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Trends and variability in weather and atmospheric deposition at UK Environmental Change Network sites (1993–2012)

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ABSTRACT

We characterised temporal trends and variability in key indicators of climate and atmospheric deposition chemistry at the twelve terrestrial UK Environmental Change Network (ECN) sites over the first two decades of ECN monitoring (1993–2012) using various statistical approaches. Mean air temperatures for the monitoring period were approximately 0.7 °C higher than those modelled for 1961–1990, but there was little evidence for significant change in air temperature over either the full monthly records or within individual seasons. Some upland ECN sites, however, warmed significantly over the first decade before cooling in the second. Summers at most sites became progressively wetter, and extremes in daily rainfall increased in magnitude. Average wind speeds in winter and spring declined at the majority of sites. Directional trends in summer precipitation could be linked to an atypically prolonged negative deviation in the summer North Atlantic Oscillation (NAO) Index. Several aspects of air quality improved markedly. Concentrations and fluxes of sulphate in precipitation declined significantly and substantially across the network, particularly during the earlier years and at the most polluted sites in the south and east. Precipitation concentrations of nitrate and ammonium, and atmospheric concentrations of nitrogen dioxide also decreased at most sites. There was less evidence for reductions in the loads of wet deposited nitrogen species, while trends in atmospheric ammonia concentration varied in direction and strength between sites. Reductions in acid deposition are likely to account for widespread gradual increases in the pH of soil water at ECN sites, representing partial recovery from acidification. Overall, therefore, ECN sites have experienced marked changes in atmospheric chemistry and weather regimes over the last two decades that might be expected to have exerted detectable effects on ecosystem structure and function. While the downward trend in acid deposition is unlikely to be reversed, it is too early to conclude whether the trend towards wetter summers simply represents a phase in a multi-decadal cycle, or is indicative of a more directional shift in climate. Conversely, the first two decades of ECN now provide a relatively stable long-term baseline with respect to air temperature, against which effects of anticipated future warming on these ecosystems should be able to be assessed robustly.

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1. Introduction

The environmental, biogeochemical and ecological character of most of the non-urban UK land surface is subject to a range of local-scale pressures resulting from its use for agriculture, water supply, forestry, recreation, etc. However, the "natural" environment is also under the dynamic influence of regional-scale pressures from climate and air pollution. The magnitude and temporal dynamics of these more pervasive drivers of change need to be taken into account in any assessment of the causes of long-term changes in ecosystem structure and function, regardless of the spatial scale of interest. The UK Environmental Change Network (ECN) was established in the early 1990s to provide UK-wide evidence supporting the detection, quantification and attribution of the impacts of environmental change on the ecological state of a wide range of UK habitats, including 12 terrestrial sites (the terrestrial ECN). While gradual long-term shifts in land use are sometimes inevitable (see Dick et al., 2016), management regimes at ECN terrestrial sites have been kept as constant as possible since the onset of monitoring, thereby maximising the sensitivity of environmental and ecological indicators to regional-scale influences, and particularly changes in climate and air pollution (Sier and Monteith, 2016).

ECN monitoring has been conducted over a period when changes in regional-scale environmental drivers might have been expected to be substantial. Global carbon emissions increased at a rate of 1.0% yr^{-1} in the 1990s and 3.1% yr^{-1} since 2000 (Peters et al., 2013), while atmospheric concentrations of carbon dioxide, the principal greenhouse gas (GHG), measured at the Mauna Loa Observatory, increased from 357 to 394 ppm between 1993 and 2012 (NOAA-ESRL data). This has been accompanied by a considerable and progressive increase in the heat content of the world's oceans (Abraham et al., 2013) and global surface temperatures (Hansen et al., 2010). Sea levels have risen by a global average of approximately 6 cm (Blunden and Arndt, 2013), while summer minimum Arctic Sea Ice area extent has contracted by between 9.4 and 13.6% $decade^{-1}$ over the past three decades (Swart et al., 2015).

Global anthropogenically-driven warming is predicted to affect the climate of the UK in the long-term through increased air temperatures, changes in the amounts and seasonal distribution of precipitation, and increases in the frequency of extreme climatic events including floods and droughts (Jenkins et al., 2009). These trends will be mediated at more local scales by relatively short-term variation in ocean temperatures and the position, and pressure gradients, of the earth's teleconnected regional atmospheric circulation systems. Inter-annual variability in UK weather is particularly well summarised by the North Atlantic Oscillation Index (NAOI) (Hurrell and Van Loon, 1997) – the standardised difference in sea level atmospheric pressure between fixed points in the Azores and Iceland. The NAO tends to vary at an approximately decadal frequency and has, in turn, been argued to be sensitive to the extra-terrestrial influence of subtle variation in solar activity (Brown and John, 1979; Lockwood et al., 2010; Scaife et al., 2013).

Separately, major reforms to energy policy in recent decades in northern hemisphere industrialised countries, influenced by statutory controls on the emission of acidifying, eutrophying and other toxic pollutants from industrial, agricultural and domestic sectors, have been implemented nationally and internationally (Schöpp et al., 2003), while the UK economy has shifted from a largely manufacturing- to more service-based economy. This has resulted in large reductions in emissions of sulphur and heavy metals to the atmosphere across Europe and North America, and smaller reductions in the emissions of reactive nitrogen species (Fowler et al., 2007). Recent reductions in the deposition of sulphur and acidity across the UK have been linked to marked chemical improvements in soil and surface water chemistry (RoTAP, 2012). In the meantime, however, rapid economic development in parts of the developing world has contributed to broadly opposite trends (Lu et al., 2011), with major implications for human health and environmental sustainability (Zhang et al., 2012).

Finally, air pollution, particularly in the form of sulphate (SO_4^{2-}) aerosol, can itself have a marked effect on climate, both directly, by reflecting short-wave radiation, and by providing condensation nuclei for cloud formation, in a process known as "solar dimming" (Stanhill and Cohen, 2001). Gedney et al. (2014) reported that river flows in some of the most polluted regions of northern Europe were up to 25% higher than normal when aerosol levels peaked around 1980, and attributed this to reduced evaporative loss. The authors proposed that hydrological trends might be reversed with more recent "global brightening". Changes in climate can also influence fluxes and concentrations of atmospheric pollutants to the land surface. Ambient pollution levels are heavily dependent on prevailing air mass trajectories (Fleming et al., 2012), while rainfall events can increase both fluxes and concentrations of pollutants, particularly in upland environments through the feeder–seeder effect (Inglis et al., 1995).

The ambient environment of semi-natural systems across the UK, including those represented by ECN, may therefore be expected to have undergone significant shifts in both climate- and pollution-related ecological stressors over the past two decades. Quantification and characterisation of these changes are essential prerequisites for the appropriate attribution of single and interactive effects on soils, surface waters, species and ecosystems. The first broad assessment of trends in physical and biogeochemical drivers of environmental change at ECN sites was conducted by Morecroft et al. (2009), who also reported on trends in ecological indicators of change. Statistical analyses were largely confined to tests of linear change in variables summarised at an annual scale. The study period (1993–2008) was characterised by marked increases in air temperature across most seasons (amounting to circa 1 °C $decade^{-1}$), in addition to large reductions in concentrations of SO_4^{2-} and acidity in precipitation. However, Swart et al. (2015), in their assessment of recent trends in Arctic sea ice, emphasise that climate change is unlikely to be uniform, and characterisation of trends using linear methods alone is thus vulnerable to the specific period chosen for analysis. A succession of relatively cool years since 2008 (e.g. Cattiaux et al., 2010) and evidence for a recent stabilisation of atmospheric pollutant deposition rates (Curtis and Simpson, 2014), render a simple repeat of previously applied linear analysis of restricted value, while acquisition of a further five years data has increased options to characterise trends using non-linear approaches.

In the following assessment, therefore, we apply both linear and non-linear statistical analyses of key meteorological and air pollutant variables at the 12 terrestrial ECN sites covering the period 1993–2012 with the aim of: (1) quantifying net change over the full period, (2) characterising temporal variation in the rate and statistical significance of change, and (3) testing for evidence of changing frequency of extreme meteorological events. We also refer to modelled meteorological data to provide longer-term context for the changes recorded over the past two decades at each site.

2. Methods

2.1. Sites

For most of the last two decades the terrestrial ECN comprised 12 sites spanning much of the UK. Information regarding location, biogeographical characteristics and dates of initiation of monitoring is provided by Sier and Monteith (2016), but sites range from lowland agricultural systems, including Rothamsted and Drayton, lowland forested sites – Wytham and Alice Holt, upland low intensity agricultural – Sourhope, Glensaugh and Moor House, to