniferous forest was found to be delayed by mid- November to end of December in different years. In comparison, towards the south UK, a relatively early end of growing season was observed within most of the vegetation types including the prominent “needle- leaved evergreen forest”. These observations were also similar with those of other researchers who have commented that higher temperature in the autumn season usually lead to delays in the end of growing season (Zhang et al., 2004, Maignan et al., 2008). Thus, it has been reported that a delayed of end of the growing season in autumn season was observed by 2- 16 Julian days due to warming temperature (Maignan et al., 2008). However, it was also found with other studies that the plant phenological activity in autumn season was little understood. Due to the weak correlation between meteorological factors and leaf senescence, has made uncertainty over the plant phenology in the autumn season (Menzel, 2002). However, a link between the seasonal cycle of atmospheric CO_2 concentrations and the vegetation autumn senescence was also observed (Talyor et al., 2007). All these cases, gave us an impression about the various uncertainties associated when dealing with the autumn period for vegetation phenology.

For the length of the growing season in the autumn anomaly, the “needle- leaved evergreen forest” establishes a close relationship with the monthly average autumn anomaly in the UK region. The delayed end of the growing season could be responsible for such an extension in the growth length. Thus, this finding is also in conjunction with those of Myneni et al., (1997) and Menzel et al., (2000). But delayed in the end of the growing season is less pronounced when compared with the higher temperature in the spring season (Menzel et al., 2000; Zhang et al., 2006).

Regarding the relationship between the integrated MTCI and the autumn anomaly, there was an increase in the integrated MTCI values during this period. As a result of the early start and a delayed end of autumn season in the corresponding years, a longer length of growth was found in 2004 and 2005 due to the autumn anomaly (Almond et al., 2007). As a result an increased integrated MTCI values were observed within the "needle- leaved evergreen forest". This result corresponds to the longer period where the vegetation maintains a productive scale up to a level and stays for that period till the autumn starts, as the integrated MTCI composite acts as a bio- indicator for net primary productivity (Curran et al., 2007). Thus, higher vegetation productivity appears to be a function of earlier onset of seasonal growing seasons, delayed end of growing season and summer air temperatures (especially for broad- leaved deciduous forest) and in addition increased photosynthetic leaf area (which is difficult in the case of needle- leaved evergreen forest). This observation can also be related to the studies done by different researchers who reported that global warming due to temperature anomaly and other phenomena such as Mt. Pinatubo effect let to an increased net primary productivity (Keeling et al, 1996, Lucht et al., 2002; Nemani et al., 2003).

Overall, as a result of autumn anomaly and associated phenomena, has revealed that delayed in the end of the dormancy season of the vegetation has caused a longer length of growing season, thus net primary productivity of the terrestrial vegetation increased. Much of the studies on the climate- phenology relationship from regional to global scales were discussed broadly within the advanced remote sensing technology, ecosystem and climatology analysis (Myneni et al., 1997; Zhou et al., 2001 and Nemani et al., 2003). All these studies were conducted using the long- term vegetation and climatic data (up to more than 3 decades) highlighting the need for a long- term investigation of the complete phenological cycle and its pattern. On the contrary, this particular study was conducted using the comparatively short- term dataset (3 years i.e., 2003, 2004 and 2005). Though, the results are in the line with the above mentioned investigators even using the short- term analysis. Most of these studies posed a greater challenging in deriving the different levels and magnitude for the vegetation phenology (Piao et al., 2006). But, they all linked up their results based on various assumptions and factors such as difference in temporal and spatial scales and focusing on different species and different phenological variables such as Start, dormancy and length of the season (Walther et al., 2002).

4.3. Comparison of Vegetation Productivity from PnET Model and Integrated MTCI Composite Values

The results regarding the relationship between the vegetation productivity using the PnET model and the time- series integrated MTCI Values showed a strong positive relationship within the "needle- leaved evergreen forest". But both the productivity has a similar relationship in both positive and inverse with the spring and autumn anomalies during the study period. This relationship could be counted as a result of the early start of onset of greenness during the spring anomaly and a delayed end of the growing season in the autumn anomaly (Aber and Federer, 1992). Though the relationship between the two output maybe weak in certain cases, both have a positive/ inverse relationship with the temperature anomaly. Hence, an increase in the net primary productivity was observed both within the temperature anomalies and this maybe due to the longer length of growing season (Zhang et al., 2004).

5. Conclusion and Recommendations

5.1. Conclusions

There is an increasing demand for understanding and monitoring the plant phenology using the satellite remote sensing technique when highlighting its interaction with the large scale impacts of global climate scenario on terrestrial ecosystem. These have promoted substantial new scientific investigations in seasonal- to- decadal scale dynamics in terrestrial vegetation and are gaining importance in the context of global change. Space- borne measurements provided a mechanism to study in different spatial and temporal observations from plant- specific to global scenario of vegetation phenology. Due to the increasing interest amongst the scientific community in context to global warming, there is an increase in the accurate estimation and capturing of the vegetation phenological cycles. Keep view in this context, this particular study aimed to highlight the short- term temperature anomalies using the meteorological data and to determine their influence on natural vegetation phenology and its productivity as captured by remotely sensed data in the parts of the United Kingdom.

In this the objectives have been addressed in a sequence order. The first objective was to estimate the vegetation phenological variables and its productivity using composite MTCI time series from 2003 to 2005. The different phenological variables (start of growing season, end of growing season, length of growing season and Integrated MTCI Values) were estimated for the natural vegetation types such as "needle- leaved evergreen forest", "mosaic of forest shrub land and grassland" and "grassland". The result shows that the "needle- leaved evergreen forest" does exhibit a fairly low integrated MTCI value range across the UK. This was due to the short length of growing season but a higher net primary productivity was observed in 2004 and 2005 both in spring and autumn seasons than in 2003 due to early start of greenness and delayed end of growing season during the study period.

The second objective of this study was to compare between the vegetation productivity derived from the composite MTCI time- series and the PnET model for needle- leaved evergreen forest. The results of this particular study highlighted that a strong positive relationship does exists between the integrated MTCI composite values and the PnET NPP foliage.

The final objective of this study was to investigate the impact of the Temperature anomaly on the productivity of "needle- leaved evergreen forest" derived from PnET model and the time series MTCI Composite. The temperature anomaly and its zone/location were derived from the meteorological records of Met Office, the UK. Eight positive anomalies and two negative anomalies were identified in the spring and autumn seasons across the country. The result reveals that the relationship between the model predicted monthly NPP foliage and the positive anomalies was very strong in 2005 than the preceding years in both the spring and the autumn anomalies.
When compared with the Integrated MTCI time- series a positive relationship does exist with the spring and autumn anomalies and a higher net primary productivity was observed in 2004 and 2005 than in 2003 for both the spring and autumn anomalies due to earlier start and delayed end of growing season.

Further, investigation within the "mosaic of forest with either Shrub land or grassland" will be carried out and looked into the responses by different vegetation types.

In conclusion, the findings can be summarized as:

- The estimation of vegetation productivity using Integrated MTCI time- series (Composite) data was successfully possible.

- A strong positive relationship exists between the PnET derived net primary productivity of foliage and the integrated MTCI / net primary productivity.

- Short- term temperature anomalies resulted in significant influences on vegetation phenological variables (led to an early start of greenness, delayed end of growing season, extended growing season length and increased net productivity).

- However, the vegetation phenological variables and the Temperature anomalies follow a similar trend between them. For instance, during the spring anomaly, there was an earlier start of onset of greenness within most of the vegetation type in all the years and similarly, a delayed in the end of the growing season was observed in the positive and negative autumn anomaly, but the magnitude was different in different years.

5.2. Recommendations

This particular study reveal that the short- term temperature anomaly have a considerable impacts on vegetation phenology/ productivity that are in conjunction with those using the long- term global mean temperatures.

These findings are encouraging but the particular study may have the following limitations.

- Phenological Variables: The method for estimating the different phenological variables is not validated with the reference ground data, thus assumed to be not perfect as of now.
- Model Limitation: Some of the parameters such as Canopy variables (leaf N concentration, FolReten) and Site Variables (such as SnowPack, Water and Carbon components in wood/ bud/ plant) were not considered properly but are used as it is per the model guideline due to lack of ground data. Even the Atmosphere/ Deposition Scenarios (Ozone, Co_2) were also not considered equally.
- The vegetation type/ species – specific in the model was not perfectly defined in this study.
- There are spatial inaccuracies amongst the input data for the PnET model.
- The soil data for estimating the water holding capacity was quite course for such study.
- There is a limitation in the model output equal to only 2000 pixels, otherwise would have produced a spatial NPP Foliage map of the UK for 2003, 2004 and 2005 respectively.

Thus, there is a need for improvement on the above cited limitations in order to meet the demand for accuracies.

Furthermore, certain points are also encouraged for the future work keeping view of the present findings:

- A detailed and broad perspective studies that takes in to account all the climatic parameters (temperature, precipitation, frost and soil conditions), ensuring that the observed in the vegetation phenological variables are infact only due to the extreme temperatures.
- Investigating the response of vegetation phenology/ productivity with the Integrated MTCI time- series, model output and ground data with the climatic anomalies, in order to capture the predictive model.
- Investigating the response of vegetation in terms of phenology/ productivity for future climate change scenarios using the predictive equation derived from ecosysytem model simulation.

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