Met Office
Hadley Centre

# Influences of EU forests on weather patterns: Final report

European Commission (DG Environment)
August 2012

Michael Sanderson, Edward Pope, Monia Santini, Paola Mercogliano and Myriam Montesarchio

## Contents

**One page summary** ........................................ **2**

**Introduction** ........................................ **3**

**Mechanisms by which forests affect weather and climate** ........................................ **4**

**Types of Forest** ........................................ **5**

Boreal Forests ........................................ 6

Temperate Forests ........................................ 6

Tropical Rain Forests ........................................ 7

Feedbacks following Deforestation ........................................ 7

**Historical changes in European forest cover** ........................................ **7**

**Changes in weather patterns in Europe** ........................................ **8**

Heat waves ........................................ 9

Droughts ........................................ 9

Cold waves ........................................ 9

Storms ........................................ 10

Floods ........................................ 10

Other factors affecting European weather and climate ........................................ 11

**Physical influences of forests** ........................................ **12**

**Simulations of the effects of forest cover change on weather** ........................................ **13**

**Comparison of methodologies for quantifying the influence of forests on weather** ........................................ **15**

**Knowledge gaps** ........................................ **16**

**Case studies identifying hot spots of forest influence on weather patterns and climate** ........................................ **19**

Mediterranean ........................................ 19

Central and Eastern Europe ........................................ 20

Northern Europe ........................................ 21

Urban Areas ........................................ 22

**Summary** ........................................ **23**

**References** ........................................ **25**

## One page summary

**General findings:** forests across Europe insulate the land surface from weather extremes, particularly by moderating temperatures, and reducing mean wind speed and variability. If forests are healthy, the leaf litter and root structures enhance soil stability, thereby improving water quality, though not necessarily quantity. Studies show that well-maintained forests can reduce the frequency of shallow (<1 m) land slides, except on the steepest hillsides, but have very little impact on deep (>3 m) land slides. In addition, while forests reduce surface runoff rates, they cannot significantly reduce the impact of floods caused by long-duration, intense rainfall. In urban areas, trees provide multiple benefits: shade and evaporative cooling in the summer (reducing demand for air conditioning), improved surface drainage (reducing the impact of localised floods), lower mean wind speeds and gust strengths (reducing damage and energy usage for heating). Forests may contribute to cloud building and influence weather conditions at regional level. However, trees in and around urban areas can cause damage and disruption particularly during storms, and can increase the risk of fire.

**Northern Europe:** observations show that the loss of forest leads to a harsher climate with higher wind speeds, lower temperatures and a deeper layer of frozen soil, making it difficult for forests to recover and stabilise the local climate. Weather simulations in this region find that small-scale increases in forest cover increase temperatures above the trees, decrease wind speeds and reduce surface moisture fluxes.

**Central Europe:** the presence of forests across Europe increases the proportion of precipitation that is returned to the atmosphere by evapotranspiration, where it can be propagated towards the interior of the continent. For this reason, forests help to maintain land productivity and reduce the severity of heat waves in this region. Weather simulations suggest a complex response of local weather to forest cover change, but indicate that increased forest cover leads to higher temperatures above the trees and reduced wind speeds.

**Mediterranean Europe:** observations show a clear historical drying trend in this region, including a reduction of precipitation from summer storms in eastern Spain. Recent work suggests that this drying is partly due to continued vegetation loss, which has reduced humidity and soil moisture levels, eventually causing increased surface temperatures. This trend is important since winter/spring precipitation deficits in this region have been associated with droughts and heat waves in the rest of Europe. In addition, the saline outflow from the Mediterranean Sea can potentially affect the Gulf Stream and the North Atlantic Oscillation, thereby influencing weather patterns across Europe.

## Introduction

The possible influence of vegetation on regional rainfall was first suggested in the 1970s in the context of drought in the Sahel (Charney, 1975; Charney et al., 1975). Theoretical arguments based on the increase in albedo[1], following the removal of vegetation via overgrazing and desertification, suggested that rainfall in the Sahel would decrease. This result was supported by early global climate model simulations, which represented changes in land surface properties using modifications to the surface albedo. In these early simulations, rainfall over the Sahel was reduced by 40% during the rainy season following desertification. Since this time, our understanding of the mechanisms by which vegetation, including forests, may influence local, regional and global climate has improved considerably and is discussed in later sections of this report.

The objective of the present study was to provide an assessment of the influences of forests in the European Union (EU) on weather and climate, with a particular focus on precipitation (i.e., rainfall), and identifying benefits that could arise as a result of increased forest cover. This objective was achieved in several stages. First, a literature review of the influences of forests worldwide on weather and climate was presented. Next, datasets which provide estimates of historical changes in Europe's forest cover and weather were identified and assessed. The influence of forests on weather-related phenomena including storms, forest fires, flooding, soil stability, water quality and quantity were also summarised. Numerical weather prediction and climate models were then used to simulate and quantify the impact of forest cover change on local and regional weather and climate in seven locations around Europe. Different modelling techniques and methodologies for assessing how forests could influence weather were compared. The main mechanisms and feedbacks by which forests affect weather across different scales were summarised and linkage diagrams using the DPSIR framework were constructed to illustrate these feedbacks. Major information and knowledge gaps inhibiting a more complete understanding of the impact of forests in the EU were highlighted. Finally, areas within the EU where forests have been shown to exert a significant influence on local and regional climate were identified, ranked, and described in detail. The major findings of the study, listed above, are described briefly in the main body of this report.

[1] The ratio of reflected to incoming radiation.

## Mechanisms by which forests affect weather and climate

In this section, the mechanisms by which forests influence weather and climate are briefly discussed. These mechanisms apply to all types of forest and may be divided into two main classes: physical and chemical. The main physical mechanisms are associated with processes involving albedo, evaporative cooling and aerodynamic drag (e.g. Betts, 2006; Bonan, 2008). Chemical mechanisms of importance include the uptake of, and interaction with, carbon dioxide ($CO_2$) and ozone ($O_3$), the release of hydrocarbons and the formation of aerosol particles (Arneth et al., 2010). Following a description of the general properties of the different mechanisms, the three main forests types are described, with the dominant mechanisms for each type being discussed in more detail.

Forests have lower albedos than other types of vegetation and soils, and consequently absorb a large fraction of the incoming solar radiation, releasing it as sensible heat which warms the air above the forest (Betts and Ball, 1997). Forests absorb more moisture from soils than other types of vegetation. The transfer of this moisture through the trees and its evaporation from the leaves into the atmosphere cools the air through the transfer of latent heat. This process is referred to as evapotranspiration. The increased moisture levels above the forest can encourage the formation of clouds and rainfall. Forests also present an aerodynamically rough surface which enhances turbulence (Rotenberg and Yakir, 2010) and reduces wind speeds (Vautard et al., 2010), and subsequently can also enhance convection, cloud formation and rainfall (Pielke et al., 2007).

Forests also affect global climate by modifying carbon dioxide ($CO_2$) concentrations. Carbon dioxide is the most important greenhouse gas whose levels in the atmosphere have increased from about 280 parts per million (ppm) in the pre-industrial era (i.e. before about 1750) to 379 ppm in 2005 (Solomon et al., 2007) and are continuing to increase. Globally, forests (especially tropical forests) absorb carbon dioxide and reduce its levels in the atmosphere, which helps to cool the climate in the absence of other effects (Bonan, 2008). It is estimated that the terrestrial biosphere (i.e. all vegetation and soils) has absorbed about 25% of carbon dioxide emitted since 1750 (Solomon et al., 2007).

In the absence of human influence, climate variability and its interaction with forests can still result in large changes in local climate (Houghton, 2009). For example, increasing levels of carbon dioxide cause the closure of the stomata on the leaves of trees. This has the effect of reducing transpiration and, hence, the moisture transferred into the atmosphere. Higher temperatures can cause the dieback of forests (e.g., tropical forests) and the northward migration forest (e.g., boreal forests in Asia). In both cases, evapotranspiration will be reduced, although the northward movement of boreal forests would increase evapotranspiration in areas where forest cover increases. Finally, warmer temperatures tend to increase soil respiration rates, thereby leading to greater emission of carbon dioxide from soils, which causes further warming. In addition, it is important to note that, while higher levels of carbon dioxide can enhance plant growth, the effect may be short-lived and will also depend on availability of soil moisture and nutrients (Solomon et al., 2007).

Forests also emit a wide range of hydrocarbons and other organic compounds (for example, isoprene and terpenes) which can modify local and global ozone levels (Wang and Shallcross, 2000) and form aerosol particles (Arneth et al., 2010). These aerosols act to cool the local climate by scattering and reflecting incoming solar radiation (Quaas et al., 2004). They can also enhance cloud formation and interact with existing clouds, altering their properties and lifetimes (Spracklen et al., 2008; Pöschl, 2010; O'Donnell et al., 2011).

Forest fires are responsible for the emission of large amounts of carbon (mostly carbon dioxide), soot, smoke and other aerosols into the atmosphere. In some areas (e.g., Canada) the area burned has increased since the 1970s which may be a consequence of the warming climate (Gillett et al., 2004). Forest fires are projected to become more likely in the future in Europe; additionally, the areas which could be burned and the length of the forest fire season are also projected to increase (Camia et al., 2008).

## Types of Forest

Forests may be classed into three main types: boreal forests, which exist at high northern latitudes in areas such as Finland and Russia; temperate forests, which occur in mid-latitude Europe, North America and other areas; and tropical rain forests, the majority of which occur in South America, central Africa and south-east Asia (Bonan, 2008). The overall impact of these different types of forest depends on the relative influence of the physical and chemical mechanisms described above, and are discussed in more detail in the following sections. These influences can vary considerably between tree species in each forest type and also as a consequence of regional differences in climate and soil moisture.

### Boreal Forests

Boreal forests are mostly thought to affect climate through their low albedos which, in the absence of other influences, act to warm the local climate (Bonan et al., 1992). However, their overall effect on global climate is less clear, as the uptake of carbon dioxide by these forests (which leads to a cooling of the climate as described above) could be larger than the warming induced by the low albedos. The exact balance changes with region – the albedo dominates in the coldest regions owing to greater snow cover and slower tree growth (Betts et al., 2000).

Boreal forests also emit terpenes which can form aerosols and cool the climate as discussed above; however, the exact mechanisms and overall effect of these aerosols on clouds is still poorly understood. As a result, while most studies suggest that boreal forests overall warm the local and global climate (e.g. Bonan et al., 1992; Snyder et al., 2004; Bala et al., 2007; Swann et al., 2010), a few others have suggested that the effect of the aerosol and cloud formation exceeds surface warming caused by the low albedos, resulting in a net cooling of the climate at high northern latitudes (Spracklen et al., 2008).

### Temperate Forests

Simulations using climate models also suggest that temperate forests warm the local and global climate, particularly during the winter, as a result of their low albedos (e.g. Snyder et al., 2004). However, owing to the higher temperatures at mid-latitudes, and the availability of soil moisture, transpiration levels are higher and the effect of evaporative cooling is also important. Consequently, the exact effect of temperate forests on climate can vary regionally and temporally between warming and cooling, depending on temperatures, prevailing rainfall patterns and soil moisture (Teuling et al., 2010).

### Tropical Rain Forests

Tropical rain forests act to cool the climate because the transpiration levels are high enough that evaporative cooling exceeds the warming due to the low albedo of the forest (Bonan, 2008). As a result of such large moisture fluxes, very large clouds form above these forests which return the moisture to the land as rainfall. Tropical forests also absorb large quantities of carbon dioxide from the atmosphere which also has a cooling effect.

### Feedbacks following Deforestation

Simulations of the effects of large-scale deforestation and afforestation at mid- and high northern latitudes (thereby affecting boreal and temperate forests) have indicated that feedbacks involving sea ice could amplify the effects on climate (Bonan et al., 1992; Lee et al., 2011). For example, afforestation would increase temperatures and cause ice and snow on land and the ocean to recede, leaving behind land and ocean surfaces which have much lower albedos than the snow and ice. The newly exposed land and ocean would absorb most of the incoming solar radiation and release it as sensible heat, which would cause further reductions in snow and ice cover. Hence, this positive feedback on snow and ice cover could enhance any warming caused by increased forest cover in temperate and boreal regions. Studies of tropical deforestation in Indonesia have suggested that feedbacks with the local ocean circulation patterns and winds have important impacts on precipitation in the wider region, although existing studies disagree on the sign of the change in precipitation (Schneck and Mosbrugger (2011) and references therein).

## Historical changes in European forest cover

Forest cover in Europe has generally decreased throughout history as the population increased, owing to a rising demand for land and wood products (Ramankutty and Foley 1999; Klein Goldewijk, 2001; Kaplan et al., 2009). However, over the past 100 years, Europe’s forest cover has increased overall, partly due to intensified land-use, abandonment of agricultural land and afforestation schemes which have emerged as a result of growing awareness of the benefits of forests (Mather, 1992).

Several databases are available which describe land-use change in Europe over the past 100 – 150 years. These fall into two main categories: i) databases which have been created using a range of satellite (e.g. DISCover[2]; GLC2000[3]) and land-based observations (e.g., HILDA[4]); ii) databases (e.g. HYDE[5]; SAGE[6]) which are generated using numerical models that combine measurements of surface climate, population statistics and ecosystem models. The latter use ecosystem models to estimate the vegetation types most suited to each location, and combine this information with assumptions about the geographical distribution of human land-use to derive vegetation cover maps. Given the different assumptions used in generating these datasets, it is no surprise that there are inconsistencies, notably prior to 1990 (after which satellite data became readily available). In addition, many of the original data sources are either hard to obtain or are not publically available (e.g., Küchler, 1964). Difficulties in comparing datasets also arise because of changes in the definitions of what constitutes a forest.

In this project, the Historical Land use Database (HILDA) was identified as having the most accurate description of where and when forest cover in Europe has changed because it is based on historical maps whenever possible. This database indicates that changes in European forest cover are scattered throughout the continent, with an exception being large-scale afforestation in southern Sweden. Consequently, these changes in forest cover are too small and localised to have an effect on the climate of Europe as a whole, but may have an impact on local weather in the immediate area.

## Changes in weather patterns in Europe

Observational studies indicate that the Europe's climate has warmed during the twentieth century, with higher rates of warming occurring in the north than the south, although considerable spatial variation in temperature trends occurs over the continent (Klein Tank et al., 2002). Furthermore, rainfall has generally increased in the north of Europe with a rise in the number of wet days and precipitation per wet day. Indeed, several regions across the north and west of Europe (particularly France and Scandinavia) have also experienced an increase in the mean number of consecutive wet

[2] Loveland and Belward (1997).
[3] Hartley et al. (2006).
[4] Historic Land Dynamics Assessment http://www.grs.wur.nl/UK/Models/HILDA
[5] http://themasites.pbl.nl/en/themasites/hyde/index.html (Klein Goldewijk, 2001)
[6] http://www.sage.wisc.edu/mapsdatamodels.html (Ramankutty and Foley, 1999)

days. Analysis of a very long rainfall record for north-western France indicates large shifts in the seasonality of rainfall. In particular, warmer and drier summers occurred in the late eighteenth and twentieth centuries, whereas summers were cooler and wetter in the first half of the nineteenth century (Masson-Delmotte et al., 2005). As well as experiencing changes in annual average temperature and precipitation, Europe has also witnessed a shift in extreme weather events of concern: heat waves (including droughts), cold waves, storms and floods which are summarised below.

### Heat waves

Observations across Europe indicate that the frequency, severity and duration of these events have increased. In general, they are less severe in the north than the south (Meehl and Tibaldi, 2004). Studies suggest that heat waves are exacerbated by low soil moisture levels in the warm summer months, which reduces the extent of evaporative cooling due to evapotranspiration from the land surface. Such conditions commonly follow below-average rainfall in the winter and spring seasons (Fischer et al., 2007). Heat waves are especially common in Mediterranean Europe, which has experienced continued drying and warming, a reduced number of wet days, and an increased number of consecutive dry days. Models indicate the drying trend in the Mediterranean could have started approximately 2000 years ago when the Romans began deforesting southern Europe (Reale and Shukla, 2000). A wide range of metrics have been used to examine changes in heat waves which makes a comparison of different studies difficult.

### Droughts

The increased frequency of droughts in southern Europe is potentially significant as winter/spring precipitation deficits in this region are linked to summer heat waves in the rest of Europe (Vautard et al., 2007). However, any trends are partly dependent on the choice of drought index (Burke, 2011). The impact of small scale deforestation is likely to affect the local climate only, and any possible influence on large-scale droughts is unclear.

### Cold waves

Extremely cold winters primarily affect northern, western and eastern Europe. Analysis of surface temperature measurements in selected regions of Europe have indicated a decrease in the frequency and duration of cold waves (Hulme et al., 2002; Mietus and

Filipiak, 2004; Radinović and Ćurić, 2012). However, there are far fewer studies of changes in cold waves than heat waves, and the range of different metrics used makes a comparison of the results difficult.

### Storms

Strong winds and heavy rainfall events are common across Europe. The inter-annual variability of storm numbers is very high, making it difficult to identify any trend over time (Matulla et al., 2008). Some studies have suggested that storminess has increased in winter and decreased during summer (Wang et al., 2008; Donat et al., 2011; but there appears to be no clear long-term trend in storminess in Europe (Matulla et al., 2008). However, a peak in activity was prevalent in the late 1980s and early 1990s, followed by a subsequent decrease (Wang et al. 2008). It seems unlikely that small changes in forest cover could strongly influence storms tracks, although there is a possibility that they may alter the moisture content and precipitation amounts from the storms.

More recently, the loss of summer storms along Spain's east coast has been attributed to reduced humidity owing to the drainage of nearby marshland and the loss of local forest cover (Millán, 2008). Consequently, the water vapour brought inland daily by the sea breeze is returned back out to sea instead of falling as precipitation.

### Floods

Severe floods have always occurred in central Europe, mostly as a result of thawing after winter (e.g. when ice dams fail, resulting in a sudden release of water) and extreme precipitation events in other seasons, such as summer Vb[7] storms which are known to cause flooding in central Europe, e.g., during August 2002 (Millán, 2008).  Analyses of reported floods for the twentieth century shows no clear trend in the numbers of floods during summer, but does show a decrease during the winter months, owing to warmer temperatures (Mudelsee et al., 2003). River engineering works and reservoir building have had very little effect on flood frequency. It is important to note that the annual frequency of floods is highly variable.

[7] Storm tracks across Europe were first classified by van Bebber (1891) into five main groups. The Vb storm track has remained in use today owing to its links with flooding events in central Europe. These storms begin over the eastern Atlantic Ocean, and travel over the Iberian peninsular and the north-western Mediterranean before moving north-eastwards into central Europe.

## Other factors affecting European weather and climate

Weather patterns across Europe are strongly influenced by the North Atlantic Oscillation (NAO) - the oscillation in the surface pressure difference between Iceland and the Azores. For example, during winter months with a high NAO index (> 1.0), northern Europe experiences higher than average rainfall, whereas southern Europe (stretching from Western Iberia to the Black Sea) experiences lower than average rainfall. The situation is reversed for winter months with a low NAO index (< -1.0), i.e. southern Europe experiences increased rainfall, while northern Europe experiences cold, dry conditions (Trigo et al., 2004).

European weather is also indirectly affected by water, salt and heat exchanges across the Gibraltar and Dardanelles Straits. Notably, the saline outflow from the Mediterranean may affect the Gulf Stream, thereby modifying storm tracks and weather across Europe (Calmanti et al., 2006). As a result, the interaction between the Atlantic and Mediterranean-Black Sea drainage basins could play a role in determining European weather. For this reason, forest cover change in southern Europe could exert an influence on weather patterns across Europe by modifying regional precipitation and, therefore, the salinity of the Mediterranean. However, the exact effect of the saline outflow from the Mediterranean on the Atlantic storm track (and the magnitude of any effect) is still poorly understood.

The physical interaction between air flows driven by the Atlantic and Mediterranean drainage basins also plays a role in determining weather patterns across Europe. The reason for this is that the drainage basins are separated by high ground, which marks the continental divide; thus, moisture tends to stay on the windward side of the divide. However, under certain meteorological conditions, significant quantities of moisture can be transported across the continental divide, notably in the case of Vb storms which are known to cause floods in central Europe. More generally, studies of central Europe show that westerly and northerly winds predominate in winter months, meaning that precipitation in this season is governed by moisture carried inland from the Atlantic Ocean. In contrast, the contribution of moisture evaporated from the central European land surface is at its most significant in the summer months. Studies of Alpine Europe suggest that the oceans provide approximately 80% of the moisture which falls as precipitation (Sodemann and Zubler, 2010). Similarly, global studies suggest that an annual average of roughly 86% of continental precipitation originates from the oceans, with just 14% from the land surface (Gimeno et al., 2010).

## Physical influences of forests

In this section, the influences of European forests on water quality and quantity, precipitation, flooding, land slides and crop yields are briefly discussed. Numerous studies have shown that forests are important for maintaining and improving water quality. For example, forests in the mountains near Vienna are recognised as being essential for ensuring supplies of clean water (Koeck et al., 2006). In this regard, the key benefit provided by the forest is a reduction in soil erosion. A well-maintained forest can limit erosion in two main ways: i) the forest understory reduces splash erosion caused by the impact of falling raindrops; ii) tree roots help to mechanically stabilise soils and reduce suspended particulates in water, and also improve soil permeability so that it can absorb rainfall more easily (FAO, 2005). The trees can also absorb gaseous species such as nitrogen oxides and sulphur dioxide, thereby preventing them from entering and polluting water courses. However, in some cases, the enhanced turbulence generated by greater tree cover can lead to higher deposition rates of atmospheric pollutants in rainfall which can subsequently acidify the soils and ground water, leading to environmental problems.

Links between forests and water quantity are less clear; the spatial scale considered may also determine whether forests are net producers or consumers of water (D'Almeida et al., 2007). In some areas (e.g., central Europe) transpiration of moisture by forests enhances local rainfall during the summer months (Ellison et al., 2012; Wulfmeyer et al., 2011). However, while forests can increase local precipitation totals, they can also reduce the quantity of fresh water available as a result of high water usage, and intercepting rainfall before it reaches the ground. The exact effects will depend on many factors, including the age and species of trees within the forest (Wattenbach et al, 2007). The magnitude of the effect of forests on precipitation and hydrology continues to be debated (van der Ent et al., 2012).

The soil stability provided by a well-maintained forest can reduce the frequency of shallow landslides (<1 m deep), except on the steepest hillsides. However, landslides are more likely in forests where large open spaces exist or the trees are in poor health. In addition, deep-seated landslides (>3 m) are not noticeably influenced by the presence or absence of forests (Rickli and Graf, 2009). Similarly, forests have only a limited ability to reduce the impact of flooding - they can absorb rainfall from short-duration storms, but cannot prevent flooding from large-scale, long-duration rainfall events (FAO, 2007).

However, forests on flood plains increase the drag experienced by the surface runoff and can, therefore, slow down the flood waters.

Several studies have indicated that small areas of trees planted as shelterbelts can enhance local crop yields. These shelterbelts prevent damage to crops by strong winds, and can enhance water use efficiency of the crops by increasing the local humidity levels (Donnison, 2012). Flooding of fields may also be reduced as the tree roots increase the permeability of the soils. However, planting trees too close to crops can increase shade and dry the soil, restricting crop growth. Therefore, it is necessary to select appropriate tree species and density of planting carefully in order to obtain the optimum benefits.

## Simulations of the effects of forest cover change on weather

The impacts of forest cover change on local and regional weather and climate were assessed using two sets of model simulations. First, the nested modelling suite, based on the Met Office weather forecast model (Webster et al., 2008), was used to simulate the effects of forest cover change in five different locations within Europe (Sweden, Germany, Austria, northern Italy and eastern Spain). The second set of model simulations used the high-resolution regional climate model COSMO-CLM (Davin et al., 2011). These latter simulations examined the effects of forest cover change and climate change in southern Italy and south-east Romania.

For the nested suite study, three simulations were performed for each location, which were identical except for the forest cover. These simulations used the present-day forest cover, a scenario where all grassland was converted to forest (afforestation), and a third where all forests were replaced by grass (deforestation). These simulations were executed for two 9-day periods in spring and summer 2002 - the aim being to elucidate any influence of forest cover change on local climate, and also on the Vb storm that resulted in a severe flood in August 2002. In every afforestation simulation, air temperatures directly above regions of increased forest cover became warmer and wind speeds decreased, with the changes being more consistent during summer than spring, and clearest in Sweden. The reverse effects were observed in the case of deforestation. Increasing the forest cover also locally reduced the overall flux of moisture from the surface. This result indicates that evaporation from the open land surface is high in these simulations, suggesting that the soil moisture levels are relatively high. Repeating the simulations during a much drier period, such as the 2003 heat wave, might produce the opposite result, i.e. the moisture flux would rise with increasing forest cover.

Summer rainfall was enhanced in the afforestation scenario relative to the deforestation scenario. However, the changes were generally small (a few percent) and were not statistically significant. The simulations also showed no obvious changes in surface humidity or cloud cover. In addition, there were no clearly discernible impacts on climate of regions outside of the area of modified forest. This is primarily due to the sensitivity of the model, in which slightly different boundary conditions (i.e. forest cover) can produce perturbations to small-scale weather phenomena, resulting in “noise”. For this reason, averaging the results from many more simulations would be required to reduce the effect of this noise and identify any meaningful signal.

The COSMO-CLM simulation study of Italy and Romania produced climate projections for the period 2015-2045 under the A1B emission scenario for three different arrangements of vegetation cover: i) present-day forest cover; ii) afforestation; iii) deforestation. For each spatial domain, the results were compared with a historical simulation for the period 1971-2000 using present-day forest cover, in order to better distinguish the effects of global climate change from those induced by land cover change. The COSMO-CLM model was driven by boundary conditions generated by the global climate model CMCC-MED (Scoccimarro et al., 2011). It is important to note that climate projections using a given emission scenario differ considerably between GCMs. If boundary conditions for the COSMO-CLM model had been supplied by a different GCM, the projected regional climate change could also be different.

In Italy, afforestation was found to cause a decrease of mean temperatures at 2 metres above the land surface, with deforestation increasing temperatures. The same trends were observed for Romania in the summer months, while winter showed the opposite result. While these findings appear contradictory to the results produced by the weather simulations using the nested suite described previously, it is not possible to make a direct comparison. Temperatures in the nested suite are calculated *above* the forest, whereas temperatures in COSMO-CLM are calculated at 2 metres above the land surface and will, therefore, be the values *within* the canopy for forested regions. As shown by observations, temperatures below the forest canopy will be insulated from the extremes of the diurnal cycle, and will be lower than those above the forest canopy, meaning that the results presented by the Met Office and CMCC are entirely consistent.

The COSMO-CLM simulations also suggest that, for both Italy and Romania, the annual mean precipitation rose slightly when forest cover was increased. Notably, the changes were concentrated in the respective wet seasons for both areas, i.e. autumn-winter in southern Italy and spring-summer in Romania. In agreement with observations, afforestation had the effect of moderating extremes in temperature, precipitation and wind speed.

## Comparison of methodologies for quantifying the influence of forests on weather

Within the scientific community, both observations and numerical models have been used to assess the impact of forests on local and regional weather and climate. For example, measurements around Europe indicate that forests insulate air temperatures from the extremes of the diurnal cycle, i.e. maximum daytime temperatures measured below the forest canopy tend to be lower than in open areas, while minimum night temperatures under the forest canopy tend to be warmer. An exception occurs during windy nights when cold pools of still air can form in densely forested areas. Wind speeds recorded in areas where forests have re-grown (owing to abandonment of agricultural land) have a clear downward trend. Studies in the far north of Europe (Finland) have shown that forest loss leads to a harsher climate, with colder temperatures, higher winds speeds and a deeper layer of frozen soil (Vajda and Venäläinen, 2005).

The Convective and Orographic Precipitation Study (COPS) employed a range of ground-based instruments and satellite data to study the formation of convective clouds and rainfall over part of south-western Germany and eastern France during summer (Wulfmeyer et al., 2011). This study demonstrated that evapotranspiration from forests made a significant contribution to the formation of convective clouds and subsequent rainfall. However, in general, suitable observations for the validation of models have mostly been made in a small number of locations for short periods of time. Thus, to provide a more accurate evaluation of the impact of forests on weather across Europe, it would be necessary to build-up long time-series of important meteorological variables, including temperature, precipitation, humidity and wind speed in both forested and open areas at many locations across Europe.

A wide range of numerical models have also been used to study the effects of forests on climate. One of the most important aspects of these models is providing a description of the interaction between the land surface and the atmosphere. This includes quantifying the transfer of moisture from soils and vegetation to the lower atmosphere, and the formation of convective clouds and rainfall. However, only very high resolution models, such as Cloud-Resolving Models (CRMs) or high-resolution Numerical Weather Prediction models (NWPs), can resolve convective processes directly. Lower resolution models, such as Regional Climate Models (RCMs) and Global Circulation Models (GCMs), solve the same equations, but necessarily employ numerical prescriptions and parameterisations to account for the processes which occur on sub-resolution spatial scales, such as convection.

As a result of the computational cost of high-resolution models, their use has generally been restricted to studying small areas (e.g. ~10 km x ~10 km) for short periods of time (e.g. days). Despite this, a few studies simulating weather using very high resolution models for up to 20 years have recently been made. Studies of the effects of forests and forest cover changes on weather and climate across continental and global scales and on longer time periods require the use of RCMs and GCMs. However, as described above, these models generally have lower spatial resolutions (e.g. ~10 - 50 km) which means they cannot resolve convective processes directly. One consequence is that climate models do not simulate the very intense rainfall seen in observations. Therefore, the choice of model will depend on the particular scientific question of interest. In general, complex questions regarding the impact of forests on weather and climate will require the use of a range of models with varying resolutions and spatial domains.

## Knowledge gaps

As described in the previous section, numerical models provide a representation of the interaction between the land surface and the atmosphere which includes descriptions of the evaporation and transpiration of moisture from soils and vegetation to the lower atmosphere, the movement of water above and below the land surface, the absorption, reflection and emission of radiation, and the aerodynamic characteristics of different land surface types. Due to the inherent complexity of land surface – atmosphere interactions land surface schemes necessarily rely on certain assumptions and approximations which can strongly influence outcomes of numerical weather predictions and climate projections. For example, land-use is categorised in terms of a number of general `types' including urban land-use, vegetation cover, lakes and snow where relevant. Within this approach, the observed vegetation is re-classified into broad categories called Plant Functional Types (PFTs). The behaviour of different each PFT is characterised in terms of phenomenological parameters such as roughness, albedo and root depth. For models in which the vegetation is assumed to be static, these parameters remain constant over time. Therefore, to improve the representation of the forest-atmosphere interaction, it will be necessary to include more PFTs (e.g. deciduous and ever-green broad leaf and needle leaf trees), and to account for vegetation growth such that leaf area, tree height, albedo and root depth change over time.

Soil moisture also strongly affects weather patterns through the exchange of heat and water between the land surface and atmosphere. In particular, it is well known that a reduction in soil moisture in spring may lead to warmer, drier summers. However, soil moisture is extremely variable over space and time, making accurate measurements difficult. In addition, soil moisture in numerical models is often initialised using results from other models. For example, the initial soil moisture for the nested suite simulations was taken from the ERA-Interim dataset produced by European Centre for Medium Range Weather Forecasting (ECMWF). These data are provided at a coarser resolution than that used by the nested suite, meaning they must be interpolated which results in locally inaccurate estimates for soil moisture and potentially leading to excess precipitation, or higher than expected temperatures. The vegetation map used to generate the ERA-Interim data will not be identical to the map used in the nested modelling studies which could also produce soil moisture levels that are too high or too low. Consequently, future simulations would benefit from higher-resolution initial conditions for soil moisture, which would be improved by better observations.

Some recent studies have suggested that the emission of Biogenic Volatile Organic Compounds (BVOCs) from boreal forests, and the resulting formation and growth of aerosol particles could have a major effect on climate, especially at high northern latitudes (Quaas et al., 2004; Spracklen et al., 2008). More specifically, while most studies suggest that boreal forests warm the local and global climate, they generally ignore the impact of BVOCs which could enhance cloud formation and cool the local climate. However, the processes governing the rate at which these compounds are produced and emitted by forests are poorly understood, as are the dependence of emissions on local weather conditions and the exact effects on clouds.  Consequently, further work, using a combination of models and observations, are needed.

The example above serves as a reminder of our limited understanding of feedbacks linking ecosystems and the atmosphere. Another related example is whether forests increase or decrease the availability of water (van der Ent et al., 2012). In reality, the effect is likely to be dependent on local conditions. Therefore, a clear understanding of local conditions is required to better evaluate management options that could maximise water availability and reduce the likelihood of extended droughts. This can be achieved through more intensive observation and modelling studies at a wide variety of locations within Europe.

Weather and climate simulations can also be limited by the method by which low-resolution global simulations are downscaled to higher resolutions. For example, both the Met Office and CMCC ran models using modified forest cover only in the high-resolution "nested" domain. In addition, the nested grids were only one-way coupled. In the case of the Met Office nested suite, this meant that a 60 km resolution global model was used to drive a 12 km resolution grid, which then drove a 4 km resolution grid over the region of interest. Consequently, changes to weather systems caused by modified forest cover in the 4 km domain cannot propagate outside the 4 km domain so that influences on larger spatial scales are not captured. In general, this approximation is probably not a significant source of error since the downstream impact of forest cover change is likely to diminish rapidly with distance. Nevertheless, it would be useful to implement two-way coupling between the nested grids, thereby providing an evaluation of the influence of forest cover change beyond the spatial extent of the 4 km domain. With more powerful computers, this may become feasible in the future.

Similarly, the computational cost of high-resolution models restricted both the length and number of simulations that could be run for this project, leading to significant uncertainties in identifying the factors which govern the response of weather and climate to changes in forest cover. Therefore, in order to obtain a better understanding of the key influences and impacts of changes in forest cover, it would be necessary to execute an ensemble of simulations for each region of interest, using a variety of different boundary conditions, durations and carbon dioxide emission scenarios.

This study has also highlighted a lack of geographically explicit historical data identifying forest cover change across Europe. However, the recently developed HILDA database goes some way to filling this information gap. In addition to this, we have highlighted the need for reliable long-term observations of a range of meteorological variables at a variety of locations around Europe to provide a better understanding of forest-weather interactions. The variables of particular importance are: rainfall, temperature, humidity, cloud cover and surface energy fluxes (e.g., sensible and latent heat). Such observations are generally only available for limited time periods in a few locations within Europe, although a few longer data series are available. Observations at locations where forest cover has changed are also scarce, but would provide valuable data on the impact of forests on local climate.

## Case studies identifying hot spots of forest influence on weather patterns and climate

By combining the results from weather and climate simulations performed for this project with an extensive review of the available literature, we have identified regions across Europe where the influence of forests on weather is particularly strong. At the local scale, land-use change has the largest effect on climate, although globally the effects of rising greenhouse gases dominate. Some change in forest cover may occur in the future as a consequence of greenhouse gas-induced climate change, which could change the ranking order below. Ranked in order of decreasing importance, the hot spots are: the Mediterranean, central and eastern Europe, northern Europe, and urban areas; these regions are described in more detail below.

### Mediterranean

A variety of observations (e.g. Klein-Tank et al., 2002) have identified a clear drying trend in the Mediterranean region, with simulations and theoretical arguments (e.g. Millán, 2008) suggesting that this trend is linked to a reduction in forest cover. In particular, climate model studies suggest that the loss of forests over the past 2000 years has resulted in a drier climate (Reale and Shukla, 2000). The most general explanation for this change is that natural vegetation typically has a lower albedo than non-forested land, leading to higher surface temperatures over the land, and consequently a larger temperature contrast between the land and the sea. This larger temperature difference is thought to have encouraged a more intense local atmospheric circulation than at the present time, which, when combined with additional water transpired by the forests, would enhance precipitation in the Mediterranean area.

Observations in eastern Spain (e.g. Millán et al., 2004) have also identified a clear reduction in the occurrence of summer storms and precipitation totals, particularly over the past 30 years. Recent work has attributed this to two main changes in the land surface: i) the drainage of coastal marshes and removal of forest cover, which have reduced the evapotranspiration rate from the land surface such that the condensation level of the Mediterranean Sea breeze no longer falls below altitude of the mountain tops; ii) the increased land surface temperatures due to vegetation loss, which result in rising air columns that carry storms up and over surrounding mountains, reducing orographic precipitation and leading to in-land drought. The reduction in summer storms is necessarily accompanied by an accumulation of moisture above the western Mediterranean basin. In principle, this should enhance the local greenhouse effect, increasing the occurrence of explosive cyclogenesis. A recent proposal also suggests that the build-up of moisture has the potential to increase the water content of Vb storms which are known to cause severe floods in central Europe.

Recent findings indicate that the continued drying trend in the Mediterranean could have implications for weather patterns across Europe. Indeed, several studies have identified a link between winter/spring precipitation deficits in southern Europe and the occurrence of heat waves throughout the rest of the Europe (e.g. Vautard et al., 2007). In addition, high evaporation rates and reduced rainfall in the region combine to increase the salinity of the Mediterranean Sea. The outflow of saline water through the Gibraltar Strait into the north Atlantic Ocean could affect the path of the Gulf Stream and, therefore, sea surface temperatures (e.g. Calmanti et al., 2006). Through this, the Mediterranean could alter the characteristic patterns of the North Atlantic Oscillation (NAO), thereby modifying weather patterns across Europe. Consequently, changes in forest cover in the Mediterranean region may have considerable implications for weather patterns across the whole of Europe. However, substantiating many of these links and feedbacks between forest cover, the Mediterranean outflow and weather patterns would require further evidence through additional research.

**Central and Eastern Europe**

Observations show that forests in this region insulate air temperatures from the extremes of the diurnal cycle (Ferrez et al., 2011; Lee et al., 2011). Maximum temperatures under the forest canopy tend to be cooler than those in open ground, whereas minimum temperatures within a forest are generally warmer than in open areas, except on windy nights where cold pools of air can form within forests.

However, as with the Mediterranean region, forests play an important role in determining precipitation totals in central and eastern Europe. The clearest indication of this is that rainfall in central and eastern Europe is generally higher during summer than winter, implying that evaporation from the land surface contributes significantly to precipitation in this part of the European continent. The availability of this moisture in the warm summer months can be attributed to forests in two main ways. First, in the absence of forests in Atlantic Europe, precipitation which falls near the coast would flow through rivers back out to sea. However, in the presence of forests, a greater fraction of the moisture will be returned to the atmosphere, where it can be propagated towards the interior of the continent, ultimately falling as precipitation. This process ensures a supply of moisture to the interior of the European continent, helping to maintain land productivity. Secondly, the presence of forests helps to regulate soil moisture levels, when compared to crops or grassland (Teuling et al., 2010). That is, in warm conditions, open land surfaces tend to lose moisture much more rapidly than forested land. Owing to its more conservative use of water, and its ability to access water at deeper levels within the soil, forested land tends to be warmer than open land in this region, except during heat waves. Consequently, the presence of forests in this region ensures that soils remain moist even during the warm summer months. Importantly for the region, the evapotranspiration of this moisture provides a significant contribution to summer precipitation. As a result, the removal of forests in central and eastern Europe could cause the region to become drier and eventually warmer, thereby making the environment less suitable for existing agricultural and natural vegetation, and more vulnerable to droughts and desertification.

**Northern Europe**

Owing to lower average temperatures at high latitudes, the effect of evaporative cooling in northern Europe is smaller than in other regions. Consequently, the influence of forests in northern Europe is dominated by their low albedo and aerodynamic roughness (Bonan, 2008). This means that increases in forest cover are expected to lead to higher temperatures and lower wind speeds. Indeed, as for central and eastern Europe, observations clearly demonstrate that forests insulate air temperatures from the extremes of the diurnal cycle (Karlsson, 2000). In addition, the loss of forest in Tuntsa, northern Finland, has been shown to have resulted in a harsher climate exhibiting lower temperatures, higher wind speeds and a deeper layer of frozen soil, making it difficult for the forest to recover and stabilise the local climate (Vajda and Venalainen, 2005). However, as described in previous sections of this report, while most studies suggest that boreal forests warm the local and global climate, they generally ignore the impact of BVOCs which could enhance cloud formation and cool the local climate. Further work is needed to verify or eliminate this possibility, and to better understand to regional impact of boreal forests.

**Urban Areas**

Studies conducted in a broad range of cities across Europe, including Lisbon (Oliveira et al., 2011), Paris (Météo-France, 2009), Freiburg (Streiling and Matzarakis, 2009), Chania (Georgi and Dimitrou, 2010) and Athens (Tsiros, 2010), provide a largely consistent picture which indicates that trees provide a variety of benefits in urban areas. In the warm summer months, urban trees provide shade and evaporative cooling, thereby reducing energy usage for air conditioning. This is important because heat island effects can make cities uncomfortable places to live and work. In addition, urban trees can intercept atmospheric pollutants, thereby improving air quality; however, the emission of BVOCs can increase local ozone concentrations, which is a known respiratory irritant. It is, therefore, important to select trees species which have a low ozone-forming potential (Streiling and Matzarakis, 2003). Urban tree cover can also reduce average wind speeds and gust strengths, helping to lower the cost of storm damage, and energy consumption for heating. During periods of rain, trees intercept water and improve the permeability of the urban land surface, reducing the risk and impact of small-scale flooding events.

Outside cities, peri-urban forests are used to protect and ensure the quality of local drinking water supplies. Simulations also suggest that sufficiently large peri-urban forests hold the potential to reduce maximum temperatures in large cities, especially during heat waves (Météo-France, 2009). However, it is important to remember that the greatest benefits of urban trees and peri-urban forests are achieved by planting the most appropriate (i.e. native) species, which are most suited to the climate and soil conditions.

The presence of trees within urban areas, or forests around cities, may also have some negative effects. The risk of fire during warm dry periods will be increased by the presence of trees. Storms can fell trees causing damage to property or disruption to transport. Tree roots can damage underground infrastructure such as water pipes, and communication and power cables. In addition, trees emit a wide range of hydrocarbons, which react in the presence of other pollutants (such as nitrogen oxides, nitric oxide (NO) and nitrogen dioxide ($NO_2$)) and can enhance ozone levels. This is significant because ozone can cause respiratory problems, especially for asthma sufferers. Hence, the tree species used in urban areas must be chosen carefully to avoid unwanted negative effects.

## Summary

From the simulations and literature reviews presented in this work, it is clear that forests influence weather and climate across the full range of spatial scales within Europe; that is, from urban areas up to regional and global scales. The key physical mechanisms through which this influence occurs are governed by the forest albedo, evapo-transpiration (and hence exchanges of sensible and latent heat), water retention capacity, aerodynamic roughness, and the emission of biogenic volatile organic compounds (BVOCs). However, many of the exact impacts remain unclear since they can vary significantly both spatially and temporally.

The regions in Europe identified in this project where forests currently exert a strong influence on weather and climate are: i) the Mediterranean; ii) central and eastern Europe; iii) northern Europe; and iv) urban areas. Given the well-known moderating influence of forests, it is no coincidence that the regions where forest impact is greatest also experience notable extremes in temperature and precipitation. The key benefits provided by forests, especially in these regions, are: i) a reduction in maximum temperatures during heat waves; ii) higher minimum temperatures; iii) increased humidity and average annual precipitation; iv) reduced mean wind speeds and gust strengths; v) improved land surface stability and water quality. In contrast, the impact of forests on weather currently appears to be less significant in Atlantic Europe, where precipitation is more frequently governed by large-scale synoptic weather patterns, rather than smaller-scale convective events. However, it is important to note that this could change in the future if large-scale weather patterns in the Atlantic region were to follow different tracks. The degree of influence of forests on controlling local and regional hydrology is still the subject of debate.

Recent evidence suggests that forest cover change on national to regional scales can influence weather patterns on Europe-wide scales. For example, studies indicate that drought in the Mediterranean region, which can be associated with deforestation, can lead to heat waves in the rest of Europe, and can also affect large-scale weather patterns via the interaction between the Mediterranean Sea and Atlantic Ocean. In addition, the presence of forests across central Europe helps to transport moisture far in-land, thereby ensuring that the land remains productive, and reducing the severity of heat waves. The removal of these forests could have significant and wide-reaching negative consequences.

In conclusion, observations and simulations clearly show that forests *do* affect weather and climate. However, much more evidence needs to be sought in order to develop a more complete understanding of the specific ways in which forests influence weather at local and regional scales, and their long-term impact under future climate scenarios.

### References

Arneth, A., Sitch, S., Bondeau, A., Butterbach-Bahl, K., Foster, P., Gedney, N., de Noblet-Ducoudré, N., Prentice, I.C., Sanderson, M., Thonicke, K., Wania, R. and Zaehle, S., 2010: From biota to chemistry and climate: Towards a comprehensive description of trace gas exchange between the biosphere and atmosphere, *Biogeosciences*, 7, 121-149.

Bala, G., Caldeira, K., Wickett, M., Phillips, T.J., Lobell, D.B., Delire, C. and Mirin, A., 2007: Combined climate and carbon-cycle effects of large-scale deforestation. *Proc. Nat. Acad. Sci. USA*, 104, 6550-6555.

Betts, A.K. and Ball, J.H., 1997: Albedo over the boreal forest. *J. Geophys. Res.*, 102, 28901-28910, doi:10.1029/96JD03876.

Betts, R.A., 2006: Forcings and feedbacks by land ecosystem changes on climate change. *J. Phys. IV France*, 139, 123-146, doi:10.1051/jp4:2006139009.

Bonan, G.B., Pollard, D. and Thompson, S.L., 1992: Effects of boreal forest vegetation on global climate, *Nature*, 359, 716-718, doi:10.1038/359716a0.

Bonan, G.B. 2008: Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science*, 320, 1444-1449, doi:10.1126/science.1155121.

Burke, E.J., 2011: Understanding the sensitivity of different drought metrics to the drivers of drought under increased atmospheric $CO_2$. *J. Hydrometeorol.*, 12, 1378-1394, doi:10.1175/2011JHM1386.1.

Calmanti, S., Artale, V. and Sutera, A., 2006: North Atlantic MOC variability and the Mediterranean outflow: A box-model study. *Tellus*, 58A, 416-423.

Camia, A., Amatulli, G. and San-Miguel-Ayanz, J., 2008: Past and future trends of forest fire in Europe, European Commission Joint Research Centre, Ispra, Italy.

Charney, J.G., 1975: Dynamics of deserts and drought in the Sahel. *Q. J. Roy. Meteorol. Soc*., 101, 193-202.

Charney, J.G., Stone, P.H. and Quirk, W.J., 1975: Drought in the Sahara: A biogeophysical feedback mechanism, *Science*, 187, 434-435.

D'Almeida, C., Vörösmarty, C.J., Hurtt, G.C., Marengo, J.A., Dingman, S.L. and Keim, B.D., 2007: The effects of deforestation on the hydrological cycle in Amazonia: a review on scale and resolution. *Int. J. Climatol*., 27, 633-647.

Davin, E.L., Stoeckli, R., Jaeger, E.B., Levis, S. and Seneviratne, S.I., 2011: COSMO-CLM2: A new version of the COSMO-CLM model coupled to the Community Land Model. *Clim. Dyn*., 37, 9, 1889-1907, doi:10.1007/s00382-011-1019-z.

Donat, M.G., Renggli, D., Wild, S., Alexander, L.V., Leckebusch, G.C. and Ulbrich, U., 2011: Reanalysis suggests long-term upward trends in European storminess since 1871, *Geophys. Res. Lett*., 38, L14703, doi:10.1029/2011GL047995.

Donnison, L. 2012: Managing the drought: A review of the evidence of the benefits of native trees species for shelter on the water regime of pasture and arable crops, The Woodland Trust, Grantham, UK.

Ellison, D., Futter, M. and Bishop, K., 2012: On the forest cover – water yield debate: From demand- to supply-side thinking. *Glob. Change. Biol*., 18, 806-820, doi: 10.1111/j.1365-2486.2011.02589.x.

FAO, 2005: Forests and floods: drowning in fiction or thriving on facts? (http://www.fao.org/docrep/008/ae929e/ae929e00.htm)

FAO, 2007: Forests and water. (http://www.fao.org/docrep/010/a1598e/a1598e02.htm)

Ferrez, J., Davison, A.C., and Rebetez, M., 2011: Extreme temperature analysis under forest cover compared to an open field. *Agric. For. Meteorol.*, doi:10.1016/ j.agrformet.2011.03.005.

Fischer, E. M., Seneviratne, S.I., Luthi, D. and Schär, C., 2007: Contribution of land-atmosphere coupling to recent European summer heat waves, *Geophys. Res. Lett*., 34, L06707, doi:10.1029/2006GL029068.

Georgi, J.N. and Dimitriou, D., 2010: The contribution of urban green spaces to the improvement of environment in cities: Case study of Chania, Greece. *Building and Environment*. 45, 1401-1414.

Gillett, N. P., Weaver, A.J., Zwiers, F.W. and Flannigan, M.D., 2004: Detecting the effect of climate change on Canadian forest fires. *Geophys. Res. Lett.*, 31, L18211, doi:10.1029/2004GL020876.

Gimeno, L., Drumond, A., Nieto, R., Trigo, R. M. and Stohl, A., 2010: On the origin of continental precipitation. *Geophys. Res. Lett.*, 37, L13804, doi:10.1029/2010GL043712.

Gulev, S., Zolina, O. and Grigoriev, S., 2001: Extratropical cyclone variability in the Northern Hemisphere winter from the NCEP/NCAR reanalysis data. *Clim. Dyn*., 17, 795-809.

Hartley, A., Pekel, J-F., Ledwith, M., Champeaux, J-L., De Badts, E., and Bartalev, S.A., 2006: The Land Cover Map for Europe in the Year 2000. *GLC2000 database*, European Commission Joint Research Centre. (http://www-gem.jrc.it/glc2000).

Houghton, J., 2009: *Global warming: The complete briefing*, 4th Edition, Cambridge University Press, New York, Chapter 7.

Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassell, D., Boorman, P., McDonald, R. and Hill, S., 2002: Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report, Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK, 120 pp.

Karlsson I.M. (2000). Nocturnal Air Temperature Variations between Forest and Open Areas. *J. Appl. Meteorol.*, 39, 851-862.

Klein Goldewijk, K., 2001: Estimating global land use change over the past 300 years: the HYDE database. *Global Biogeochem. Cycles*, 15, 417-433.

Klein Goldewijk, K., Beusen, A., van Drecht, G., and de Vos, M., 2010: The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. *Glob. Ecol. Biogeogr.*, 20, 73-86.

Klein Tank, A., et al. 2002: Daily dataset of 20th-century surface air temperature and precipitation series for the European climate assessment. *Int. J. Climatol.*, 22, 1441-1453.

Koeck, R., Magagna, B. and Hochbichler, E., 2006: Drinking water protection in forested karstic headwaters, in: ETFRN News 45/46: Forests, Water and Livelihoods, Brinkman, W. and van Duijl, E. (Eds), pp.32-34.

Küchler, A.W., 1964: World natural vegetation map. In Epenshade, E.B., Jr., editor. *Goode's World Atlas*. Rand-McNally, Chicago, Illinois, USA.

Lee, X., et al., 2011: Observed increase in local cooling effect of deforestation at higher latitudes. *Nature*, 479, 384-387, doi:10.1038/nature10588.

Loveland, T.R. and Belward, A.S. 1997: The IGBP-DIS global 1km land cover data set, DISCover: first results. *Int. J. Remote Sens.*, 18, 3289-3295.

Masson-Delmotte, V., Raffalli-Delerce, G., Danis, P.A., Yiou, P., Stievenard, M., Guibal, F., Mestre, O., Bernard, V., Goosse, H., Hoffmann, G. and Jouzel, J., 2005: Changes in European precipitation seasonality and in drought frequencies revealed by a four-century-long tree-ring isotopic record from Brittany, western France. *Clim. Dyn.*, 24, 57-69.

Mather, A.S., 1992: The forest transition. *Area*, 24, 367-379.

Matulla, C., Schöner, W., Alexandersson, H., von Storch, H. and Wang, X. L., 2008: European storminess: late nineteenth century to present, *Clim. Dyn.*, 31, 125-130.

Meehl, G.A., and Tebaldi, C., 2004: More intense, more frequent and longer lasting heat waves in the 21st century, *Science*, 305, 994-997.

Météo-France, 2009: Research Report 2009, Météo-France, Paris, pp.34-35. (http://www.cnrm-game.fr/spip.php?rubrique54).

Miętus, M. and Filipiak, J., 2004: The temporal and spatial patterns of thermal conditions in the area of the southwestern coast of the Gulf of Gdańsk (Poland) from 1951 to 1998. *Int. J. Climatol*., 24, 499-509, doi:10.1002/joc.1007.

Millán, M.M, Estrela, M.J. and Miró, J., 2004: Rainfall Components: Variability and Spatial Distribution in a Mediterranean Area (Valencia Region). *J. Climate*, 18, 2682-2704.

Millán, M.M., 2008: Drought in the Mediterranean and summer floods in the UK and central and eastern Europe: What global climate models cannot see regarding the hydrological cycles in Europe and why. Unpublished internal Gammeltoft-RACCM CIRCE report produced for the European Commission.

Mudelsee, M., Boerngen, M., Tetzlaff, G. and Gruenewald, U., 2003: No upward trends in the occurrence of extreme floods in central Europe. *Nature*, 425,166-169.

O'Donnell, D., Tsigaridis, K. and Feichter, J., 2011: Estimating the direct and indirect effects of secondary organic aerosols using ECHAM5-HAM. *Atmos. Chem. Phys.*, 11, 8635-8659, doi:10.5194/acp-11-8635-2011.

Oliveira, S., Andrade, H. and Vaz, T., 2011: The cooling effect of urban green spaces as a contribution to mitigating urban heat. A case study in Lisbon. *Building and Environment*, 46, 2186-2194.

Pielke, R.A., Adegoke, J., Beltran-Przekurat, A., Hiemstra, C.A., Lin, J., Nair, U.S., Niyogi, D. and Nobis, T.E., 2007: An overview of regional land-use and landcover impacts on rainfall. *Tellus,* 59, 587–601, doi:10.1111/j.1600-0889.2007.00251.x.

Pöschl, U., et al., 2010: Rainforest aerosols as biogenic nuclei of clouds and precipitation in the Amazon. *Science*, 329, 1513-1516.

Quaas, J., Boucher, O., Dufresne, J.L. and le Treut, H., 2005: Impacts of greenhouse gases and aerosol direct and indirect effects on clouds and radiation in atmospheric GCM simulations of the 1930–1989 period. *Clim. Dyn.*, 23, 779-789, doi:10.1007/s00382-004-0475-0.

Radinović, D. and and Ćurić, M., 2012: Criteria for heat and cold wave duration indexes, *Theor. Appl. Climatol*., 107, 505-510.

Ramankutty, N. and Foley, J.A., 1999: Estimating historical changes in global land cover: croplands from 1700 to 1992. *Global Biogeochem. Cycles*, 13, 997-1027.

Reale, O. and Shukla, J., 2000: Modeling the effects of vegetation on Mediterranean climate during the Roman classical period: II. Model simulation. *Glob. Planet. Change*, 25, 185–214.

Rickli C. and Graf, F., 2009: Effects of forests on shallow landslides – case studies in Switzerland. *For. Snow Landsc. Res.*, 82, 33-44.

Rotenberg, E. and Yakir, D., 2010: Contribution of semi-arid forests to the climate system. *Science*, 327, 451-454.

Schneck, R. and Mosbrugger, V., 2011: Simulated climate effects of Southeast Asian deforestation: Regional processes and teleconnection mechanisms. *J. Geophys. Res.*, 116, D11116, doi:10.1029/2010JD015450.

Scoccimarro, E., et al., 2011: Effects of tropical cyclones on ocean heat transport in a high-resolution coupled general circulation model. *J. Climate*, 24, 4368-4384, doi:10.1175/2011JCLI4104.1.

Sodemann, H. and Zubler, E., 2010: Seasonal and inter-annual variability of the moisture sources for Alpine precipitation during 1995-2002. *Int. J. Climatol*, 30, 947-961.

Solomon, S., D. Qin, M. Manning, R.B. Alley, T. Berntsen, N.L. Bindoff, Z. Chen, A. Chidthaisong, J.M. Gregory, G.C. Hegerl, M. Heimann, B. Hewitson, B.J. Hoskins, F. Joos, J. Jouzel, V. Kattsov, U. Lohmann, T. Matsuno, M. Molina, N. Nicholls, J. Overpeck, G. Raga, V. Ramaswamy, J. Ren, M. Rusticucci, R. Somerville, T.F. Stocker,

P. Whetton, R.A. Wood and D. Wratt, 2007: Technical Summary. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Snyder, P.K., Delire, C., and Foley, J.A., 2004: Evaluating the influence of different vegetation biomes on the global climate. *Clim. Dyn.,* 23, 279-302, doi:10.1007/s00382-004-0430-0.

Spracklen, D.V., Bonn, B. and Carslaw, K., 2008: Boreal forests, aerosols and the impacts on clouds and climate. *Phil. Trans. Roy. Soc. A*, 366, 4613-4626.

Streiling, S. and Matzarakis, A., 2003: Influence of single and small clusters of trees on the bioclimate of a city: a case study. *J. Aboriculture*, 29, 309-316.

Swann, A.L., Fung, I.Y., Levis, S., Bonan, G.B., and Doney, S.C., 2010: Changes in arctic vegetation amplify high-latitude warming through the greenhouse effect. *Proc. Nat. Acad. Sci. USA*, 107, 1295-1300.

Teuling, A.L., *et al.*, 2010: Contrasting response of European forest and grassland energy exchange to heatwaves. *Nature Geosci.*, 3, 722-727, doi:10.1038/ngeo950.

Trigo, R.M., Pozo-Vázquez, D., Osborn, T.J., Castro-Díez, Y., Gámiz-Fortis, S. and Esteban-Parra, M.J., 2004: North Atlantic oscillation influence on precipitation, river flow and water resources in the Iberian Peninsula. *Int. J. Climatol*., 24, 925-944. doi: 10.1002/joc.1048.

Tsiros, I.T., 2010: Assessment and energy implications of street air temperature cooling by shade trees in Athens (Greece) under extremely hot weather conditions. *Renewable Energy*, 35, 1866-1869.

Vajda, A. and Venäläinen, A., 2005: Feedback processes between climate, surface and vegetation at the northern climatological tree-line (Finnish Lapland). *Boreal Env. Res*. 10, 299-314.

van der Ent, R.J., Coenders-Gerrits, A.M.J., Nikoli, R. and Savenije, H.H.G., 2012: The importance of proper hydrology in the forest cover-water yield debate: commentary on Ellison et al. (2012) Global Change Biology, 18, 806-820. *Glob. Change Biol*., 18, 2677–2680, doi:10.1111/j.1365-2486.2012.02703.x.

Vautard, R., Cattieux, J., Yiou, P., Thépaut, J.N., and Ciais, P., 2010: Northern Hemisphere atmospheric stilling partly attributed to an increase in surface roughness. *Nature Geosci.*, 3, 756-761, doi:10.1038/ngeo979.

Vautard, R., Yiou, P., D'Andrea, F., de Noblet, N., Viovy, N., Cassou, C., Polcher, J., Ciais, P., Kageyama, M. and Fan, Y., 2007: Summertime European heat and drought waves induced by wintertime Mediterranean rainfall deficit. *Geophys. Res. Lett.*, 34, L07711, doi:10.1029/2006GL028001.

Wang, K.-Y. and Shallcross, D.E, 2000: Modeling terrestrial biogenic isoprene fluxes and their potential impact on global chemical species using a coupled LSM-CTM model. *Atmos. Environ*., 34, 2909-2925.

Wang, X., Zwiers F., Swail, V. and Feng, Y., 2008: Trends and variability of storminess in the Northeast Atlantic region, 1874–2007. *Clim. Dyn*., 33, 1179-1195, doi:10.1007/s00382-008-0504-5.

Wattenbach, M., et al., 2007: Hydrological impact assessment of afforestation and change in tree-species composition – a regional case study for the Federal State of Brandenburg (Germany). *J. Hydrology*, 346, 1-17.

Webster, S., Uddstrom, M., Oliver, H. and Vosper, S., 2008: A high-resolution modelling case study of a severe weather event over New Zealand. *Atmos. Sci. Lett*., 9, 119-128, doi:10.1002/asl.172.

Wulfmeyer, V., Flamant, C., Behrendt, A., Blyth, A., Brown, A., Dorninger, M., Illingworth, A., Mascart, P., Montani, A. and Weckwerth, T., 2011: Advances in the understanding of convective processes and precipitation over low-mountain regions through the Convective and Orographically-induced Precipitation Study (COPS). *Q. J. R. Meteorol. Soc.*, 137, 1–2. doi:10.1002/qj.799.

**Met Office**
FitzRoy Road, Exeter
Devon EX1 3PB
United Kingdom

Tel: 0870 900 0100
Fax: 0870 900 5050
enquiries@metoffice.gov.uk
www.metoffice.gov.uk