CLIMATE CHANGE 2009
SCIENCE COMPENDIUM

EARTH'S ECOSYSTEMS

Earth's Ecosystems

Since the compilation of the IPCC's Fourth Assessment Report, serious and irreversible changes in Earth's Ecosystems due to anthropogenic activities are increasingly recognized with greater confidence and better quantification of the processes.

Mau Complex, the largest closed-canopy forest in Kenya, is under severe threat from land use change and could suffer further degradation from a changing climate. *Source: A. Kirk*

For both marine and terrestrial ecosystems, the most challenging irreversible climate-related changes include altered chemical characteristics of the ambient environment, inundation of many small-islands and low-lying coastal ecosystems by sea-level rise, loss of wetland quantity and quality, and increased aridity in subtropical areas. These expected irreversible changes and their cumulative effects, proceeding at unprecedented rates, will alter ecosystem characteristics resulting in potential species extinction.

Local and subnational research into ongoing climate-related ecosystem changes is proliferating in countries and regions that support active investigative science programmes. The understanding gained from these efforts could provide analogues for changes in less well-documented regions. Only a sampling of new research can be addressed in this Compendium and hopefully their worth as potential analogues will be eventually proven.

Documenting the effects of climate change on ecosystems at global scales has consistently challenged the IPCC, mainly because of the scarcity of peer-reviewed research findings from Latin America, Africa, and Asia (McCarthy *et al.* 2001, Rosenzweig *et al.* 2008). However, since the closing date for submissions to the IPCC's Fourth Assessment Report (AR4), wide-ranging surveys have been conducted and analysis suggests that ecological changes in the phenology and distribution of plants and animals are occurring in all well-studied marine, freshwater, and terrestrial groups (Parmesan 2006). Range-restricted species, particularly polar and mountaintop species, show severe range contractions and have been the first groups in which species have gone extinct due to recent climate change. Tropical coral reefs and amphibians have been most negatively affected. Predator-prey and plant-insect interactions have been disrupted when interacting species have responded differently to warming (Parmesan 2006).

A comprehensive 2008 analysis of more than 29,000 data series from all continents, some covering over 35 years of observations, verifies these findings and goes further by attributing such changes to anthropogenic climate change (Rosenzweig *et al.* 2008). In marine ecosystems these responses include shifts from cold-adapted to warm-adapted communities, phenological changes, and alterations in species' interactions. In terrestrial ecosystems, responses include shifts to earlier onset of spring events such as leaf unfolding, blooming date, migration, and reproduction timing; change in species distribution; and modification of community structure. Contributing changes in physical systems include shrinking glaciers, melting permafrost, coastal erosion, shifts in river discharge peaks, and warming in lakes and rivers with effects on stratification and chemistry (Rosenzweig *et al.* 2008).

The 2008 analysis explicitly considered the influence of land-use change, management practices, pollution, and human demographic shifts as drivers of the observed environmental changes and was able to eliminate the affected data series from their review (Rosenzweig *et al.* 2008). This broad consideration strengthens the robustness of the findings and offers a model for future analyses. The approach has stimulated further documentation and synthesis in recent months (Lyon *et al.* 2008, Pörtner and Farrell 2008, Hegland *et al.* 2008, Chazal and Rounsevell 2009, Lawler *et al.* 2009, Cheung *et al.* 2009, Füssel 2009).

MARINE ECOSYSTEMS

The effects of climate variability on marine life have been under observation for decades. Thus the empirical evidence, and the theory that frames it, indicate that environmental conditions in the oceans including temperature, acidity, currents, and productivity are continuing to exhibit signs of change (Cheung *et al.* 2008, Rahel and Olden 2008, Dulvy *et al.* 2008, Beaugrand *et al.* 2009). Marine biodiversity, however, remains poorly understood and scarcely studied at the global scale: The influence of human impact on marine ecosystems has only been recently mapped at a global scale using standardized categories of effects (Halpern *et al.* 2008). Only a very limited number of studies have attempted to investigate the impacts of climate change on species richness, community assemblages, and distributions of biodiversity at the ocean basin or global scales. Previous research has focused on specific regions and particular ranges of taxa (Rosenzweig *et al.* 2008, Jackson 2008, Miles 2009).

Researchers are now able to project global patterns of invasion, extinction, and the combined effect of species turnover to the year 2050 using a recently developed dynamic climate envelope model (Cheung *et al.* 2009). The study plotted future distributional ranges of 1,066 economically valuable marine fish and invertebrate species. The results suggest that the global scale and pattern of consequences for marine biodiversity from climate changes are consistent with those found for terrestrial ecosystems. By 2050, ecosystems in subpolar regions, the tropics, and semi-enclosed seas will have undergone numerous local extinctions. Conversely, the Arctic and Southern Oceans will experience severe species invasions. The impacts of climate change on marine biodiversity may result in a dramatic species turnover of up to 60 per cent in this first quantitative estimation of marine biodiversity impacts at the global scale (Cheung *et al.* 2009).

In the face of such challenges, the cumulative effects of higher temperatures, changes in ocean circulation, and ocean acidification are under serious examination (Jackson 2008, Miles 2009). Additional variables involving oxygen and nitrogen levels are also being incorporated into models and analyses

Table 4.1: Marine ecosystem disturbance

	Symptoms	Drivers
Coral reefs	—Live coral reduced 50-93 per cent; fish populations reduced 90 per cent —Apex predators virtually absent; other megafauna reduced by 90-100 per cent —Population explosions of seaweeds; loss of complex habitat —Mass mortality of corals from disease and coral bleaching	—Overfishing —Warming and acidification due to increasing CO_2 —Runoff of nutrients and toxins —Invasive species
Estuaries and coastal seas	—Marshlands, mangroves, seagrasses, and oyster reefs reduced 67-91 per cent —Fish and other shellfish populations reduced 50-80 per cent —Eutrophication and hypoxia, sometimes of entire estuaries, with mass mortality of fishes and invertebrates —Loss of native species —Toxic algal blooms —Outbreaks of disease —Contamination and infection of fish and shellfish, human disease	—Overfishing —Runoff of nutrients and toxins —Warming due to rise of CO_2 —Invasive species —Coastal land use
Continental shelves	—Loss of complex benthic habitat, fishes and sharks reduced 50-99 per cent —Eutrophication and hypoxia in 'dead zones' near river mouths —Toxic algal blooms —Contamination and infection of fish and shellfish —Decreased upwelling of nutrients —Changes in plankton communities	—Overfishing —Trophic cascades —Trawling —Runoff of nutrients and toxins —Warming and acidification due to increasing CO_2 —Species —Escape of aquaculture species
Open ocean pelagic	—Commercially targeted fishes reduced 50-90 per cent —Increase in nontargeted fish —Increased stratification —Changes in plankton communities	—Overfishing

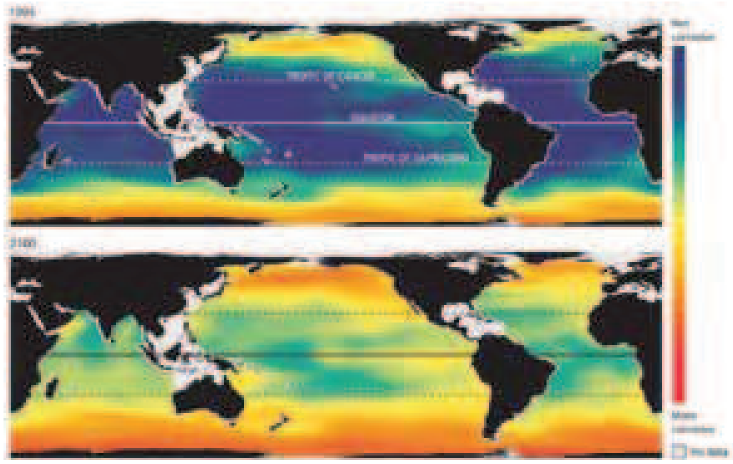
Status and trends of major ocean ecosystems defined by principal symptoms and drivers of degradation in more than 99 per cent of the global ocean that is unprotected from exploitation. *Source: Jackson 2008*

(Kwon *et al.* 2009, Scheffer *et al.* 2009, Voss and Montoya 2009, Ward *et al.* 2009). The implications of these cumulative effects and of chemical cycle responses have profound significance for marine species and for the harvests that humans expect to reap through the 21st century (Schubert *et al.* 2006, Jackson 2008, Brewer and Peltzer 2009, Doney *et al.* 2009).

Ocean acidification

Preliminary findings from the field are verifying results from laboratory experiments, and scientific understanding of ocean acidification's effects on the marine species and ecosystems is underway (see Earth's Oceans, Chapter Three). Initial concerns over ocean acidification focused on reduced calcification in coral reefs and other calcareous organisms, but other concerns are emerging. Elevated dissolved CO_2 concentrations may impose a physiological strain on marine animals, impairing performance and requiring energy that would otherwise be used for locomotion, predation, reproduction, or coping with other environmental stresses such as warming oceans (Guinotte *et al.* 2008, Brewer and Peltzer 2009). However, long-term progress and consequences of changing seawater chemistry on marine ecosystems and their various member species can only be theorized. Some data sets have allowed an identification of ocean chemistry thresholds when acidification will cause net carbonate dissolution rates to exceed net calcification rates in whole coral reef systems (Hoegh-Guldberg *et al.* 2007).

Figure 4.1: Modelled ocean acidification



If CO_2 concentration continues to rise unchecked, models show that acidification will deplete carbonate ions in much of the global ocean by 2100, turning the waters corrosive for many shell-building animals. *Source: National Geographic 2007*

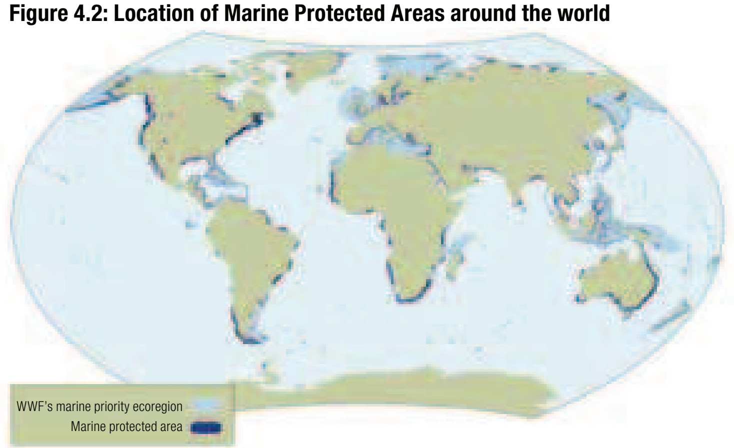
The degree to which ocean acidification influences critical physiological or ontogenetic processes is essential knowledge for the proper response: These processes are important drivers of calcification, ecosystem structure and function, biodiversity, and ultimately ecosystem health. Research into the synergistic effects of ocean acidification and other human-induced environmental changes on marine food webs and the potential transformative effects these changes could have on marine ecosystems is urgently needed (Guinotte *et al.* 2008).

Some success has been seen through establishment and enforcement of marine protected areas (MPA) in efforts to encourage growth of fish populations (UNEP 2008b, UNEP 2009). Climate change represents a new and serious threat to marine ecosystems, but, to date, few studies have specifically considered how to design MPA networks to be resilient to this emerging threat. Researchers have compiled the best available information on MPA network design and supplemented it with specific recommendations for building resilience into these networks to help MPA planners and managers design MPA networks that are more robust in the face of climate change impacts (MacLeod *et al.* 2008).

Coastal processes

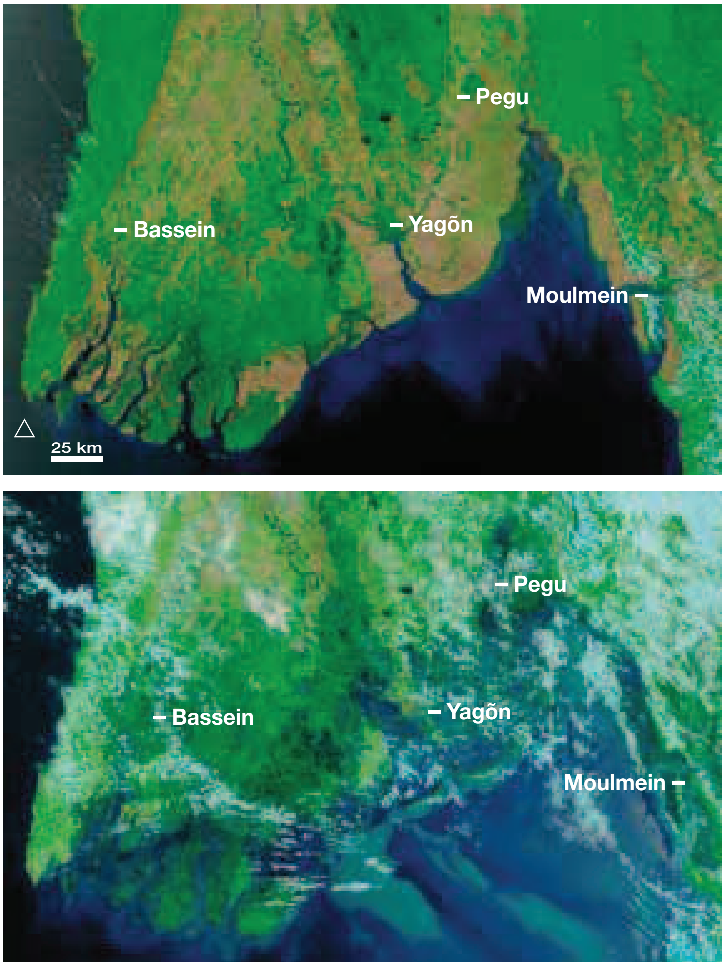
Ecological studies often focus on average effects of environmental factors, but ecological dynamics and ecosystem functioning may depend as much or more upon environmental extremes and variability, especially in coastal regions where extreme events are expected to increase in

Figure 4.2: Location of Marine Protected Areas around the world



The map shows priority ecoregions as well as the global distribution of Marine Protected Areas in 2005. *Source: WWF 2005*

Figure 4.3: Irrawaddy River Delta washes away



Satellite images of the Myanmar coast on 15 April 2008 (top) before Cyclone Nargis and 5 May 2008 (bottom) after Nargis hit the region, showing the devastation of flooding over the coastal area. *Source: UNEP 2009, NASA 2008*

intensity and frequency. Theoretically, as ocean surface and atmospheric temperatures warm, the hydrologic cycle will speed up—more moisture will evaporate from oceans and lakes, and plants and soils will give up more water through transpiration and evaporation because warmer air is capable of holding more water vapour. Also, as oceans warm, they should have more energy to supply tropical cyclonic winds. Sporadic observations over the long-term and changing data analysis abilities render varying conclusions. Some analyses have detected little change in frequency and intensity of cyclones globally during the last 20 years, while other evidence shows that the strongest cyclones have become more intense in all storm-prone regions (Klotzbach 2006, Elsner *et al.* 2008).

However, models and observations agree that sudden downpours will become more common in some regions, leading to more frequent flooding and associated soil erosion and slope collapse. In fact, observed increases in rainfall are greater than the models have predicted, implying that the expected intensity of rainfall may have been underestimated (Allan and Soden 2008).

In addition, human populations and the ecosystems that supply them with food, fibre, water, building material, and other resources are still threatened by the storms that will penetrate further inland with rising sea levels (Aumann *et al.* 2008). Storm surges, such as the one delivered by Cyclone Nargis to the Irrawaddy Delta, can contaminate coastal fields with saltwater at the surface while sea-level rise can result in saltwater incursions in freshwater aquifers that supply groundwater resources (UNEP 2009).

Researchers are evaluating how two aspects of climate change, sea-level rise and intensification of windstorms, will influence the structure, function, and capacity of coastal and inland forest ecosystems to deliver ecosystem services such as carbon sequestration, storm protection, pollution control, habitat support, and food production. The evaluation is considering coastal wetland and inland forest sites across the US representing continental-level gradients of precipitation, temperature, vegetation, frequency of occurrence of major windstorms, tidal range, watershed land use, and sediment availability. Once the methodologies are established, similar networks could be created in other regions to evaluate the implications of sea-level rise and windstorm effects at local and subnational scales (Hopkinson *et al.* 2008).

Physiological and biogeochemical responses of terrestrial ecosystems are determined by prevailing ecological and meteorological conditions. However, sudden extreme events can provoke the crossing of mortality thresholds for certain organisms and trigger population decline, decrease resilience, and alter community and ecosystem structure over time (Fagre *et al.* 2009, Running and Mills 2009).

Another less appreciated but critical determinant of terrestrial ecosystem structure and functioning, particularly as it relates to life-cycle timing of seasonal plant phenology and plant growth responses, is the amplification of variability in climate and environmental conditions (Post *et al.* 2008, Fagre *et al.* 2009, Running and Mills 2009). Amplification in natural variability intensities due to climate change introduces a new urgency for understanding the biological consequences of environmental extremes (Knapp *et al.* 2008).

Recent work on changes in, and predictability of, return times demonstrate that the coincidence of otherwise normal events can lead to environmental extremes. Using techniques based on paleontological species-resilience models, researchers are developing methods to measure disturbance from extreme events and their effects on species throughout particular ecosystems. Further efforts will focus on distinguishing between events resulting from coincidence of background variabilities and new stresses introduced by climate change (Denny *et al.* 2009).

Mangroves

Mangrove forests, those vast twisted habitats found in tidal zones along many tropical and subtropical coastlines, provide aquatic feeding grounds and nurseries for fish. In addition to their crucial and well-documented role in estuarine and coastal fishery food chains, mangrove forests have recently been found to provide important protection and stabilization services for low-lying coastal lands (Thampanya *et al.* 2006, Bosire *et al.* 2008, Kairo *et al.* 2008).

A number of studies have suggested that the resilience of mangrove ecosystems can be observed in their recovery patterns following severe natural disturbance. Mangroves have demonstrated considerable resilience over timescales proportional to shoreline evolution, demonstrated by current soil accretion rates in mangrove forests that are effectively keeping pace with average sea-level rise (Alongi 2008).

Despite their tremendous ecological value, mangroves suffer one of the fastest degradation rates of any global habitat—exceeding 1 per cent of total mangrove area per year (Kairo *et al.* 2008). Roughly half the world's mangrove area has already been lost since the beginning of the 20th century. The major causes for this decline include over-exploitation, harvesting, pollution, and shrimp farming. About 35 per cent of that mangrove loss has occurred since 1990—and 25 per cent of that total is from shrimp farms (Gilman *et al.* 2006, Thampanya *et al.* 2006, Bosire *et al.* 2008).

Mangroves might be able to adapt to rising sea levels and continue to protect coasts from storm surges, to filter sediments, and to shelter fish larvae and fingerlings. But, with the build-up of human settlements and other infrastructure in coastal zones, there is no place to which mangroves can retreat (Alongi 2008, MacLeod and Salm 2006). The consequences of losing these critical coastal ecosystems on marine biology, and ultimately on human beings, are enormous (Hoegh-Guldberg *et al.* 2009, Brown 2007, Alongi 2008, Chatenoux and Peduzzi 2007, UNEP-WCMC 2006, Vermaat and Thampanya 2007, Brown 2007).

Along many lowland sea coasts, tidal marshes provide significant levels of productivity but the threat from ongoing sea-level rise is not well understood. Study of tidal marshes at the lower and upper salinity ranges, and their attendant delivery of ecosystem services, will be most affected by accelerated sea-level rise, unless human demographic and topographic conditions enable tidal freshwater marshes to migrate inland, or unless vertical accretion of salt marshes increases as it does in mangroves, to compensate for accelerated sea-level rise (Craft *et al.* 2009).

Islands

Sea-level rise presents an imminent threat to freshwater-dependent ecosystems on small oceanic islands, which often harbour rare and endemic species. Once sea level reaches a critical threshold, the transition from a landscape characterized by dryland forests and freshwater wetlands to one dominated by sea grasses and mangroves can occur suddenly, following a single storm-surge event. Efforts to manage species' survival and to support conditions that form refuges for threatened ecosystems are currently under development with the goal of serving as models for species-rich coastal ecosystems under threat globally (Ross *et al.* 2008).

Saltwater contamination is particularly difficult to handle on small islands because there is little possibility to retreat to available land at higher levels. Together with shore erosion, saltwater incursions into agricultural areas are already driving island populations from their communities (UN 2008).

TERRESTRIAL ECOSYSTEMS

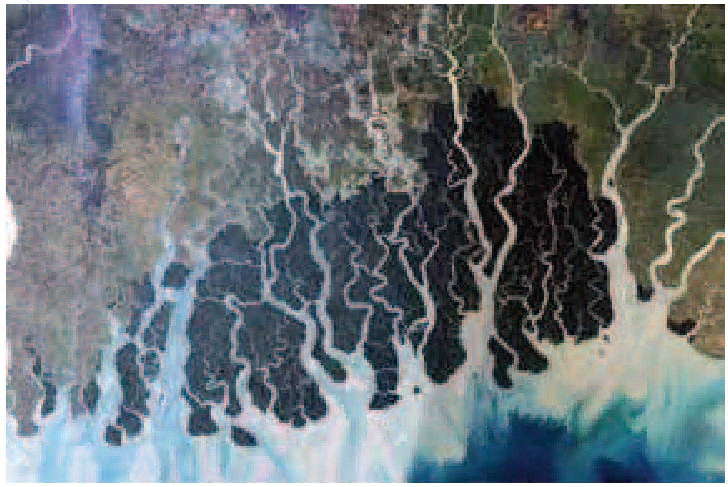
As has been presented, climate change affects a wide range of components of the Earth's systems. Individual components of the systems react with a wide range of response times at different scales to increasing GHG concentrations in the atmosphere. While radiative forcing changes almost instantaneously as atmospheric GHG levels rise, warming of surface air temperatures, melting of ice sheets, and sea-level rise will continue long after atmospheric GHG levels have been stabilized. These long-term changes are referred to as the 'climate change commitment': Conditions that we have already committed to because of earlier actions—or inactions. The concept of unavoidable commitments has so far mostly applied to physical properties of the climate system. However, the concept can be extended to terrestrial ecosystems (Jones *et al.* 2009, Plattner 2009).

The global terrestrial biosphere shows significant inertia in its response to climate change. As well, it will continue to change for decades after climate stabilization (Brovkin *et al.* 2009). Ecosystems can be committed to long-term change long before any response is observable: For example, the risk of significant loss of forest cover in Amazonia rises rapidly for a global mean temperature rise of about 2 degrees Celsius. Such unavoidable ecosystem changes must be considered in the definition of dangerous climate change (Jones *et al.* 2009).

Increases in temperature over the last century have clearly been linked to shifts in species' distributions. Given the magnitude of projected future climatic changes, even larger range shifts can be expected for the 21st century. These changes will, in turn, alter ecological communities and the functioning of ecosystems. Uncertainties in climate change projections at local and sub-national scales make it difficult for conservation managers and planners to proactively adapt to climate stresses (Post *et al.* 2008, Seastedt *et al.* 2008, UNEP 2009).

One study addressed this uncertainty by assessing the potential effects of expected changes on the geographic ranges of about 3,000 Western Hemisphere species of amphibians, birds, and mammals using 30 future climate simulations with coupled atmosphere–ocean general circulation models. Eighty per cent of the climate projections based on a relatively low greenhouse-gas emissions scenario resulted in the local loss of at least 10 per cent of the vertebrate fauna over much of North and South America. The largest changes in fauna are predicted for the tundra, Central America, and the Andes Mountains where certain areas are likely to experience over 90 per cent species change, so that future faunal assemblages, diversities, and distributions will bear little resemblance to those of today (Lawler *et al.* 2009).

Figure 4.4: Sundarbans Protected Area



This satellite image shows mangrove forest in the Sundarbans protected area. The mangroves appear deep green, surrounded to the north by a landscape of agricultural lands, which appear lighter green; and by towns, which appear tan; and by streams, which appear blue. *Source: NASA 2006b*

Disappearing and novel climates

The loss of whole, or even parts of, faunal assemblages entails the disappearance of species and ecosystems—and the evolution of new ones. Based upon an appreciation of paleobiogeographical principles, researchers suggest that the concept of disappearing and novel climates might be useful for understanding the changes that are expected over the next century and more (Williams *et al.* 2007, MacDonald *et al.* 2008, Seastedt *et al.* 2008).

Climate is a primary control on species distributions and ecosystem processes, so novel 21st century climates may promote formation of novel species associations and other ecological surprises, whereas the disappearance of some extant climates certainly threatens extinction for species through loss of habitat and of ecosystem integrity. Novel climates are projected to develop primarily in the tropics and subtropics, whereas disappearing climates are concentrated in tropical montane regions and the poleward portions of continents.

New Caledonia is one of many small island developing states that are vulnerable to climate change. *Source: L.G. Roger/Stillpictures*

Table 4.2: Interlinkages among climate changes, plant and animal response, and economic activity

Effects on Species		CHANGE: Phenology – spring arrival – autumn arrival – growing season length	Temperature – means – extremes – variability – seasonality	Rainfall – means – extremes – variability – seasonality	Extreme events – storms – floods – droughts – fires	CO_2 concentrations – atmospheric – ocean – ocean pH
Changes in competitive ability	Fisheries		●			●
Uncoupling of mutualisms (including pollinator loss and coral bleaching)	Agriculture, Fisheries	●	●	●		
Changes in fecundity leading to changing population structure	Agriculture, Fisheries, Animal husbandry		●	●	●	
Uncoupling of parasite-host relationships	Human health, Agriculture	●	●			
Inability to form calcareous structures and dissolving of aragonite	Fisheries					●
Change in distribution ranges	Agriculture, Fisheries		●	●	●	
Desynchronization of migration of dispersal events	Agriculture, Fisheries	●	●	●		
Increased physiological stress causing direct mortality and increased disease suspectibility	Human health, Animal husbandry, Fisheries		●	●	●	●
Uncoupling of predator-prey relationships	Animal husbandry, Fisheries	●	●	●		
Changes in sex ratio	Agriculture, Fisheries, Animal husbandry		●	●		
Loss in habitat	Animal husbandry, Fisheries		●	●	●	
Interactions with new pathogens and invasives	Agriculture, Fisheries, Human health	●	●	●		

Agriculture | Animal husbandry | Fisheries | Human health

The changing climate is affecting the timing and quantity of water availability, the length of growing seasons, and the life cycles of pests and pathogens. These in turn put pressure on various species of plants and animals, with ultimate consequences for a variety of economic and development activities. *Source: Foden et al. 2008*

Under the highest IPCC emissions scenario—the one that most closely matches current trends—12–39 per cent of the planet's terrestrial surface could experience novel climate conditions and 10–48 per cent could suffer disappearing climates by the end of this century. Dispersal limitations—imposed by fragmented habitats and physical obstructions, including those built by humans—increase the risk that species will experience the loss of existing climates or the emergence of novel climates. There is a close correspondence between regions with globally disappearing climates and previously identified biodiversity hotspots. While most changes are predicted to occur at high latitudes and high altitudes, many tropical species are incapable of tolerating anything beyond mild temperature variations. Even slight warming may threaten them. Ecosystem niche gaps left by migrating species in tropical lowland ecosystems may endanger those species that are able to adapt to changes within an ecosystem at a particular location, but not to the absence of a key player in that ecosystem (Williams *et al.* 2007, Tewksbury *et al.* 2008, Colwell *et al.* 2008).

To address the problems of ecosystem loss in the face of climate change, ecosystem management efforts are increasingly recognizing that many ecosystems are now sufficiently altered in structure and function to qualify as novel systems. Given this assumption, attempts to 'restore' systems to within their historical range of location, characteristics, or processes may not be possible. In such circumstances, management activities directed at removing undesirable features of novel ecosystems may perpetuate or create ecosystems that will not survive. Management actions should attempt to maintain genetic and species diversity while encouraging the biogeochemical characteristics that favour the more desirable species (Seastedt *et al.* 2008).

SHIFTING CLIMATIC ZONES

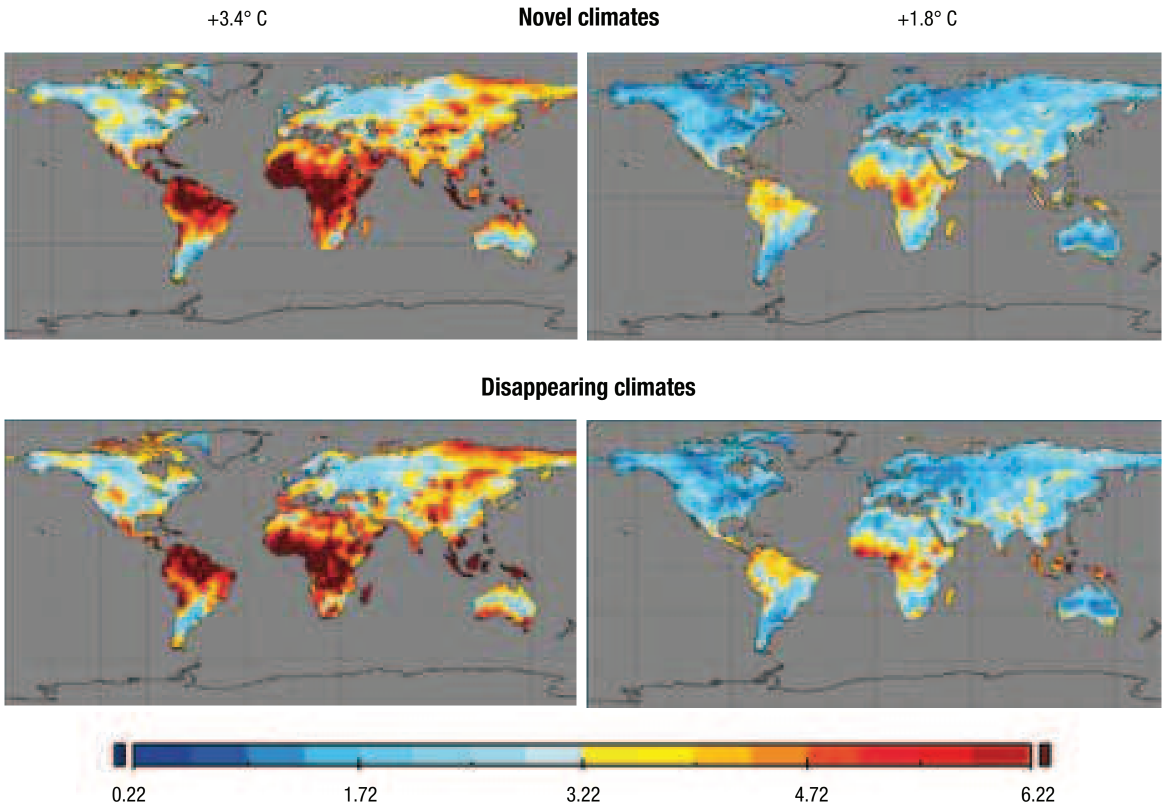
Changes in the tropics are becoming more apparent. Several lines of evidence show that over the past few decades the tropical belt, which roughly encompasses equatorial regions, is expanding. This influences all latitudinally determined climatologies, including the intertropical convergence zone, the subtropical dry zones, and the westerlies that dominate weather at subpolar latitudes. The observed rate of expansion already exceeds climate model projections for expansion during the 21st century. This expansion of the tropics not only has a cascading effect on large scale circulation systems but also on precipitation patterns that determine natural ecosystems, agricultural productivities, and water resources for urban and industrial demands. Expansion of the hot and humid tropical zone leads to poleward displacement of the subtropical zones, areas occupied by most of the world's deserts (Seidel *et al.* 2008, Lu *et al.* 2009, Seager *et al.* 2007, Johanson and Fu 2009, Sachs *et al.* 2009).

Precipitation changes and dry-season rainfall reduction

In many regions of the world, water is already scarce and, given increased pressures from agriculture and urban expansion, is likely to become more so as global climate change advances. Shortages of water for agriculture and for basic human needs are threatening communities around the world. Southeastern Australia has been short of water for nearly a decade and southwestern North America may have already transitioned to a perennial drought crisis climate (Murphy and Timbal 2008, MacDonald *et al.* 2008).

According to projections, areas expected to be affected by persistent drought and water scarcity in coming years include the southern and northern parts of Africa, the Mediterranean, much of the Middle East, a broad band in Central Asia and the Indian subcontinent, southern and eastern Australia, northern Mexico, and the southwestern United States—a distribution similar to current water-stressed regions (IPCC 2007a, Solomon *et al.* 2009). Regional studies are following up on these projections and others from drought-threatened regions.

Figure 4.5: Novel and disappearing climates



World map of disappearing climates and novel climates under two of the IPCC scenarios, one that projects a 3.4° C temperature increase and one that projects an increase of 1.8° C. Changes occur almost everywhere—yellows and reds indicate more change from current conditions, blue indicates less change. *Source: Williams et al. 2007*

Northern Africa

Debate continues about whether the Sahel, one of the world's most vulnerable regions to climate variability, is at a tipping point. Some projections suggest that the Sahel region of West Africa could see a sudden revival of rains if global warming and changes in ocean temperatures in the North Atlantic combine to trigger a strengthening of the West African monsoon. This tipping point has been crossed in the past: Between 9,000 and 5,000 years ago, large parts of the Sahel were verdant after an exceptionally dry period around 10,500 years ago. Evidence published in 2008 suggested that even if this revival occurs it may not be as abrupt as some suggest. A study of pollen and lake sediments in the Sahara investigated how the Sahel went from wet to dry conditions over a 1,000 year period that began 6,000 years ago. Other studies suggest this shift happened within a few decades. The search for a reliable means of predicting future precipitation patterns in the Sahel region of Africa continues, with one study suggesting that links to sea surface temperatures that held in the 20th century might not apply in the 21st century (Kröpelin *et al.* 2008, Brovkin and Claussen 2008, Cook 2008).

Mediterranean

New research confirms that by the end of the 21st century the Mediterranean region will experience more severe increases in aridity than previously estimated. This aridity will render the entire region, particularly the southern Mediterranean, vulnerable to water stress and desertification. Using the highest resolution projections published for the entire Mediterranean basin, researchers project a substantial northward expansion of dry and semi-arid regime lands across the Iberian, Italian, Hellenic, and Turkish peninsulas. These results imply a corresponding retreat of temperate oceanic and continental climate regimes and a likely shift in vegetation cover, with huge implications for agriculture in the region. This study adds to the body of work that corresponds to and projects from the region's ongoing observations of warming and drying trends (Iglesias *et al.* 2007, Diffenbaugh *et al.* 2007, Gao and Giorgi 2008, Lionello *et al.* 2008).

Southwestern North America

In the southwestern region of North America, modelled trajectories toward intensified aridity in the 21st century and a sustained drier climate in the region are consistent with observed patterns. Researchers suggest that a transition to a more arid climate in the southwestern US is already underway, perhaps since 2000. It will likely be only a matter of years before drought becomes the region's new climatology. Unlike the multi-year droughts of 1950s western North America—attributed to variations in sea surface temperatures or El Niño Southern Oscillation effects—the projected intensified aridity in the Southwest is the result of an increased divergence of large-scale moisture regimes and other changes in atmospheric circulation cells linked to poleward expansion of the subtropical dry zones. The 21st century drying of these subtropical areas in the region is unlike any climate state seen in the instrumental record. The most severe future droughts will still occur during persistent La Niña events, but they will be worse than current extremes because the La Niña conditions will be perturbing a drier base state (Seager *et al.* 2007, Barnett *et al.* 2008, MacDonald *et al.* 2008).

Amazon rainforest

Amazonia faces dual threats from deforestation and from climate change in the 21st century (Malhi *et al.* 2008). While deforestation is the most visible threat to the Amazon ecosystem, climate change is emerging as a creeping threat to the future of the region. Currently, the major agent of change in the Amazon forest ecosystem is likely to be decreased dry-season precipitation (Betts *et al.* 2008). The Andean flank of the Amazon

Thermokarst emerges across the permafrost tundra landscape. *Source: S. Kazlowski*

is home to exceptional biodiversity, adjoins the most biodiverse regions of lowland Amazonia, and hosts a number of sheltered wet spots in otherwise dry areas. The cloud forests between 1,500 and 3,000 metres of elevation, considered to be a potentially disappearing climate, are susceptible to drying as cloud levels rise in the face of warming temperatures, and higher elevation restricted endemics would be particularly vulnerable (Killeen *et al*. 2007, Malhi *et al*. 2008).

Since Amazon forests appear vulnerable to increasing dryness, the potential for large carbon losses serving as positive feedbacks to climate change must be considered. According to some researchers, the exceptional growth in global atmospheric carbon dioxide (CO_2) concentrations in 2005, the third greatest in the global record, may have been partially caused by Amazon die-off resulting from drought effects effects (Cox *et al*. 2008, Phillips *et al*. 2009).

An annual increase of only 0.4 per cent in Amazon forest biomass roughly compensates for the entire fossil fuel emissions of Western Europe, so a switch from a moderate carbon sink to even a neutral state or a moderate carbon source would have significant implications on the build-up of CO_2 in the atmosphere. Considering that a 0.4 per cent of annual biomass sink represents the difference between two much larger values, the stand-level growth average approximating 2.0 per cent and mortality averaging of about 1.6 per cent, either a small decrease in growth or a small increase in mortality could shut the sink down (Phillips *et al.* 2008).

Peatlands and permafrost soils

The consequences of persistent climate warming of Arctic and subarctic terrestrial ecosystems, and associated processes, are ominous. The releases of carbon dioxide (CO_2), methane (CH_4), and more recently, nitrous oxide (N_2O) in these regions have accelerated in recent decades (Canadell and Raupach 2009).

Arctic permafrost soils store enormous amounts of carbon. Including all northern circumpolar regions, these ecosystems are estimated to hold twice as much carbon than is currently held in the atmosphere in the form of CO_2 (Zimov *et al.* 2006, UNEP 2008c, Schuur *et al*. 2008, Canadell and Raupach 2009). If Arctic warming accelerates as expected, one of the possible global implications of ensuing feedbacks is that ecosystems could cross critical thresholds as discussed in Earth Systems (Chapter One). Current warming in the Arctic is already causing increased emissions of CO_2 and CH_4 and feedbacks may have already begun (UNEP 2008c, UNEP 2009, Walter *et al*. 2007, Westbrook *et al.* 2009).

Most of the carbon released from thawing soils originates from the decomposition of organic matter—plant, animal, and microbial remains—deposited thousands of years ago. This organic matter has been kept relatively stable as a result of low temperatures in the permafrost in which it was trapped. As permafrost thaws, it creates thermokarst, a landscape of collapsed and subsiding ground with new or enlarged lakes, wetlands and craters on the surface (UNEP 2008c).

In this newly thawing landscape, upland areas with good drainage and oxygen available for microbial activity, are usually sources of CO_2. In the waterlogged areas and in lakes where anaerobic microbes decompose the organic matter, CH_4 becomes the dominant emission. Carbon emissions from Arctic terrestrial ecosystems are increasing because longer growing seasons and warmer temperatures support extended and vigorous plant growth. The interactions of these and other processes will determine the net effect of GHG emissions from the Arctic. Ultimately, Arctic emissions to the atmosphere will outpace potential carbon storage processes while changes in landscape will result in more of the Sun's energy being absorbed and released as heat, accelerating both global and local climate change (Canadell and Raupach 2009, Ise *et al.* 2008, Schuur *et al*. 2008, Canadell *et al*. 2007, Tarnocai *et al*. 2009).

Mountains

As climates change, sea levels rise, wetlands and drylands adjust, and ecosystems evolve, species seeking conditions that are cooler or that feature some other advantageous characteristics will move inland and upslope. Observations already demonstrate these trends (Parmesan 2006, Rosenzweig *et al*. 2008, Lenoir *et al*. 2008, Kelly and Goulden 2008). As these species adapt at higher altitudes, they may be classified as non-native—or even as invasive. The same characteristics that are advantages when recognizing resiliency and adaptability also identify weeds and invasive species.

Traditionally, biological invasions have been recognized as a major driver of biodiversity decline and altered ecosystem services in lowland regions where most studies have been conducted to document large-scale effects facilitated by human-mediated propagation (Dietz and Edwards 2006, Pauchard *et al*. 2009). In contrast, high-elevation environments seemed less affected by invasions—an assumption based on harsher climatic conditions and comparatively low human population densities. However, recent analysis estimates that over a thousand non-native species have become established in natural areas at high elevations worldwide, and although many of these are not considered invasive, some may threaten extant native mountain ecosystems (Pauchard *et al*. 2009).

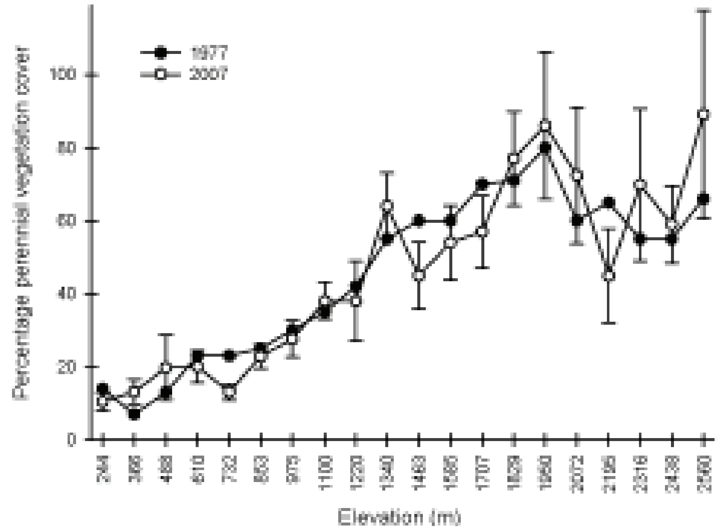
In fact, recent studies have observed both rapid and significant shifts in plant distribution to high altitudes. The findings confirm a strong correlation between the observed changes in the distributional margins of these plant species with observed changes in regional climate conditions. Comparing surveys of plant cover from 1977 and 2007 along a 2,314 metre elevation gradient of California's Santa Rosa Mountains, researchers found that in just 30 years the average elevation of the dominant plant species expanded upward by 65 metres (Kelly and Goulden 2008). During that same period, southern California's climate experienced surface warming, increased precipitation variability, and a decrease in snow cover. The upward shifts were uniform across elevation, suggesting that the vegetation responded to a uniformly distributed causal factor. In addition, the vegetation shifts resulted in part from mortality during two distinguished periods of drought, implying a temporal sign-switching 'fingerprint' of climate change due to water balance. Following these lines of evidence, researchers attributed the shift to climate change rather than to either air pollution or fire (Kelly and Goulden 2008).

Another recent study across the temperate and Mediterranean mountain forests in western Europe revealed a similar upward shift in forest plant species. Here, researchers compared the altitudinal distribution of 171 plant species spanning from 0 to 2,600 metres above sea level. The results indicate a significant upward shift of 29 metres per decade in the optimum elevation of species over the 20th century (Lenoir *et al*. 2008).

As ecosystems shift, native species may adapt in ways that have the effect of an invasive species. Among insects especially, changing conditions may bring advantages that throw relationships evolved over millennia out of balance. Many insects in temperate zones are surviving at temperatures that inhibit their optimal metabolic capabilities. With warmer temperatures their reproductive seasons and rates may increase, with consequential increase in population. Many insect species also modulate metabolism to carbon dioxide availability and increasing atmospheric concentrations will grant advantage from that factor as well (DeLucia *et al*. 2008, Deutsch *et al*. 2008).

A 2008 study examined insect damage in over 5,000 fossil leaves from five different sites originating in the Paleocene-Eocene Thermal Maximum—an era of high carbon dioxide concentrations 55 million years ago. As carbon dioxide concentrations increased, so did the insect damage. When CO_2 concentrations decreased, the insect damage did as well. When CO_2 concentrations were at their peak, every leaf from that time was severely damaged by herbivore insects. The researchers conclude that increased insect damage is likely to be a net long-term effect of anthropogenic atmospheric CO_2 increase and warming temperatures (Currano *et al*. 2008).

Figure 4.6: Total per cent coverage by perennial plants along the Deep Canyon Transect (Southern California's Santa Rosa Mountains) in 1977 and 2007



Source: Kelly and Goulden 2008

These findings have implications for human health as well as that of ecosystems. Increased duration of seasons and rates of reproduction in vectors of human disease are considered immediate threats to human health due to anthropogenic climate change (Huss and Fahrländer 2007, Costello *et al*. 2009, Clement *et al*. 2009).

ECOSYSTEM ADAPTATION

Ecosystems influence climate by affecting the energy, water, and carbon balance of the atmosphere at local and larger scales. However, current management efforts to mitigate climate change through ecosystem instruments focus on modification of one pathway, carbon sequestration. Using only one approach will only partially address the issue of ecosystem–climate interactions. The cooling of climate that results from carbon sequestration in forests may be partially negated by reduced surface albedo: This increases solar energy absorption, local longwave radiation, and local temperatures. Consideration of multiple interactions and feedbacks in climate management through ecosystems could lead to innovative climate-mitigation strategies, including GHG reductions primarily in industrialized nations, reduced desertification in arid zones, and reduced deforestation in the tropics. Each of these strategies has multiple ecological and societal benefits. Assessing their effectiveness requires better understanding of the interactions among feedback processes, their consequences at local and global scales, and the connections that link changes occurring at various scales in different regions (Chapin III *et al*. 2008).

Climate change threatens ecological systems at every scale throughout the world. Managing these systems in a way that ignores climate change will fail to meet the most basic management objectives. However, uncertainty in projected climate change impacts is one of the greatest challenges facing ecosystem managers. To select successful management strategies, managers need to understand the uncertainty inherent in projected climate impacts and how these uncertainties affect the outcomes of management activities. Perhaps the most important tool for managing ecological systems in the face of climate change is active adaptive management, in which systems are closely monitored and management strategies are altered to address expected and ongoing changes (Lawler *et al*. 2009).