Chapter 3
Climate Change: Overview of Data Sources, Observed and Predicted Temperature Changes, and Impacts on Public and Environmental Health

David H. Levinson and Christopher J. Fettig

Abstract This chapter addresses the societal and the environmental impacts of climate change related to increasing surface temperatures on air quality and forest health. Increasing temperatures at and near the earth's surface, due to both a warming climate and urban heat island effects, have been shown to increase ground-level ozone concentrations in cities across the U.S. In terms of forest health, elevated surface air temperatures and increased water stress are raising the possibility that forests world-wide are increasingly responding to warming climate conditions, which may lead to widespread tree mortality. The importance of climate datasets is also addressed, specifically as it relates to understanding the observed and predicted changes in surface temperatures at the global, regional and local scale.

Keywords Anthropogenic-induced changes • Forest health • Change in surface temperature • Changing distribution of conifers • Phytophagous insects • Climate-induced forest mortality

Anthropogenic-induced changes to the earth's climate are among the most complex and difficult issues to be addressed by modern science and the scientific community. Small changes in the concentrations of atmospheric gases, such as carbon dioxide (CO_2) and methane (CH_4), have large impacts on society, ecosystems, and the hydrologic cycle [1]. Given the magnitude of observed and potential impacts,

D.H. Levinson, M.S., Ph.D. (✉)
Watershed, Fish, Wildlife, Air and Rare Plants, USDA Forest Service,
2150A Centre Avenue, Fort Collins, CO 80526, USA
e-mail: dlevinson@fs.fed.us

C.J. Fettig, M.S., Ph.D.
Pacific Southwest Research Station, USDA Forest Service,
1731 Research Park Drive, Davis, CA 95618, USA
e-mail: cfettig@fs.fed.us

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numerous interagency and international efforts have been initiated over the past 3 decades to attempt to analyze every aspect of the earth's climate and to address the adaptation and mitigation options that have the potential to aid in addressing this important challenge. The most well known of these efforts is the Intergovernmental Panel on Climate Change (IPCC), formed by the United Nations in 1988 to help address the scientific, economic, and policy aspects of global climate change.

In this chapter, several areas of research will be elucidated that address both the societal and the environmental impacts of climate change. Specifically, these are the impacts related to increasing surface temperatures on air quality and forest health. The importance of quality climate datasets is also addressed as it relates to understanding the observed and predicted changes in surface temperatures at the global, regional, and local scale.

Observations of Changes in Surface Temperature

Previous studies, including both international assessments and independently published peer-reviewed articles, have demonstrated that surface temperatures have increased globally by approximately 0.7 °C per century since 1900 and 0.16 °C per decade since 1970 [2, 3] (Fig. 3.1). The slight differences in the estimates of annual means, rankings, and trends in global surface temperatures are the result of differences in the methods used to construct each of the three primary independent datasets that determine surface temperatures spatially across global ocean and land areas [4]. These three global datasets are those developed and maintained by NASA-GISS [5], HadCRUT3 [6], and NOAA-NCDC [7]. Despite the observed differences that result in variations in annual rankings of global surface temperature, each of these datasets is in close agreement, and all three have identified 2010 as tied for the warmest year or ranked as second warmest in the historical record since 1880 (Table 3.1).

Increased occurrences of public health and environmental impacts due to changes in climate over the past several decades have been attributed to rising surface and lower tropospheric temperatures, and these impacts include heat stress and increased occurrence of heat waves, respiratory stress due to degraded air quality conditions, impacts on food safety and water quality, increasing aeroallergens and pollen sources, and the spread of vector-borne diseases [8]. However, in most cases the impacts are primarily related to increasing extreme temperatures, specifically increases in the daily maximum temperature, rising nocturnal temperature, or both [3, 9, 10]. Figure 3.2 shows the global trend in the maximum and minimum temperature, along with the diurnal temperature range (DTR) ($T_{max} - T_{min}$) over the period 1950–2004 [9]. The observed decrease in the DTR is primarily a result of larger increases in the minimum temperature at land-based observing sites. Since the heat-related mortality is correlated primarily by nocturnal temperatures, the increases in minimum temperatures are of widespread concern [11–13].

For most applications related to analyzing regional or local public health and the environmental impacts of climate change, it is important to use those data sources that provide the highest quality information and rigorous quality assurance and

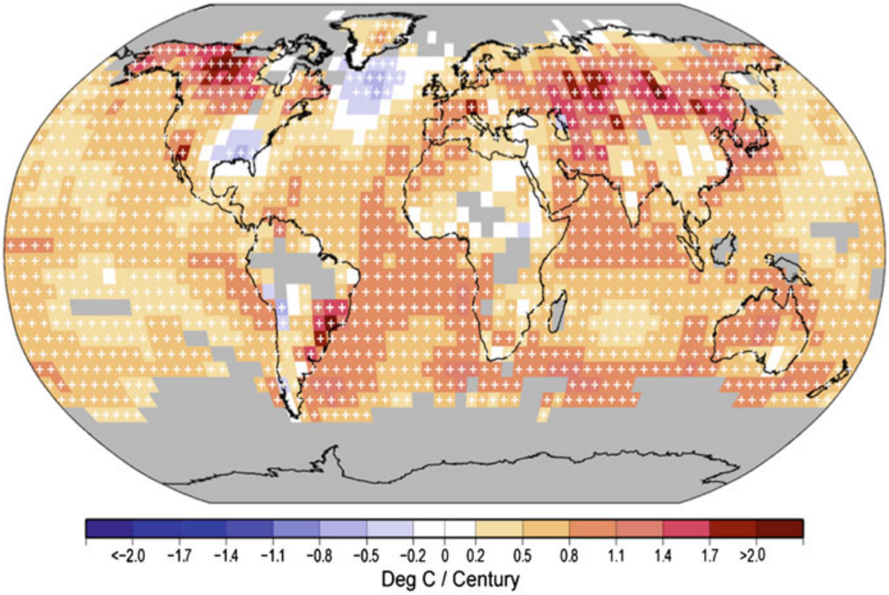

Fig. 3.1 Observed trend in annual average surface air temperature (°C per century) over the period 1901–2005 using the NOAA-NCDC Global Blended Dataset [71] and adapted from Trenberth et al. [2] (Fig. 3.9). Trends significant at the $\alpha = 5\ \%$ level are indicated by *white* "*plus*" signs, and *grey* areas have insufficient data to determine statistically reliable trends. Requirements for inclusion were a minimum of 66 years needed to calculate a trend value and 10 valid monthly temperature anomaly values needed for inclusion of an individual year (adapted from Trenberth KE, Jones PD, Ambenje P, Bojariu R, Easterling D, Klein Tank A, Parker D, Rahimzadeh F, Renwick JA, Rusticucci M, Soden B, Zhai P (2007) Observations: Surface and Atmospheric Climate Change. 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, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, with permission)

Table 3.1 The observed differences in annual global temperature anomaly for 2010 and its rank relative to the entire historical record since 1880 for the three primary datasets used to determine global average temperatures

	2010 Global anomaly relative to the 1961–1990 annual mean	Rank of 2010 to all years since 1880
HadCRUT3	0.50 °C	Second warmest after 1998
NASA-GISS	0.56 °C	Tied warmest with 2005
NOAA-NCDC	0.52 °C	Tied warmest with 2005

From Sanchez-Lugo A, Kennedy JJ, Berrisford P (2011) Surface temperatures. In "State of the Climate 2010," *Bull Amer Meteor Soc* 92:6:S36-S37, with permission

quality control (QA/QC) methods. For surface temperature, that is the NOAA Global Historical Climate Network (GHCN) dataset [14] and its subset the US Historical Climate Network (USHCN) dataset. NOAA's GHCN Monthly data (versions 2 and 3) can be accessed at http://www.ncdc.noaa.gov/ghcnm/, the routinely

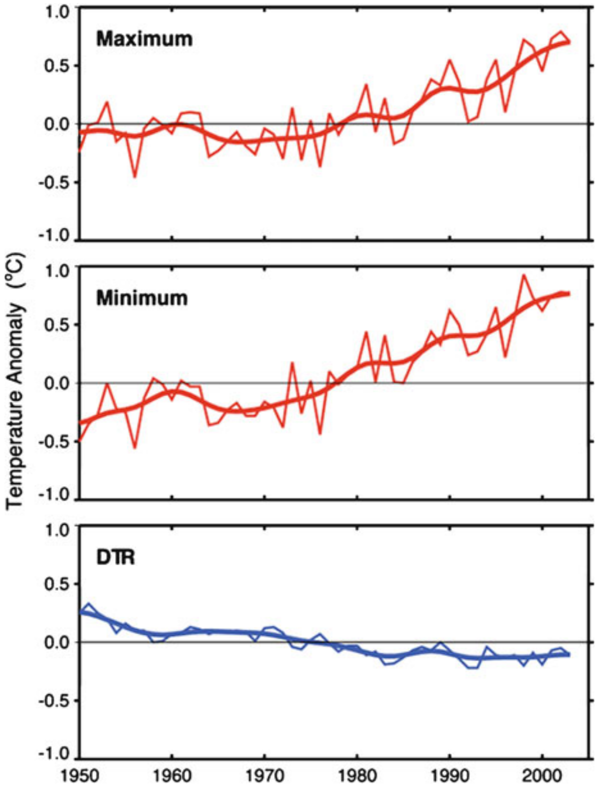

Fig. 3.2 Global annual anomalies of surface maximum (*top*), minimum (*middle*), and diurnal temperature range (DTR, *bottom*) in °C, over the period 1950–2004, with the *thinner line* the annual values and the *thicker line* showing the smoothed, decadal variations. Anomalies were determined relative to the 1961–1990 mean and averaged over the 71 % of land areas where data were available during the period of record (adapted from Vose RS, Easterling DR, Gleason B (2005) Maximum and minimum temperature trends for the globe: An update through 2004. Geophys Res Lett 32:L23822, with permission)

updated GHCN-Daily dataset can be found online at http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/, and the USHCN dataset is available at http://cdiac.ornl.gov/epubs/ndp/ushcn/ushcn.html. These high-quality, integrated climate datasets provide the researcher the requisite information regarding the construction, maintenance, and historical provenance of data sources that are needed for reliable analysis of observed changes in temperatures at the global, regional, or local scale. To illustrate the variability of climate changes related to surface temperature, Fig. 3.1 shows the spatial variation in surface temperature trends covering the period from 1901 to 2005; the vast majority of the earth's surface has warmed since the start of the twentieth century, with the largest increases observed at continental mid- to high-latitudes in the Northern Hemisphere. Only a few areas have shown a decreasing trend in surface temperatures, and the vast majority of the surface temperature trends (both positive and negative) are statistically significant at the 95 % confidence level.

Predictions of Changes in Surface Temperature

Despite the well-documented uncertainty in the simulations of future climate conditions, associated with different emissions scenarios [15], it is clear that global temperatures will continue to rise due to the increasing radiative effects of greenhouse gases, primarily a result of increases in CO_2 but also increases in other greenhouse gases such as methane (CH_4), nitrous oxide (N_2O), and halocarbons. Based on simulations realized from multiple ensembles of global circulation models (GCMs), surface temperatures are predicted to continue to rise over the remainder of the twenty-first century. Predictions from the most recent IPCC report (AR4) include the following statement regarding the magnitude of the change expected: "Continued greenhouse gas emissions at or above current rates will cause further warming, and induce many changes in the global climate system during the twenty-first century that would *very likely* be larger than those observed during the twentieth century" [15].

In terms of the impacts of these warming temperatures, predicted increases in global temperatures due to a warming climate in the twenty-first century will result in an increase in heat waves, often measured as the number of days that maximum temperatures exceed 100 °F (37.78 °C), which are predicted to increase significantly for the USA. Figure 3.3 shows the occurrence of days exceeding 100 °F over the USA during a recent period in the past (1961–1979), compared with two different scenarios for the end of the twenty-first century based on a low and a high emissions scenario. In both cases, the number of days that are predicted to exceed 100 °F will increase, but as expected the increase is more dramatic with the higher emissions scenario. In both scenarios, large areas of the continental USA will experience a dramatic increase in heat waves (Fig. 3.3).

The rise in extreme temperatures and their potential impacts are of growing concern, given that the increasing temperatures across the USA are expected to accelerate between the middle (by 2050, using a 2041–2059 average) and the end of the twenty-first century (by 2090, using a 2081–2099 average) (Fig. 3.4). As shown in Fig. 3.5, the precise rise in temperature will depend largely on the eventual increase in greenhouse gas concentrations, which will depend on the future path of global emissions of CO_2, CH_4, and other greenhouse gases. Lower emissions will result in a smaller rise in surface temperatures, while larger increases in emissions of greenhouse gases will lead to more significant rises in surface temperatures. Either way, it is imperative to improve the scientific understanding of the observed and potential impacts of climate change, given the widespread potential for significant impacts to society and the environment. To address this issue, the following sections present the observed and potential future impacts on air quality and forest health, two areas of extensive research over the past several decades.

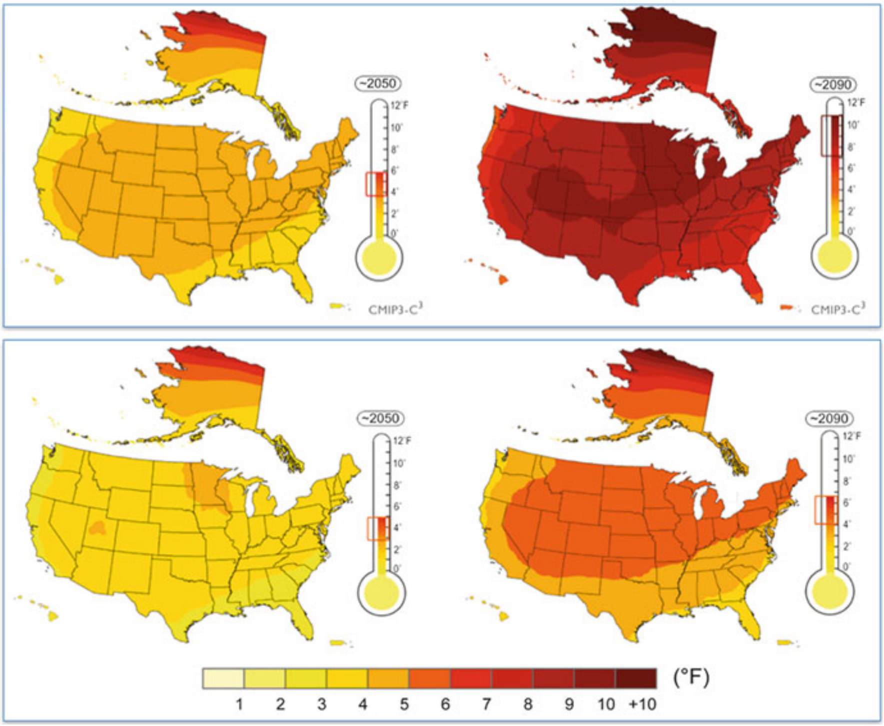

Fig. 3.3 Projected changes of the US (including Alaska and Hawaii, inset) surface air temperature (in °F) relative to the 1961–1979 base period for two different emissions scenarios: higher (*top*) and lower (*bottom*). Emissions scenarios are based on projections of future temperature by 16 of the Coupled Model Intercomparison Project Three (CMIP3) climate models using two emissions scenarios from the IPCC *Special Report on Emissions Scenarios* (Nakićenović N, Swart R (eds.) (2000) *Special Report on Emissions Scenarios*. A special report of Working Group III of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, UK, and New York, NY, USA (http://www.grida.no/publications/other/ipcc_sr/?src=/climate/ipcc/emission/)). The "lower" scenario is B1, while the "higher" is the A2 scenario. The *brackets* on the thermometers represent the likely range of model projections, though lower or higher outcomes are possible (adapted from Karl TR, Melillo JM, Peterson TC (2009) *Global Climate Change Impacts in the United States*, (eds.) Cambridge University Press, with permission)

Climate Change and Air Quality

Climate and weather conditions directly impact air pollutants, specifically their formation, transport, dispersion, and deposition (both wet and dry). Stagnant weather patterns (i.e., light winds due to the influence of surface high-pressure systems and boundary layer inversions) are conducive to the trapping and production of certain atmospheric pollutants that may lead to elevated concentrations of some pollutants, especially ozone (O_3) and particulate matter (PM). Increasing temperatures, due to both a warming climate and urban heat island (UHI) effects, have

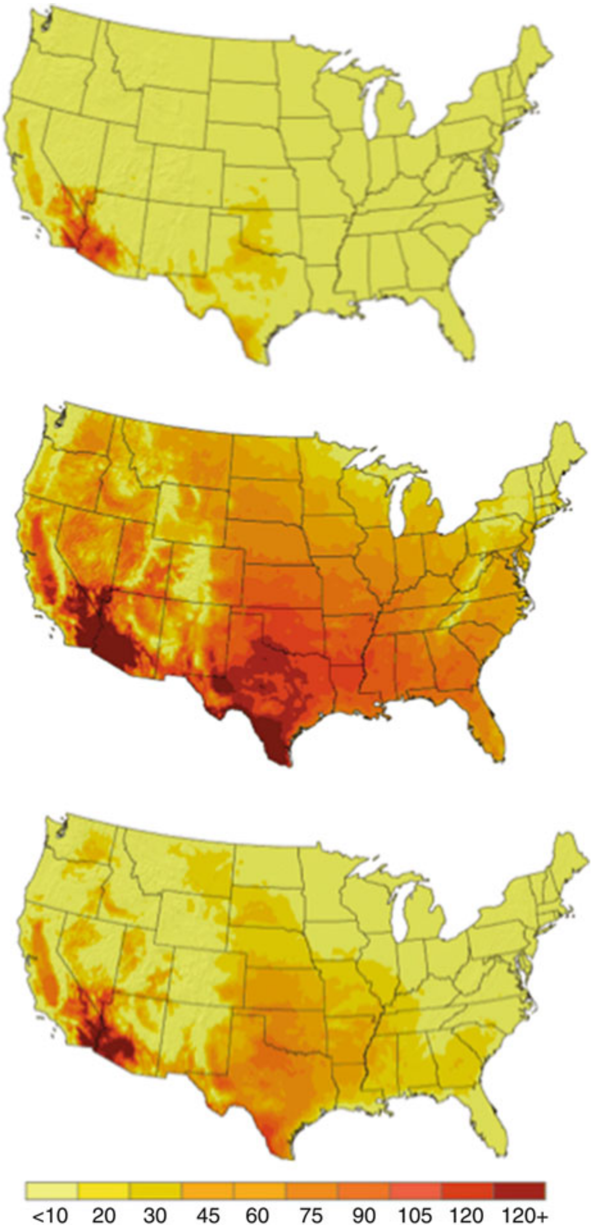

Fig. 3.4 Observed and projected increase in the annual number of days with temperature over 100 °F. The recent past 1961–1979 (*top*) shows significantly less days exceeding 100 °F when compared to the end-of-century (2080–2099) period under both the lower and the higher IPCC emissions scenarios (adapted from Karl TR, Melillo JM, Peterson TC (2009) *Global Climate Change Impacts in the United States*, (eds.) Cambridge University Press, with permission)

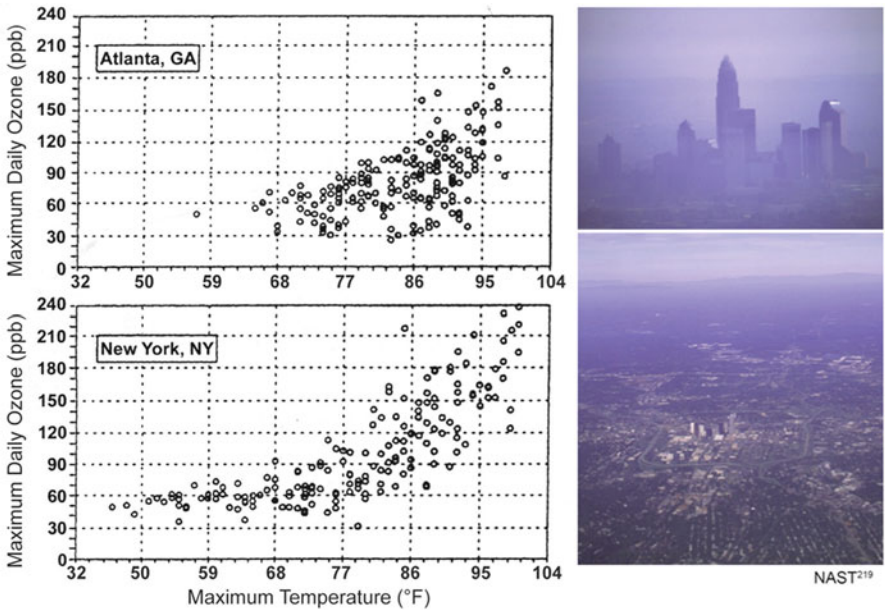

Fig. 3.5 Observed relationship between daily maximum ground-level ozone concentration (in parts per billion, ppb) and maximum surface temperature (°F) based on measurements from (*top*) Atlanta, GA, and (*bottom*) New York, NY. Data are for the warm season (May to October) covering the period 1988–1990 at each location. The projected higher temperatures across the USA in the twenty-first century are likely to increase the occurrence of high ozone concentrations, although this will also depend on emissions of ozone precursors and meteorological factors that can enhance or suppress ozone formation in the lower troposphere (http://www.usgcrp.gov/usgcrp/Library/nationalassessment/)

been shown to increase concentrations of ground-level ozone [16], since it is both naturally occurring and a secondary pollutant formed through photochemical reactions of sunlight (solar radiation) with nitrogen oxides (N_2O) and volatile organic compounds (VOCs). Previous studies have clearly identified that ozone formation is positively correlated with temperature, but formation is primarily related to incoming shortwave solar radiation, since concentrations are typically highest during the summer months. However, concentrations are not seasonally dependent in all cities with above normal concentrations of ozone, as exceptions have been noted [17].

To illustrate the relationship between ground-level ozone concentrations and surface temperatures, Fig. 3.6 shows data from New York, New York, and Atlanta, Georgia. In terms of the overall relationship, measurements from both cities show that most high ozone level days occur when maximum daily temperatures (T_{max}) are higher and concentrations systematically decrease with lower temperatures. Both cities have the potential for high concentrations, but the data show that the potential for extremely high ozone concentrations (above 200 ppb) is greater in New York, where ground-level concentrations reached 220 ppb when T_{max} was only 85 °F (29.5 °C). Therefore, the variability of observed daily peak ground-level O_3 concentrations is higher in New York, but the potential for higher concentrations

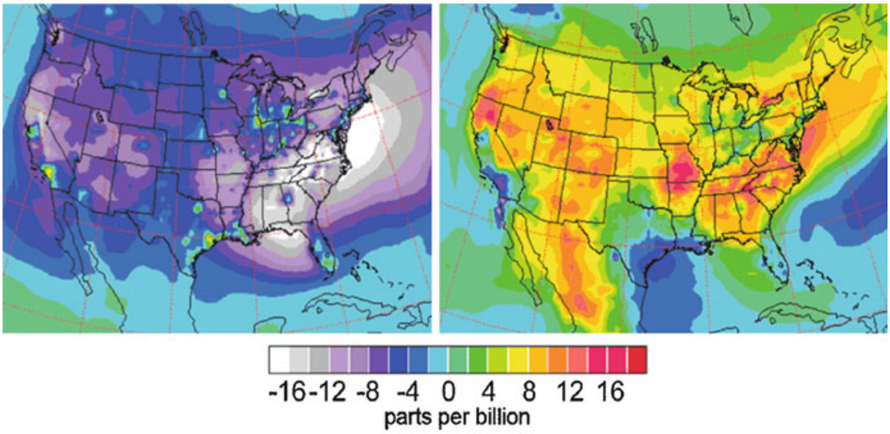

Fig. 3.6 Projected changes in ground-level ozone for the 2090s, averaged over the summer months (June–August) and relative to 1996–2000 under lower and higher emissions scenarios. The scenarios include both greenhouse gases and other emissions that lead to ozone formation, some of which decrease under the lower emissions scenario. By themselves, higher temperatures and other projected climate changes would increase ozone levels under both scenarios. However, future projections of ozone depend heavily on emissions, with the higher emissions scenario increasing ozone by large amounts, while the lower emissions scenario results in an overall decrease in ground-level ozone by the end of the century (adapted from Karl TR, Melillo JM, Peterson TC (2009) *Global Climate Change Impacts in the United States*, (eds.) Cambridge University Press, with permission)

at lower temperatures is more likely in Atlanta. Similar relationships have been found for Los Angeles, California, Phoenix, Arizona, and other cities with well-documented ground-level ozone concentration issues.

The impact of climate change has also been observed on aeroallergens and their sources, as the observed warming has caused an earlier onset of pollens in the spring in the Northern Hemisphere [18–20]. This is due to both the earlier initiation of pollen production in spring and also the introduction and spread of invasive plant species with highly allergenic pollen, such as ragweed (*Ambrosia artemisiifolia*), which is spreading in several areas of the world [21–24]. Laboratory studies have confirmed that increasing CO_2 concentrations and surface temperatures increase the production of ragweed pollen and lengthen the pollen season [25–29]. Therefore, the issue of increased length of the pollen season and the production of pollen from a variety of sources is expected to increase concentrations of aeroallergens in the twenty-first century as the climate continues to warm [8].

Climate Change and Forest Health

Forests cover ~42 million km^2 (~30 %) of the earth's surface and are found in all regions at elevations and latitudes capable of sustaining tree growth, except where disturbances, whether natural or human-induced, are too frequent and/or too severe to enable establishment. Forests provide immeasurable ecological, economic, and social goods and services to both natural systems and humankind. These include, among others, purification of the air that we breathe; regulation of edaphic formation and control of runoff and soil erosion; provision of fish and wildlife habitat; provision of food, medicine, shelter, and water; provision of wood and other forest products; provision of aesthetics, outdoor recreation, and spiritual renewal; and regulation of climate through carbon storage and complex physical, chemical, and biological processes that affect planetary energetics [30]. In short, forests represent one of the earth's most important ecosystems and are critical to the health, welfare, and survival of human societies.

Large amounts of CO_2 are released when forests are burned, defoliated, or deforested and converted to structures that have relatively small carbon pools. In these cases, forests that were once carbon sinks may become carbon sources [31–33]. Alternatively, healthy forests have the potential to assimilate, accumulate, and sequester large amounts of carbon from the atmosphere, thus reducing one of the primary drivers of climate change. We use "forest health" in the context of ecosystems functioning within their natural range of historic variability. The effects of climate change on forest health include both positive (e.g., increased growth through elevated water use efficiency and longer growing seasons) and negative impacts (e.g., increased frequency and severity of disturbances). Forest disturbances (storms, wildfire, herbivory, etc.) are relatively discrete events that affect the structure, composition, and function of forest ecosystems through alterations of the physical environment [34]. They release growing space, alter nutrient cycling, and affect other key processes essential to the proper functioning of ecosystems [35].

Schelhass et al. [36] provided a quantitative overview of the role of natural disturbances in European forests, which they suggested was useful as a basis for modeling the future impacts of climate change by establishing a baseline. They reported storms were responsible for 53 % of the net volume affected over a 40-year period, while biotic factors (e.g., bark beetle outbreaks) contributed 16 %. In the intensively managed forests of Europe and elsewhere (e.g., portions of the USA), natural disturbance cycles have been altered by active management aimed at reducing forest susceptibility to certain types of disturbances. In some cases, human interference in these natural disturbance cycles has later exacerbated their effects. For example, dry forests in portions of the western USA were once dominated by open and parklike stands of widely dispersed trees prior to Euro-American settlement. Frequent thinning of small-diameter and fire-intolerant tree species by low-intensity surface fires and competitive exclusion of tree seedlings by understory grasses are believed to have maintained such conditions. Many of these forests are now denser, have more small trees and fewer large trees, and are dominated by more shade-tolerant and fire-intolerant tree species, primarily as a result of fire suppression activities and harvesting practices implemented in the twentieth century. These changes have led to heavy accumulations of forest fuels [37] that feed severe wildfires when natural- or human-induced ignitions occur. Today, thinning and prescribed fire are commonly used to increase the resiliency of forests to wildfires (Fig. 3.7), which is important given increased wildfire activity is expected as a

Fig. 3.7 Current conditions of many seasonally dry forests in the western USA, especially those that once experienced low-to-moderate intensity fire regimes, leave them uncharacteristically susceptible to high-severity wildfire. Creating more fire-resilient stands generally requires treatment of surface and ladder fuels, reductions in crown density, and maintenance of large-diameter trees. A combination of thinning and prescribed burning is commonly used and highly effective when applied within prescription. Most evidence suggests that these treatments are typically accomplished with few unintended consequences as most ecosystem components (e.g., carbon sequestration, soils, wildlife) exhibit very subtle impacts or no measurable impacts. Since increased wildfire activity is expected as a result of climate change and desired treatment effects are transient, forest managers need to be persistent and repeat the application of fuel reduction treatments over time (photo credits: left, C.J. Fettig, and right, S.R. McKelvey, USFS Pacific Southwest Research Station)

consequence of climate change. In particular, a combination of thinning and prescribed fire has been shown to be highly effective for reducing the severity of wildfires [38] and will increase the resiliency of forests to other disturbances imposed on them by climate change [39].

Climate has always shaped the world's forests [40] and minor climatic shifts may have significant effects on community compositions [41]. Even under conservative scenarios, future climatic changes are likely to include further increases in temperature with significant drying in some regions and increases in the frequency and severity of extreme weather events [42]. These changes are predicted to further increase the frequency and severity of many other disturbances that shape forest ecosystems. A recent global assessment of forest health reported 88 unique episodes of tree mortality over the last 30 years [43]. Since then, several additional episodes have been identified [44]. The common implicated causal factor in these examples is elevated temperatures and/or water stress, raising the possibility that the world's forests are increasingly responding to ongoing warming and drying attributed to climate change [43]. While these episodes are well documented, the underlying causes are complex and uncertain and likely involve numerous predisposing, inciting, and contributing factors [45]. Reports of climate-induced forest mortality are now common in both the popular press and scientific journals but are by no means a new phenomenon [43].

Across North America, temperature increases are projected to exceed global mean increases and more frequent extreme weather events are expected [42]. Associated changes in precipitation patterns may result in earlier and longer dry seasons across the western USA, with a greater frequency and duration of drought [46]. It is thought that these changes will significantly affect the condition, composition, distribution, and productivity of multiple ecosystems [47]. Since temperature increases are expected to be greatest at higher elevations and latitudes, conifers (the predominate vegetation of forests in these areas) are expected to be significantly affected.

The current distribution of coniferous vegetation across western North America resulted from climatic shifts dating back millions of years [48], in addition to more recent recolonization of deglaciated lands [49]. These historical patterns perhaps foreshadow changes to current coniferous vegetation as climate change accelerates. For example, based on the best existing data for 130 tree species in North America and associated climate information, McKenney et al. [50] predicted that on average the geographic range for a given tree species will decrease by 12 % and shift northward 700 km during the twenty-first century. Under a scenario where survival only occurs in areas where anticipated climatic conditions overlap with current climatic conditions, niches for tree survival decrease by 58 % and shift northward 330 km. In terms of tree species, there will be winners (e.g., ponderosa pine) and losers (e.g., Engelmann spruce, *Picea engelmannii*) [51]. By the end of the twenty-first century, others predict that ~48 % of the western USA landscape will experience climate profiles with no contemporary analog for the current coniferous vegetation [51]. The fate of any tree species will depend on genetic variation, phenotypic variation, fecundity and dispersal mechanisms, and their resilience to a multitude of disturbances. We consider three major disturbances (i.e., phytophagous insects, forest pathogens, and wildfire) that will serve as catalysts for much of this change.

Phytophagous insects are major components of forest ecosystems, representing most of the biological diversity and affecting virtually all forest processes and uses. Insects influence forest ecosystem structure and function by regulating certain aspects of primary production, nutrient cycling, ecological succession, and the size, distribution, and abundance of forest trees [52–54]. Elevated insect activity reduces tree growth and hastens decline, mortality, and subsequent replacement by other tree species and plant associations. Such effects are often amplified by other natural disturbances. The nature and extent of impacts are dependent upon the resource of concern, type of insect activity, size and distribution of the insect population, and metric used for evaluation [55]. Climate change is generally thought to increase levels of tree mortality attributed to insects, for example, bark beetles [56] and defoliators [57], but there are exceptions to this trend, for example, larch budworm (*Zeiraphera diniana*) [58].

In specific, bark beetles are commonly recognized as a primary disturbance agent in coniferous forests. Of the hundreds of native species in western North America, few species (<1 %) attack and reproduce in live trees. Frequently referred to as “aggressive” bark beetles, these species can kill healthy trees and have the capacity to cause landscape-scale tree mortality. The last decade has seen elevated levels of tree mortality attributed to bark beetle outbreaks in spruce forests of south-central Alaska and the Rocky Mountains, lodgepole pine (*P. contorta*) forests of western Canada and the Rocky Mountains, pinyon-juniper woodlands of the south-western USA, and ponderosa pine forests of Arizona, California, and South Dakota [59]. Because bark beetles, like many insects, are highly sensitive to thermal conditions conducive to population survival and growth, and water stress can influence host tree vigor, outbreaks have been correlated with shifts in temperature [60] and precipitation [61]. The life histories and ecological roles of the majority of bark beetle associates are not well understood, hampering full comprehension of the consequences of climate change on bark beetle population dynamics. However, Bentz et al. [56] predicted increases in thermal regimes conducive to population success for two economically important species, spruce beetle (*Dendroctonus rufipennis*) and mountain pine beetle (*D. ponderosae*), although there was considerable spatial and temporal variability in their predictions. These suggested a northward and upward in elevation movement of temperature suitability and identification of regions with a high potential for bark beetle outbreaks and associated levels of tree mortality in the twenty-first century. Evangelista et al. [62] predicted that suitable habitats for the mountain pine beetle and pine engraver (*Ips pini*) will stabilize or decrease under future climate conditions, while habitats for the western pine beetle (*D. brevicomis*) will increase (Fig. 3.8). Their work represents an estimate of potential distribution and not specific impacts to forest health.

As with phytophagous insects, outbreaks of forest diseases caused by native and introduced forest pathogens are generally predicted to become more frequent and severe as a result of climate change [63]. However, diseases caused by pathogens directly affected by climate (e.g., needle blights) are predicted to have a reduced impact under warmer and drier conditions. These groups of pathogens may cause disease in healthy hosts if the pathogen’s environmental requirements are met, many of which require moist conditions [64]. Forest diseases caused by pathogens indirectly affected by climate (e.g., root diseases) are generally predicted to have an increased impact [63]. While the ability of these pathogens to spread and infect new hosts is affected by moisture, factors associated with climate change that stress their hosts are generally considered to be more important to host invasion. Models frequently predict a reduction in the potential geographic distribution of forest diseases as a result of climate change [63, 65].

Increased wildfire activity is also expected as a result of climate change. In the western USA, increases in wildfire frequency have been well documented since the mid-1980s and concentrated between 1680 and 2590 m in elevation [66]. Wildfires at these elevations have been episodic, occurring during warm years and strongly associated with changes in spring snowmelt timing, which in turn is sensitive to changes in temperature [66] and precipitation. As a result, concerns regarding air quality (as discussed earlier), human safety, and protection of critical infrastructure are important, especially in the wild land urban interface where the presence of housing developments increases the cost and complexity of implementing fuel

Fig. 3.8 The western pine beetle (*Dendroctonus brevicomis*) is a primary disturbance agent in ponderosa pine (*Pinus ponderosa*) forests. Unlike many other bark beetles, western pine beetle is unique in that it has a very narrow host range. The only other common host is Coulter pine (*P. coulteri*), a species indigenous to the mountains of southern California, USA, and northern Baja California, Mexico. In the early 2000s, the mountain ranges of southern California started to experience elevated levels of tree mortality. Most experts attributed this mortality to drought (i.e., precipitation was the lowest in recorded history during 2001–2002) and elevated populations of bark beetles, specifically western pine beetle. Mortality was dispersed across >259,000 ha by 2004 and concentrated in several tree species, most notably ponderosa and Coulter pines. Significant mortality occurred in other plant associations as well. The resultant western pine beetle outbreak that occurred during 2001–2004 is considered by many experts to be the largest in recorded history for this species of bark beetle. In some areas, tree mortality was >80 %. Climate change is generally thought to increase levels of tree mortality attributed to insects. Western pine beetle is unique in that the range of its primary host is expected to increase as a result of climate change. The species is likely to become a more important disturbance agent in the future (photo credits: C.J. Fettig, USFS Pacific Southwest Research Station)

reduction treatments to reduce fire risk (Fig. 3.7). Increases in wildfire activity are likely to magnify other threats to forest health. While in many cases it is recognized that bark beetle outbreaks and wildfire will serve as the catalyst for much of the ecological change to be associated with climate change in coniferous forests, few studies have thoroughly examined the interactions between these disturbances until recently [67]. There is evidence that bark beetle outbreaks and associated levels of tree mortality affect subsequent fire risk and severity in some forest types.

Rapid and broad-scale tree mortality events can have long-term impacts to both forest health [43] and human health [68] with feedbacks that further influence climate and land use [33, 69]. Complex interactions must be considered at numerous scales (e.g., from tree to forest to global scales) and on various aspects of the life histories of the numerous species that comprise these ecosystems. For example, the recent loss of whitebark pine (*P. albicaulis*) stands due to mountain pine beetle underscores the need for a greater understanding of climate change effects on complex interactions important to ecosystem resiliency and stability (Fig. 3.9). Characterizing thresholds for systems beyond which such changes are irreversible

Fig. 3.9 In western North America, recent outbreaks of mountain pine beetle (*Dendroctonus ponderosae*) have been severe, long lasting, and well documented. Since 2001, >25 million ha of lodgepole pine (*Pinus contorta*) forest have been impacted. The species ranges throughout British Columbia and Alberta, Canada, most of the western USA, into northern Mexico, and colonizes several pine species, most notably, lodgepole pine, ponderosa pine (*Pinus ponderosa*), sugar pine (*P. lambertiana*), limber pine (*P. flexilis*), western white pine (*P. monticola*), and whitebark pine (*P. albicaulis*). Episodic outbreaks are a common occurrence, but the magnitude of recent outbreaks have exceeded the range of historic variability and have occurred in areas where mountain pine beetle outbreaks were once rare and of limited scale (e.g., whitebark pine forests) or previously unrecorded (e.g., jack pine forests (*P. banksiana*) in Canada). Several scientists speculate that under continued warming the loss of whitebark pine, and the unique ecological services that this species provides, is imminent in many areas. The US Fish and Wildlife Service announced in 2011 that it determined whitebark pine warranted protection under the Endangered Species Act but that adding the species to the Federal List of Endangered and Threatened Wildlife and Plants was precluded by the need to address other listing actions of higher priority (photo credits: left, C.J. Fettig, and right, C.J. Hayes, USFS Pacific Southwest Research Station)

is important. There are tools available to restore forest health and to increase the resiliency of forests to disturbances [39, 54]. Resource managers can intervene and mitigate some of the effects of climate change [70]. Uncertainty is inherent, but it is clear that healthy forests have a vital role to play in combating climate change.

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