INCREASING CLIMATE VARIABILITY AND CHANGE

Reducing the Vulnerability of Agriculture and Forestry

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INCREASING CLIMATE VARIABILITY AND CHANGE: REDUCING THE VULNERABILITY

Guest Editorial

Since time immemorial, climate variability and change have triggered natural disasters and climate extremes causing heavy losses of life and property, forcing civil society to "learn to live" with these calamities. Floods, droughts, hurricanes, storm surges, heat waves precipitating wild fires and such other natural calamities have claimed more than 2.8 million lives all over the world in the past 25 years, adversely affecting 828 million people. Damage caused by these climate extremes during the same period was estimated at 25–100 billion dollars, dramatically affecting agriculture and forestry systems in regions where these have occurred.

Agricultural and forestry production is highly dependent on climate, and is adversely affected by increasing climate variability and anthropogenic climate change leading to increases in climate extremes. There is strong evidence that global warming over the last millennium has already resulted in increased global average annual temperature and changes in rainfall, with the 1990s being likely the warmest decade in the Northern Hemisphere at least. During the past century, changes in temperature patterns have, for example, had a direct impact on the number of frost days and the length of growing seasons with significant implications for agriculture and forestry. Land cover changes, changes in global ocean circulation and sea surface temperature patterns, and changes in the composition of the global atmosphere are leading to changes in rainfall. These changes may be more pronounced in the Tropics.

During the course of the 21st century, scientific evidence points to global-average surface temperatures are likely increasing by 2–4.5 °C as greenhouse gas concentrations in the atmosphere increase. At the same time there will be changes in precipitation, and climate extremes such as hot days, heavy rainfall and drought are expected to increase in many areas. The combination of global warming will be superimposed on decadal climate variability, such as that caused by the Interdecadal or Pacific Decadal Oscillation, and interannual fluctuations caused by the El Niño/Southern Oscillation and the North Atlantic Oscillation. All these may lead to a century of increasing climate variability and change that are expected to be unprecedented in the history of human settlement and agrarian activities.

The main purpose of the United Nations Framework Convention on Climate Change (UNFCCC, 1992) is to reduce the growth of greenhouse gases. Article 2 of the Convention states that its ultimate objective is "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."

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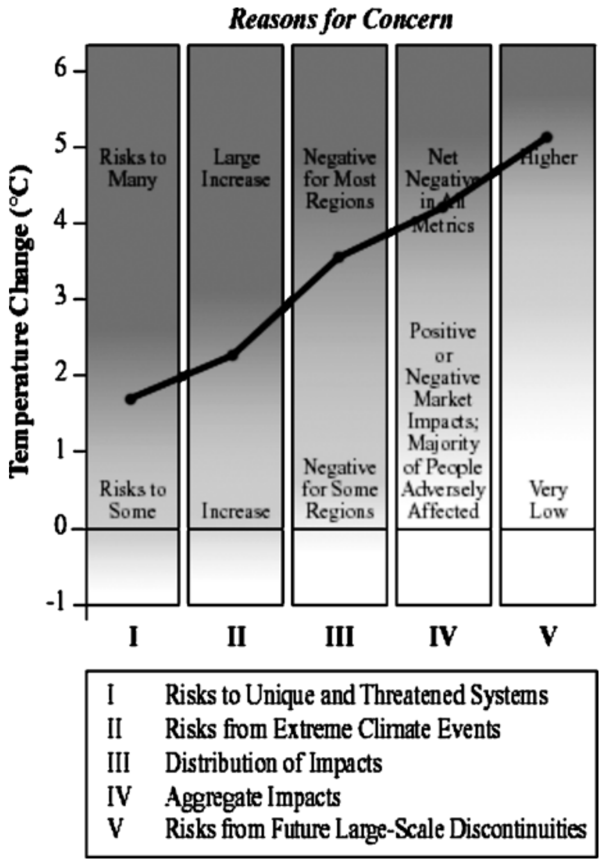

Figure 1. The risk of adverse impacts increase with the magnitude of climate change. Global mean annual temperature is used as a proxy for the magnitude of climate change (IPCC WG2, as modified by Mastrandrea and Schneider, 2004).

The natural greenhouse effect keeps the planet and biosphere at an equable temperature for planetary processes to operate. The current rate of global warming is 2 °C per century, and this rate is projected as a lower range for the remainder of the 21st century. Thus, increases in greenhouse gases released by human activities are creating a potential situation where the stability of agriculture and forestry systems is threatened by dangerous climate change (Figure 1).

Adapting to increasing climate variability then provides tools to reduce the vulnerability of agriculture and forestry. Some farming systems with an inherent resilience may adapt more readily to climate pressures, making long-term adjustments to varying and changing conditions. Other systems will need interventions for adaptation. Traditional knowledge and indigenous technologies should not be ignored. Age-old technologies such as planting calendars, intercropping and mulching reduce the vulnerability to climate extremes.

However, the path of increasing variability and change will require the introduction of much more sophisticated technologies. Seasonal to interannual climate forecasting is a relatively new branch of climate science, and it promises reducing vulnerability. Improved seasonal forecasts are now being linked to decision making for cropping, developing climate risk practices to improve the application of climate information for the management of grazing practices, and developing climate risk practices to enhance the productivity and performance of forests. The application of climate knowledge to the improvement of risk management will increase the resilience of farming systems.

Consequently, the occurrence of seasonal to interannual climate variability and their extremes can be forecast with a greater degree of accuracy. Availability of such crucial information in advance can greatly assist in taking effective measures for prevention and mitigation of losses by agricultural and forestry. Thus, the resultant disastrous effect can be reduced considerably through proper planning and more effective preparedness. Vulnerability associated with climate can be controlled to some extent by accurate and timely prediction and by taking counter-measures to reduce their impacts on various sectors of agriculture.

One fact is for certain though – the historical record shows that our climate has changed in the past, and will continue to vary and change during the coming seasons and decades. The underlying theme of global warming is likely to cause increases in temperature and their extremes of heat waves, with climate scenarios of changing rainfall patterns as the 21st century progresses, with increasing extremes of floods and droughts. These will provide a challenge unparalleled in the history of civil society to agriculture and forestry: the papers in the this issue of *Climatic Change* assess the likely impacts of change and examine the adaptation and capacity building options to reduce vulnerability and increase resilience.

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FOREWORD

One of the major challenges facing humankind is to provide an equitable standard of living for the current and future generations: adequate food, water and energy, safety, shelter and a healthy environment. Human-induced climate change, and increasing climate variability, as well as other global environmental issues such as land degradation, loss of biological diversity, increasing pollution of the atmosphere and fresh water and stratospheric ozone depletion, threaten our ability to meet these basic human needs. Considerable efforts have been deployed in monitoring and projecting the changes and in evolving possible options for managed systems including agriculture and forestry.

Today, there is certainty from the surface temperature data, collected by WMO's Global Observing System, that the globally averaged surface temperatures are rising. According to records maintained by members of WMO, the global surface temperature has increased since the beginning of instrumental records in 1861. Over the 20th century that increase was about 0.6 °C. The rate of change for the period since 1976 is roughly three times that of the past 100 years. Analyses of proxy data for the Northern Hemisphere indicate that the late 20th century warmth is unprecedented for at least the past millennium. Over the same period, the 1990s were the warmest decade, the year 1998 was the warmest year and the years 2002 and 2003 the second and third warmest, respectively. The projected temperature rise by the end of the century is between 1.4 and 5.8 °C.

Scientific assessments have shown that over the past several decades, human activities, especially burning of fossil fuels for energy production and transportation, are changing the natural composition of the atmosphere. Proxy records indicate that for over at least the last 400,000 years, up to about 1800 AD, the atmospheric concentration of carbon dioxide (CO_2) varied only by 1–3 per cent. Since then, it has increased by more than 33 per cent, and reached 376 parts per million by volume (ppmv) at the end of 2003. WMO's Global Atmosphere Watch observing network monitoring atmospheric chemistry show that today's atmospheric CO_2 concentration has not been exceeded during the past 420,000 years. More than half of that increase in CO_2 concentration has occurred since 1950.

It is also possible, even likely in some cases, that human-induced climate change will affect naturally occurring climate variability such as the frequency or intensity of El Niño/Southern Oscillation (ENSO) events. A growing number of extreme weather and climate events, some of which have been of unprecedented intensity, continue to be observed with associated degradation of the environment. This requires the global community to give urgent attention and high priority to addressing key issues related to climate change through appropriate measures and policies at national and regional levels.

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Climate variability affects all economic sectors, but agricultural and forestry sectors are perhaps two of the most vulnerable and sensitive activities to such climate fluctuations. Climate change and variability, drought and other climate-related extremes have a direct influence on the quantity and quality of agricultural production and in many cases, adversely affect it, especially in developing countries, where the pace of technology generation, innovation and adoption does not allow them to counteract the adverse effects of varying environmental conditions. For example, inappropriate management of agroecosystems, compounded by severe climatic events such as recurrent droughts in many parts of the world, have tended to make the drylands increasingly vulnerable and prone to rapid degradation and hence desertification. Even in the high rainfall areas, increased probability of extreme events can aggravate nutrient losses due to excessive runoff water logging. Projected climate change can influence pest and disease dynamics with subsequent crop losses. Improved adaptation of food production, particularly in areas where climate variability is large, holds the key to improving food security for the global population.

The range of adaptation options for managed systems such as agriculture and forestry is generally increasing because of technological advances, thus opening the way for reducing the vulnerability of these systems to climate change. However, some regions of the world, particularly developing countries, have limited access to these technologies and appropriate information on how to implement them. Here successful traditional technologies used over the centuries should be maintained. Incorporation of climate change concerns into resource-use and development decisions and plans for regularly scheduled investments in infrastructure will facilitate adaptation.

Agriculture and forestry are currently not optimally managed with respect to today's natural climate variability because of the nature of policies, practices and technologies currently in vogue. Decreasing the vulnerability of agriculture and forestry to natural climate variability through a more informed choice of policies, practices and technologies will, in many cases, reduce the long-term vulnerability of these systems to climate change. For example, the introduction of seasonal climate forecasts into management decisions can reduce the vulnerability of the agriculture to floods and droughts caused by the ENSO phenomena.

It is with this background that WMO had organized the International Workshop on Reducing Vulnerability of Agriculture and Forestry to Climate Variability and Climate Change in conjunction with the 13th session of the Commission for Agricultural Meteorology of WMO held in October 2002 in Ljubljana, Slovenia. The workshop was co-sponsored by the Asia-Pacific Network for Global Change Research (APN), the Canadian International Development Agency (CIDA), the Centre Technique de Coopération Agricole et Rurale – Technical Centre for Agricultural and Rural Co-operation (CTA), the Environmental Agency of the Republic of Slovenia, the Ministry of Agriculture, Forestry and Food of the Republic of Slovenia, the Ministry of Environment, Spatial Planning and Energy of the Republic of Slovenia, the Food and Agriculture Organization of the United Nations (FAO), the Fondazione per la Meteorologia Applicata and the Laboratory for Meteorology & Climatology (F.M.A.-La.M.M.A.), Météo-France, the International START Secretariat (START), the Ufficio Centrale di Ecologia Agraria (UCEA), the United Nations Environment Programme (UNEP) and the United States Department of Agriculture (USDA).

The workshop reviewed the latest assessments of the science of climate variability and climate change, and their likely impacts on agriculture and forestry in different agroecological regions during the 21st century. It also surveyed and presented a range of adaptation options for agriculture and forestry and recommended appropriate adaptation strategies required to reduce vulnerability of agriculture and forestry to the observed and projected climate variability and climate change highlighted earlier. I hope that the papers presented in this special issue will serve as a major source of information to all services, agencies and organizations at national, regional and global levels involved with designing and implementing appropriate programmes in using agrometeorological techniques to reduce vulnerability to climate variability and climate change through the course of the 21st century.

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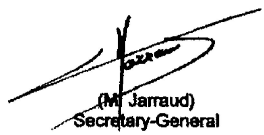

CLIMATE VARIABILITY AND CHANGE: PAST, PRESENT AND FUTURE – AN OVERVIEW

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Abstract. Prior to the 20th century Northern Hemisphere average surface air temperatures have varied in the order of 0.5 °C back to AD 1000. Various climate reconstructions indicate that slow cooling took place until the beginning of the 20th century. Subsequently, global-average surface air temperature increased by about 0.6 °C with the 1990s being the warmest decade on record. The pattern of warming has been greatest over mid-latitude northern continents in the latter part of the century. At the same time the frequency of air frosts has decreased over many land areas, and there has been a drying in the tropics and sub-tropics. The late 20th century changes have been attributed to global warming because of increases in atmospheric greenhouse gas concentrations due to human activities. Underneath these trends is that of decadal scale variability in the Pacific basin at least induced by the Interdecadal Pacific Oscillation (IPO), which causes decadal changes in climate averages. On interannnual timescales El Niño/Southern Oscillation (ENSO) causes much variability throughout many tropical and subtropical regions and some mid-latitude areas. The North Atlantic Oscillation (NAO) provides climate perturbations over Europe and northern Africa. During the course of the 21st century global-average surface temperatures are very likely to increase by 2 to 4.5 °C as greenhouse gas concentrations in the atmosphere increase. At the same time there will be changes in precipitation, and climate extremes such as hot days, heavy rainfall and drought are expected to increase in many areas. The combination of global warming, superimposed on decadal climate variability (IPO) and interannual fluctuations (ENSO, NAO) are expected lead to a century of increasing climate variability and change that will be unprecedented in the history of human settlement. Although the changes of the past and present have stressed food and fibre production at times, the 21st century changes will be extremely challenging to agriculture and forestry.

1. Introduction

In the course of climate history over the last millennium, there has been intense interest on the cooling documented to the 19th century for the Northern Hemisphere (NH) at least, the cooler period of climate in the 19th century and rapid global warming during the late 20th century. Over the last millennium climate has varied by as much as 1 °C globally (IPCC, 2001a). Key questions of any future impacts of global warming are the effects on human society and economics, and in particular, on agriculture and forestry. History can provide very valuable lessons on effects of climatic variability on the human dimensions. The multidecadal cooling of the late 16th century in Europe resulted in one of the peak cooling excursions of the so called Little Ice Age epoch of Europe. This example of climate variability provides impacts of a mere 0.5 °C cooling in annual mean temperature on society.

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Increases were observed in surface global temperatures during the 20th century, and interannual climate variability has been observed in many regions of the globe (Salinger, 1994; Salinger et al., 1997). The 1982/83 and 1997/98 El Niños and the 1991 Mt. Pinatubo volcanic eruption (Salinger et al., 2000) caused considerable variability in the interannual climate of tropical regions in the late 20th century. Recently IPCC (2001a) reported on warming trends, confirmation of continuing climate change based on observations from Arctic and Antarctic sea ice, from later ice appearance days and earlier ice breakup days particularly in European Russia, the Ukraine and Baltic countries. Observations of shrinking mountain glaciers during the 20th century and the increase of permafrost temperatures in many areas occurring provides additional confirmation.

Perhaps of more importance are the implications on agriculture that arise from the multidecadal climate fluctuations. If climatic variability in the order of 0.5 °C can cause such dramatic effects on glaciers, flood events and storm surges, agricultural commodity prices, wine yields and other societal effects as documented for the 16th century, then this poses questions of what are the impacts of the projected increasing climatic variability and change during the 21st century. There is now better understanding of the climate system, and the natural and anthropogenic factors that have caused climate variability and change over the past century, and likely changes in climate and its variability during the 21st century (Salinger, 1994; Salinger et al., 1997, 1999; IPCC, 1996, 2001a). The latest IPCC projections (IPCC, 2001a) from the entire range of 35 IPCC scenarios place temperature increases in the range of 1.4 to 5.8 °C by the end of the 21st century, with likely increases in heavy rainfall events. The 90% range is 2 to 4.5 °C.

Although agrometeorology provides methods and technologies to allow adaptation of food and fibre production to cope with increasing climate variability and climate change (Salinger et al., 2000) lessons from the past are that the consequences can only be dramatic. An overview of past climate trends over the last millennium is provided as a context to view current climate variability and future trends for providing increasing preparedness of agriculture and forestry to future variability and change. Climate trends during the 21st century from scenarios of human activities are described, together with broadscale implications for agriculture and forestry. The United Nations Framework Convention on Climate Change has clauses on ‘Dangerous Climate Change’. This concept will be examined in terms of the ability of agriculture and forestry to adapt to anthropogenic climate change this century.

2. Past Climate

2.1. THE LAST THOUSAND YEARS

The course of annual average temperature change for the Northern Hemisphere over the past 1,000 yr is shown in Figure 1. This is a particularly important time frame

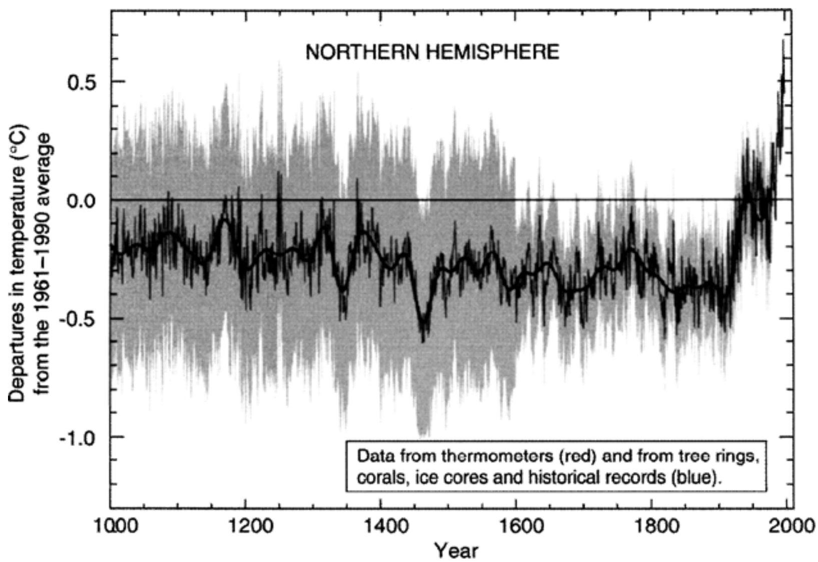

Figure 1. Northern Hemisphere average annual surface air temperature variations over the last millennium from proxy, historical and instrumental observations (IPCC, 2001a). Temperature reconstruction and instrumental data from AD 1000–1999. Smoother version of NH series and two standard error limits (gray shaded) are shown.

for assessing the background natural variability of climate, to place 21st century changes in context of which both modern and traditional agricultural and forestry systems developed over the past millennium.

Palaeoclimate proxy indicators (Folland et al., 2001) include tree rings, which provide precisely dated annual information, corals that provide information on past variability of the tropical and sub-tropical oceans and ice cores from polar regions of Greenland and Antarctica, which can have annual resolution. Other information can be gleaned from borehole measurements, which provide broadscale temperature trends, historical documentary evidence particularly from Europe and China, and mountain glacier moraines providing evidence of past glacial advances.

From these sources there is enough evidence to reconstruct temperature patterns over the Northern Hemisphere back to AD 1000 (Folland et al., 2001). These reconstructions show a slow cooling peaking around AD 1450 and 1880 over the last 1,000 yr, with the most recent cool period being around the end of the 19th century. Lamb (1982) has documented the downturn of climate in the North Atlantic/European region commencing with the storminess and cooling and wetness of 14th century Europe. Desertion of farms and village settlements are noted all over northern and central Europe. The prevailing wetness led to more prevalent disease. During the late 1500 s many years of general death and famine occurred in Scotland. For Norway extremely stormy years are noted in the 1600 s with changes in fisheries around Scandinavia.

Documentary evidence by Pfister et al. (1999) illustrates the impacts of climate excursions of similar magnitude (of the order of 0.2 °C) that occurred in late 16th century Europe on agricultural commodity prices and wine production. A clear link is made with grain price fluctuations. Wine yields and prices show a more dramatic response. The interannual deterioration from 1586 to 1587 decimated yields, with wine prices jumping and beer sales tripling in the 1590s. It is interesting to note though that for the Northern Hemisphere the coldest period occurred in the late 15th century when temperatures were 0.5 °C below the 1961–1990 average.

Evidence for Southern Hemisphere temperature trends in past centuries is quite sparse. There is evidence of some large-scale hydrological changes, which are best documented by lake levels in Africa (Nicholson, 1989).

2.2. THE OBSERVED RECORD

2.2.1. *Temperature*

Measurements of global-average air temperature of the land surface are available from thousands of station records distributed over the land surfaces of the globe. Marine temperature series have been derived from sea surface temperature (SST) and night marine air temperature records from ships. These have been blended and area averaged to produce anomalies of globally averaged surface air temperatures shown in Figure 2.

The global average of the surface air temperature has increased by about 0.6 °C since about 1860, the earliest date for which sufficient data for global estimates are available to present. New analyses indicate that the warming in the 20th century is likely to be the largest of any century during the past 1,000 yr for the Northern Hemisphere, as indicated by Figure 1. Further, on a global basis, the 1990s were the warmest decade and 1998 was the warmest year since 1860. Two periods of temperature rise occur: one between 1910–1945, where the global temperature increase was 0.14 °C, and the other from 1976–1999 when temperatures increased by 0.17 °C.

The distribution of temperature increase is shown in Figure 3. The warming observed in the period 1910–1945 was greatest in Northern Hemisphere latitudes. In contrast the period 1946–1975 shows cooling in the Northern Hemisphere relative to much of the Southern Hemisphere. For the most recent period (1976–1999) increases in average temperature have been greatest over the mid-latitude of the Northern Hemisphere continents, particularly in winter. There has been relatively faster warming of land-surface temperature than of the ocean surface temperature in the last 25 yr of the 20th century (Figure 3).

On average, night-time daily minimum temperatures over land have increased at about the twice the rate of daytime daily maximum temperatures since about 1950 (approximately 0.2 °C, compared to 0.1 °C per decade). This trend has lengthened

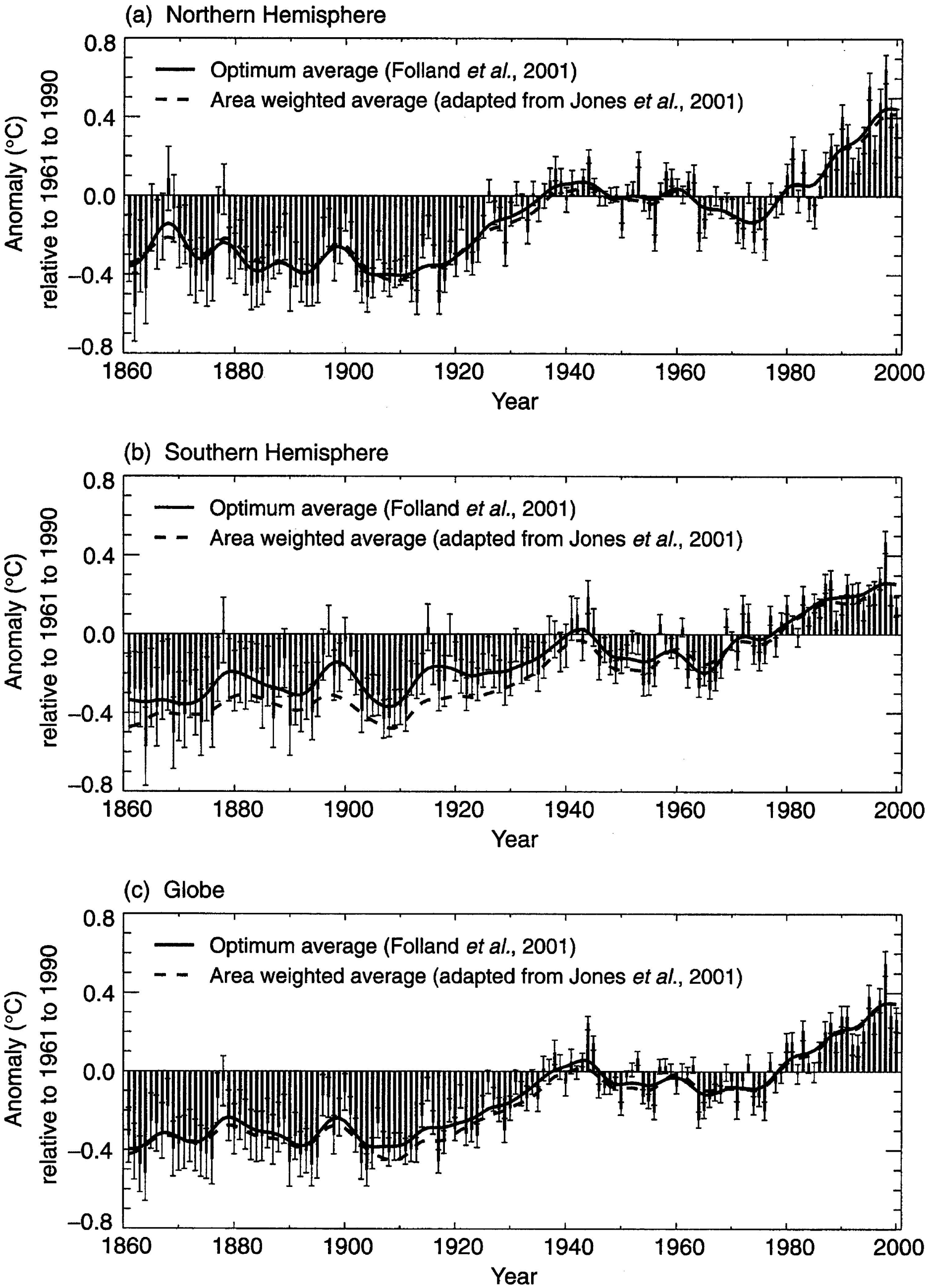

Figure 2. (a) to (c). Combined annual land-surface air and sea surface temperature (SST) anomalies relative to 1961 to 1990 (°C) 1861 to 1999, calculated using optimum averages of United Kingdom Meteorological Office ship and buoy and Climatic Research Unit land surface air temperature data (bars and solid smoothed curves) taken from Folland et al. (2001): (a) Northern Hemisphere; (b) Southern Hemisphere; (c) Globe. The dashed smoothed curves are corresponding area weighted averages, updated from Jones et al. (2001).

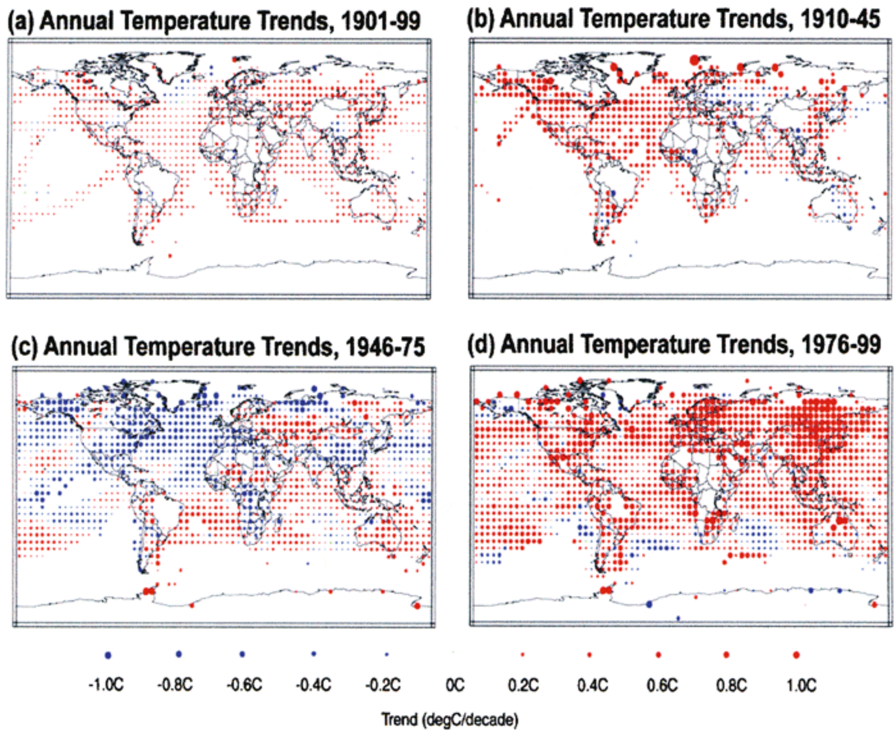

Figure 3.

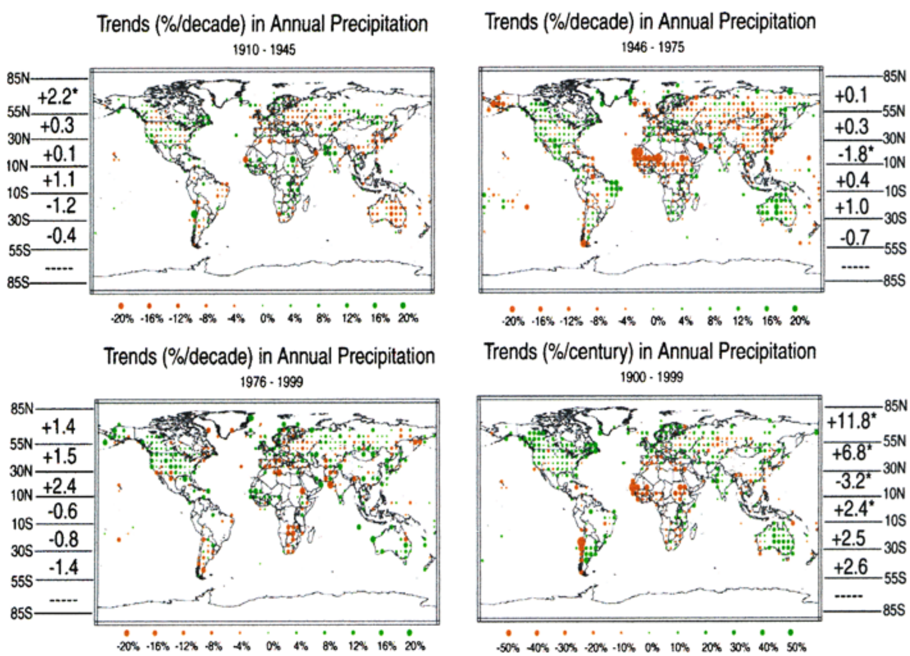

Figure 4.

the frost-free season in many mid- and high-latitude regions (Figure 5). Analysis of numbers of days with air frost (days with minimum temperature below 0 °C) across much of the globe (Frich et al., 2000) shows a reduction in the order of 10%.

2.2.2. *Precipitation*

Overall, global land precipitation has increased by about 2 percent over the 20th century (Hulme et al., 1998). This increase is neither spatially nor temporally uniform (Figure 4). Over the mid- and high-latitudes of the Northern Hemisphere precipitation increased by between 7 and 12 percent between 30 and 85 °N, especially during the boreal autumn and winter, but these increases vary both in space and time. Over North America precipitation has increased in the order of 10%, a 5% increase in western Russia and a slight decrease in eastern Russia and China. This general increase contrasts with decreases in the northern sub-tropics. Record low precipitation has been observed in equatorial regions in the 1990s. Small increases are observed in the southern sub-tropical landmasses.

Figure 3. (a) to (d): Annual temperature trends for the periods 1901–1999, 1910–1945, 1946–1975 and 1976–1999 respectively. Data from Jones et al. (2001). Trends are represented by the area of the circle with red representing increases, blue representing decreases. Trends were calculated from annually averaged gridded anomalies with the requirement that the calculation of annual anomalies include a minimum of 10 months of data. For the period 1901–1999, trends were calculated only for those grid boxes containing annual anomalies in at least 66 of the 100 yr. The minimum number of yr required for the shorter time periods (1910–1945, 1946–1975, and 1976–1999) was 24, 20, and 16 yr respectively.

Figure 4. Annual trends for the three periods of changing rates of global temperature of figure 3 and the full period, 1900–1999. During the 100 yr period, calculation of grid cell trends required at least 66% of the ys without missing data and at least 3 yr of data within each decade except the first and last. During the shorter periods, calculation of grid cell trends required at least 75% of the years without missing data. Stations with more than 1/6 of their data missing during the normal period and grid cells with more than one season or year without any measurable precipitation during the normals period were excluded from consideration. Precipitation trends are represented by the area of the circle with green representing increases and brown representing decreases. Annual trends were calculated using the following method. Precipitation anomalies in physical units were calculated for each station based on 1961–1990 normals and averaged into 5 ° × 5 ° grid cells on a monthly basis. The 1961–1990 monthly mean precipitation for each grid cell was added to the monthly anomalies and the resulting grid cell values summed into annual totals. This serieswas converted into percentages of normal precipitation, and trends calculated from the percentages. Average trends within six latitude bands are shown in the legend of each map. The 1961–1990 monthly mean precipitation for the latitude band was added to the anomaly time series and the resulting values totaled across all months within the year. The significance of each trend (based on a 0.5 level) was determined using a *t*-test and a non-parametric test statistic. Trends found to be significant under both tests are indicated with a '*'.

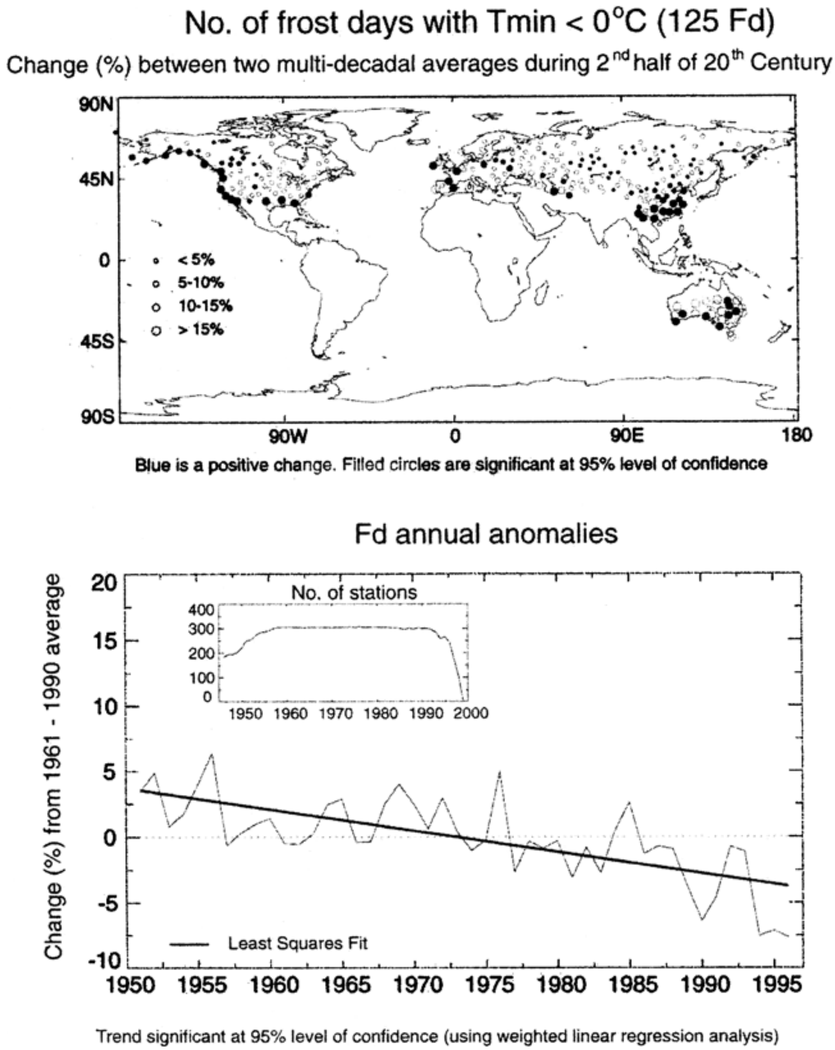

Figure 5. Changes in the number of frost days during the second half of the 20th century. The upper panel shows percentage changes in the total number of frost days, days with a minimum temperature of less than 0 °C, between the first and second half of the period 1946–1999. The size of each circle reflects the size of the change it represents. The lower panel shows the average annual numbers of frost days as percentage differences from the 1961–1990 average value. The trend shown is statistically significant at the 5% level. The analysis shown is from Frich et al. 2000.

3. Present Climate

Beneath the earlier mentioned trends, current climate shows significant variability, on timescales of seasons to decades, which are of importance to agriculture and forestry. Those that are most important interannually are the El Niño/Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), and decadally the recently described Interdecadal Pacific Oscillation (IPO). These quasi-periodic variations are superimposed on the general trend of global warming, but their frequencies may be influenced by global warming.

3.1. INTERANNUAL VARIABILITY

3.1.1. *El Niño/Southern Oscillation (ENSO)*

ENSO is the primary global mode of natural climate variability in the 2–7 year time band defined by sea surface temperature SST anomalies in the eastern tropical Pacific. The Southern Oscillation is a measure of the atmospheric pressure across the Pacific-Indian Ocean region. Atmospheric and oceanic conditions in the tropical Pacific vary considerably during ENSO, fluctuating somewhat irregularly between the El Niño phase and the opposite La Niña phase. In the former, warm waters from the western tropical Pacific migrate eastwards, and in the latter cooling of the tropical Pacific occurs.

As the El Niño develops, the trade winds weaken and warmer waters in the central and eastern Pacific occur, shifting the pattern of tropical rainstorms eastward. Higher than normal air pressures develop over northern Australia and Indonesia with drier conditions or drought. At the same time lower than normal air pressures develop in the central and eastern Pacific with excessive rains in these areas, and along the west coast of South America. Approximately reverse patterns occur during the La Niña phase of the phenomenon.

The ENSO phenomenon's trigger is in the tropical Pacific Ocean. The observed global influences occur as teleconnections as the atmosphere transmits the anomalous heating in the tropics to large-scale convection and thus to anomalous winds in the atmosphere. The main global impacts are that El Niño events cause above average global temperature anomalies above the trend. Since the mid-1970s El Niño events have been more frequent, and in each subsequent event global temperature anomalies have been higher (Trenberth and Hoar, 1997). Figure 6 shows the Southern Oscillation Index since 1930; the Tahiti minus Darwin normalized pressure

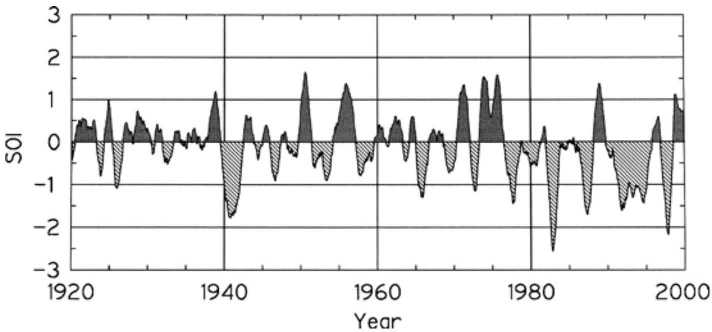

Figure 6. The Southern Oscillation Index 1930–2000. Negative values represent El Niño and positive values of this index La Niña conditions.

index, which measures whether the climate system is in the El Niño or La Niña state. A negative index indicates the El Niño state, and a positive index the La Niña state.

Reconstructions of ENSO from proxy climate indicators (Stahle et al., 1998; Mann et al., 2000) show that ENSO fluctuations have prevailed since at least 1700, but also suggest that the 1982–83 and 1997–98 very large warm events could be outside the range of variability of the past few centuries. Instrumental records show both the activity and periodicity of ENSO have varied considerably since 1871 with considerable irregularity in time. There was an apparent "shift" in the temperature of the tropical Pacific around 1976 to warmer conditions (Salinger et al., 1996), which appeared to continue until at least 1998 (Figure 6). It is unclear whether this warm state continues now as the current moderate but increasingly long La Nina, that began in late 1998 finally subsided during early 2001. The 1990s have received considerable attention, as the recent behaviour of ENSO has seemed unusual relative to that of previous decades. A protracted period of low SOI occurred from 1990–1995, during which several weak to moderate El Niño events occurred with no intervening La Niña events, which is extreme rare (Trenberth and Hoar, 1997) statistically.

3.1.2. *North Atlantic Oscillation (NAO)*

This large-scale alternation of atmospheric pressure between the North Atlantic regions of the sub-tropical high (near the Azores) and sub-polar low pressure (extending south and east of Greenland) determines the strength and orientation of the poleward pressure gradient over the North Atlantic, and the mid-latitude westerlies in this area. This is measured by the NAO Figure 7). One extreme of the NAO occurs in winter when the westerlies are stronger than normal, bringing cold winters in western Greenland and warm winters to northern Europe. In the other phase the westerlies are weaker than normal which reverses the temperature anomalies. In addition, European precipitation is related to the NAO (Hurrell, 1995). When this index is positive, as it has been for winters in the last decade, drier than normal conditions occur over southern Europe and the Mediterranean, with above normal precipitation from Iceland to Scandinavia. The NAO also affects conditions in North Africa and possibly the Sahel.

There is a seesaw of atmospheric mass between the polar cap and mid-latitudes in both the Atlantic and Pacific Ocean basins, which has been named the Artic Oscillation (AO). The time series of the AO and NAO (Figure 7) are quite similar (Thompson and Wallace, 2000) and the NAO is regarded by some as the regional expression of the AO.

3.2. INTERDECADAL VARIABILITY

Recently shifts in climate have been detected in the Pacific basin, driven by a newly described climate feature, the IPO, which shifts climate every one to three decades (Power et al., 1999; Salinger et al., 2001). This is an 'ENSO-like' feature of the climate system that operates on time scales of several decades. There is a

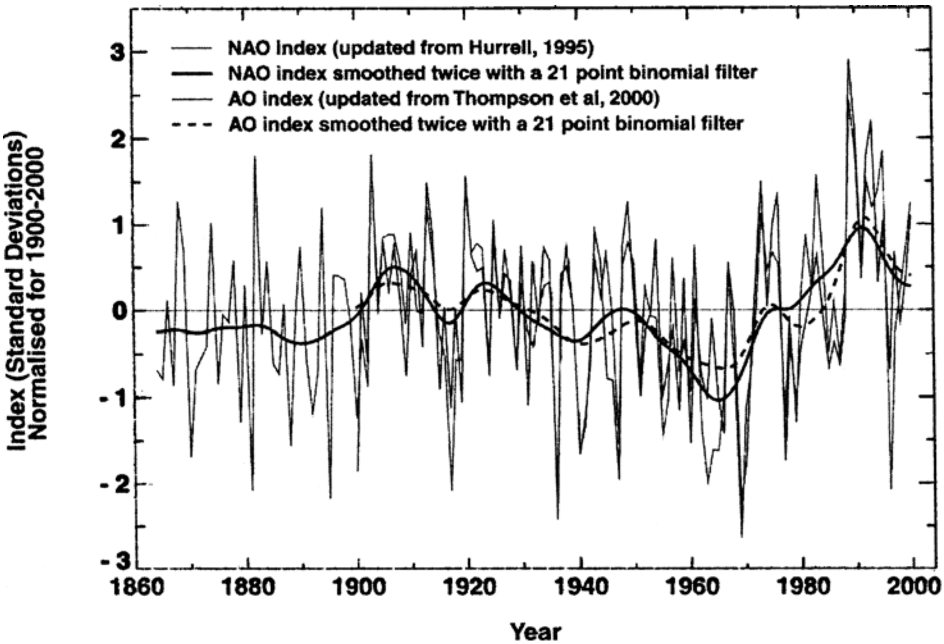

Figure 7. December to March North Atlantic Oscillation (NAO) indices, 1864–2000, and Arctic Oscillation (AO) indices, 1900–2000, updated from Hurrell (1995) and updated from Thompson and Wallace (2000) and Thompson et al. (2000) respectively. The indices were normalised using the means and standard deviations from their common period, 1900–2000, smoothed twice using a 21 point binomial filter where indicated and then plotted according to the years of their Januarys.

tight coupling between the ocean and atmosphere. The main centre of action in SST is in the north Pacific centred near the Date-Line at 40 °N, with an opposing weaker centre just south of the equator in the eastern Pacific, north of Easter Island at 10 °S. There is also another weaker centre of action, in the southwest Pacific centred near the Cook Islands at 20 °S, which is in the same phase as the north Pacific centre. The matching atmospheric sea level pressure pattern is one of an east/west seesaw at all latitudes, but again centred over the north Pacific, with the centre of action over the Aleutian Islands. The IPO has been shown to be a significant source of decadal climate variation throughout the South Pacific and Australia, and also the North Pacific. Future research may determine whether this feature could contribute to decadal climate variability throughout Pacific-rim countries.

Three phases of the IPO have identified during the 20th century: a positive phase (1922–1946), a negative phase (1947–1976) and the most recent positive phase (1977–1998). There is now evidence that the recent positive phase has ended (Figure 8). Prior to the end of the 19th century there is not enough information to derive an IPO index. Power et al. (1999) show that the two phases of the IPO appear to modulate year-to-year ENSO precipitation variability over Australia. The IPO is

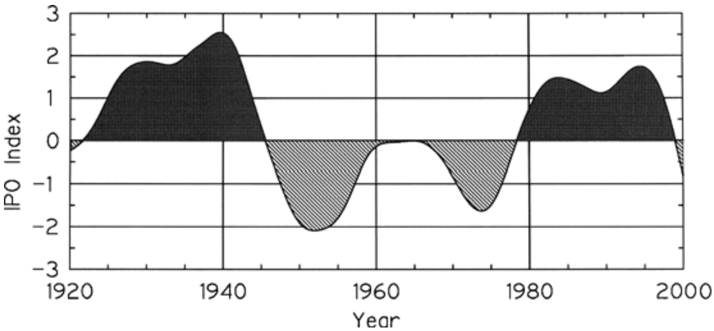

Figure 8. Smoothed index denoting the phases of the Interdecadal Pacific Oscillation (IPO).

a significant source of decadal climate variation throughout the South Pacific, and modulates ENSO climate variability in this region (Salinger et al., 2001). It may also play a key role in modulating ENSO teleconnections across North America on interdecadal time scales (Livezey and Smith, 1999). The results demonstrate that the IPO is a significant source of climate variation on decadal time scales throughout the South West Pacific region. The IPO also modulates interannual ENSO climate variability over the region.

3.3. GLOBAL WARMING

The three features, ENSO, NAO and the IPO all impinge on aspects of global climate, and two are dominant features of the tropical Pacific and oceanic Southern Hemisphere which effect climate variability of the three southern continents of Southern Africa, Australasia, and South America, as well as the Pacific basin. It is on this background of internal climate variability that external mechanisms such as volcanism and the increase of greenhouse gases from anthropogenic activities have acted (Salinger et al., 2000). Modelling studies are best able to identify the importance of these external factors in the period of current climate.

A climate model can be used to simulate the temperature changes that occur both from natural and anthropogenic causes. Figure 9 shows the results of global mean surface temperature anomalies relative to the 1880–1920 instrumental record compared with ensembles of four simulations with a coupled ocean-atmosphere climate model (Stott et al., 2000; Tett et al., 2000; IPCC, 2001a).

From these simulations IPCC (2001a) concluded that climate forcing from changes in solar radiation and volcanism is likely to have caused fluctuations in global and hemispheric mean temperatures in the first part of the 20th century. However, these have been too small to produce the mean temperature increases in the latter part of the 20th century. Well-mixed greenhouse gases (carbon dioxide, methane, chlorofluorcarbons, etc) must have made the largest contribution in radiative forcing to warm the climate in the late 20th century, as now validated by the above mentioned climate model simulations of global-average surface temperature.

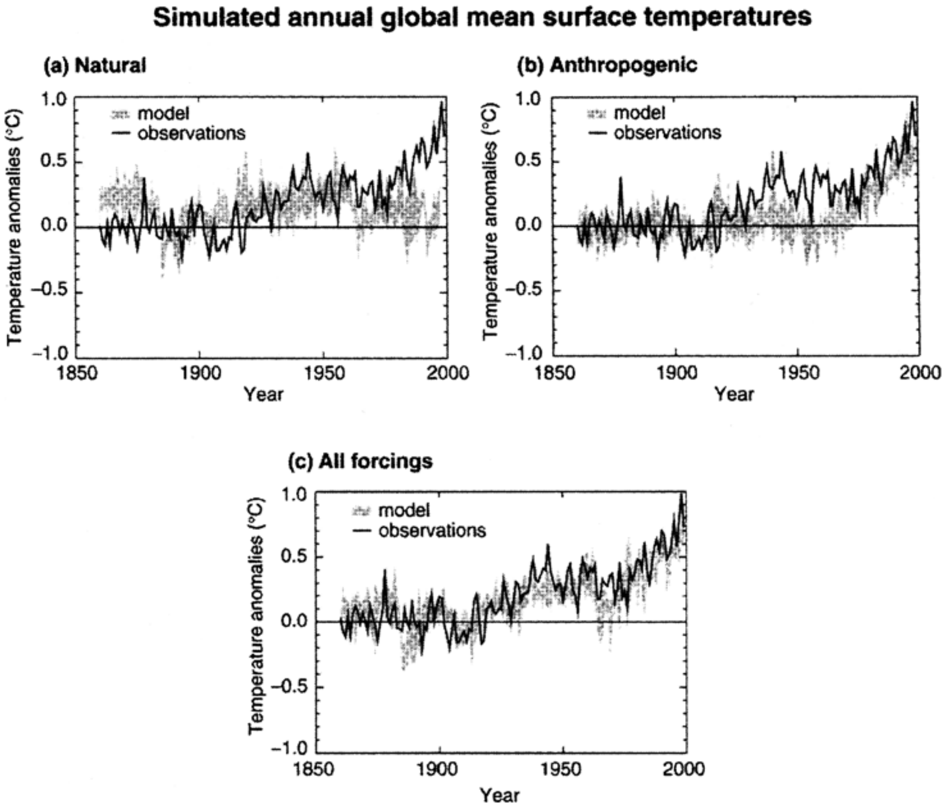

Figure 9. The simulations represented by the band in (a) were done with natural forcings: solar variation and volcanic activity. Those encompassed by the band in (b) were done with anthropogenic forcings: greenhouse gases and an estimate of sulphate aerosols and those encompassed by the band in (c) were done with both natural and anthropogenic forcings included.

4. Future Climate in the 21st Century

The growth in greenhouse gases in the atmosphere because of anthropogenic activities is also expected to be the most important factor forcing climate to change during the 21st century. Within the atmosphere there are naturally occurring greenhouse gases, which trap some of the outgoing infrared radiation emitted by the earth and the atmosphere. The principal greenhouse gas is water vapour, but also carbon dioxide (CO_2), ozone (O_3), methane (CH_4) and nitrous oxides (N_2O), together with clouds, keeps the Earth's surface and troposphere 33 °C warmer than it would otherwise be. This is the *natural greenhouse effect*. Changes in the concentrations of these greenhouse gases will change the efficiency with which the Earth cools to space. The atmosphere absorbs more of the outgoing terrestrial radiation from the surface when concentrations of greenhouse gases increase. This is emitted at higher altitudes and colder temperatures and results in a positive radiative forcing which tends to warm the lower atmosphere and Earth's surface. This is the *enhanced* *greenhouse effect* – an enhancement of an effect that has operated in the Earth's atmosphere for billions of years due to naturally occurring greenhouse gases e.g. Salinger et al., (2000) IPCC, (2001a). The natural concentration ranged from about 190 to 280 parts per million (ppm). When CO_2 concentrations were low, so too were temperatures, and when CO_2 concentrations were high, it was warmer. Greenhouse gases in the atmosphere are expected effectively double or quadruple by 2100.

In order to make projections of future climate, models incorporate past, as well as future emissions of greenhouse gases and aerosols. The IPCC has modeled climate using seven main scenarios of greenhouse gas and other human-related emissions, based on the IPCC Special Report on Emissions Scenarios (SRES) (IPCC, 2000). From these a full range of 42 SRES scenarios have been produced, based on a number of climate models. The pattern of temperature increase from these is shown in Figure 10.

The model results show that globally averaged surface temperature is projected to increase by 1.4 to 5.8 °C over the period 1990–2100 (IPCC, 2001a) for the full range of SRES scenarios. This projected rate of warming is much larger than the observed changes during the 20th century and is without precedent during at least

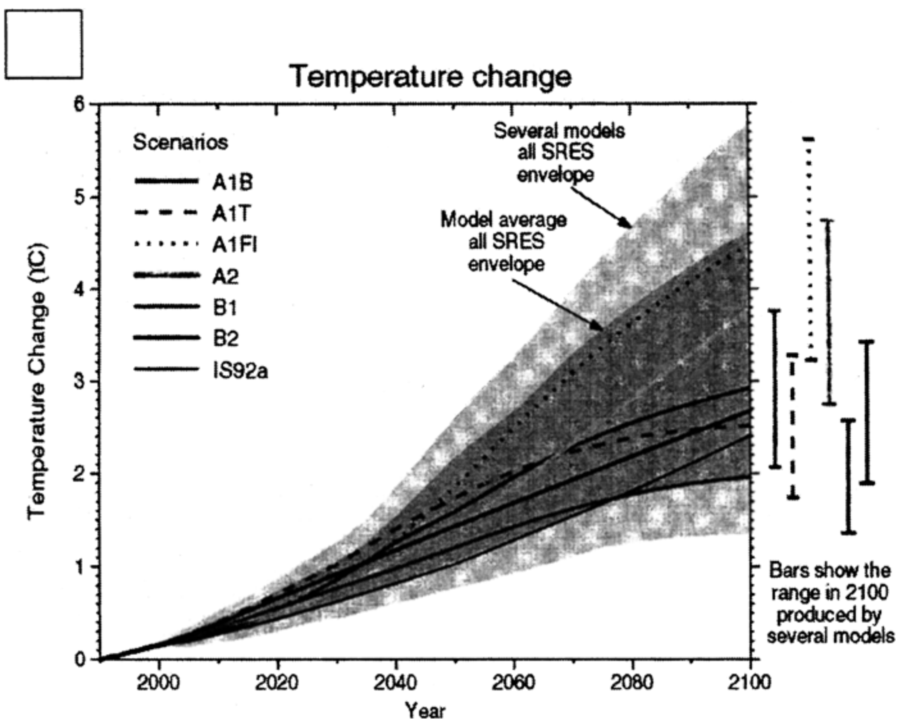

Figure 10. Estimated anthropogenic global temperature change for 1990–2100 for the seven illustrative SRES scenarios using a simple climate model tuned to seven atmosphere-ocean general climate models. The dark shading represents the full envelope of the full set of 42 SRES scenarios. The bars show the range of model results in 2,100 for the six climate model tunings.

the last 10,000 yr – and certainly during the period of settled agriculture and forestry. The global model simulations indicate that nearly all land areas will warm more rapidly than the global average, especially those located at northern high latitudes (IPCC, 2001a). Most notable of these is the warming in the northern regions of North America, and northern and central Asia. In contrast, the projected warming is less than the global mean change in southeast Asia in summer and in southern South America in winter.

More crucial to agriculture and forestry, especially in areas at low latitudes where activities are rainfed, are the likely changes in precipitation. Global model simulations (IPCC, 2001a) indicate that by the second half of the 21st century, it is likely that precipitation will have increased over northern mid- to high-latitudes. At low latitudes both increases and decreases have been projected over land areas. Trends in these regions will be critical.

TABLE I

Estimates of confidence in observed and projected changes in extreme weather and climate events. (IPCC, 2001a)

Confidence in observed changes (latter half of the 20th century)	Changes in phenomenon	Confidence in projected changes (during the 21st century)
Likely	Higher maximum temperatures and more hot days over nearly all land areas	Very likely
Very likely	Higher minimum temperatures, fewer cold days and frost days over nearly all land areas	Very likely
Very likely	Reduced diurnal temperature range over most land areas	Very likely
Likely, over many areas	Increase of heat index (Footnote 12) over land areas	Very likely, over most areas
Likely, over many Northern Hemisphere mid-to high-latitude land areas	More intense precipitation events*	Very likely, over many areas
Likely, in a few areas	Increased summer continental drying and associated risk of drought	Likely, over most mid-latitude continental interiors. (Lack of consistent projection in other areas)
Not observed in the few analyses available	Increase in tropical cyclone peak wind intensities**	Likely, over some areas
Insufficient data for assessment	Increase in tropical cyclone mean and peak precipitation intensities**	Likely, over some areas

*For other areas, there are either insufficient data or conflicting analyses.

**Past and future changes in tropical cyclone location and frequency are uncertain. For more details see IPCC (2001a).

Extreme events have important impacts on agriculture and forestry. Currently climate models lack the spatial detail required to make confident projections. However, broadscale assessments of observed changes in extremes for the 20th century and projected changes for the 21st century have been made (IPCC, 2001a) and are given in Table I. Similar tabulations at broad regional levels are also available in the IPCC 2001 synthesis report (IPCC, 2001c). The theory of changes in extremes, as a result of changes in both means and variability is illustrated in Figure 11. This

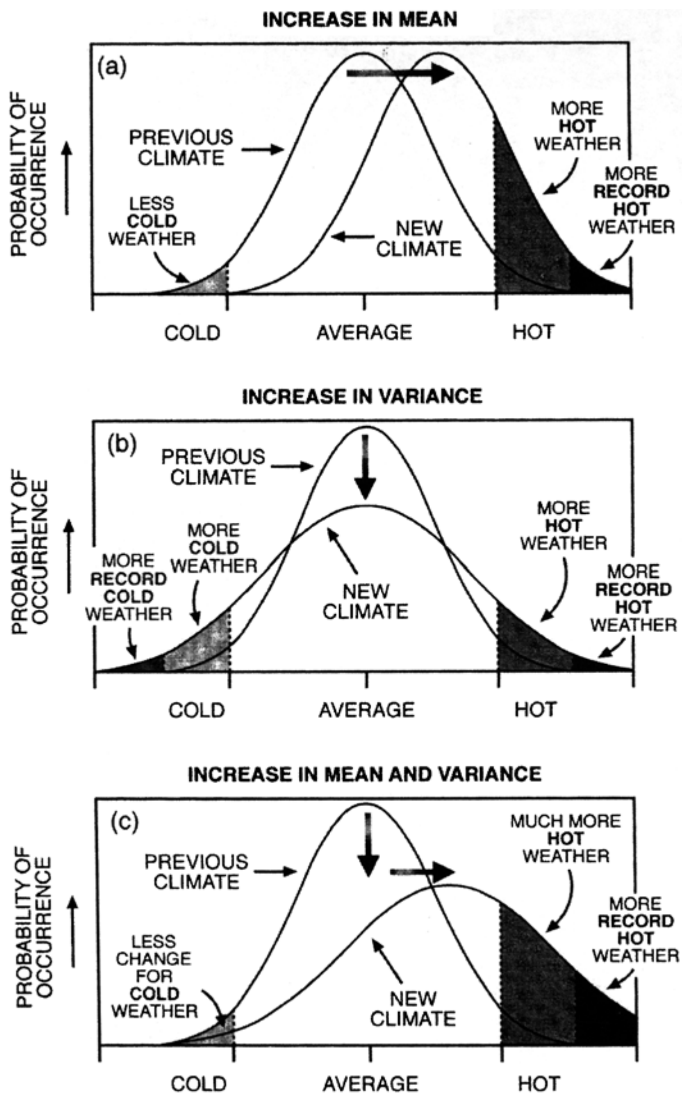

Figure 11. Schematic theory showing the effect on extreme temperatures when (a) the mean temperature increases, (b) the variance increases, and (c) when both the mean and variance increase for a normal distribution of temperature.

shows that shifts in both means and variance can have a profound effect on the frequency of extremes.

5. Implications for Agriculture and Forestry

5.1. IMPLICATIONS

The implications of both past and present climate variability and change on agriculture and forestry are the subject of impact studies, some of which have been summarized in the IPCC Third Assessment Report (IPCC, 2001b). Broad scale future impacts have already been identified. From the most well understood trends in climate during the 21st century the key trends that have been identified are

1. The continued rapid temperature increase in high latitudes of the Northern Hemisphere;
2. Further drying in Mediterranean areas, and some tropical and sub-tropical latitudes;
3. The accentuation of climate extremes as a consequence of increasing climate variability especially in sub-tropical and tropical latitudes.

All these aspects will be considered in later papers in this volume. The purpose of this contribution is to identify the underlying trends in climate change and variability during the 21st century. This will be a blend of the centennial scale trends induced by anthropogenic climate warming, on which will be superimposed decadal scale variability from the IPO and interannual variability imposed by ENSO and the NAO, of which the frequencies may be influenced by global warming.

5.2. DANGEROUS CLIMATE CHANGE

Throughout historical time, and agrarian settlement, climate has varied. Both natural climate change and variability has occurred, which past and current agricultural and forestry systems have adapted to. Where systems in the recent geological past, such as those in the Indus valley, in this case to changing soil conditions, have not adapted, they have not survived. The record of observed climate, by instruments and proxy indicators, suggest that the rate and magnitude of change and variability has been quite modest, with centennial temperature changes globally in the order of 0.5 °C, and locally 1 °C. Natural variability because of ENSO has been a factor throughout recorded history.

However, the magnitude and rates of change that are projected for the 21st century fall outside that range. The 90% confidence range of global warming is in the range of 2 to 4.5 °C (Wigley and Raper, 2001). Although agriculture and forestry might adapt given a modest rate of climate change, the rapidity of projected change is unprecedented in the last 10,000 yr. The current rate of global warming since the mid-1970s has been at 0.2 °C per decade, which is consistent with the lower projected warming rates for the 21st century.

The United Nations Framework Convention on Climate Change (United Nations, 1992) main purpose is to reduce the growth of greenhouse gases in the atmosphere and stabilize climate.

"the ultimate aim of this Convention... is to achieve... Stabilisation of greenhouse gas concentrations in the atmosphere..to prevent dangerous climate change[1]"

The natural greenhouse effect keeps the planet and biosphere at an equable temperature for planetary processes to operate (e.g. Salinger et al., 2000).

Climate, agriculture and forestry are thus inextricably linked. The mean surface air temperature of the earth can be used as a measure of the stability of the climate system. It responds to energy inputs, and cycling processes such as the hydrological (water) cycle. Temperature is part of the process of life systems. Over the last 420,000 yr climate has varied by 6 °C between glacial and interglacial periods, with the most rapid change being about 1 °C per century. Temperature increases or decreases outside these ranges will create an unstable climate, as parts attempt to adjust to rapidly changing temperatures. Native forests take centuries to adjust their range, and agriculture would face almost impossible adjustments.

The current rate of global warming is 2 °C per century, and this rate is projected as a lower range for the remainder of the 21st century. Thus increases in greenhouse gases released by human activities are creating a potential situation of dangerous climate change where the stability of agriculture and forestry systems is threatened. Greenhouse gases are likely to double during this century. This could bring with it unknown climate surprises and their impacts, such as flooding from unmanageable catchments and inundation of land areas due to storm surges and sea level rise.

Adaptation strategies are going to be of crucial importance. These can range from traditional to new technologies. Traditional management practices such as intercropping, mulching and agroforestry will be important. Changes in agronomic practices such as earlier planting or cultivar switching are simple adaptive strategies for the tropics. Earlier planting and sowing, shorter rotations and larger spacing in areas undergoing drying and use of shelterbelts can be used in temperate regions. Understanding of impacts, modeling and improved spatial measurement of agriculture and forestry will provide new methods of adaptation. The improvement of seasonal climate forecasting will increase preparedness and risk management on seasonal to interannual time-scales for increasing climate variability. All these strategies and others discussed in later papers in this volume will be of critical importance to cope with the increasing climate variability and change of the 21st century to prevent these variations being dangerous to agriculture and forestry.

6. Conclusions

Climate variability and change have gone on throughout time, and on geological time scales of millions of years the climate system has undergone large changes as the earth has evolved. During the last glacial maximum, approximately 20,000 yr ago global temperatures were 5 to 6 °C less than those at the beginning of the 21st century (IPCC, 2001a). Even though temperatures have increased by this amount, the rise occurred over thousands of years, and stabilized into the modern climate regime about 10,000 yr ago.

In the perspective of human settlement and agriculture and forestry activities over the last 10,000 yr at least climate changes have been quite small, and certainly in the documented record for the last 1,000 yr small variations in global temperature have occurred compared with the glacial/interglacial changes. Hydrological variations may have been larger though. The projected global mean temperature trends for the 21st century are without precedent, with rates expected of between 2 and 4.5 °C for the century.

Underneath the strands of 21st century climate warming due to anthropogenic activities, interdecadal and interannual climate variability will continue and possibly increase. Decadal climate variability, as induced by the IPO, will continue throughout the Pacific basin. Both will impact on regional and global climate and hence temperature and rainfall.

Interannual climate variabilities, particularly that caused by ENSO and NAO are expected to continue and possibly increase throughout this century. In fact global warming has been identified to lead to greater extremes of drying and heavy rainfall and increases the risk of droughts and floods that occur with ENSO events in many different regions, thus increasing climate variability from these sources.

As well, extremes are expected to increase (Table I). More hot days are expected over nearly all land areas and more intense precipitation events over many Northern Hemisphere mid- to high-latitude land areas. Increased summer continental drying and associated drought risk is likely in a few areas and peak wind and precipitation intensities in tropical cyclones are assessed to increase in some areas.

Climates of the globe have always varied over the last millennium, because of natural phenomena such as ENSO and the IPO. However, as the century progresses the interannual and decadal phenomenon will be superimposed on an unprecedented global warming trend. Together these will produce rapid climate change, increasing climate variability and climate extremes. Thus agriculture and forestry will face unprecedented challenges in the 21st century.

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