Part II Section C

A BASELINE APPRAISAL OF WATER-DEPENDANT ECOSYSTEM SERVICES, THE ROLES THEY PLAY WITHIN DESAKOTA LIVELIHOOD SYSTEMS AND THEIR POTENTIAL SENSITIVITY TO CLIMATE CHANGE

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April 2008

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SUMMARY

CONTEXT AND STRUCTURE

This report is based on information drawn from an Endnote library of over 1100 scientific papers that were assembled for this project. Together, this report and the Endnote library provide an annotated bibliography of our findings concerning 'water-dependant ecosystem services, the roles they play within desakota livelihood systems and their potential sensitivity to climate change'. In the following summary, numbers in bold parentheses refer to the sections of our report where items are explored in greater depth.

Water plays numerous roles not just as a resource but also as a contributor to climate, chemical and biological processes and systems, and so it is a crucial part of numerous ecosystem services **(2.1)**. ***However, the range and quality of water ecosystems are moderated in complex ways as a result of the connectivity of the hydrological system across both time and space*** **(2.2).** Freshwater ecosystems are connected by flows of energy and matter (water, sediment, organisms) within catchments, such that any changes in energy conditions or the quantity or quality of matter within or flowing through any part of the catchment system can induce changes in other parts of the system. Such changes can vary in space and/or time according to seasonal or longer term changes in climate (particularly precipitation and temperature), consumptive use by plants and animals including humans, and also human-induced manipulations of the system. Pressures imposed at any place or point in time can be propagated through the system to yield responses that are often difficult to predict.

Massive pressures on global hydrological systems are expressed in growing water scarcity and major declines in aquatic biodiversity worldwide **(2.3).** Management of both water quantity and quality has been so extensive, with widespread overuse, that anthropogenic impacts are clearly distinguishable across the entire global water cycle and the full range of water body types. These pressures are set to intensify under scenarios of climate change.

We investigate the impact of desakota within a landscape framework of terrestrial biomes (global to regional scales) or a catchment framework (regional to meso-scales) – these are the 'natural' frameworks for water-related ecosystems science. Whilst accepting that 'desakota' is a multi-layered and extremely complex socio-economic phenomenon, in an ecosystem science context we consider it as a 'landscape treatment' or 'catchment treatment' of varying intensity that is controlled by: (i) increased population density and (ii) increased overall land use pressure, related to (iii) an increasingly patchy, complex and mixed mosaic of agricultural, industrial, commercial and urban land uses. In this way we are able to make the broadest use of the environmental sciences literature to assess potential desakota impacts on water-related ecosystems services within a context of climate change.

We attempt to unravel the above complexities and identify research needs within the desakota context. Our report first explores the nature of freshwater ecosystem services, their natural functioning and the impact that land use intensification may have under the influence of the desakota phenomenon **(2)**. Thereafter we evaluate interactions between climate change and desakota activity from global **(3)** through regional (ESPA region) **(4)** to local (case study catchment) **(5)** scales.

GLOBAL SCALE (3)

The key climate variables for the hydrological system are temperature and precipitation. We have focused on contemporary patterns and projected changes in these variables during the 21st century.

Global mean temperature has been increasing since the late nineteenth century and this pattern is projected to continue through the twenty-first century **(3.2)** under various climate change scenarios, with the greatest warming occurring in the high latitudes.

Global trends in precipitation are harder to locate but projections from climate models suggest large decreases over the Mediterranean and Caribbean regions, and the subtropical western coasts of each continent in the 21st century, whereas increases are projected over eastern Africa, central Asia, the equatorial Pacific Ocean, and at most high latitudes **(3.3).**

These changing patterns have major implications for snow and ice storage **(3.4)**, drought and flood occurrence **(3.5)**, and river flow regimes **(3.6)**, although the sign and magnitude of the changes will vary spatially across all scales.

RESEARCH NEEDS AT THE GLOBAL SCALE

1. Although enormous effort has been directed towards understanding and forecasting changes in global climate, ***linkages and feedbacks between human modification of the earth surface (particularly modification of vegetation distribution and biomass)***, are under-researched and of particular relevance to the ESPA programme.

2. Interactions between climate and hydrology have received considerable research attention, but ***the crucial associations between climate and river flow regimes, which integrate the impact of intervening hydrological flows and stores, is under-researched***.

3. The ***intimate association between river flow - sediment - quality regimes and water-related ecosystems, which have been recognised to some degree at finer spatial scales, remain an important research gap at continental to global scales***.

REGIONAL SCALE (4)

CLIMATE CHANGE (4.2).

At the regional scale of the four ESPA regions, projected climate changes vary widely. Whilst multi-model means project that all regions will warm significantly, there are regional contrasts in the consistency between model projections and also in spatial variability within regions. Projections for precipitation are more uncertain than for temperature and also vary between regions.

Precipitation is forecast to increase by 10% on average across China, with the largest increases in the north (+4 to +14%), especially in winter (+63%), and with smaller or no increases and a decline in winter precipitation (-36%) in the south.

In India and the Hindu Kush, precipitation is projected to decrease during the dry season (-5%) and the monsoon is projected to intensify, bringing precipitation increases where the monsoon is currently strong and decreases where monsoon rain is weaker.

In southern Africa, precipitation is projected to decrease in the south, particularly in summer, with little change or a small increase towards the equator and an increase in east Africa.

In Amazonia, precipitation is projected to decrease towards the north and increase towards the south.

These changes will greatly influence ice and snow storage and melt, which will have major consequences for the Asian ESPA regions (4.3) and significant implications for Amazonia. Ice and snow melt within the major glacierised catchments of the Himalayas are projected to yield a runoff increase of up to 70% towards the middle of the 21st century, followed by a decline as glaciers disappear towards the end of the century. This change will also lead to significant temporal shifts in the annual flow regime of major rivers systems draining this area and may also have important implications for levels and timing of groundwater recharge.

VEGETATION CHANGE (4.4).

Changes in climate stress native and planted vegetation cover, leading to changes in species composition and vigour and shifts in terrestrial biomes and their contained ecoregions. Whilst changes in temperature and precipitation affect the performance of different species in different ways, rising atmospheric CO2 induces stomatal closure, implying a decrease in evapotranspiration losses, but this is more than compensated by the plant-fertilising effect of CO2, which increases plant productivity and leaf area and thus evapotranspiration losses.

Direct changes in vegetated land cover, particularly the intensity of changes associated with the desakota phenomenon, are likely to accelerate landscape change trajectories within biomes and ecoregions, and particularly at their boundaries. Relationships between vegetation and climate are complex and non-linear. Areas of high vegetation biomass can act as environmental engineers, significantly influencing local hydrological and energy fluxes and so influencing local climate.

Patchiness and poor health of vegetation cover can indicate a landscape close to threshold conditions and highly sensitive to small changes in resource availability (e.g. temperature, moisture, nutrients) that may be induced by climate change or human exploitation of water and other resources. Such landscapes are also highly sensitive to increased, direct, human manipulations of vegetation cover (overgrazing, cutting, burning, groundwater exploitation, surface drainage). Different landscapes and land uses have different sensitivities to changes in vegetation and the resources (particularly water) that support vegetation growth.

Once critical environmental thresholds are crossed, the moderating effects of vegetation engineers are also lost and, as a result very substantial resource inputs are needed to reverse any changes that may occur.

LAND USE CHANGE (4.5.2)

Land use and management along the rural-urban continuum, and particularly within 'peri-urban' areas, is central to the desakota phenomenon. Changes in land use transform the hydrological response of catchments and also the routing of water through different hydrological pathways. Major land use changes such as clearance of forests, extension of urban cover and intensification of grazing or cultivation all have major effects on catchment hydrology and biogeochemistry. These changes have resulted in increases in runoff worldwide during the 20th century that are independent of climate change. Increases in the proportion of rainfall running off and decreases in infiltration/percolation to soil moisture and groundwater stores are well-known hydrological consequences of land use changes that involve reduction of vegetation biomass, compaction or reduction of the fertility of soils, or the imposition of impervious surfaces, as are the accompanying increases in soil erosion and sediment yields. Intensification of land use has the same hydrological effects but also results in increasing demands for water from both surface and groundwater sources and increases in other resources, such as fertilisers. The result is increasingly polluted return flows that contaminate the entire hydrological system.

Because of the sensitivity of land cover to climate change, land use intensification and change can have the most dramatic effects on catchment hydrology close to biome or ecoregion boundaries. Examples include, reinforced climate warming in response to overgrazing on the Tibetan plateau, reduction of downstream water resources as a result of intensive cattle grazing and cultivation within the páramo of the northern Andes, and acute hydrological and fertility changes accompany expansion of grazing, cultivation and woodland clearance in the Tigray Highlands.

The impacts of land use change on hydrological processes vary with spatial scale, pattern and intensity and there are thresholds of change, which vary between studies, and beyond which major hydrological impacts occur. These findings imply that patchy land use which maintains areas of semi-natural woodland or grassland not only supports varied, sustainable livelihoods but also reduces adverse hydrological and ecological effects and sustains water-related ecosystem services.

The most extreme impacts of land use change on the form and function of river systems accompany urban and peri-urban development and the introduction of new industrial and commercial activities. Catchment hydrology, river flow and sediment regimes are transformed by the removal of vegetation and the construction of stormwater drainage systems and heavily compacted or completely impervious surfaces. River water and sediment quality are affected by stormwater and waste-water drainage from both point and diffuse inputs. These widespread hydrological effects impact severely on river margins and their inhabitants through increases in flood frequency.

River channel engineering can counteract flooding problems by improving channel conveyance of floodwaters but it imposes severe changes in the functioning of the river ecosystem, reducing or removing the connectivity of flows, sediment movements and organisms between the river and floodplain, severely constraining river channel dynamics and often inducing channel bed incision, which can cut off water supply systems from the river.

In the unplanned peri-urban interface between urban and rural environments, the very mixed mosaic of land covers is both intensive and patchy, with adverse consequences for water resources and quality, sediment yield, and river ecosystems. Access to water and facilities for waste-water disposal are rarely governed by need. Surface drainage systems, where they exist, are usually combined; industrial wastewater is rarely treated; and, when water resources are limited, farmers may use untreated wastewater for irrigation. In addition, many people gain income from water-intensive activities, such as food production, brick and block making, and tanning and dyeing, placing enormous pressure on water supplies, which as a consequence become heavily exploited. All of these practices lead to massive deterioration in water quantity and quality, and high exposure of peri-urban dwellers to disease, particularly since many of the poorest people inhabit low-lying areas that are susceptible to flooding by contaminated water.

The water cycle, water quality and riparian zones come under enormous pressure in peri-urban areas, placing even higher stresses on water ecosystem services than in fully-developed urban areas where infrastructure is planned and managed more effectively. Amelioration of these effects to support ecosystem services depends upon similar actions to those for more developed urban watersheds: essentially ‘making space for water’ by ensuring the heterogeneous landscape contains sufficient ‘buffer’ patches to moderate hydrological connectivity to and from river and groundwater systems, encouraging self-purification of water quality, and preserving/promoting ecosystem complexity.

MANIPULATIONS OF HYDROLOGICAL STORES (4.5.3)

Direct human manipulations of hydrological stores through groundwater and lake exploitation, dam construction and water diversion (including inter-catchment transfers) have enormous effects on the hydrological, geomorphological and ecological functioning of catchments and, in aggregate, have very significant effects at the regional and global scales. Large dams currently store over 5000 km^3 water worldwide of which over 3000 km^3 are used in regulating river flows. Average aging of water passing through these large water stores is of the order of two to three months, demonstrating that these artificial water storage structures strongly influence both the timing as well as the magnitude of downstream river flows. ‘Aquifer mining’ or overabstraction of groundwater stores also has deleterious impacts on catchment hydrology and river networks. In arid and semi-arid regions of the world, groundwater pumping for irrigation usually greatly exceeds recharge rates and recharge from irrigated agriculture mobilizes salts accumulated in the unsaturated zone, resulting in widespread ground and surface water contamination. At the same time the disposal of untreated industrial, domestic, and municipal wastes into soils and open water bodies, and extensive use of insecticides, pesticides, herbicides, and chemical fertilizers are polluting aquifers that are used for drinking water.

RIVER FLOW REGIMES (4.5.3)

Manipulations of both surface and subsurface water stores have important effects on river flows, which in turn impact on aquatic and riparian ecosystems and the services they provide. Functioning, biologically complex aquatic ecosystems provide many economically valuable services including food, flood control, purification of wastes, and habitat for biota. However, these ecosystem services depend upon maintenance of aquatic and riparian ecosystem integrity, which in turn depend upon the quantity, quality, timing, and temporal variability of water flow and are, therefore, strongly linked to hydrological processes and water stores within the catchment. The flow regime is thought to be the fundamental driver of both aquatic and riparian ecosystems, acting as a transport and dispersal mechanism, habitat regulator, process modulator and disturbance. Any changes to the flow regime are likely to have significant consequences for ecosystem services.

WATER-RELATED DISEASES (4.6)

Climate change directly affects human health, aggravates pre-existing health conditions, and increases exposure to infectious diseases. Climate impacts on exposure to infectious diseases are particularly complex and, in some cases controversial. These include changes in the spatial extent and time periods of peak transmission, which may reflect interactions and feedbacks between climate trends, variability, sequencing and particular phenomena such as El Nino; physico-chemical environmental conditions; and the life histories of relevant organisms. Uncertainty and scientific controversy are particularly notable in relation to associations between climate trends and the occurrence of malaria.

Human population pressures impact directly and indirectly on human health through intensified encroachment on natural environments; reductions in biodiversity, particularly reductions in natural predators of vector organisms; increased, close proximity to particular livestock, crops, and production methods that support disease transmission; and direct pressures on water resources imposed by uncontrolled urbanization or urban sprawl associated with the desakota phenomenon. Under increasing population pressure, naturally-produced water-quality problems can have severe health consequences, such as the occurrence of fluorosis and arsenicosis. Also deforestation and increased irrigation, human settlement, industry and road construction can be accompanied by increases in diseases such as malaria and schistosomiasis.

A lack of waste-water treatment facilities coupled with contamination of domestic water supplies is the prime cause of deterioration in human health in desakota areas because of the direct link between faecal / urine contamination of water supplies and numerous bacterial and viral diseases, and also the need for safe water to maintain personal hygiene in treating and preventing others.

RESEARCH NEEDS AT THE REGIONAL SCALE

A number of research areas require further investigation, that are relevant to the understanding of desakota landscapes, catchments, river flows and networks at the regional scale:

1. ***Improved understanding of the nature, symptoms and consequences of landscapes that are approaching threshold conditions.*** We need to know the nature of land-cover/management thresholds in relation to temperature, precipitation, water quantity, water quality (e.g. nutrients, salinity) change; be able to recognise vegetative warnings of thresholds including plant diseases, declines in productivity, species disappearances, patchiness; and the implications of patchiness and threshold crossing for local climate and water resources, hydrological and water quality regimes.

2. ***Improved understanding of the importance of flow regimes, the consequences of flow regime change and relevant flow management options***, so that appropriate environmental flows can be defined and water resource exploitation potential identified under changing climate and desakota pressures. We need to determine their implications for groundwater and surface water contributions, sediment, water quality and temperature regimes, and physical habitat dynamics and to identify their consequential impacts on organisms (alien and native), particularly fisheries (lotic and lentic).

3. ***Understanding of the actual and potential functioning and productivity of river margins within desakota areas.*** This includes their inundation/connectivity and sediment/fertility dynamics, importance for surface-groundwater interactions and water quality dynamics, potential provision of habitat/landform/landuse complexity mosaic and dynamics, and role in supporting fisheries

4. ***Improved understanding of relationships between climate, land use, water resource use and pressure and water-related diseases, particularly infectious diseases, in desakota areas.***

MESO-SCALE (6)

The ESPA regions include very large catchments and river systems, where integrated understanding is limited but where management based on sound science, at least at the subcatchment scale, could yield enormous benefits. At this scale we investigated a series of case studies, which provided specific examples of the characteristics and issues raised at the regional scale. As a result, these case studies not only reveal particular research needs in their own right, but they also provide concrete examples of general desakota-related issues.

In all of the case study catchments, desakota activity has increased water demand and changed usage, which has impacted the natural hydrological regime. Increases in water abstractions have resulted in significant depletions in lake (shown in Tanzania and Colombia), river (Nepal, China) and groundwater (China, India, Pakistan, Nepal) levels with serious consequences for the aquatic ecosystems and the services that they provide (e.g. fisheries, transport, water supply). This increase in demand has been attributed to land use change (for example, land use shift from agriculture to industry) and intensification (for example, from an intensification of agricultural activity and increase in population density).

The intensification and change of land use within desakota areas also has impacted the hydrological regime through changes in vegetation cover. Removal of the natural vegetation has increased runoff and surface erosion, floods and low flows in many areas. Increasing fragmentation and patchiness of the natural vegetation also has threatened the integrity of the ecosystems and the services that they provide. In some catchments, such as Fuquene (Colombia) and Mwanza (Tanzania), competing land uses have stressed the ecosystem to the extent that it may be approaching threshold conditions. Conversely, in some areas (such as Nepal) the complementary reduction in agricultural activity and increased employment in industry and commerce associated with the desakota phenomenon has resulted in afforestation in the catchment, which may help mitigate against some of the aforementioned hydrological changes.

In all of the case studies, desakota development has caused declines in water quality, from disposal of domestic and industrial waste and from agricultural activity with marked consequences for human health. For example, small industries and mining activity in desakota areas around Lake Victoria, Tanzania have caused severe water quality problems and the intensification of the dairy industry around Lake Fuquene, Colombia, has caused eutrophication. In many areas, quality has declined to the extent that it threatens water-based ecosystem services and human health.

One of the major impacts from desakota has been the degradation of riparian, littoral and wetland habitats, whose ecology is intimately linked to the hydrological regime of the catchment. These habitats are of importance in terms of provisioning services (food, water, fiber) and in their ability to regulate against some of the impacts from desakota, such as flood risk, low flows, and water pollution. Therefore, further research into the functioning of these environments is needed.

In all of the case study catchments, climate change is predicted to have further significant ecological and hydrological impacts. Precipitation is projected to increase in variability, and in some, such as in the Tanzania and Pakistan case studies, precipitation is projected to decrease, which will exacerbate many of the issues of water scarcity that are already arising from desakota development. Similarly, increases in precipitation projected within some areas of Latin America will intensify problems of runoff and soil erosion caused by deforestation.

RESEARCH NEEDS AT THE MESO SCALE

1. ***The overviews of the case study areas presented in this report were designed as a backdrop for detailed socio-economic research that is presented elsewhere. As a result, they do not identify generic or stand-alone research needs, although each case study has yielded some specific research questions and has highlighted the general need for a deeper understanding of the relationships between ecology and hydrology within catchments***. With many ecosystems coming under increased stress, an understanding of catchment process and function would support the development of integrated management options that could help secure the provision of ecosystem services into the future.

2. Although not directly related to the desakota and climate change theme of this report, some of the case studies, notably Lake Victoria, Tanzania, demonstrated extremely adverse impacts of alien invasive species on biodiversity and water-related ecosystem services. Whilst this is a widely-recognised problem for Lake Victoria, ***investigations of the causes and consequences of invasions by alien species across the ESPA regions is a general research need that is highly relevant to livelihoods of the poor***.

1. INTRODUCTION

This report forms part of a larger research programme on ‘Reinterpreting the Urban-Rural Continuum’, which conceptualises and investigates current knowledge and research gaps concerning ‘the role that ecosystems services play in the livelihoods of the poor in regions undergoing rapid change’. The report aims to conduct a baseline appraisal of water-dependant ecosystem services, the roles they play within desakota livelihood systems and their potential sensitivity to climate change. The appraisal is conducted at three spatial scales: global, regional (four consortia areas), and meso scale (case studies within the four regions). At all three scales of analysis water resources form the interweaving theme because water provides a vital provisioning service for people, supports all other ecosystem processes and because water resources are forecast to be severely affected under climate change scenarios. This report, combined with an Endnote library of over 1100 scientific papers, provides an annotated bibliography of water-dependant ecosystem services, the roles they play within desakota livelihood systems and their potential sensitivity to climate change.

We investigate the impact of desakota within a landscape framework of terrestrial biomes (global to regional scales) or a catchment framework (regional to meso-scales) – these are the ‘natural’ frameworks for water-related ecosystems science. Whilst accepting that ‘desakota’ is a multi-layered and extremely complex socio-economic phenomenon, in an ecosystem science context we consider it as a ‘landscape treatment’ or ‘catchment treatment’ of varying intensity that is controlled by: (i) increased population density and (ii) increased overall land use pressure, related to (iii) an increasingly patchy, complex and mixed mosaic of agricultural, industrial, commercial and urban land uses. In this way we are able to make the broadest use of the environmental sciences literature to assess potential desakota impacts on water-related ecosystems services within a context of climate change.

Section 2 of the report defines water-related ecosystem services and how these are affected by human activities. Current knowledge and research gaps are then explored in relation to global scale climate and related hydrological changes (e.g. floods, droughts, flow regimes) (section 3). The report then discusses the impacts of climate changes on the ESPA regions, emphasising potential responses of biomes to the combined effects of climate change and human activities (particularly land use and management), and how these effects coupled with water store and flow regime manipulation by humans may affect the functioning of catchments and their ecosystem services (section 4). Finally, at the meso-scale, case studies are presented from within the ESPA regions to illustrate the close coupling of human activities and catchment performance in the context of environmental change (section 5). At the end of each section, research needs are identified and justified. These research needs are then amalgamated in section 6.

2 ECOSYSTEM SERVICES

2.1 Definitions

The Millenium Ecosystem Assessment (2005) defined an *ecosystem* as ‘a dynamic complex of plant, animal, and microorganism communities and the nonliving environment interacting as a functional unit’ and *ecosystem services* as ‘the benefits people obtain from ecosystems, including provisioning services such as food and water; regulating services such as regulation of floods, drought, land degradation, and disease; supporting services such as soil formation and nutrient cycling; and cultural services such as recreational, spiritual, religious and other nonmaterial benefits’. Changes in ecosystem services affect *human well-being* through impacts on security, the basic materials to support a good life, health, and social and cultural relations and such changes disproportionately affect the poor. Interlinkages between ecosystem services and human well-being were summarized in the MEA (Reid et al., 2005) by the diagram shown in Figure 1.

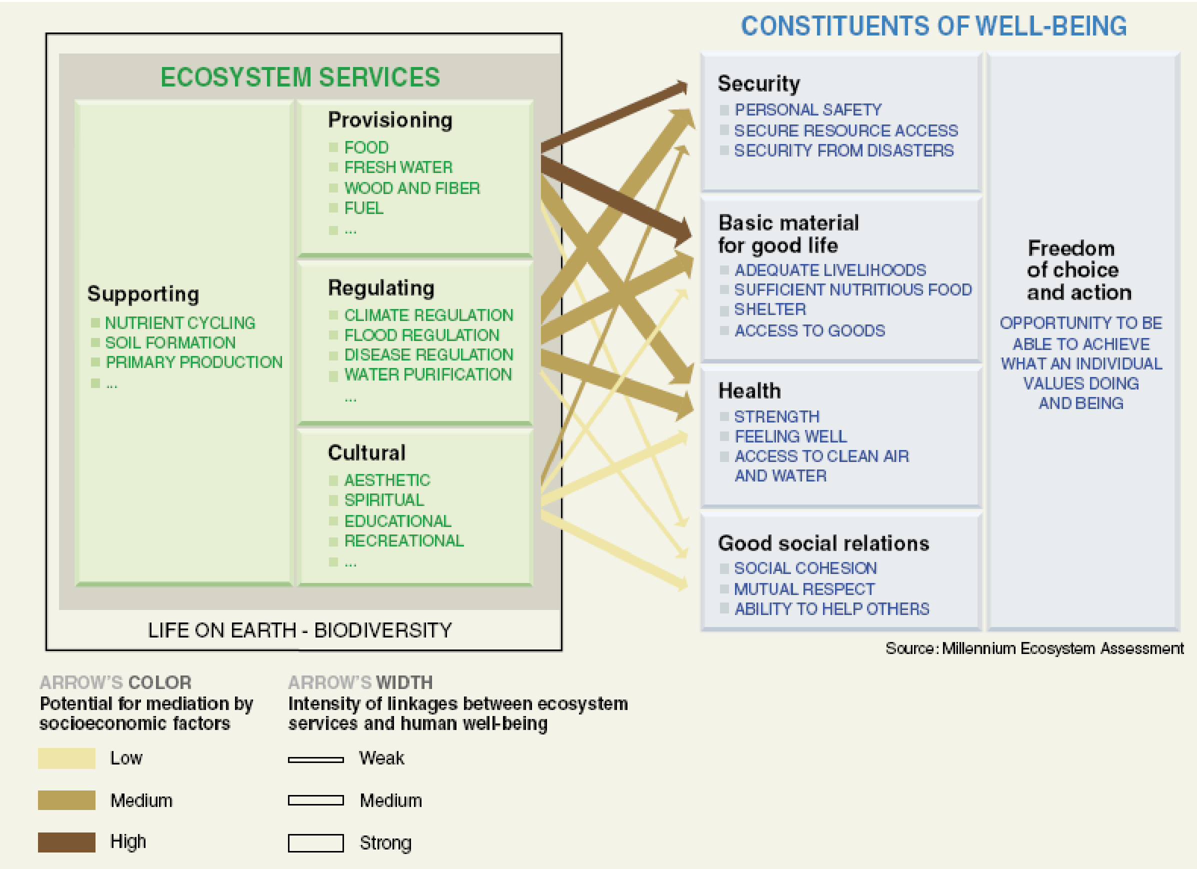

Figure 2.1 Ecosystem Services and their links to Human Well-being (MEA, Reid et al., 2005)

2.2 The functioning of freshwater ecosystems

Freshwater ecosystems are connected by flows of energy and matter (water, sediment, organisms) within catchments. As a result any changes in the quantity or quality of matter within or flowing through any part of the catchment system can induce changes in other parts of the system. Such changes can vary in space and/or time according to seasonal or longer term changes in climate (particularly precipitation and temperature), consumptive use by plants and animals including humans, and also human-induced manipulations of the system.

Freshwater ecosystems are highly sensitive to changes in the functioning of the catchment hydrological or sediment systems. Research within the natural sciences has demonstrated that there are four dimensions to this sensitivity, all of which may be crucial to the delivery of water-related ecosystem services: three spatial dimensions (longitudinal, lateral, vertical) and time. The form, biodiversity and ecosystem services offered by freshwater ecosystems reflect disturbance and recovery along these gradients.

The *longitudinal dimension* encompasses transfer of matter from upstream to downstream within catchments. This not only describes the gravity-dependent flows of surface, soil water and groundwater, but also the crucial interactions between water, sediment and biota, which control the characteristics of channels within the river network and also the regulation of water quality. Along the longitudinal dimension there are characteristic changes in river flow magnitude and velocity, sediment transport and calibre, and river channel slope, width and depth (Schumm, 1977, Church 2002), river channel pattern and bedforms (Church, 1992, 2002), water temperature, the balance between different food sources, driven by a downstream reduction in allochthonous detritus inputs, an increase in autochthonous primary production (River Continuum Concept: Vannote et al, 1980), and consequential changes in fauna (Illies and Botosaneanu, 1963; Hynes, 1970; Hawkes, 1975, Vannote et al, 1980).

Interruption of these longitudinal patterns as a result of human interventions has consequences for the hydrological, geomorphological and ecological character of the river system. Thus any change in the discharge and sediment regime at the catchment scale (eg by land use change), along major sectors of the river system (e.g. by flow manipulation or regulation such as flow augmentation or dam construction), or locally by engineering works that alter sediment supply or channel dimensions, have repercussions for the entire river ecosystem at the site of the changes and downstream. Furthermore any additional changes in water quality combine with the physical changes to impact on biota. If these physical changes are sufficiently small, the ecosystem can retain its integrity and resilience, biodiversity can be sustained and water quality can recover. However, significant changes in physico-chemical condition can cause a direct deterioration in ecosystem services as well as undermining the potential for ecosystem recovery.

Research has particularly focused on the ecological importance of river flow variability. Varying river flows erode, transport and deposit sediment to determine landforms along the river's course (Church, 2002). The flow regime is also the key driver of river ecosystems (Poff et al., 1997, Bunn and Arthington, 2002). Annual floods (e.g. Junk, 1989, Junk and Wantzen, 2004) and particular parameters of the flow regime (e.g. Poff et al., 1989, Harris et al., 2000) are important for ecosystem functioning. As a result, dams (Petts and Gurnell, 2005) and flow regulation in general (Nilsson and Svedmark, 2002), which change the flow regime, have adverse impacts that were conceptualised within a river continuum framework by the Serial Discontinuity Concept of Ward and Stanford (1983).

The *lateral dimension* relates to the significance of hydrological - geomorphological - ecological connectivity across the 'riparian zone'. In their natural state, riparian zones are one of the most dynamic components of the landscape, where frequent disturbances create complex mosaics of landforms and biological communities (Gregory et al., 1991; Naiman et al., 2005). Varying river flows transfer energy and matter to and from the riparian zone (Paetzold et al., 2005), inducing strong gradients in soil moisture, oxygen dynamics, disturbance, substrate calibre and plant communities. A naturally-functioning riparian zone supports high biodiversity, buffers the transfer of fine sediment downstream, and supports important biogeochemical pathways (Johnston et al., 2001). Thus, lateral connectivity of river systems with functioning riparian zones is crucial to maintaining ecosystem integrity, biodiversity and water quality.

The *vertical dimension* describes connection between surface water and groundwater bodies. This connectivity drives river flows in many environments and is important for regulating the temperature and quality of both surface and subsurface waters as well as water availability in the riparian zone (Naiman et al., 2005, Smith et al., 2008).

Linkages between these three spatial dimensions and process-form variability in time drive a hierachy of landforms and their turnover (Frissell et al., 1986, Naiman et al., 2002) and associated biogeochemical processes, which in turn provide varied habitat for biota and refuges across the range of flow stages. It is the complexity of the processes, forms and interactions across these gradients that support water-related ecosystem services.

2.3 Freshwater ecosystem services

Water plays numerous complex roles not just as a resource but as a contributor to climate, chemical and biological processes and systems, and so it is a crucial part of numerous ecosystem services (MEA, Finlayson et al., 2005, Table 2.1).

There are already massive pressures on global water resources that are expressed in growing water scarcity and major declines in aquatic biodiversity (Johnson et al., 2001). Management of both water quantity and quality has been so extensive, with widespread overuse, that anthropogenic impacts are clearly distinguishable across the entire global water cycle and the full range of water body types.

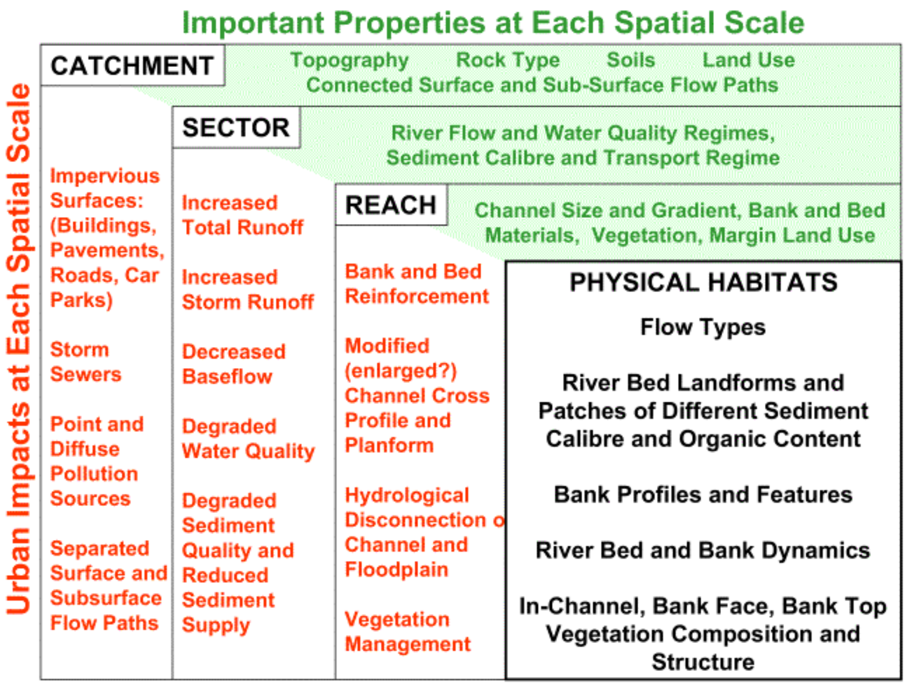

Figure 2.2 Impacts of urban areas on freshwater systems (from Gurnell et al., 2007

Of particular relevance to this review is the extension of urban areas (Gurnell et al., 2007). Urban development, whether planned or unplanned, imposes massive changes on the form and function of river systems. Catchment hydrology, river flow and sediment regimes are transformed by the removal of vegetation and the construction of impervious surfaces and stormwater drainage systems. River water and sediment quality are affected by stormwater and waste-water drainage and by point and diffuse inputs of pollutants. These catchment-wide hydrological effects impact severely on river margin inhabitants through increases in flood frequency. Whist widespread river channel engineering improves the conveyance of floodwaters, it also imposes major changes in the characteristics of the river network, reducing or removing the connectivity of flows, sediment movements and organisms between the river and floodplain and severely constraining river channel dynamics and at the same time, usually increasing longitudinal connectivity. In short, urban development changes all key processes that drive river corridor form, dynamics and biocomplexity. These changes are elaborated in Figure 2.2, illustrating how urban development affects catchment and river network functioning at all spatial scales from the entire catchment, through major sectors of the river network (i.e. sections of river channel between major channel junctions, typically several kilometres in length) and shorter reaches (i.e. sections of river channel of particular physical character within sectors and typically several hundred metres in length) to individual habitats within the channel and its margins (typically several tens of metres in length). As a result, urban rivers tend to be severely morphologically and ecologically degraded. Walsh et al. (2005) call this the ‘urban stream syndrome’.

Arthurton et al. (2007) tabulated the impact of human pressures on the state of hydrological processes, stores and types of water bodies and their consequences for ecosystem services and human well-being. Tables 2.2 and 2.3 are developed from those in Arthurton et al. (2007) and reflect the complex impacts of human pressures that reflect the multidimensional nature of water-related ecosystems. Many of these pressures are explored in the following sections of this report.

Table 2.1. Ecosystem Services Provided by or Derived from Wetlands (based on Finlayson et al., 2005)

Services	Comments and Examples
Provisioning	
Food	Production of fish, wild game, fruits, and grains
Fresh water	storage and retention of water for domestic, industrial, and agricultural use
Fiber and fuel production	logs, fuelwood, peat, fodder
Biochemical extraction	medicines and other materials from biota
Genetic materials	genes for resistance to plant pathogens, ornamental species, etc.
Regulating	
Climate regulation	source of and sink for greenhouse gases; influencing local and regional temperature, precipitation, and other climatic processes
Water regulation (hydrological flows)	groundwater recharge/discharge
Water purification and waste treatment	retention, recovery, and removal of excess nutrients and other pollutants
Erosion regulation	retention of soils and sediments
Natural hazard regulation	flood control, storm protection
Pollination	habitat for pollinators
Cultural	
Spiritual and inspirational	source of inspiration; many religions attach spiritual and religious values to aspects of wetland ecosystems
Recreational	opportunities for recreational activities
Aesthetic	many people find beauty or aesthetic value in aspects of wetland ecosystems
Educational	Opportunities for formal and informal education and training
Supporting	
Soil formation	sediment retention and accumulation of organic matter
Nutrient cycling	storage, recycling, processing, and acquisition of nutrients

Table 2.2 Linkages between state changes in the freshwater environment, environmental and human impacts(modified from Arthurton et al, 2007)

		HUMAN WELL-BEING IMPACTS			
State Changes	**environmental/ ecosystem impacts**	**Human health**	**Food security**	**Physical security and safety**	**Socioeconomic**
HYDROLOGICAL PROCESS CHANGE					
↕ precipitation	↑ flooding	↑ water-related diseases	↑ crop destruction	↑ drowning ↑ flood damage	↑ property damage
	↑ drought	↑ malnutrition	↑ crop reduction		
↑ temperature	↑ evapo-transpiration ↓ soil moisture ↔ trophic structure, food web		↔ species distribution ↕ crop reliability and change ↓ agriculture and aquaculture production		↑ irrigated agriculture ↓ profits
streamflow modification	↑ abstractions	↓ down- stream drinking water ↑ water borne diseases	↑ irrigated agriculture ↓inland fish stocks ↑salinization ↓floodplain cultivation	↑ flood control ↑ community displacement	↑ hydropower ↑ irrigated agriculture ↑ allocation conflicts ↓ freshwater fisheries ↓ water transport
	↑ ecosystem fragmentation, wetland infilling and drainage		↓ coastal wetland food resources ↓ prawn fishery		
	↓ sediment transport to coasts		↓ reduced floodplain sediment storage	↑ coastal erosion	↓ reservoir life
↓ groundwater levels	↑ drying of shallow wells ↑ salinity and pollution		↓ groundwater for irrigation ↓ groundwater quality	↑ competition for groundwater	↑ access costs ↑ premature well abandonment ↑ inequity
	↓ discharge to surface waters	↓ available surface water	↓ surface water for irrigation		

	↑ land subsidence				↑ building and infrastructure damage
	↑ reverse groundwater flow (downward movement)	↑ groundwater pollution from surface (river and canal beds, land surface)	↓ groundwater quality		↑ cost of water treatment
WATER QUALITY CHANGE					
↑ microbial contamination		↑ water bourne diseases ↑ fish and shellfish contamination			↓ working days ↓ recreation and tourism
↑ nutrients	↑ eutrophication	↑ nitrate contamination of drinking water	↑ production of macrophytes for animal fodder		↑ cost of water treatment
	↑ harmful algal blooms	↑ fish and shellfish contamination ↑ neurological and gastrointestinal illness	↓ livestock health ↓ food available for humans		↓ livelihood income ↓ recreation and tourism
↑ oxygen demanding materials	↓ dissolved oxygen in water bodies		↓ high oxygen-demanding species		↓ recreation and tourism
↑ suspended sediment	↓ ecosystem integrity		↓ fish and livestock health		↑ cost of water treatment
↑ persistent organic pollutants (POPs)		↑ fish and livestock contamination ↑ chronic disease			↓ commercial fish value
↑ heavy metal pollution		↑ fish and shellfish contamination ↑ chronic disease	↑ contamination of agricultural land (floods)		↑ cost of water treatment
↑ solid waste	↑ ecosystem and wildlife damage	↑ threat to human health			↓ recreation and tourism ↓ fisheries

↑ increase ↑ decrease ↔ direction of change uncertain

Table 2.3 Linkages between state changes in water-related ecosystems and environmental / human impacts(modified from Arthurton et al, 2007)

		HUMAN WELL-BEING IMPACTS			
Pressures	**State Changes**	**Human health**	**Food security**	**Physical security and safety**	**Socioeconomic**
RIVERS, STREAMS, FLOODPLAINS					
- flow regulation (damming, withdrawal) - water loss by evaporation - eutrophication - pollution	↑ water residence time ↑ ecosystem fragmentation ↑ disconnection of river – floodplain connectivity ↓ habitat ↑ disruption of fish migration ↑ blooms of blue-green algae	↓ quantity of freshwater ↓ natural purification processes, water quality ↑ incidence of water-bourne diseases	↓ fish stocks	↓ flooding	↓ tourism ↓ fisheries ↓ livelihoods ↑ poverty
LAKES, RESERVOIRS					
- infilling, drainage - eutrophication - pollution - over—fishing - invasive species - warming impact on physical and ecological properties	↓ habitat ↑ algal blooms ↑ anaerobic conditions ↑ alien fish species ↑ water hyacinth	↓ natural purification processes, water quality	↓ fish stocks		↓ tourism ↓ fisheries ↑ displacement of human communities ↓ livelihoods ↑ poverty
SEASONAL LAKES, MARSHES, SWAMPS, FENS, MIRES					
- conversion, infilling, drainage - change in flow regime - change in fire regime - overgrazing - eutrophication	↓ habitat and species ↓ flow and water quality ↑ algal blooms ↑ anaerobic conditions ↑ threat to indigenous species	↓ water inflow and storage ↓ natural purification processes, water quality		↑ flash flood frequency and magnitude ↓ flood mitigation ↓ drought mitigation	↓ buffering of flow extremes ↓ livelihoods

- invasive species - if forested, conversion through tree felling					
ALPINE AND TUNDRA WETLANDS					
- climate change - habitat fragmentation	↑ scrubland and forest ↓ area of surface water and lakes	↓ natural purification processes, water quality	↓ fish stocks	↑ flash flood frequency and magnitude	↓ livelihoods
PEATLANDS					
- drainage, withdrawal	↓ habitat and species ↓ carbon storage ↑ soil erosion	↓ water inflow and storage ↓ natural purification processes, water quality		↑ flash flood frequency and magnitude	
OASES					
- water withdrawal - pollution - eutrophication	↑ degradation of water resources	↓ available water quantity and quality		↑ conflicts and instability	↑ drought frequency and magnitude ↓ livelihoods
AQUIFERS					
- water withdrawal - pollution		↓ available water quantity and quality	↓ agriculture extent and productivity	↑ conflicts and instability	↓ livelihoods
MANGROVE FORESTS AND ESTUARINE MARSHES					
- reclamation - pollution - eutrophication	↓ decreased spatial extent ↓ tree density, biomass, productivity	↑ malaria risk due to standing water	↓ coastal fish stocks	↓ coastal buffering capacity	↓ timber products ↓ fisheries ↓ tourism ↓ livelihoods ↑ displacement of human communities

↑ increase ↑ decrease

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3. GLOBAL SCALE

3.1 INTRODUCTION

This section gives an assessment of current knowledge of the changing patterns of temperature and precipitation and their implications for snow and ice storage, hydrological extremes (flood and drought occurrence) and hydrological regimes (average monthly distribution of flows) under a variety of climate change scenarios. Section 3.2 and section 3.3 cover the literature that examines the changing global patterns of surface temperature and precipitation respectively. The associated implications that these changes will have on global snow and ice storage, global flood and drought occurrence, and hydrological regimes are then reviewed in sections 3.4, 3.5 and 3.6 respectively. There is increasing evidence that climate changes have already been observed, therefore we examine the evidence for observed changes and projected changes in each of sections 3.2 to 3.6. This approach is particularly useful because in some cases the changing patterns associated with observed changes are likely to be replicated and exacerbated under climate change scenarios.

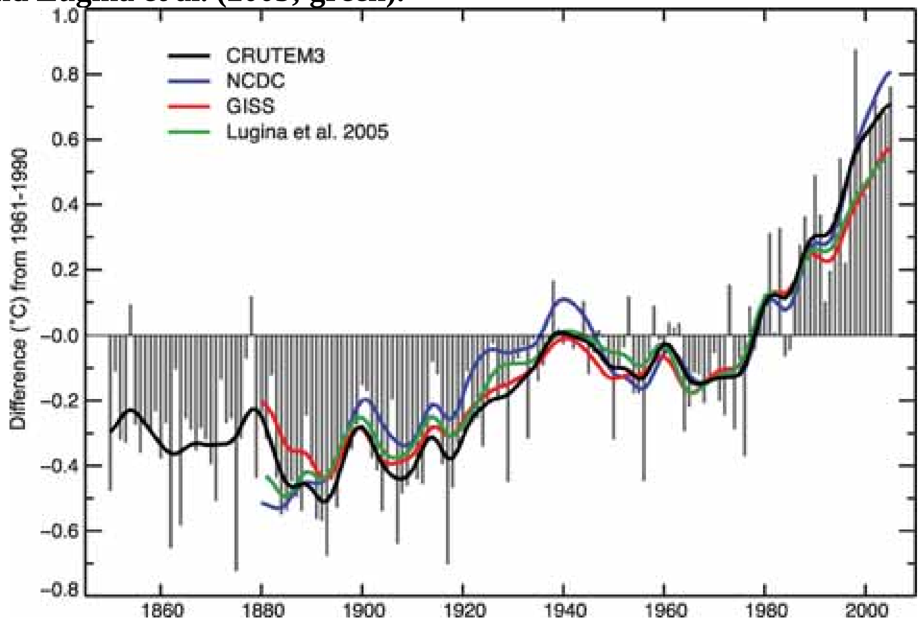
3.2. CHANGING GLOBAL PATTERNS OF SURFACE TEMPERATURE

3.2.1 Observed changes

Observed changes in mean global temperature are evident from global databases of instrumental temperature records. Several of these databases exist, including the Climatic Research Unit (CRU)/Hadley Centre gridded land-surface air temperature version 3 (CRUTEM3; Brohan et al. 2006), the operational version of the Global Historical Climatology Network (GHCN) dataset (National Climatic Data Centre (NCDC); Smith and Reynolds, 2005; Smith et al. 2005), the National Aeronautics and Space Administration's (NASA) Goddard Institute for Space Studies database (GISS; Hansen et al., 2001), and analyses by Lugina et al. (2005). The vertical bars in Figure 3.1 present annual global land surface air temperature anomalies for 1850-2005 relative to the 1961-1990 mean for CRUTEM3. The black curve is a smoothed fit that represents the decadal variations. Also shown are the anomalies from the NCDC, GISS and Lugina et al. (2005) databases.

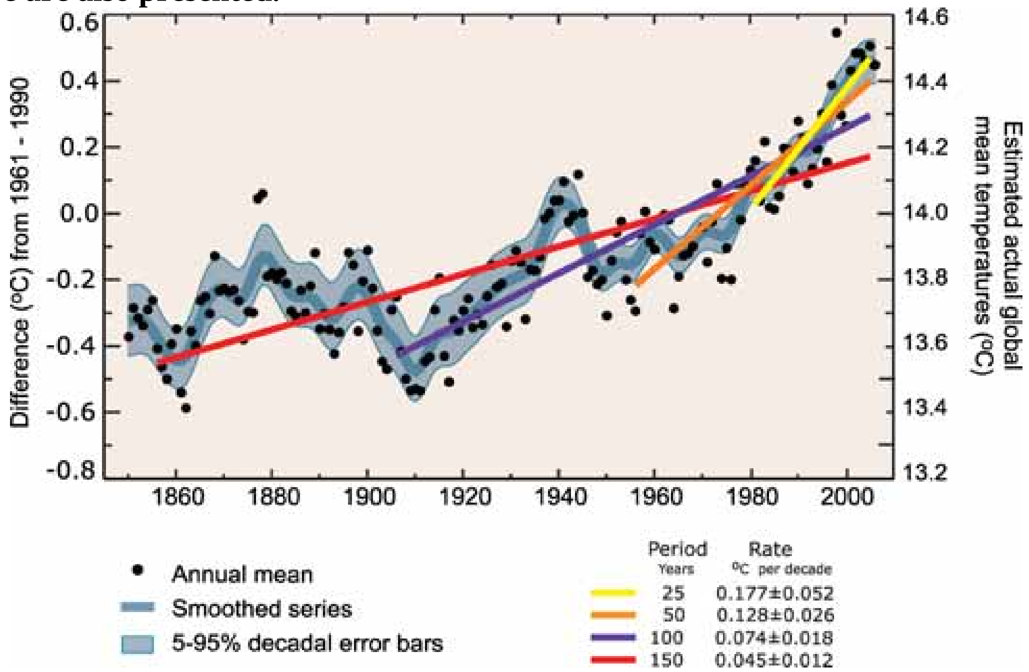
All four of the databases are in agreement that there has been a general warming trend since the late 19th century. The small differences between the databases are largely due to different spatial averaging techniques. To a smaller degree they are due to the methods used to treat gaps in the data and interpolate between them. From further examination of Figure 3.1, it is apparent that the warming trend has accelerated in the 20th century. Figure 3.2 demonstrates this more explicitly. The black dots indicate annual global mean observed temperatures from the CRUTEM3 database. The temperatures are represented as anomalies relative to the 1961-1990 mean (left axis), and also represented as the estimated actual temperature (right axis). Therefore they present a similar pattern to that illustrated in Figure 3.1. Linear fits have been applied to the temperature data for four different periods to illustrate the trend. The steeper slopes associated with the more recent, shorter periods, indicate that there has been an acceleration in the warming trend. Several detection and attribution studies have linked the accelerated recent warming to human driven emissions of greenhouse gases (Hegerl et al. 2007; Hegerl et al. 2006; Ingram 2006; Jones et al. 2005). A major proportion of the early 20th-century warming was due to solar radiation changes, volcanism and natural variability; all natural mechanisms. However, increasing industrialisation following World War II increased pollution in the Northern Hemisphere from 1940-1970, which contributed to a

Figure 3.1. Annual anomalies of global land-surface air temperature (°C), 1850 to 2005, relative to the 1961 to 1990 mean for CRUTEM3 (vertical bars). The smooth black curve shows decadal variations. Smoothed curves from other databases are included: NCDC (blue), GISS (red) and Lugina et al. (2005; green).



Source: Trenberth et al. (2007), p. 242.

Figure 3.2. Annual global mean observed temperatures from the CRUTEM3 database (black dots). Temperatures are represented as anomalies relative to the 1961-1990 mean (left axis), and also as the estimated actual temperature (right axis). Linear trend fits to the last 25 (yellow), 50 (orange), 100 (purple) and 150 years (red) are shown, and correspond to the periods 1981-2005, 1956-2005, 1906-2005, and 1856-2005, respectively. The smooth blue curves show the decadal variations. Decadal 5% to 95% (light grey) error ranges about the blue curve are also presented.



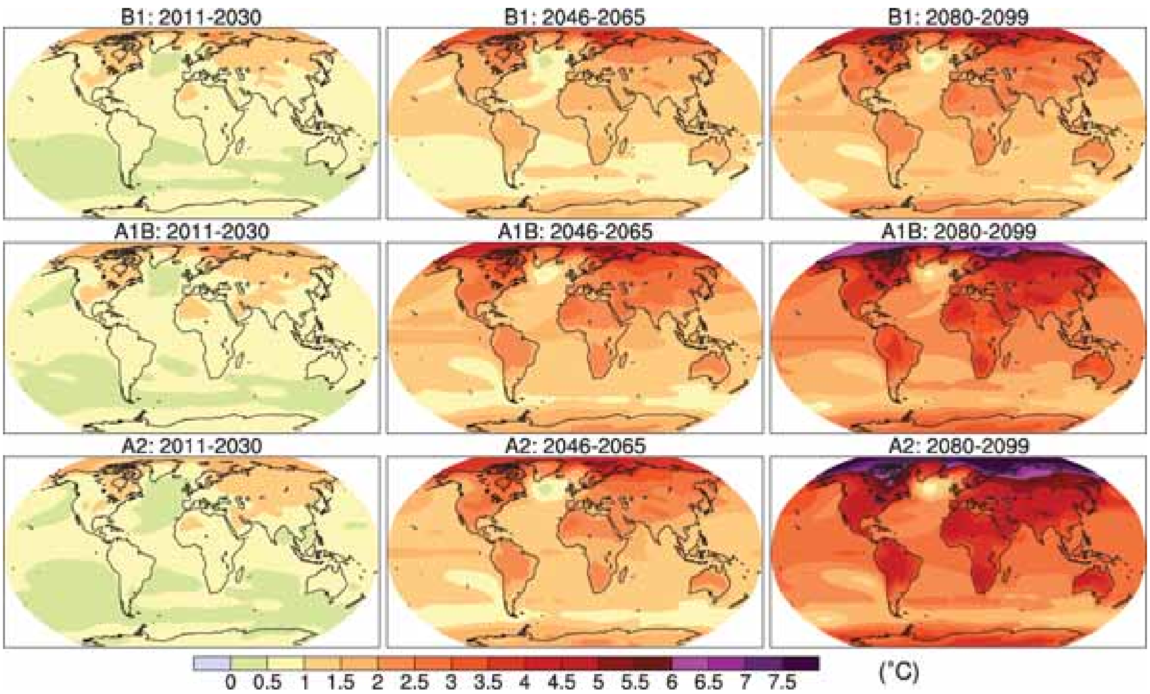
Source: Trenberth et al. (2007), p. 253.

mean global cooling.

3.2.2 Projected changes

Even if the atmospheric concentrations of greenhouse gases in the atmosphere were stabilised today, the temperature would continue to rise due to the unrealised effect of past climate forcing increases (Meehl et al. 2005). Future increases in greenhouse gas concentrations, from future emissions, will add to the committed warming thus leading to even higher temperatures. The spatial pattern of surface atmospheric temperature change will not be uniform, with air over land warming more than over the ocean, enhanced warming at high northern latitudes, and some dry continental areas warming much more as they become further depleted of moisture and the capacity to offset potential warming by increased latent heat fluxes; see Figure 3.3.

Figure 3.3. Multi-model mean of annual mean surface warming for the SRES scenarios B1 (top), A1B (middle) and A2 (bottom), and three time periods, 2011-2030 (left), 2046-2065 (middle) and 2080-2099 (right). Anomalies are relative to the mean of the period 1980-1999. Notice temperatures over land warm more than over the ocean, enhanced warming at high northern latitudes, and some greater warming over dry continental areas.



Source: Meehl et al. (2007), p. 766.

Extremes of temperature are also likely to change in future. The IPCC states that there will be an increased risk of more intense, more frequent and longer-lasting heat waves in a warmer future climate, and that events such as the European heat wave in 2003 would be more common (Meehl et al. 2007). Clark et al. (2006) state that the largest increases in frequency, duration and magnitude of summer heat waves will be found over Europe, North and South America, and East Asia. Although there is a wide uncertainty range surrounding the projections for some regions, the increases are still expected to be substantially greater than the present climate even for the most conservative of simulations.

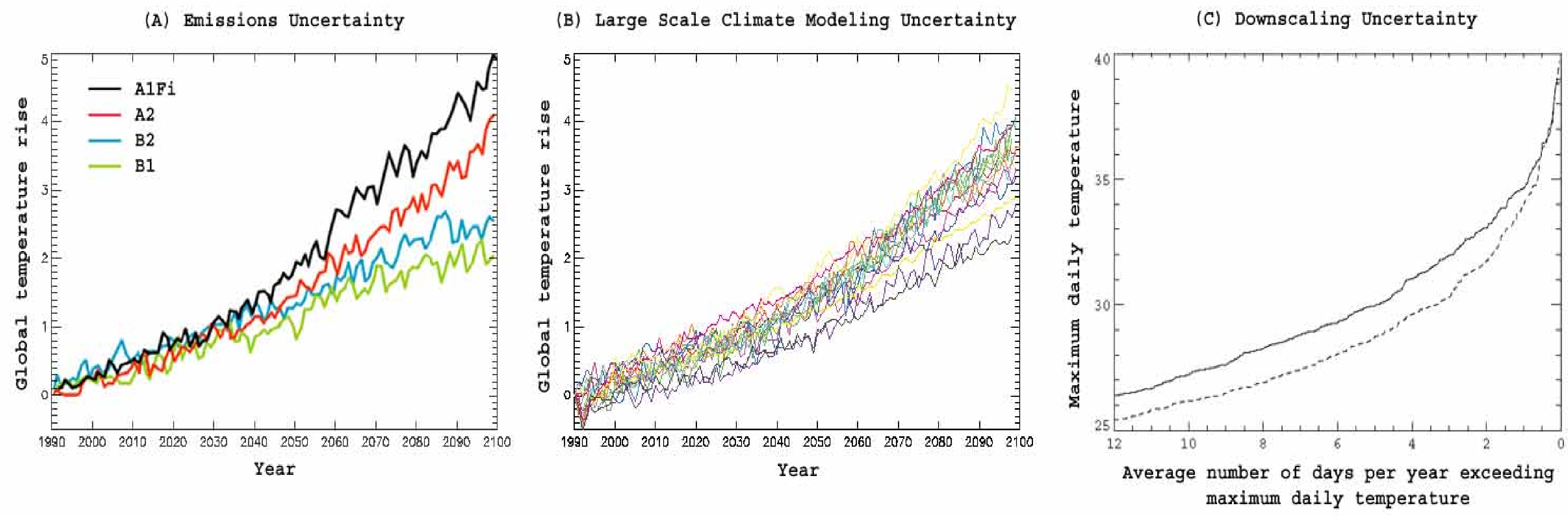
Climate change uncertainty typically comprises contributions from: future emissions, large-scale climate modelling, and downscaling of climate change to smaller scales. Socio-economic factors such as population, economic growth and technology will influence future emissions of greenhouse gases. There are uncertainties in how these will change in the future, which means there is uncertainty surrounding the extent of warming projected for the future.

Considering this, the IPCC Special Report on Emission Scenarios (Nakićenović and Swart, 2000) produced four families of plausible "storylines", or scenarios, detailing how these factors may develop in the future. Each group may be given a marker scenario, labelled A1Fi, A2, B2 and B1 that assume different increases in greenhouse gas emissions in the future. For the 21st century, the HadCM3 climate model projects around a 2°C global average warming for the lowest scenario, B1, and 5°C for the highest, A1Fi; see Figure 3.4(A). Interesting to note is that the warming up to 2040 is similar for each scenario. This indicates that the uncertainty in emissions scenario choice makes little contribution to uncertainty in climate change over the next 40 years but by 2100 it is much higher (Stott and Kettleborough, 2002). The similarity in pre 2040 response is partly due to the large inertia of the climate system and partly due to the fact that while the CO^2 emissions vary considerably between the SRES scenarios the total forcing (carbon dioxide, other greenhouse gases and aerosols) does not have such a large percentage spread early in the century.

The projections presented in Figure 3.4(A) are from one climate model (HadCM3). However, different modeling centres use different plausible representations of the climate system in their climate models. Therefore climate projections for a single emissions scenario differ between modeling centres. Figure 3.4(B) demonstrates a range of projections for the SRES A2 emissions scenario from different climate models. The projections presented in Figure 3.3 are in fact a multi-model mean of projections from several climate models.

The third source of uncertainty concerns the statistical downscaling and/or dynamical downscaling of GCM results to finer spatial scales. The former uses statistical relationships to convert the large-scale projections from a GCM to fine scales, while the latter uses a dynamic model similar to a GCM to cover a region. The dynamic model is then forced at its lateral boundaries using results from the coarse scale GCM. The ability to simulate extremes of temperature is different in global and regional climate models. Figure 3.4(C) shows a regional climate model simulation having more hot days on average than the global model from which its boundary conditions were derived, except for the hottest day of the year. For instance, the regional model simulation has greater than 35% more days reaching 27°C than the global model.

Figure 3.4. Uncertainties in climate change: (A) emissions uncertainty, (B) large scale climate modeling uncertainty, and (C) downscaling uncertainty. (A) illustrates the simulated mean global temperature rise (°C) relative to present (1961-1990) from one climate model (HadCM3) for four SRES emissions scenarios. (B) illustrates the same as (A) but only for the SRES A2 emission scenario and for several climate models. (C) illustrates the average number of days per year in a simulated 1961-1990 period that reach extreme temperatures for an atmospheric global model (dashed line) and a regional model that was driven by the global model (solid line) for the grid box that contains London (UK).



Source: Gosling et al. (submitted)

3.3 CHANGING GLOBAL PATTERNS OF PRECIPITATION

3.3.1. Observed changes

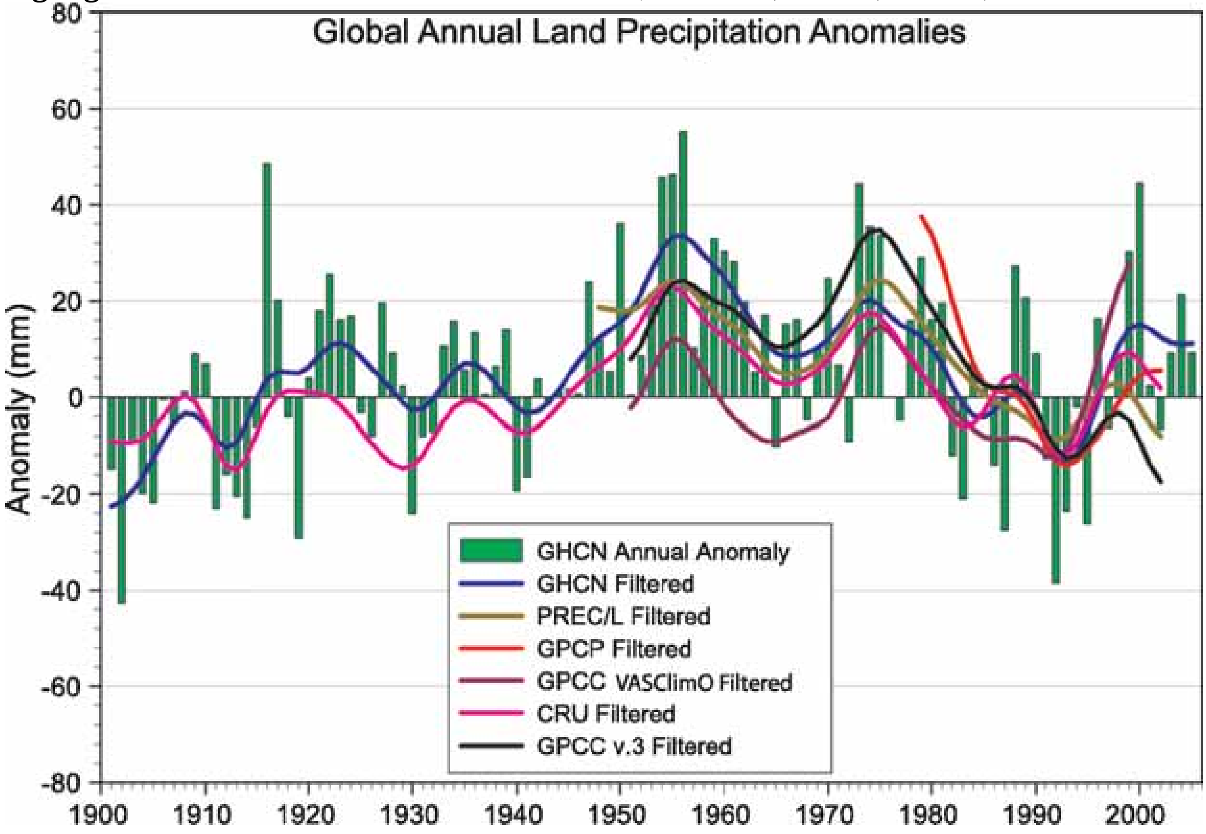
Observed changes in global land precipitation are demonstrated by datasets similar to the ones that demonstrate changes in global mean temperature. Global land precipitation datasets include the operational version of the GHCN dataset (NCDC; Smith and Reynolds, 2005; Smith et al. 2005), the Precipitation Reconstruction over Land (PREC/L) dataset (Chen et al. 2002), the Global Precipitation Climatology Project (GPCP) dataset (Adler et al. 2003), the CRU dataset (Mitchell and Jones, 2005), and several held by the Global Precipitation Climatology Centre (GPCC). The GPCC v.3 includes precipitation data from all available precipitation stations, while the GPCC VASClimO dataset (Beck et al. 2005) uses only stations whose long-term homogeneity can be assured.

Figure 3.5 presents a time series for 1900-2005 of annual global land precipitation anomalies (mm) from the GHCN dataset relative to 1981-2000. Decadal variations are also shown for the GHCN dataset, and the other datasets described previously. These observations can be examined for linear trends, in the same way as was done in Figure 3.2. Considering the two datasets with the longest available records, there is no statistically significant linear trend over the period 1900-2005 for the GHCN dataset, or over the period 1900-2002 for the CRU dataset. However, it should be noted that the global mean land changes do not even appear to be linear. There is a general increase until the 1950s, followed by a decline until the early 1990s, and then a recovery. Trends can be examined in more datasets if the period is selected as 1951-2005. Trenberth et al. (2007) have observed that trends range from –7 to +2 mm per decade for this period but that the 5 to 95% error bars range from 3.2 to 5.3 mm per decade. Trends for the PREC/L and GPCC v.3 series appear to be statistically significant, but again the uncertainties in the estimates are large.

These uncertainties mean it is not possible to determine whether there have been any significant changes in observed global land precipitation. It is difficult to interpret global land mean changes in precipitation because it is often comprised of large regional anomalies of opposite sign; i.e. precipitation has large variability spatially and temporally. Furthermore, there are relatively large discrepancies between the changes observed by each dataset in Figure 3.5, when compared to the changes observed in temperature time series (see Figure 3.2 for instance). These differences are partly due to difficulties in the measurement of precipitation. For example, *in situ* measurements are affected by wind effects on the gauge catch. Radar and satellite based measurements (remotely sensed) suffer from uncertainties in the algorithms for converting radiometric measurements (radar, microwave, infrared) into precipitation rates at the surface.

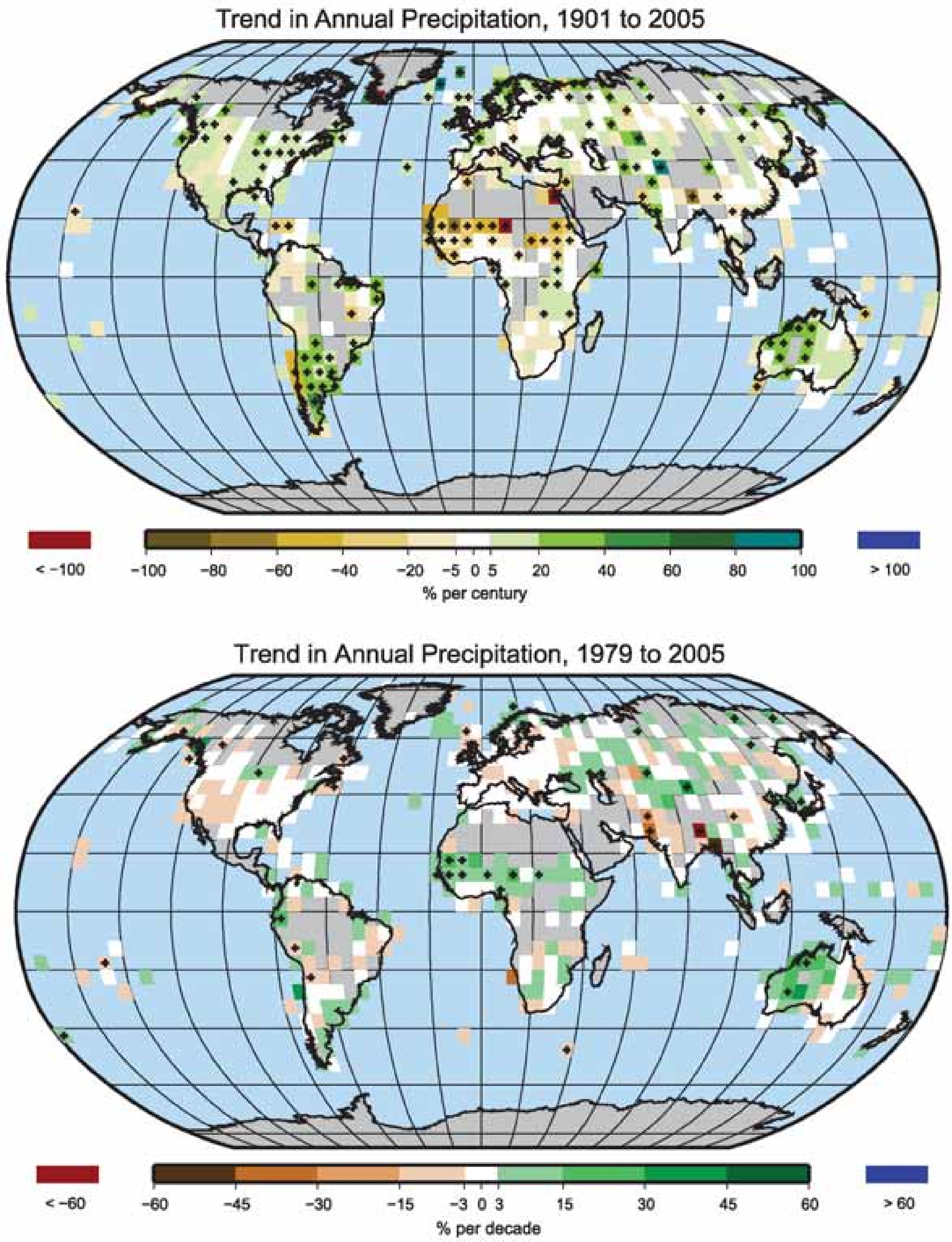
Given the high spatial variability of precipitation, trends in observed precipitation are more likely to be present when the spatial area over which the values are averaged is decreased. GHCN station data was interpolated to a 5°×5° latitude/longitude grid to illustrate spatial patterns of trends in annual precipitation (% per century or per decade) during the periods 1901-2005 and 1979-2005 in Figure 3.6 (Trenberth et al. 2007). Statistically significant trends at the 5% level are indicated by black + marks. Over both time periods, the largest and most commonly occurring negative trends occurred over the Sahel and western Africa. The strongest positive trends in precipitation occurred over northwestern Australia, the Amazon Basin and southeastern South America, including Patagonia. However, negative trends in annual precipitation were observed over Chile and parts of the western coast of the continent. Increases of more than 20% per century were observed over much of northwestern India during 1901-2005 but there were strong decreases during 1979-2005 for the same location.

Figure 3.5. Time series for 1900-2005 of annual global land precipitation anomalies (mm) from the GHCN dataset relative to 1981-2000. The smooth curves represent filtered data to highlight the decadal variations for the GHCN, PREC/L, GPCP, GPCC, and CRU datasets.



Source: Trenberth et al. (2007), p. 254.

Figure 3.6. Trend of annual land precipitation for 1901-2005 (top, % per century) and 1979-2005 (bottom, % per decade), using the GHCN precipitation dataset, interpolated to a 5°×5° latitude/longitude. Percentages are based on the average for 1961-1990. Areas in grey have insufficient data to produce reliable trends. Trends significant at the 5% level are indicated by black + marks.



Source: Trenberth et al. (2007), p. 256.

3.3.2. Projected changes

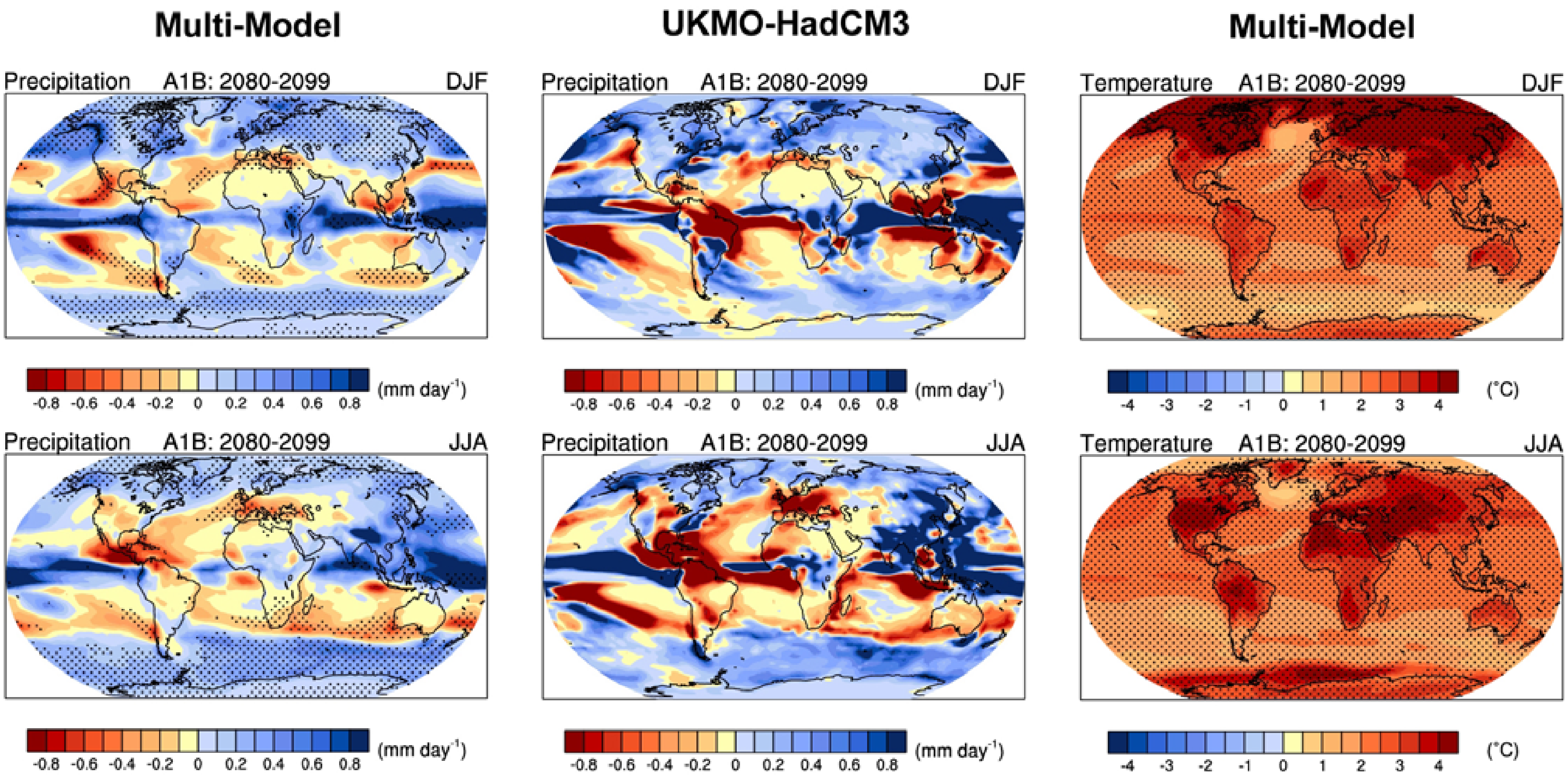
Climate models project increases in global mean precipitation associated with global warming (Meehl et al. 2007). However, similar to the observed records there are large spatial variations. For example, multi-model mean projections of mean changes in global precipitation, for the SRES A1B scenario, for 2080-2099 (relative to 1980-1999), for boreal winter and summer, are presented in the left panels of Figure 3.7. Emori and Brown (2005) have examined the precipitation changes projected by this ensemble of models. They estimate that precipitation over land increases by about 5% and precipitation over the oceans increases by 4%. The net change over land accounts for 24% of the global mean increase in precipitation. Large decreases up to 20% occur over the Mediterranean and Caribbean regions, and the subtropical western coasts of each continent. Increases of over 20% are projected over eastern Africa, central Asia, the equatorial Pacific Ocean, and at most high latitudes.

These findings are based on the multi-model mean, but the projections of individual climate models will sometimes be in disagreement. For example, compare the left panels (multi-model mean) in Figure 3.7 with the middle panels (UK Met Office HadCM3 climate model). Increases in precipitation at the high latitudes are in general agreement. Much of the high latitude areas in the left panels are stippled, meaning there is little variation in the magnitude of change among the ensemble of models for these areas. However, non-stippled areas highlight where there is a large variation in the magnitude of change. A clear example is north-eastern South America. This is further highlighted by HadCM3 projecting a strong mean drying during DJF, yet the multi-model indicating a moderate wetting.

Hence the non-stippled areas help to give an indication of the degree of uncertainty surrounding the projections. Considering this, Wang (2005) has concluded that a decrease in precipitation over several subtropical areas is commonly evident and that there is often a high consistency in the sign of change among the models, especially in regions such as the tropical Central American Caribbean. Neelin et al. (2006) concluded that increases in precipitation over the tropical oceans and in some monsoon regimes, such as the South Asian JJA monsoon and Australian DJF monsoon, are evident.

The disagreement between climate models for precipitation is considerably greater than it is for temperature. Figure 3.7 includes a stippled multi-model mean plot for temperature (right panels). Comparison with the panels on the left of Figure 3.7 highlights there is little variation in the magnitude of the temperature change among the ensemble of models for most of the globe, relative to the precipitation projections.

Figure 3.7. Multi-model mean changes in precipitation (mm day^{-1}, left) and surface air temperature (°C, right) for boreal winter (DJF, top) and summer (JJA, bottom). Changes are given for the SRES A1B scenario, for the period 2080-2099 relative to 1980-1999. Stippling denotes areas where the magnitude of the multi-model ensemble mean exceeds the inter-model standard deviation. The middle panels show mean changes in precipitation (mm day^{-1}) for the UK Met Office HadCM3 model only (no stippling), for the same time periods and scenario.



Source: adapted from Meehl et al. (2007), p. 767

3.4 GLOBAL SNOW AND ICE STORAGE

3.4.1 Observed changes

Observed warming trends such as those presented in Figure 3.1 and Figure 3.2 are also displayed in time series of polar (north and south of 65°N and 65°S respectively) surface air temperature, as shown in Figure 3.8. A greater rate of warming has been observed in the northern hemisphere (NH) polar regions than in the southern hemisphere (SH) polar regions. Associated with this have been declines in arctic sea ice extent, arctic frozen ground extent, arctic snow cover extent, and the global glacier mass balance (Figure 3.8). There has, however, been a slight increase for antarctic sea ice extent.

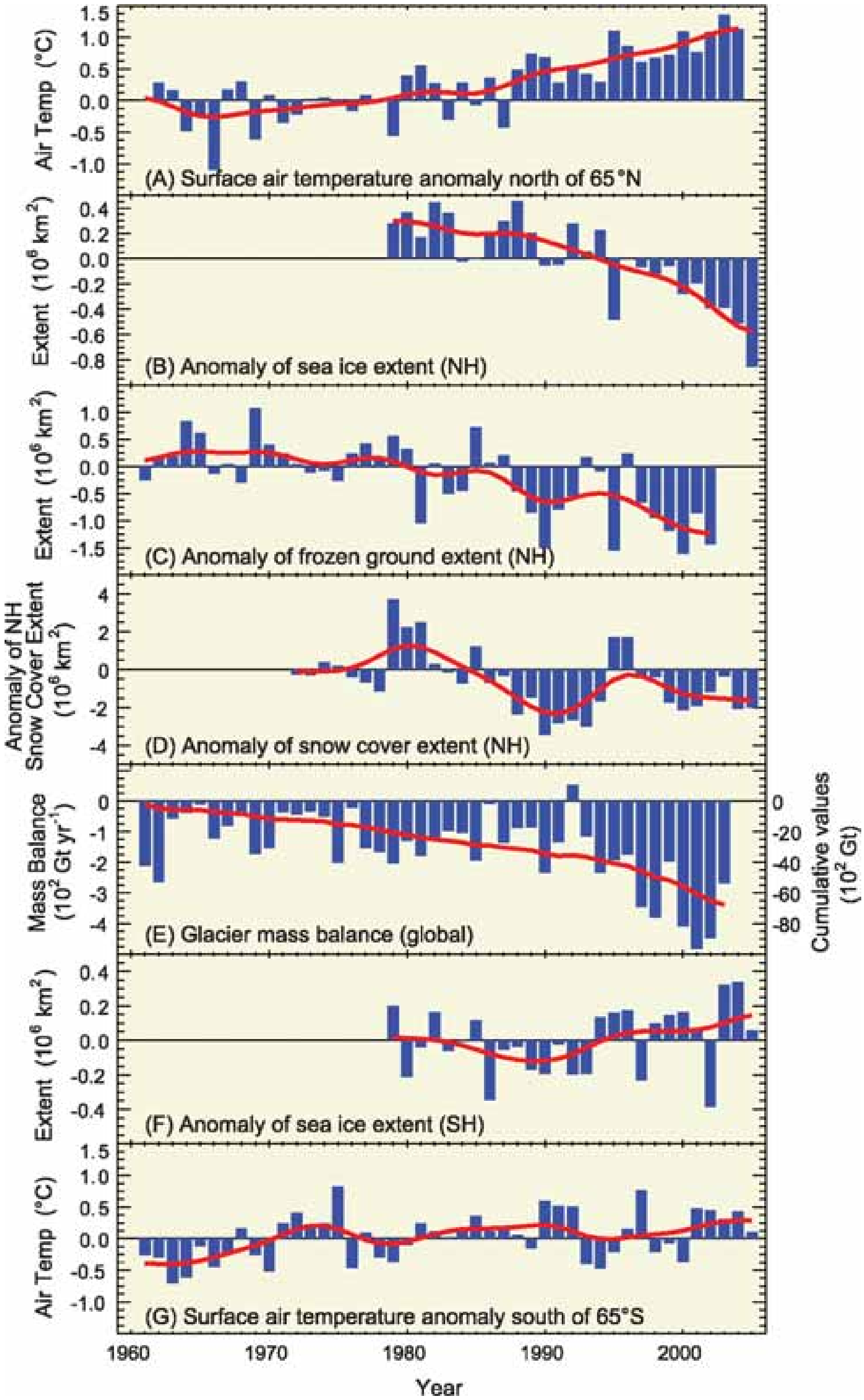
Analyses of sea ice extents by Comiso (2003) and Lemke et al. (2007) for the period November 1978 to December 2005 demonstrated a significant decreasing trend in arctic sea ice extent of –2.7 ± 0.6% per decade. Similar to that illustrated in Figure 3.8, a small positive trend of 0.47 ± 0.8% per decade was observed for the antarctic sea ice extent but this was not statistically significant and on the scale of the negative trends aforementioned.

Studies by Cogley (2005) and Dyurgerov and Meier (2005) have shown that the global average mass balance of glaciers and ice caps has been declining at an increasing rate since the 1960s. The declines can be represented in terms of the effect they have on sea level rise. Melting of glaciers and ice caps contributed 0.37 ± 0.16 mm yr^{-1} to sea level rise between 1961-1990. Between 1991-2004 the melting contributed 0.77 ± 0.22 mm yr^{-1} to sea level rise. These strong declines in global glacier mass balance are clearly seen in Figure 3.8.

Analyses of NH large-scale snow covered area (SCA) have been conducted by Robinson and Frei (2000) and Brown (2000). Robinson and Frei (2000) demonstrated that between 1967-1987 mean annual SCA was 24.4 x 10^6 km^2 and that since 1988 the mean annual extent has been 23.1 x $10^6 km^2$, which represents a statistically significant reduction of approximately 5%. Brown (2000) examined a longer period from 1922-2005 but only included SCA data for March and April. For these two months there was a statistically significant reduction in SCA of 7.5 ± 3.5%.

Seasonally frozen ground refers to a soil layer that freezes and thaws annually regardless of whether there is underlying permafrost. Zhang et al. (2003) have estimated that NH seasonally frozen ground has decreased by about 7% from 1901-2002. The decrease in spring was up to 15%. Another indication of the changing state of frozen ground is the analysis of permafrost temperature. Studies generally point to small increases in permafrost temperature. For example, Osterkamp (2005) observed a 2-3°C temperature change in the permafrost of North Alaska over 1983-2003. Walsh et al. (2004) discovered permafrost warming of about 1.3°C over East Siberia for the period 1960-2002.

Figure 3.8. Anomaly time series (departure from the long-term mean) of polar surface air temperature (A, G), arctic and antarctic sea ice extent (B, F), Northern Hemisphere (NH) frozen ground extent (C), NH snow cover extent (D) and global glacier mass balance (E). The solid red line in E denotes the cumulative global glacier mass balance; in the other panels it shows decadal variations.



Source: Lemke et al. (2007), p. 376.

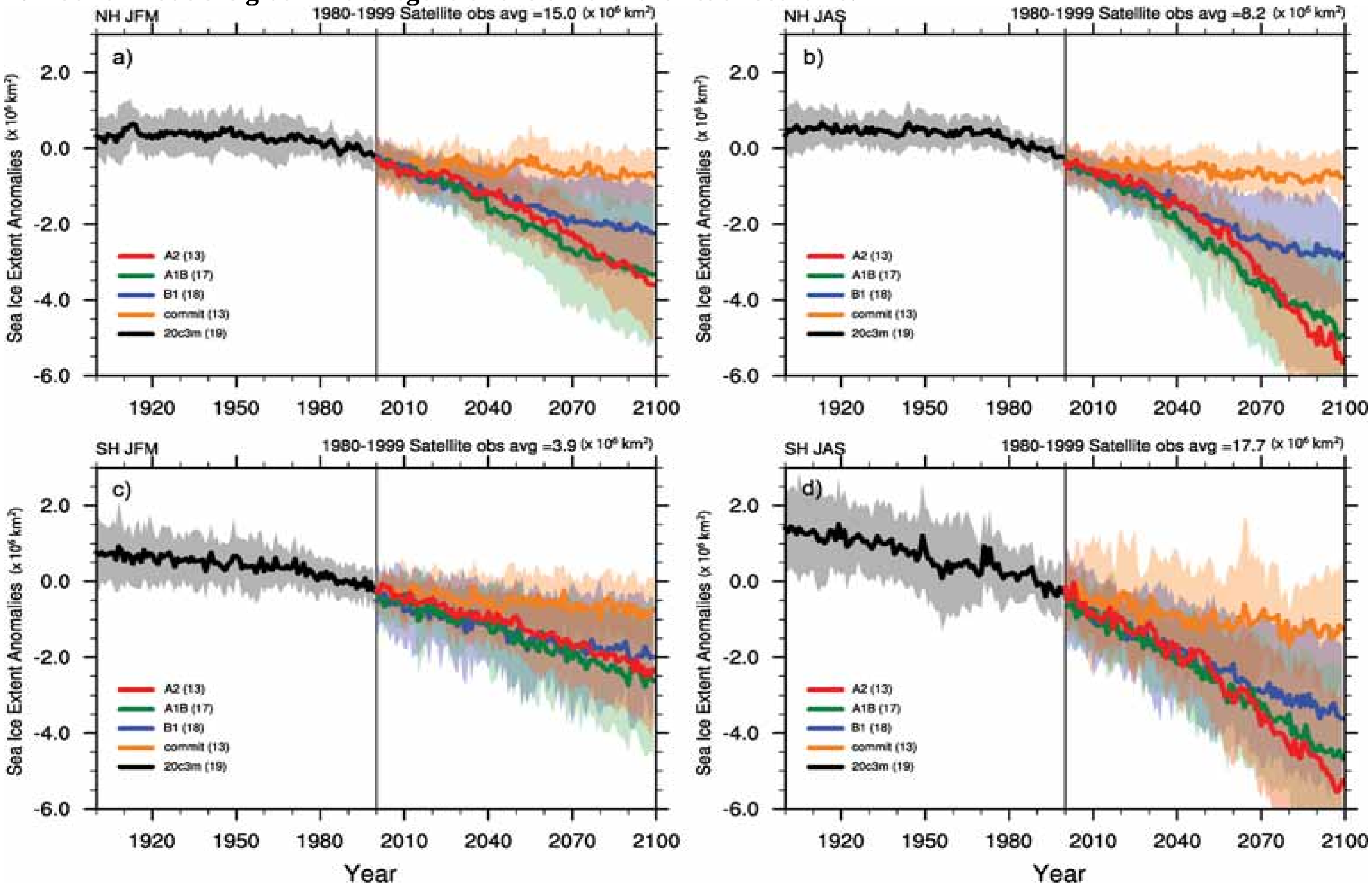
3.4.2 Projected changes

Figure 3.3 and Figure 3.7 previously illustrated that some of the greatest warming under climate change scenarios is expected to occur in the high latitudes. This is a result of positive surface albedo feedbacks involving snow and sea ice. As will be shown below, poleward retreats of terrestrial snow and sea ice are projected to occur with increasing temperatures from increased greenhouse gas concentrations. Climate models simulated responses to this are an increase in absorbed solar radiation due to the retreat of highly reflective snow or ice cover in a warmer climate. This is arguably the most important simulated feedback associated with the cryosphere (Randall et al. 2007). Indeed Hall (2004) has demonstrated that this albedo feedback is responsible for about half the simulated high-latitude warming response to a doubling of atmospheric CO^2. The responses to the projected high latitude amplified warming will include further declines in sea ice extent and snow cover, which have already been observed (Section 4.1).

Zhang and Walsh (2006) have synthesized sea ice extent results from several climate models that have simulated the climate of the twentieth century and for global warming scenarios (SRES A2, A1B, B1 and Commitment). The multi-model simulated anomalies in sea ice extent for these simulations are presented in Figure 3.9 for the NH and SH for the months January-March (JFM) and July to September (JAS). The multi-model ensemble means for the simulated twentieth century were found to provide estimates very close to the observations described in Section 3.4.1. Twenty-first century sea ice areas generally decrease more for the A1B and A2 scenarios, than for the B1 scenario. The mean reductions are estimated as $-3.54 \pm 1.66 \times 10^5$ km^2 decade^{-1} in A1B, $-4.08 \pm 1.33 \times 10^5$ km^2 decade^{-1} in A2, and $-2.22 \pm 1.11 \times 10^5$ km^2 decade^{-1} in B1. The corresponding percentage reductions are 31.1%, 33.4%, and 21.6% in the last 20 years of the twenty-first century, relative to 1979–99. Statistical analysis showed that many of the models are consistent in the sea ice change projections among all scenarios. Figure 3.9 also demonstrates that antarctic sea ice cover is projected to decrease more slowly than in the arctic.

In most areas that receive seasonal snow cover, there is a strong negative correlation between the amount of snow cover and temperature (Randall et al. 2007). Given the global warming projected by climate models (Figure 3.3 and Figure 3.7), widespread reductions in snow cover over the twenty-first century is therefore projected. An international project of the Arctic Council and the International Arctic Science Committee (IASC) was the Arctic Climate Impact Assessment (ACIA, 2004). Individual climate models projected reductions in the annual mean NH snow cover of 9-17% for the B2 scenario at the end of the twenty-first century. The multi-model mean reduction was 13%. A shortening of the snow cover season was also projected.

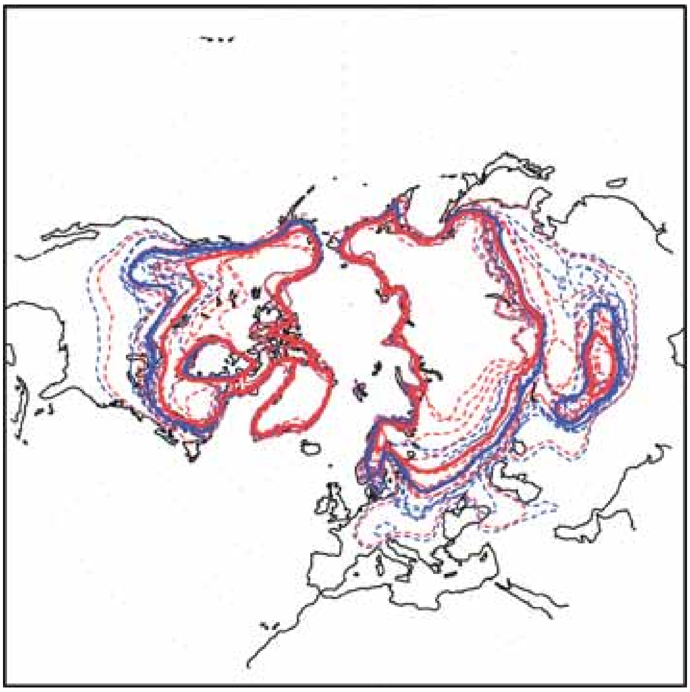
Figure 3.9. Multi-model simulated anomalies in sea ice extent for the 20th century (20c3m) and 21st century using the SRES A2, A1B and B1 and commitment scenario for (a) NH January to March (JFM), (b) NH July to September (JAS). Panels (c) and (d) are as for (a) and (b) but for the SH. The solid lines show the multi-model mean, shaded areas denote ±1 standard deviation. Sea ice extent is defined as the total area where sea ice concentration exceeds 15%. Anomalies are relative to the period 1980 to 2000. The number of models is given in the legend and is different for each scenario.



Source: Meehl et al. (2007), p. 771

Figure 3.10 presents individual model and multi-model mean snow cover and projected changes over the twenty-first century from 12 climate models. Clear reductions can be seen in the multi-model means (solid lines). However, note the inherent uncertainty across individual climate models (dashed lines). For example, the snow area fractions are larger for 1980-1999 than for 2080-2099 for some individual climate models, although the multi-model mean shows the opposite. The strongest reductions are projected for north-western USA, western Canada, and continental Europe. However, in a few regions such as Siberia, snow amount is projected to increase due to an increase in precipitation from autumn to winter (Hosaka et al. 2005).

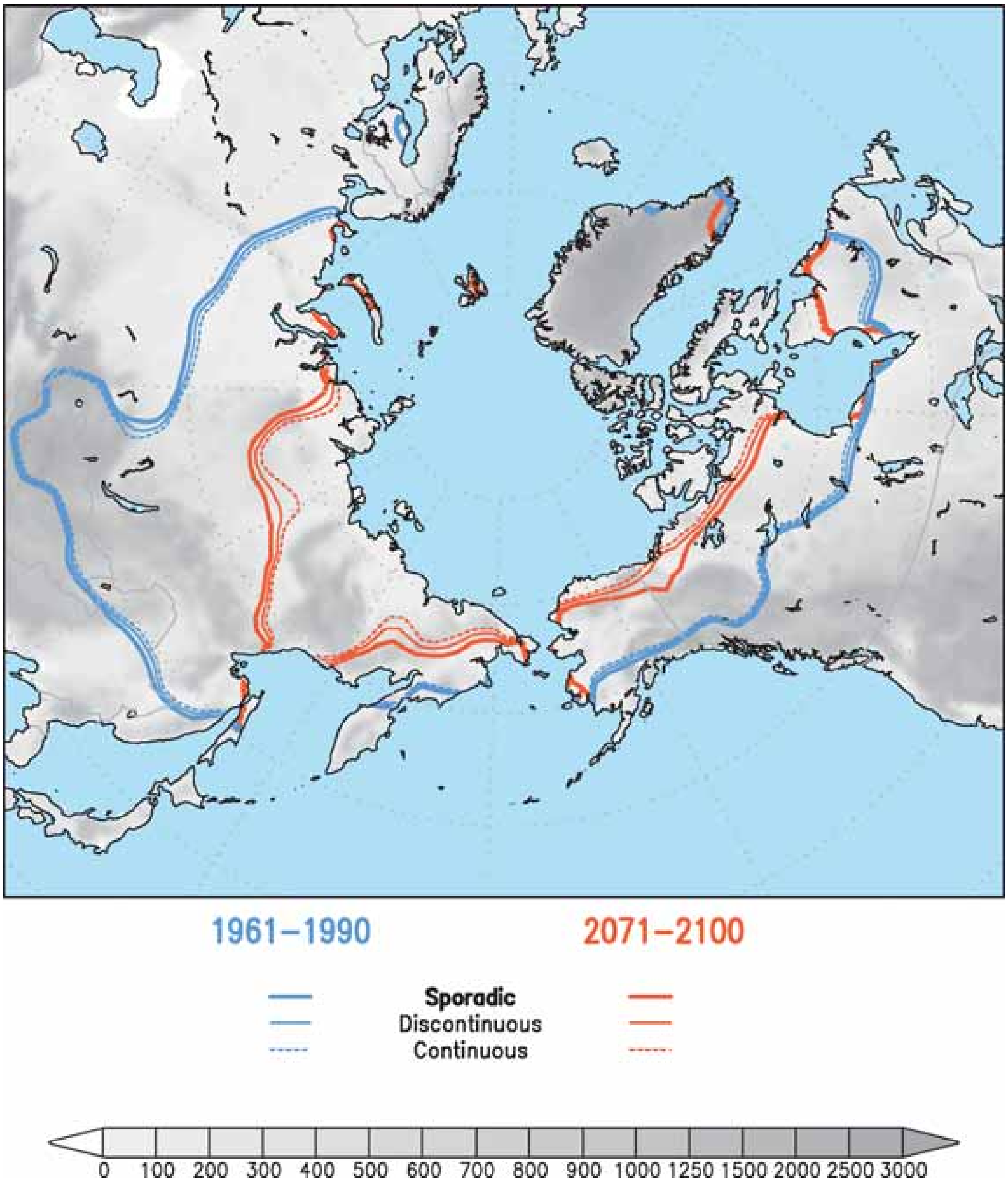
Figure 3.10. Multi model mean snow cover and projected changes over the twenty-first century from 12 climate models. Contours mark the locations where the December to February (DJF) snow area fraction exceeds 50%, blue for 1980–1999, and red for 2080–2099, dashed for the individual models and solid for the multi model mean.



Source: adapted from Meehl et al. (2007), supplementary materials, SM. 10-5.

The projected warming at the high northern latitudes and increased precipitation due to changes in circulation patterns are associated with changes in permafrost. However, this relationship is complicated by the competing effects of warming and increased snowfall in those regions that remain below freezing. Stendel and Christensen (2002) have examined the warming impacts of the A2 scenario by the end of the twenty-first century on NH permafrost distributions and the thickness of the 'active layer' (the top layer of soil that thaws during the summer). The projections indicated a 30-40% increase in active layer thickness. The largest changes were observed in Siberia and western Canada. A poleward movement of permafrost extent was also observed (Figure 3.11).

Figure 3.11. Simulated and projected NH permafrost distribution for the period 1961-1990 (blue) and 2071-2100 (red) respectively. Simulation is for the A2 scenario. Elevation map is underlaid in grey. Sporadic, discontinuous and continuous permafrost are marked by three different lines.



Source: Stendel and Christensen (2002), p. 10-2.

3.5 GLOBAL FLOOD AND DROUGHT OCCURRENCE

3.5.1 Observed changes

Numerous definitions of drought exist and it can be numerically defined using indices that integrate variables that affect evapotranspiration and soil moisture. The most commonly used index is the Palmer Drought Severity Index (PDSI; Heim, 2002) that uses precipitation, temperature and local available water content data to assess soil moisture in a hydrological accounting system. Recent analyses by Dai et al. (2004a; 2004b) have demonstrated global changes in the PDSI since 1900. The top panel of Figure 3.12 illustrates the spatial pattern of the monthly PDSI for 1900-2002, and the bottom panel shows how the sign and strength of this pattern has changed since 1900. It is possible to observe widespread increasing African drought, especially in the Sahel. Wetter areas include eastern North and South America and northern Eurasia. The very dry areas, which are defined as areas with a PDSI less than −3.0 have more than doubled since the 1970s, with a large jump in the early 1980s due to an ENSO-induced precipitation decrease and a subsequent increase primarily due to surface warming. Global very wet areas (PDSI greater than +3.0) declined slightly during the 1980s. Combined, the global land areas in either very dry or very wet conditions have increased from around 20% to 38% since 1972. Surface warming is the primary cause after the mid-1980s. Dai (2004a) concludes that this provides observational evidence for an increasing risk of droughts as global temperatures increase.

Changes and trends in observed floods are harder to explore, and less reliable than observations for droughts. Available streamflow gauge records cover only about two-thirds of the global actively drained land areas (Dai and Trenberth, 2002). Furthermore they often include missing time periods and vary in record length. Also, the construction of large dams and reservoirs that can increase low flow and reduce peak flow mean that large changes and trends in seasonal streamflow rates for many of the world's largest rivers should be treated with caution (Trenberth et al. 2007). The association between flooding and precipitation means that responses will vary regionally. In some areas there will be increased peak flows, and in other areas there will be reductions. This makes it difficult to recognise any global trends. For example, Kundzewicz et al. (2005) examined annual extreme flows for 195 rivers across the world. Increases were observed in 27 cases, and decreases in 31 cases. There were no significant long-term changes in annual extreme flows for 137 cases. Over regions with increased precipitation (see Figure 3.6), increased river flow has been observed during the latter half of the twentieth century. Examples include many parts of the USA (Groisman et al. 2004) and southeastern South America (Genta et al. 1998). Also, snowmelt earlier in the season and the breaking up of river ice due to accelerated warming since the 1970s has been associated with increases in peak flow in the western USA (Cayan et al., 2001) and many Canadian rivers (Zhang et al. 2001). In other regions, decreases in precipitation have been associated with declines in streamflow. For example, Zhang et al. (2001) reported decreased flows over several Canadian river basins during the last 30-50 years.

3.5.2 Projected changes

The IPCC concluded that an increasing trend in the number of areas affected by drought since the 1970s is *likely* (IPCC, 2007). They also concluded that these trends would *likely* continue on in to the twentieth century, based on projections from climate change scenarios. Mid-latitude continental interiors in summer are most at risk. For example, Wang (2005) examined projections from 15 climate models and observed that in a warmer climate the models simulated summer dryness in most parts of the northern subtropics and mid-latitudes. Burke et al. (2006) have suggested that such changes will result in the proportion of the global land surface in extreme drought increasing from 1% to 30% by the 2090s, using the HadCM3 climate model and A2 scenario. Burke et al. (2006) also estimated that the number of extreme drought events per 100 years and mean drought duration are likely to increase by factors of two and six, respectively, by the end of the twenty-first century. The projections made by Burke et al. (2006) did indicate strong wetting in some regions by the 2090s, but the net overall response to global warming was a drying trend.

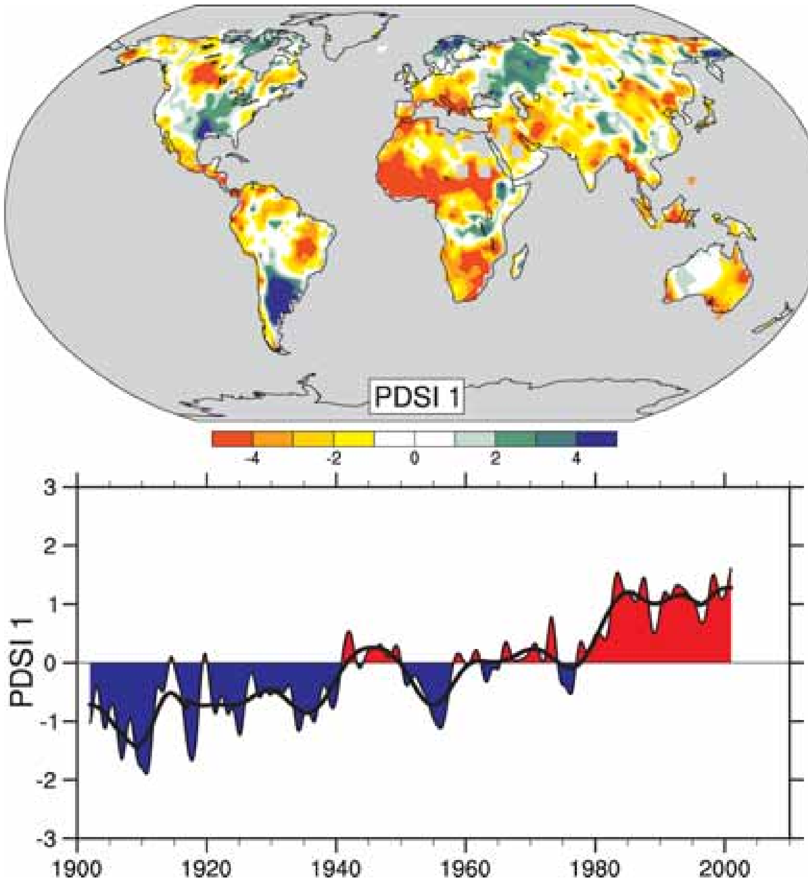
The spatial patterns of increasing dryness can be observed by examining projections of soil moisture and 'dry days' (defined as the annual maximum number of consecutive dry days; Tebaldi et al. 2006) – see Figure 3.13 and Figure 3.14(c and d) respectively. Figure 3.13 illustrates declines in soil moisture over most parts of the northern subtropics, mid-latitudes and high latitudes based on the multi-model mean for the A1B scenario. However, note that there is little agreement across the individual climate models in the magnitude of the changes for many parts of the world. Figure 3.14(c) illustrates that the historical simulated positive trend in dry days continues and strengthens for the A2 and A1B scenarios. The sub-tropics and lower mid-latitudes experience the greatest increase in the number of dry days (Figure 3.14(d)).

In a warmer climate, the chances of precipitation falling as snow decreases, especially in areas with autumn and spring temperatures close to 0°C (IPCC, 2007). Furthermore, a shortening of the snow cover season is projected (Section 3.4.2) and snowmelt is projected to be earlier and less abundant in the melt period (ACIA, 2004). Barnett et al. (2005) showed that these changes may lead to drought problems in regions that depend heavily on glacial melt water for their main dry-season water supply. The entire Hindu Kush-Himalaya ice mass has decreased in the last two decades meaning that hundreds of millions of people in China and India will be negatively affected by the reduction in melt water. Other regions likely to be effected by drought include the Andes, and small glacial regions in Bolivia, Ecuador and Peru. Reductions in glacial melt water is likely to be a major cause of drought in a warmer world, especially considering that one-sixth of the Earth's population rely on melt water from glaciers and seasonal snow packs for their water supply (Kundzewicz et al. 2007).

Importantly, associated with the increased risks of drying described above, there will be increased risks of flooding. This is because in a warmer world, Tebaldi et al. (2006) have shown that precipitation *intensity* increases almost everywhere (i.e. proportionately more precipitation for each precipitation event), especially at the mid- and high latitudes (see Figure 3.14 a and b) where mean precipitation also increases (see Figure 3.7). More intense precipitation events will be common, but the periods of time between those intense events will become longer. This directly affects the risk of flash flooding and urban flooding. Furthermore, Coudrain et al. (2005) has shown that river flash flooding and outburst floods are more likely due to the rapid melting of glaciers in glacial regions such as the Andes. However, Zhang et al. (2005) have demonstrated that in many temperate regions, the snowmelt contribution to spring floods is likely to decline on average.

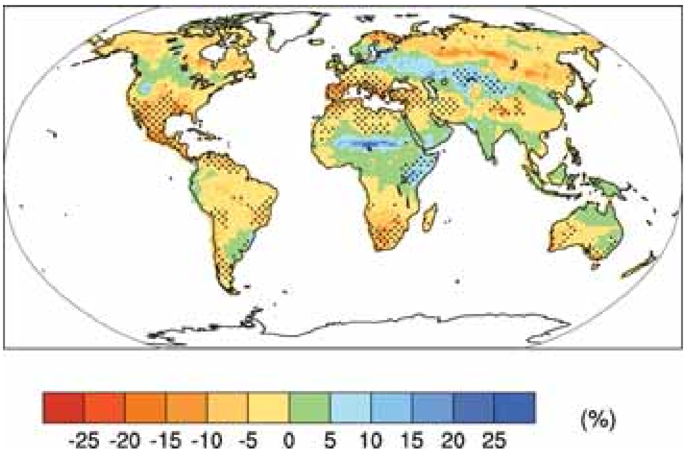
Several other studies have linked increased rainfall intensity in a warmer world with increased flooding. In a multi-model analysis conducted by Palmer and Räisänen (2002), an increase in intense precipitation due to winter mid-latitude storms suggested an increase in the possibility of very wet winters with increased flood risk for much of central and northern Europe. Palmer and Räisänen (2002) also suggested increased summer flooding in the Asian monsoon region in a warmer climate. Milly et al. (2002) examined monthly peak volume discharges for 16 large river basins across the globe, for a climate change scenario that involved atmospheric carbon dioxide concentrations quadrupling from present levels. They observed that in some areas, what is presently regarded as a 100-year flood was projected to occur much more frequently, and in some cases every 2 to 5 years. Of the 16 basins examined, 15 of them experienced increases in the frequency of 100-year floods under the climate change scenario.

Figure 3.12. The spatial pattern (top) of the monthly PDSI for 1900-2002. The bottom panel shows how the sign and strength of this pattern has changed since 1900. Red and orange areas are drier (wetter) than average and blue and green areas are wetter (drier) than average when the values shown in the lower plot are positive (negative). The smooth black curve shows decadal variations.



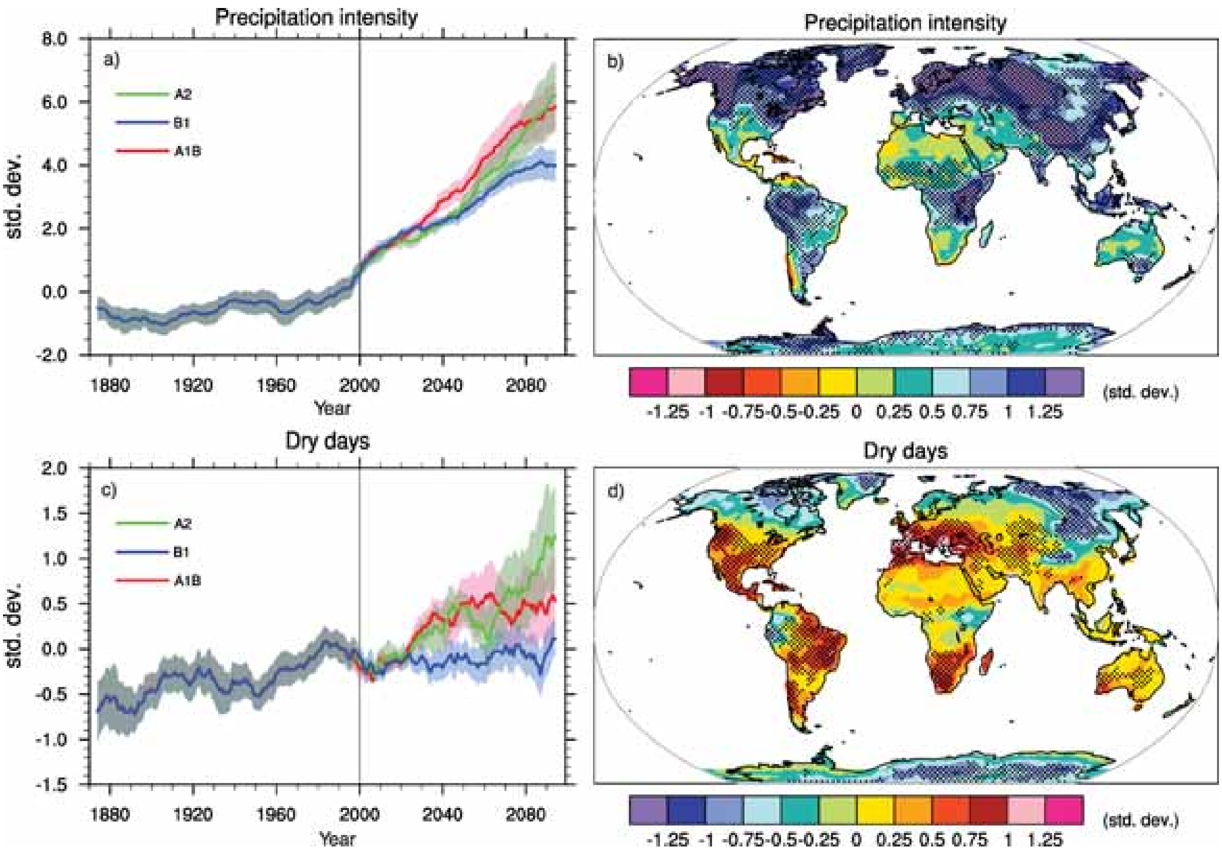
Source: Adapted from Dai et al. (2004b) and cited in Trenberth et al. (2007), p. 263.

Figure 3.13. Multi-model mean changes in soil moisture (%). Changes are given for the SRES A1B scenario, for the period 2080-2099 relative to 1980-1999. Stippling denotes areas where the magnitude of the multi-model ensemble mean exceeds the inter-model standard deviation.



Source: adapted from Meehl et al. (2007), p. 769.

Figure 3.14 Changes in precipitation intensity (top) and dry days (bottom; defined as the annual maximum number of consecutive dry days) based on multi-model simulations from nine climate models. (a) Globally averaged changes in precipitation intensity (defined as the annual total precipitation divided by the number of wet days) for B1, A1B and A2 scenarios. (b) Changes in simulated precipitation intensity between two 20-year means (2080–2099 minus 1980–1999) for the A1B scenario. (c) Globally averaged changes in dry days. (d) Changes in simulated dry days between two 20-year means (2080–2099 minus 1980–1999) for the A1B scenario. Solid lines in (a) and (c) are the 10-year smoothed multi-model ensemble means; the shading indicates the ensemble mean standard deviation. Stippling in (b) and (d) denotes areas where at least five of the nine models agree in determining that the change is statistically significant.



Source: adapted from Tebaldi et al. (2006) and cited in Meehl et al. (2007), p. 785.

Manabe et al. (2004) state that the impacts of flooding and drought are likely to occur disproportionately in countries with low adaptation capacity. According to Kleinen and Petschel-Held (2007) increased flood hazards associated with global warming are likely to affect up to 20% of the world's population that live in river basins. For example, projections that include a mean global temperature rise of 2°C indicate that the flooded area in Bangladesh will increase by 23-29% (Mirza, 2003).

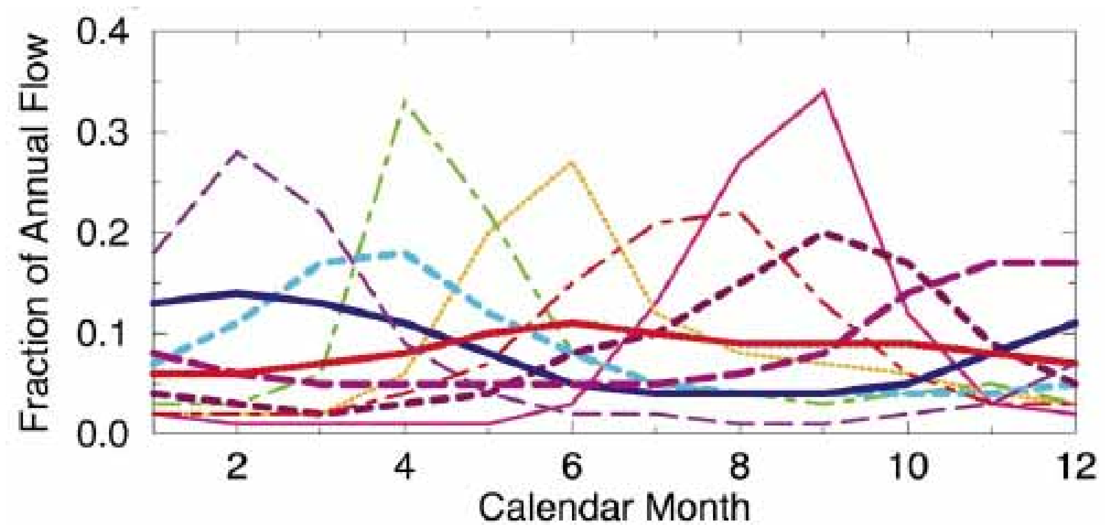
3.6 GLOBAL FLOW REGIMES

River flow regimes reflect the impact of all of the above hydroclimatological properties. Whereas the linkage between extreme floods and droughts can often be directly related to particular climate events, the relationship between lesser flow events or river flow regimes and climate is often less obvious. This is because these relationships are strongly moderated by the intervening state of hydrological stores (snow and ice, surface waters, soil moisture, groundwater) and processes (interception, evapotranspiration, overland flow, infiltration, percolation), which can induce lags between climate and hydrological events and can also moderate the amplitude of river flow response to precipitation. The impact of human activities (land use, irrigation, abstractions, flow regulation) on the magnitude and timing of river flows is extremely large and introduces a further enormous complexity to linking climate to river flows.

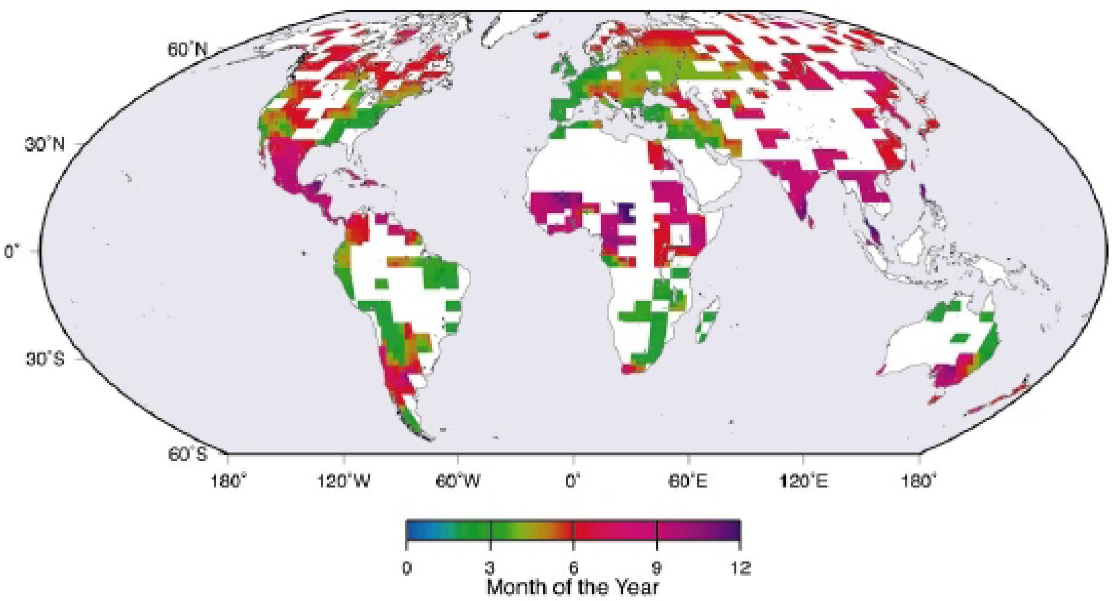
In this section, we consider the flow regime to be composed of an annual pattern or cycle, of monthly flows where the difference between high and low flows has both a lag or timing and an amplitude (Harris et al., 2000). By focussing on these scales of timing and magnitude and their variances, it is possible to characterise or classify different flow regimes (e.g. Dettinger and Diaz, 2000) and to explore relationships between flow regimes and water-related ecosystem function and integrity (e.g. Junk, 1989; Junk and Wantzen, 2004; Poff et al., 2003).

Dettinger and Diaz (2000) used cluster analysis to classify global river flow regimes and thus characterise global patterns and variability. Figure 3.15 shows the enormous variety in flow timing between different areas (Fig 3.15a) and its global distribution (Fig 3.15b), whilst Figure 3.16 links these to climate by indicating the average delay between the month of peak difference between precipitation and evapotranpiration and the month of peak streamflow. Figure 3.17 illustrates the percentage of total streamflow that occurs in the peak month.

Figure 3.15
a) average fractional monthly flows for identified global flow regimes

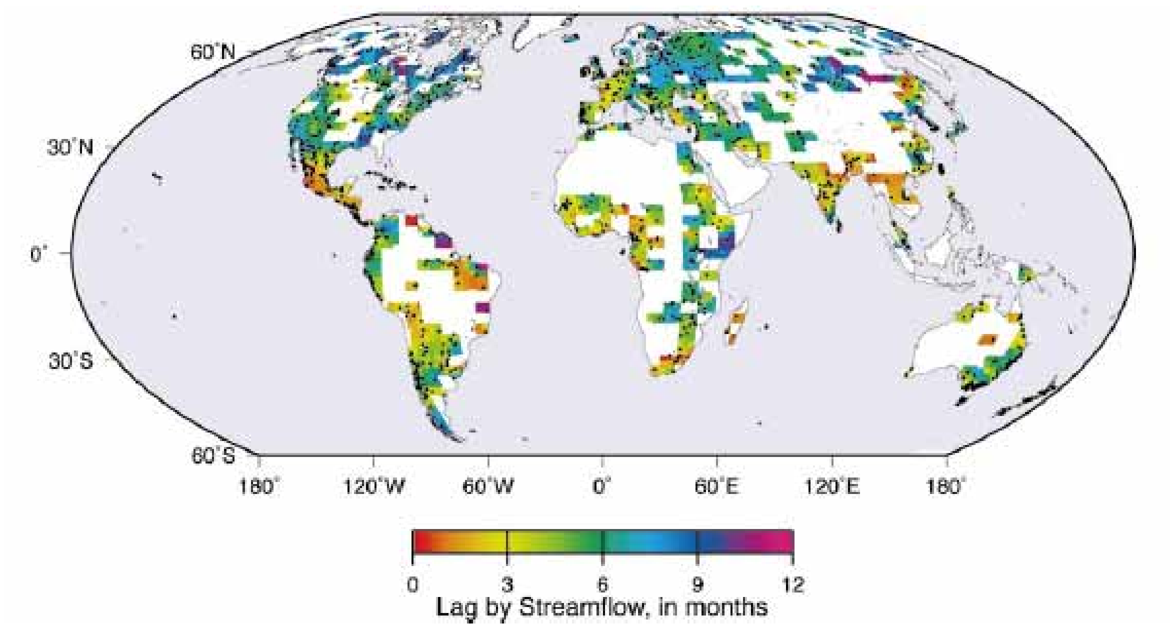


b) distribution of the sites in the flow regime clusters coloured by the month of peakflow



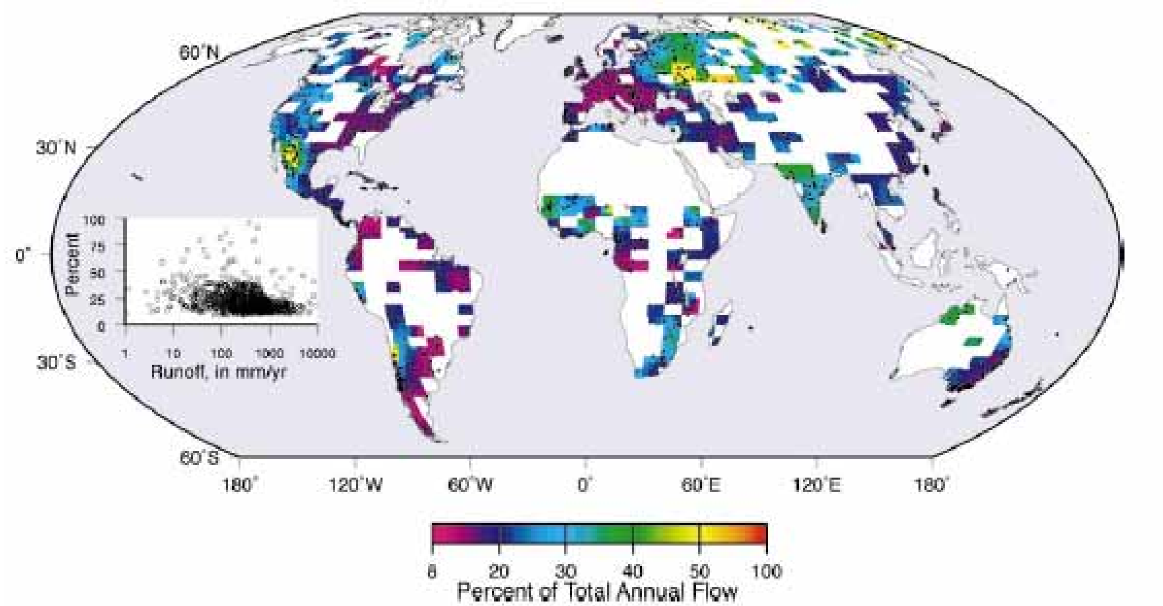
source: Dettinger and Diaz, 2000

Figure 3.16 Average lag between month of peak difference between precipitation and evapotranspiration (i.e. effective rainfall) and peak river flow.



source: Dettinger and Diaz, 2000

Figure 3.17 Percentage of total streamflow that occurs in the peak month.



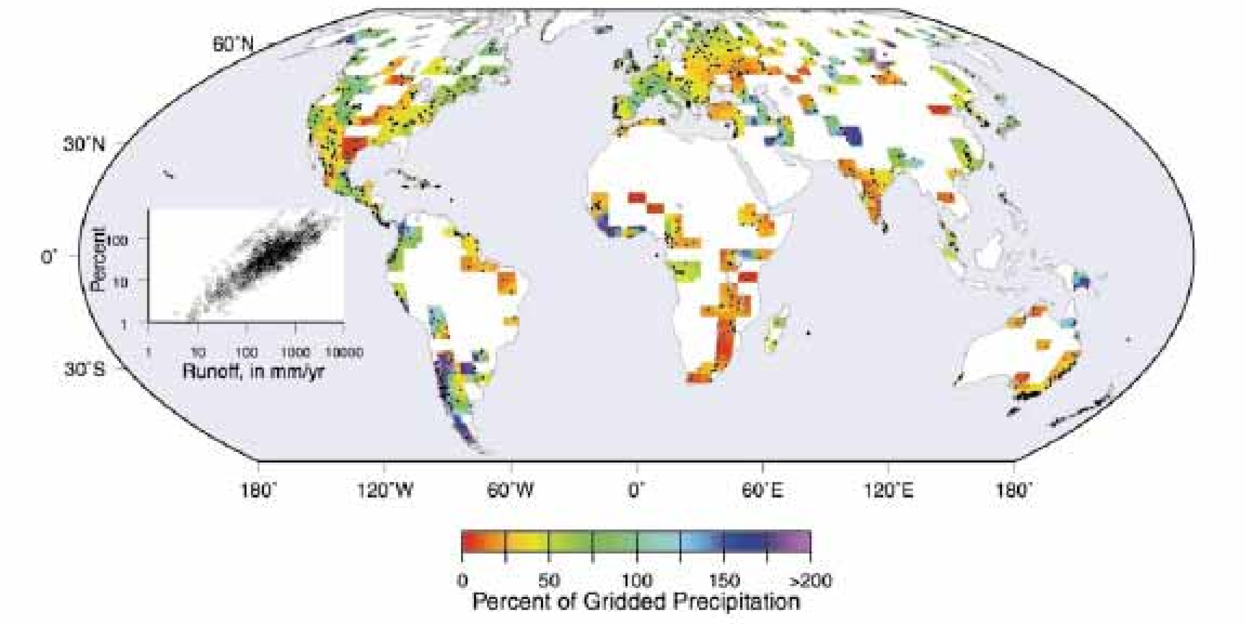
source: Dettinger and Diaz, 2000

Figures 3.18 and 3.19 provide a picture of the reliability of global runoff regimes. Figure 3.18 shows the long term average runoff efficiency (the proportion of precipitation that runs off) whereas Figure 3.19 shows the coefficient of variation of annual streamflow.

From Figures 3.15 to 3.19 broad global patterns, magnitudes and reliabilities of flow regimes can be identified. The month of maximum streamflow tends to reflect maximum precipitation, although there may be significant lags in areas of significant snow and ice cover (high latitudes and major mountain ranges) or where strong evaporation can disrupt the pattern. Dettinger and Diaz recognised springtime ice- and snowmelt and monsoon rainfall as the main contributors to stream flow seasonality. They noted that runoff efficiency and variability varies broadly with climate aridity, and that correlations between annual stream flow and Southern Oscillation and North Atlantic oscillation indices demonstrated differences in mean runoff are about five times larger than differences in precipitation from El Nino to La Nina years.

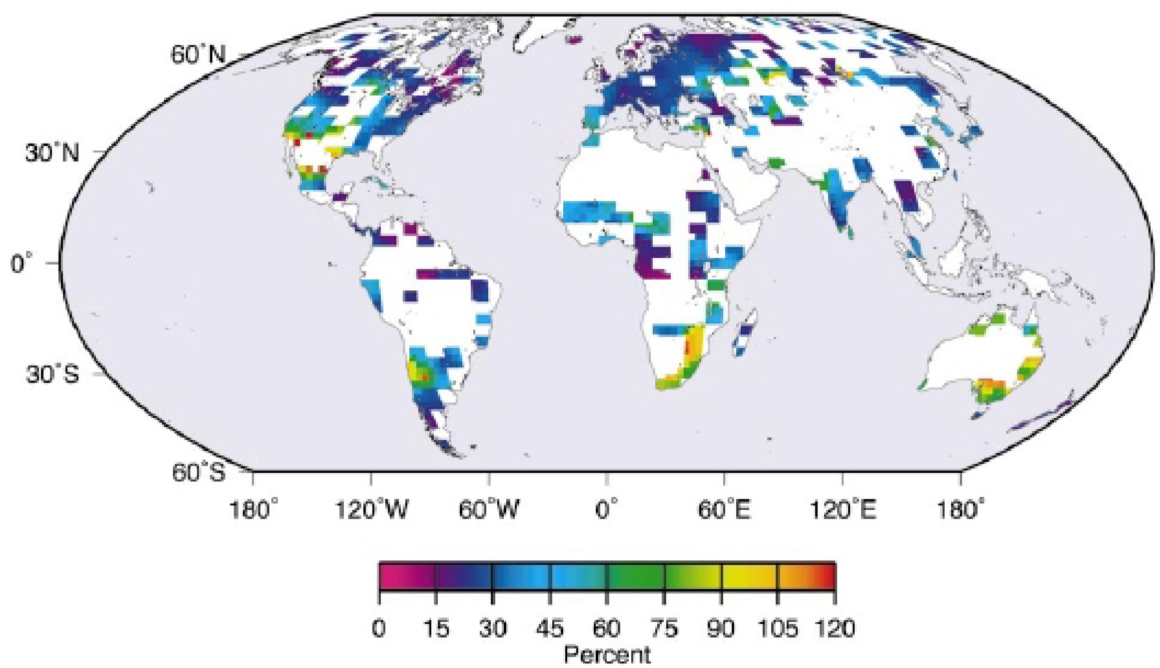
Given the strong links between flow regime, precipitation, evaporation and snow/ice melt; changes in climate and snow-ice storage are likely to induce major shifts in flow regimes and changes in their year-to-year reliability, reflecting an apparent intensification of the global water cycle (Huntington, 2006). They will also impact on the thermal regimes of rivers. These broad global patterns induced by global climate change will be intensified locally by human activity (e.g. Rosenberg et al., 2000, Tockner and Stanford, 2002, Vorosmarty and Sahagian, 2000) and will be considered in detail in this report at the regional scale (Section 4). Both flow and thermal regimes are crucial to ecosystem health (Anderson et al., 2006, Caissie, 2006) and thus to water-related ecosystem services, but linkages between flow regime changes and ecosystem changes are even more uncertain than those between climate and flow regime changes.

Figure 3.18 Long term average runoff efficiency (note values over 100% are generally in very humid often mountainous areas and reflect biases generated through measurement and data processing)



source: Dettinger and Diaz, 2000

Figure 3.19 Coefficient of variation of annual streamflow



source: Dettinger and Diaz, 2000

3.7 SUMMARY AND RESEARCH GAPS

Global mean temperature has been increasing since the late nineteenth century and this pattern is projected to continue in to the twenty-first century for various climate change scenarios, with the greatest warming occurring in the high latitudes. Observed trends in global precipitation are harder to locate but projections from climate models suggest large decreases over the Mediterranean and Caribbean regions, and the subtropical western coasts of each continent. Increases are projected over eastern Africa, central Asia, the equatorial Pacific Ocean, and at most high latitudes. These changing patterns will have implications for snow and ice storage, drought and flood occurrence, and river flow regimes, although the sign and magnitude of the changes will vary spatially across all spatial scales.

Research gaps at the global scale that are relevant to water-related ecosystem services include intensification of already highly-researched areas and the addition from some less researched areas. Specifically:

- There has been enormous research effort towards understanding and forecasting changes in global climate. Models are becoming more sophisticated and there seems to be increasing convergence in the projections based on particular scenarios of change. However, this crucial research area demands continuing and substantial research effort
- An area of particular relevance to the ESPA programme is to improve understanding of linkages and feedbacks between human modification of the earth surface, manipulation of the hydrological system and climate (e.g. Piao et al., 2007). Whilst land cover provides an important input to global climate models, research at finer spatial scales is suggesting interesting complexities in interactions between plants and their environment, which are highly relevant to ecosystems and their services. We will revisit this theme in section 4 of this report.
- Interactions between climate and hydrology have received considerable research attention, although the crucial association between climate and river flow regime (which integrates the impact of intervening hydrological flows and stores) is under-researched.
- Finally, the intimate association between river flow-sediment-quality regimes and water-related ecosystems, which were highlighted in section 2 and have been recognised to some degree at finer spatial scales, remain an important research gap at continental to global scales.

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4. REGIONAL SCALE

4.1 INTRODUCTION

At the regional scale, we focus on the provision and storage of precipitation, its translation into runoff and its potential ecosystem consequences within the ESPA regions, exploring both contemporary conditions and possible future changes (section 4.2). Particular emphasis is given to likely changes in snow and ice storage within the ESPA regions (section 4.3). In order to provide a spatial structure for a regional assessment that accords with water-related ecosystems, we use a simplified distribution of the 14 global biomes identified by Olson et al. (2001). In particular, we focus on sensitivity, changing condition and spatial shifts in ecotonal areas along biome margins (section 4.4). Lastly, we consider the consequences of major hydrological manipulations and human pressures (e.g. land use changes, extensive groundwater or reservoir development, direct river abstractions) on hydrological stores, fluxes and flow regimes (section 4.5).

4.2 CHANGES IN PRECIPITATION AND TEMPERATURE

In assessing provision and storage of precipitation valuable regional projections can be obtained from the coordinated set of 21 climate model simulations archived at the Program for Climate Model Diagnosis and Intercomparison (PCMDI). These simulations are hereafter referred to as the multi-model data set (MMD). Projections from PRECIS (Providing Regional Climates for Impacts Studies), a regional climate modeling system developed by the Met Office Hadley Centre, are also referred to.

4.2.1 China

Figure 4.1 illustrates the multi-model mean projected changes in temperature and precipitation over Asia, including China, for the 2090s relative to the 1990s, from the MMD for the A1B scenario. Mean temperature is projected to increase all over China, annually, and in the winter and summer respectively. The warming tends to be greatest in winter, and for the central continental areas of China, rather than along the eastern coast. Xu et al. (2005) estimated that the mean surface temperature for China increases by 3.89°C and 3.20°C by the period 2071-2080 relative to 1961-1990 for A2 and B2 scenarios respectively. The projections were based on PRECIS. Gao et al. (2002) and Xu et al. (2005) projected a reduced diurnal temperature range in China and larger increases in daily minimum than maximum temperatures.

Substantial changes in precipitation are also projected by the MMD (Figure 4.1). Increases in mean precipitation are projected over most of China, annually and seasonally. Similar to the projected patterns in temperature, the strongest changes occur in the winter. However, within China there are large regional differences in the magnitude of these changes. For example the largest increases in precipitation occur over northern and northeast China, especially in winter. The bottom panels in Figure 4.1 demonstrate that most of the 21 MMD models are in agreement about the increases here. South China exhibits smaller, or no increases in precipitation, and declines in precipitation are projected during the winter. Furthermore, less of the models project an increase in precipitation here.

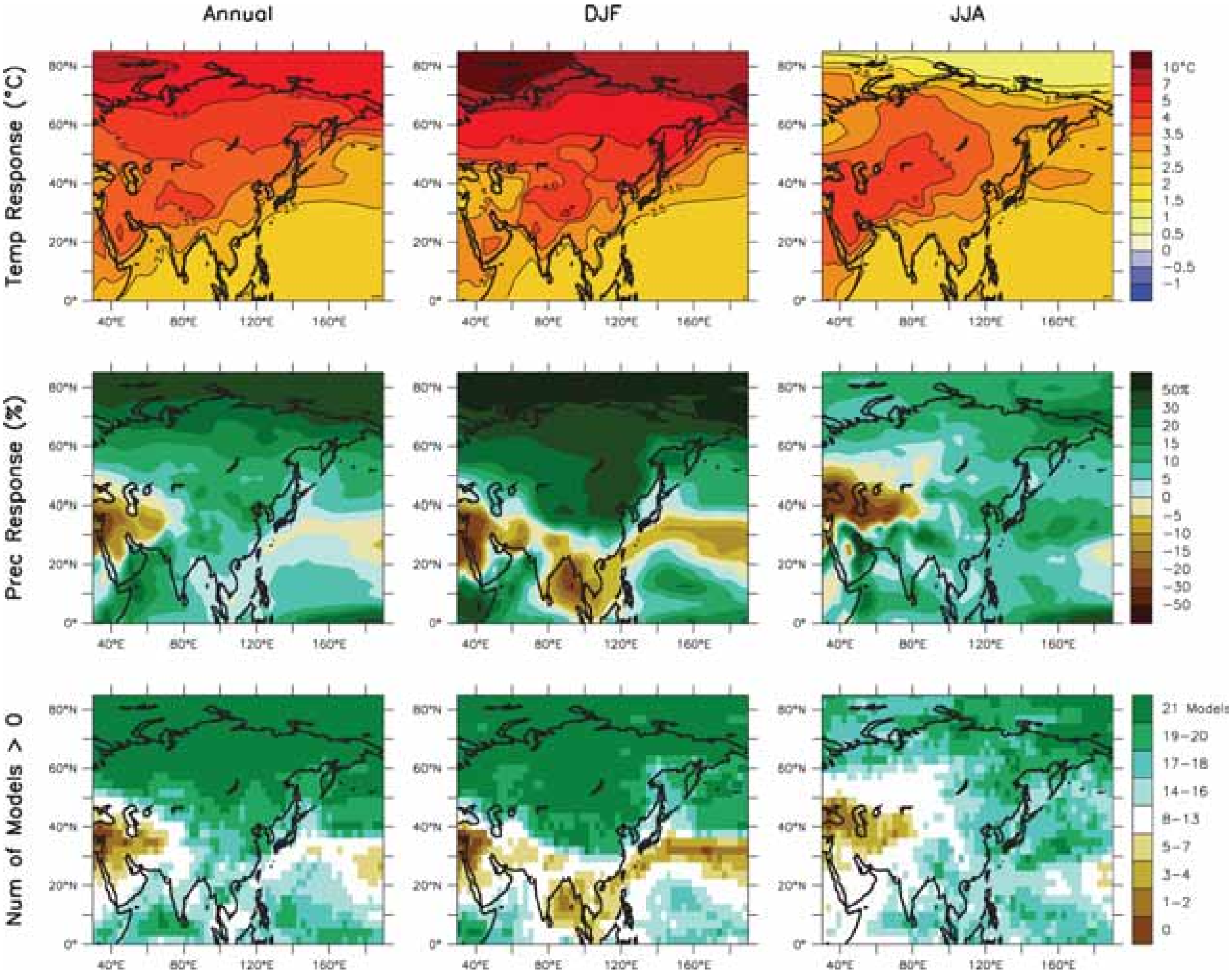
Xu et al. (2005) have quantified the magnitude of these changes by 2071-2100 relative to 1961-1990, for seven regions within China, using PRECIS and the B2 scenario (Table 4.1). Annually, precipitation increased in all regions, from 4% in northeast China to 13-14% in northwest and north China. The change for the whole of China was projected as 10%, and precipitation intensity was found to increase, as well as mean precipitation. In summer, mean precipitation changes were projected from 1-2% in northeast and north China, up to 15% in south China. The pattern changes in winter, when mean precipitation projections ranged from -36% in south China up to 63% in north China. Increases in summer temperature were projected for northeast China, north China, and northwest China, which coupled with the small increases in summer precipitation of less than 4% for the same regions, means that the climate would become warmer and drier over these three regions in the northern part of China. The increase in summer precipitation over south China would result in more flooding here, and in winter, drought would be exacerbated due to increased temperature and strong declines in precipitation. Projections analysed by Gao et al. (2002) would support this. They simulated an increase in the number of rainy days in northwest China, and a decrease in rain days but an increase in days with heavy rain over South China.

4.2.2 Southern Asia

Projected mean temperature changes for southern Asia from the MMD-A1B simulations are illustrated in Figure 4.1. The median increase in annual mean temperature by the end of the twenty-first century relative to present, from the 21 models for southern Asia is 3.3°C – the maximum warming projected by any model is 4.7°C and the minimum is 2.0°C (Christensen et al. 2007). The warming tends to increase northwards in the area, from sea to land, especially in the winter. Results from PRECIS, presented by Kumar et al. (2006) indicate that daily minimum temperatures increase a greater amount than daily maximum temperatures, which suggests that cold extremes are very likely to be less severe by the end of the twenty-first century. Similarly, Krishna Kumar et al. (2003), used HadRM2 (the Hadley Centre Regional Model) to demonstrate that under the IPCC Scenario IS92a, by the mid-twenty-first century, daily maximum and minimum temperature would increase by 2-4°C over southern Asia.

Most of the MMD-A1B models project a decrease in precipitation during the dry season (DJF; see Figure 4.1), which when coupled with the increases in temperature will increase the risks of drought, especially for in-land areas. By the end of the twenty-first century, the MMD-A1B median change in DJF precipitation for southern Asia is –5% (Christensen et al. 2007). However, there is a large spread in the changes across models. For example, the lowest change in DFJ precipitation is projected as –35%, whereas the greatest is opposite in sign, being 15%. The media JJA change is estimated as 11%, and with slightly less uncertainty in the sign of the change (minimum model change is –3% and the maximum change is 23%; Christensen et al. 2007). Annually, the MMD-A1B models project increases in precipitation – the median change is 11% by the end of the twenty-first century. However, the bottom panel of Figure 4.1 illustrates that there is still a large spread across the 21 models, regarding whether they project an increase in annual precipitation. Likeweise, Tebaldi et al. (2004) employed a probabilistic Bayesian analysis to demonstrate that only 3 of the 21 models projected a decrease in annual precipitation. Krishna Kumar et al. (2003) present projections from HadRM2 under

Figure 4.1. Temperature changes (°C) and precipitation changes (%) over Asia from the MMD-A1B simulations. Top row illustrates the annual mean, DJF and JJA temperature change between 1980-1999 and 2080-2099, averaged over 21 models. Middle row illustrates same as top, but for fractional change in precipitation. Bottom row illustrates the number of models out of 21 that project increases in precipitation. Note that the plots cover 2 of the 4 regions assessed in this report: China and Southern Asia.



Source: Christensen et al. (2007), p. 883.

Table 4.1. 2071-2100 average changes (%), relative to 1961-1990, of mean precipitation under the B2 scenario over seven regions in China from PRECIS.

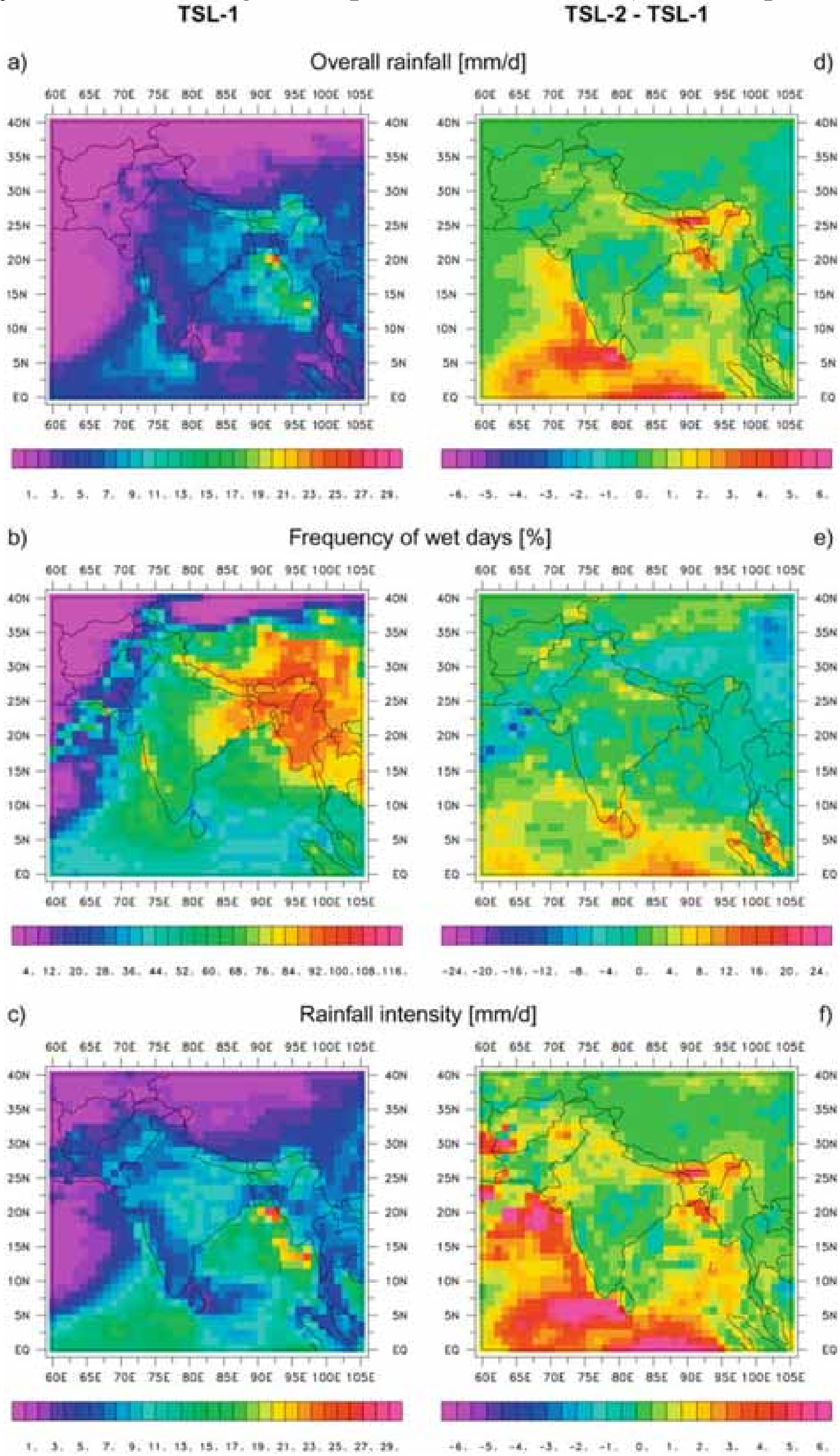
Region	Annual	Summer	Winter
Northeast China	4	1	43
North China	14	2	63
Central China	11	8	2
East China	9	11	2
South China	8	15	-36
Southwest China	9	7	8
Northwest China	13	4	38
Whole China	10	6	9

Source: Adapted from Xu et al. (2005), p. 52.

the IS92a scenario that indicate a general decrease of up to 15 days in the annual number of rainy days over much of southern Asia by the 2050s. However, the HadRM2 projections did indicate increases in precipitation intensity and extreme precipitation.

Several other studies have examined how precipitation intensity may change with global warming in southern Asia. Analyses by Kumar et al. (2006) used PRECIS and the A2 and B2 scenarios to show substantial increases in extreme precipitation over much of southern Asia, especially over the west coast of India and west central India. Simulations from HadRM2, analysed by Unnikrishnan et al. (2006) demonstrate increases in the frequency and intensity of tropical cyclones in the 2050s under the IS92a scenario in the Bay of Bengal. These cyclones would cause more heavy precipitation than currently observed in the surrounding coastal regions of South Asia, during both southwest and northeast monsoon seasons. May (2004) used the ECHAM4 climate model to demonstrate that a climate warming associated with a doubling of atmospheric CO_2 concentrations relative to present, would be associated with general increases in the intensity of future heavy rainfall events. Large increases were observed over the Arabian Sea, the tropical Indian Ocean, northern Pakistan, northwest India, northeast India, Bangladesh and Myanmar. These results are presented clearly in Figure 4.2. Figure 4.2d) shows that overall rainfall is projected to increase in areas where the monsoon rainfall is rather strong, such as on the Indian west coast, the northern areas of the Bay of Bengal reaching into Bangladesh, and in northeast India. However, overall rainfall is reduced over areas where monsoon rainfall is weaker, including the northern part of the Indian peninsula and over the adjacent part of the Bay of Bengal, and southern Pakistan. These changes are indicative of an overall intensification of monsoon rainfall caused by a strengthening of the atmospheric moisture transport into the Indian region (May, 2004). However, the increase in monsoon rainfall over the tropical Indian Ocean is due to a northward shift of the tropical convergence zone in the future. The positive changes in intensity (Figure 4.2f)) are projected to be larger in magnitude over the tropical Indian Ocean and the northern part of the Arabian Sea because the frequency of wet days (Figure 4.2e) is considerably smaller than 100%. Similar to overall rainfall, rainfall intensity is reduced in the northern part of the Indian peninsula, over the adjacent part of the Bay of Bengal, and in southern Pakistan. Similar findings to May (2004) are presented by Dairaku and Emori (2006). A doubling of atmospheric CO_2 concentrations from present day levels was associated with a northward shift of lower tropospheric monsoon circulation, and an increase in mean precipitation during the Asian summer monsoon. Furthermore, the number of extreme daily precipitation events increased significantly. Increases in mean and extreme precipitation were both attributed to thermodynamic changes (a greater atmospheric moisture content, and dynamic changes (an enhanced upward motion due to the northward shift of monsoon circulation). Dynamic changes played a greater role in the enhanced precipitation over land in South Asia.

Figure 4.2. Simulated present day rainfall (left column; TSL-1), and the difference between future (climate change) rainfall and present day rainfall (right column; TSL-2 – TSL-1). A) and d) illustrate the overall mean daily rainfall; b) and e) the frequency of wet days; c) and f) the mean daily rainfall on wet days during the monsoon season (June to September).

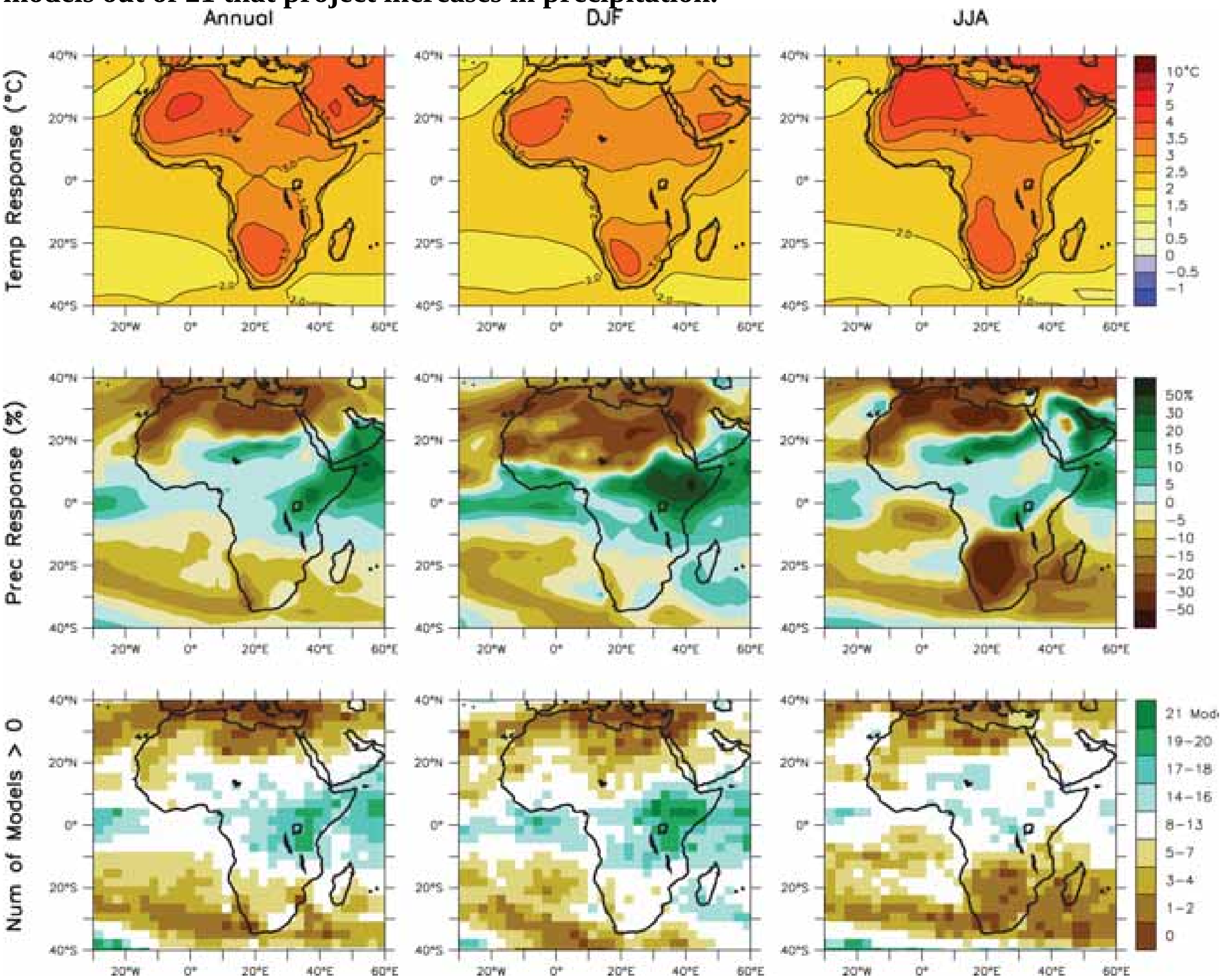


Source: May (2004), p. 191.

4.2.3 Sub-Saharan Africa

The median temperature increase for Sub-Saharan Africa across all 21 MMD-A1B models, by the end of the twenty-first century, relative to 1980-1999, is between 3.2°C and 3.4°C, which is approximately 1.5 times the global mean response (Christensen et al. 2007). The inter-model spread of the projections is relatively small, with half of the models projecting warming within about 0.5°C of these median values. The spatial patterns of the MMD-A1B projections of surface temperature for Africa, including the Sub-Saharan region, are displayed in Figure 4.3. The greatest warming occurs in JJA, and in southern Africa (excluding the Western Sahara), away from coastal regions. Warming in coastal regions is typically 0.5-1.0°C lower than in-land.

Figure 4.3. Temperature changes (°C) and precipitation changes (%) over Africa from the MMD-A1B simulations. Top row illustrates the annual mean, DJF and JJA temperature change between 1980-1999 and 2080-2099, averaged over 21 models. Middle row illustrates same as top, but for fractional change in precipitation. Bottom row illustrates the number of models out of 21 that project increases in precipitation.



Source: Christensen et al. (2007), p. 869.

The bottom 2 rows of Figure 4.3 illustrate robust patterns across the 21 MMD-A1B models in precipitation change over Sub-Sahara Africa. These changes are principally a drying in southern Africa, and an increase or little change in precipitation in the tropics, especially over East Africa, extending into the Horn of Africa where 18 of 21 models project an increase in precipitation. Clearly, there is also a strong drying in the subtropics over the Sahara, but this region is not the focus of this review. This pattern of wetting and drying is most likely a hydrological response to a warmer atmosphere - increased water vapour in the atmosphere would result in increased vapour transport from regions of moisture divergence to regions of moisture convergence (Hegerl et al. 2007). Similarly, a poleward shift in the circulation across the South Atlantic and Indian Oceans might explain the winter drying observed across the south-west coast of the region (Christensen et al. 2007).

The patterns of precipitation change described above have been observed in other studies, although the majority focus on southern Africa. Ruosteenoja et al. (2003) examined seven climate models with the A2 and B2 scenarios. Precipitation decreases over southern Africa in the second half of the year, by the end of the twenty-first century, were observed in all seven of the models. This confirms the robustness of the decreases presented in Figure 4.3. Hulme et al. (2001) examined the same 7 climate models as Ruosteenoja et al. (2003) and demonstrated that by the late twenty-first century East African rainfall increased by 5-30% in DJF, and decreased by 5-10% in JJA, under the B1 scenario. Significant decreases in DJF rainfall of 15-25% were projected over much of South Africa and Namibia. Tadross et al. (2005) examined two RCMs, PRECIS and the Mesoscale Model version 5 (MM5) under the A2 scenario. Increases in total rainfall in January and February towards the east of the region were projected by both models. Hewitson and Crane (2006) analysed precipitation projections for the 2080s from six climate models under the A2 scenario. The ensemble means showed increased precipitation in east Africa extending into southern Africa, especially in JJA, strong drying in the core Sahel in JJA with some coastal wetting, and moderate wetting in DJF.

However, projections over the Sahel are less robust than over other tropical areas in the region. For example, Christensen et al. (2007) state that the GFDL/CM2.1 (NOAA's Geophysical Fluid Dynamics Laboratory Climate Model 2.1) climate model projects very strong drying in the Sahel and throughout the Sahara, but the MIROC3.2 (The Model for Interdisciplinary Research on Climate) climate model shows a very strong trend towards increased rainfall in the same region. Hence more research is needed to understand the variety of modelled precipitation responses in the Sahel. Paethe and Hense (2004) argue that the slight demise of the Sahel drought since the 1990s may be indicative of greenhouse-gas driven increased rainfall, which would support models such as MIROC3.2 where the Sahel moistens into the twenty-first century.

4.2.4 Amazonia

The spatial patterns of the MMD-A1B projections of surface temperature for South America, including the Amazonia region, are displayed in Figure 4.4. The annual mean warming between 1980-1999 and 2080-2099 in the Amazonia region varies across the climate models from 1.8°C to 5.1°C, with half of the models within 2.6°C to 3.7°C. The median warming estimated by the 21 MMD-A1B models is 3.3°C, which is about 30% above the global mean value. The greatest warming is projected to occur in inner Amazonia, with less warming around coastal areas. There is some seasonal variation, with the warming in central Amazonia tending to be greater in JJA than DFJ.

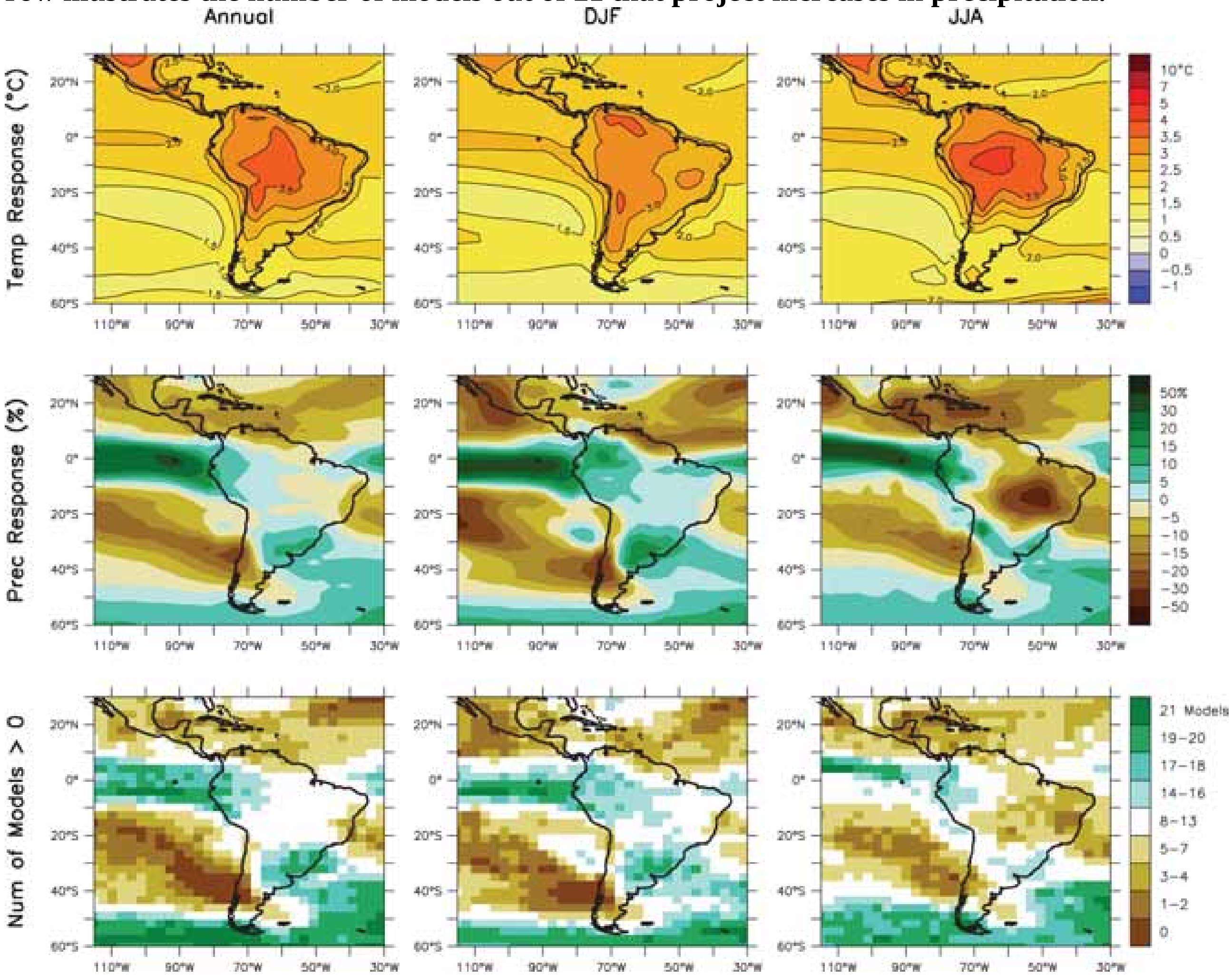
Figure 4.4 displays MMD-A1B precipitation projections for Amazonia. The inter-model median of annual precipitation change averaged over the Amazonia region is 0% (Christensen et al.

2007). This implies that no change in annual precipitation is projected by the late twenty-first century. However, the left middle panel of Figure 4.4 illustrates that there is spatial variation in the magnitude of projected annual precipitation change within the Amazonian region. Precipitation decreases over northern South America near the Caribbean coasts, and over large parts of northern Brazil. Increases are projected over Colombia, Ecuador and around the equator. These changes are modulated by the seasonal cycle, in particular over the Amazon Basin where monsoon precipitation increases in DJF and decreases in JJA. Note that the magnitude of the JJA drying is greater than the magnitude of the DFJ wetting. Also, the sign of the response is preserved throughout the seasonal cycle over the northern tip of the region (JJA and DJF drying) and along the western coast (JJA and DJF wetting). Boulanger et al. (2007) analysed results from seven climate models using neural networks and Bayesian statistics. General decreases were observed over the Amazonian Basin under the A2 scenario, although there were strong divergences across the models. The divergence is hardly surprising given results from the MMD-A1B models – the lowest change between 1980-1999 and 2080-2099 in annual precipitation projected by any model was -21% and the maximum was 14%, with a median of 0%.

Multi-model projections of the global climate indicate a weak shift towards conditions which may be described as 'El Niño-like' (Meehl et al. 2007). El Niño-like conditions are represented by a warming in sea surface temperatures in the central and eastern equatorial Pacific, which is greater than the warming in the west, and with an eastward shift in mean precipitation. It is possible that the drying over east-central Amazonia and northeast Brazil could be a partial consequence of the El-Niño like response projected by the MMD-A1B models. Cox et al. (2004) demonstrated that high CO2 concentrations in the Hadley Centre climate-carbon cycle global climate model lead to an El-Nino-like SST warming pattern which suppresses rainfall across northern Amazonia. CO2-fertilisation of photosynthesis maintains the rainforest cover for the first half of the 21st century, but the extreme warming and drying eventually leads to abrupt reductions in the forest fraction. The loss of rainforest, known as Amazonian dieback, was found to exacerbate the Amazonian climate change by releasing CO2 to the atmosphere, and by changing the properties of the land-surface.

Little research is available on extremes of temperature and precipitation for this region. Hegerl et al. (2004) examined an ensemble of simulations from two climate models. Both models projected more intense wet days per year over large parts of south-eastern South America and central Amazonia and weaker precipitation extremes over the coasts of northeast Brazil. The intensification of the rainfall amounts are consistent, given the agreement between the MMD-A1B model simulations over most of Amazonia in Figure 4.4. However, longer periods are projected between the rainfall events, i.e. a reduction in frequency (Tebaldi et al. 2006).

Figure 4.4. Temperature changes (°C) and precipitation changes (%) over South America, including Amazonia, from the MMD-A1B simulations. Top row illustrates the annual mean, DJF and JJA temperature change between 1980-1999 and 2080-2099, averaged over 21 models. Middle row illustrates same as top, but for fractional change in precipitation. Bottom row illustrates the number of models out of 21 that project increases in precipitation.



Source: Christensen et al. (2007), p. 895.

4.2.5 Summary of expected changes

To aid consideration of water-related ecosystems in the remainder of this section, we now attempt a simplified summary of projected changes in precipitation and temperature in the four ESPA regions

China: Mean temperature is projected to increase (> 3^{o}C by 2080-99) all over China, both annually and seasonally, with greatest warming during winter and across the central continental areas of China, rather than along the eastern coast. Daily minimum temperatures are projected to increase more than maximum temperatures, giving a reduction in diurnal temperature range. Mean precipitation is also projected to increase over most of China both annually and seasonally, with the strongest increases in winter (average of +10% by 2071-2100). However, there are large regional differences within China in the magnitude of these changes. The largest increases are projected to occur over northern China (+4% in northeast to +13 to14% in northwest and north), especially in winter (+63%), whereas south China exhibits smaller, or no increases in precipitation, with declines in precipitation during the winter (-36%). Overall, the climate in northeast, north and northwest China is projected to become warmer and drier, whereas in south China, drought will be exacerbated due to increased temperature and strong declines in precipitation, especially in winter, although flooding may be induced by increased rainfall intensity.

Southern Asia: The median modelled increase in annual mean temperature by the end of the twenty-first century relative to present for southern Asia is 3.3°C. The warming increases northwards and from sea to land, especially in the winter. Daily minimum temperatures are projected to increase more than maximum temperatures, giving a reduction in diurnal temperature range. Precipitation is mainly projected to decrease during the dry season (-5%), increasing the risk of drought in drier areas. Within the region, an intensification of monsoon rainfall is projected, with an increase in areas where the monsoon rainfall is strong (e.g. Indian west coast, northeast India, the northern areas of the Bay of Bengal, Bangladesh) and a decrease over areas where monsoon rainfall is weaker (e.g. northern part of the Indian peninsula and the adjacent part of the Bay of Bengal, and southern Pakistan). However, there are large differences in projections between models. Intensity of extreme precipitation events is projected to increase over much of southern Asia, especially over west and west central India, with increases in the frequency and intensity of tropical cyclones in the Bay of Bengal.

Sub-Saharan Africa: The median temperature increase for Sub-Saharan Africa by the end of the twenty-first century is consistently projected to be between 3.2°C and 3.4°C. Greatest warming is projected to occur in winter and away from coastal regions. Precipitation is projected to decrease in southern Africa with little change or an increase northwards into the tropics. Increases are especially projected for East Africa (5-30% in summer, 5-10% in winter) and the Horn of Africa. A significant decrease (15-25% in summer) is projected for much of South Africa and Namibia. However, projections are uncertain, varying widely between models, particularly for the Sahel region.

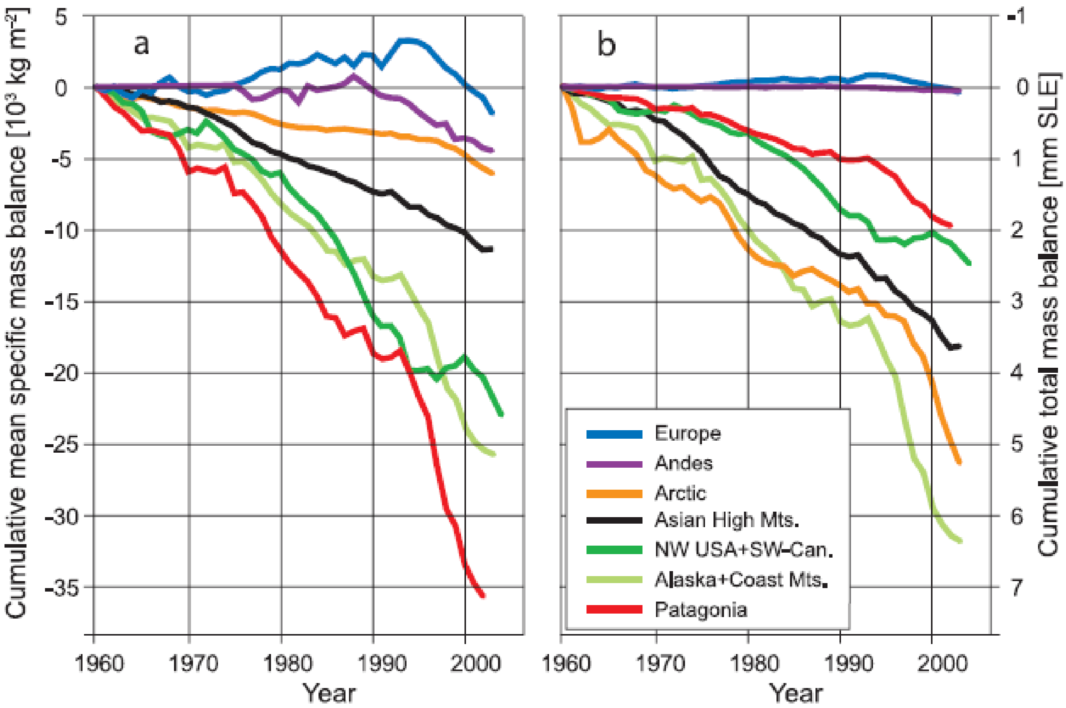
Amazonia: The annual mean warming projected in the Amazonia region for 2080-2099 varies widely across models from 1.8°C to 5.1°C, although several give projections between 2.6°C and 3.7°C, with an overall median projection of 3.3°C. Greatest warming is projected to occur in inner Amazonia. Seasonal warming in central Amazonia is projected to be greater in JJA than DFJ. Median projected annual precipitation change is 0%, with a decrease over northern South America near the Caribbean coasts, and over large parts of northern Brazil and an increase projected over Colombia, Ecuador and around the equator. Changes in the seasonal cycle are projected over the Amazon Basin with monsoon precipitation increases in DJF and decreases in JJA. However, high CO2 concentrations in the Hadley Centre climate-carbon cycle global climate model lead to an El-Nino-like warming pattern which suppresses rainfall across northern Amazonia. CO2-fertilisation of photosynthesis maintains the rainforest cover for the first half of the 21st century, but the extreme warming and drying eventually leads to abrupt reductions in the forest fraction, known as Amazonian dieback, which then exacerbates climate change by releasing CO2 to the atmosphere and changing land-surface properties.

4.3 SNOW AND ICE

The accumulation and melt of precipitation in snow and ice stores under global warming is particular relevant to two of the ESPA regions. Snow and ice melt driven river regimes are particularly important to large parts of the China and S Asia ESPA regions, but also influence the water resources of parts of Amazonia (Bradley et al, 2006).

Approximately one-sixth of the Earth's population relies on glaciers and seasonal snow packs for a very significant component of their water supply (Barnett et al., 2005; UNEP, 2007). Snow and glacier masses feed major rivers supplying large populations and confer unique runoff characteristics on these river systems. Over the last decade, glaciers have generally been shrinking and within the ESPA regions, this has been particularly marked in Asia (Figure 4.5, Meier et al, 2003, Lemke et al., 2007). Precipitation falling as snow is forecast to reduce dramatically (Figure 4.6, UNEP, 2007), implying further major shrinkage of glaciers and snowpacks.

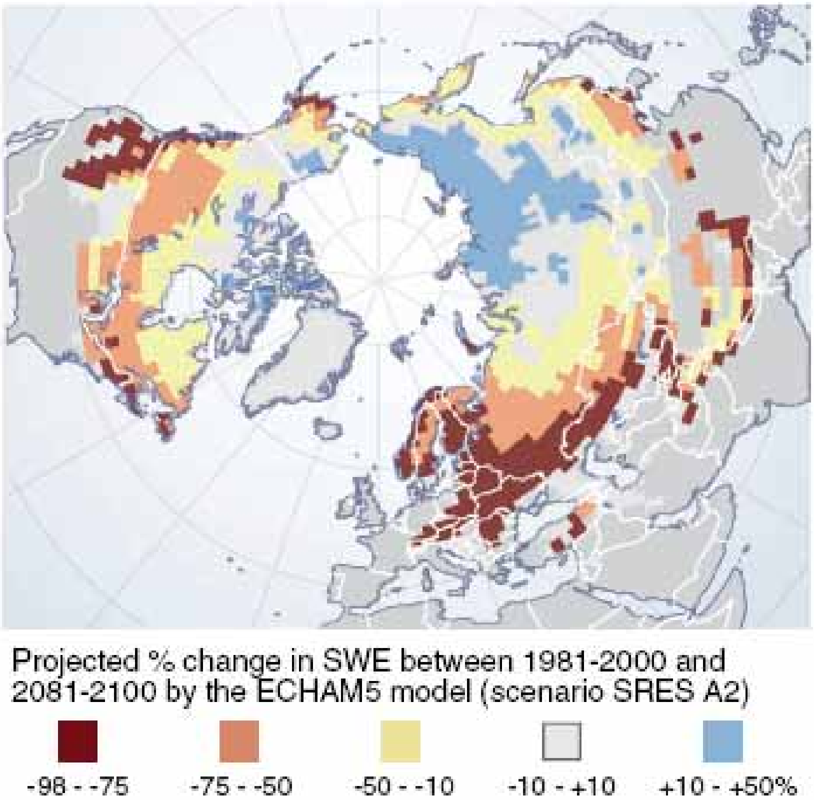
Figure 4.5 Cumulative mean specific mass balances (a) and cumulative total mass balances (b) of glaciers and ice caps for different regions (based on information from Dyurgerov and Meier, 2005).



source: Lemke et al. (2007)

With global warming, less precipitation will fall as snow, whereas melt from snow and ice storage will increase. Changes in albedo of glacier surfaces as a result of a decrease in precipitation input as snow and an increase in snow and ice melt, will lead to additional ice melt (Fujita et al., 2007) as will the fragmentation of large (slower responding) glaciers into smaller (highly-responsive) glaciers (e.g. Kulkarni et al., 2007). Such trends may influence both annual and seasonal runoff. For example, there may be an increase in the reliability of seasonal water supply in some areas, since increases in precipitation falling as water may extend the snow and ice melt runoff season and buffer the range in seasonal and annual river flows. However, accelerated glacier melt often lubricates the flow of warm-based glaciers, transporting more ice down to lower elevations where rapid melt can occur and also inducing hazardous events such as meltwater outburst floods through the disruption of englacial and subglacial hydrological pathways. In contrast, global warming may induce thinning and basal warming of cold-based glaciers, leading to a predominance of glacier motion by basal sliding rather than ice deformation to provide an extended melt regime. Continuing shrinkage of glaciers in response to global warming may lead to the disappearance of glaciers from many mountain regions, with major implications for water resources in the Himalayas–Hindu Kush (Cyranoski, 2005), where strategies for water management and land-use planning are urgently needed to reduce vulnerability to the impacts of global warming (UNEP, 2007).

Figure 4.6 Percent change in monthly maximum snow water equivalent between 1981–2000 and 2080–2100 (simulated by the ECHAM5 climate model under conditions defined by the SRES A2 emission scenario).



source: UNEP (2007)

The potential complexities of these changes within and between river basins are illustrated by attempts to model the consequences of climate warming across the Himalayan arc. For example, Singh and Bengtsson (2004) modelled the sensitivity of runoff to warming for the Satluj River basin (western Himalaya, area 22275 km^2, elevation range 500-7000 m), which receives rain, snow- and glacier-melt runoff. They found a reduction in melt in the lower part of the basin, reflecting a reduction in snow covered area and shortening of the summer melting season, and an increase in the melt from the higher, glacierized part, reflecting higher melt rates and a longer ablation period. Whilst these interacted to buffer the impact on total annual runoff, there was a marked change in the annal flow regime with less water available during the summer period, when water resource demands, particularly for irrigation and hydropower, are highest. Rees and Collins (2006) used a degree-day model to investigate changing responses under warming scenarios along the entire

Himalayan arc. The monsoon weakens and summer precipitation declines from east to west. Westerly winds bring precipitation in the west and at higher elevations throughout the Himalaya in winter, but total annual precipitation generally increases from west to east. As a result of the arid conditions at lower elevations in the west, meltwater from snow and ice accumulations is the major component of runoff for great distances downstream and so is crucial to regional water resources. For example, the population and economy of Pakistan are heavily dependent on an annual influx of about 180 billion cubic meters of water into the Indus river system, that comes largely from snow-melt in the Himalayas (World Bank, 2005). In contrast, monsoonal precipitation is an important flow component at all elevations along river systems in the more humid east. Rees and Collins (2006) estimated that under a uniform warming of $0.06^oC.yr^{-1}$, flows for highly glacierized subcatchments (>50%) would achieve runoff maxima at approximately 150-170% of initial flow around 2050 and 2070 in the west and east, respectively, before declining until the glaciers disappeared in 2086 and 2109, respectively.

Even in areas where exotic water from snow and glacier melt is not crucial to total water resources, a transfer from melt- to rainfall-dominated river flows will be accompanied by major seasonal shifts in river flow and groundwater regimes. Changes in the amount of precipitation will affect the volume of runoff whereas temperature changes will largely affect the timing of runoff. Warming will generally result in earlier runoff in the spring-winter and reduced flows in summer-autumn (Barnett et al. 2005), which could represent a crucial change in areas where summer water demands are high. Where warming reduces permafrost extent (e.g. NE China, some high areas of the Himalayas), catchments become less responsive to melt during winter with a greater proportion of runoff routed through the active layer and contributing to an attenuated hydrograph during spring snow melt (e.g. Liu et al., 2003). Another impact of changing snow and ice extent is a change in loads and calibre of sediment transported in river systems (e.g. Gurnell et al., 1996).

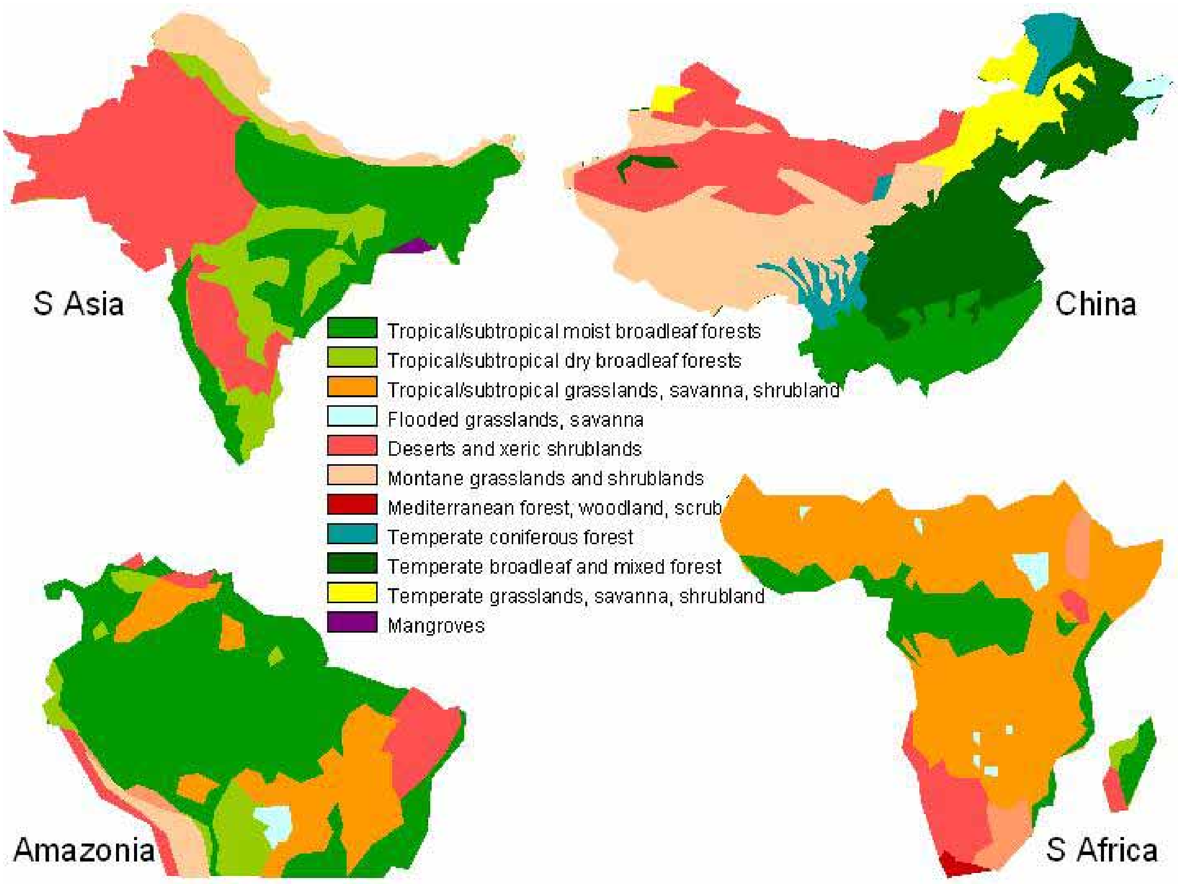
4.4 ECOREGIONS, CLIMATE AND HYDROLOGICAL CHANGE

4.4.1 Terrestrial Biomes in the ESPA Regions

Important feedbacks exist between landcover and hydroclimatic conditions. Therefore, ecoregions or biomes provide a useful framework for investigating the sensitivity of different regions to changes in climate, land cover and water-related ecosystems.

Figure 4.7, shows a simplified distribution of the 14 global terrestrial biomes identified by Olson et al. (2001). These biomes were further subdivided into 867 ecoregions, but the biome scale provides an appropriate resolution for the present regional assessments. 11 of the 14 biomes are found within the ESPA regions. Descriptions of the biomes and associated ecoregions can be obtained from the WWF website (see: http://www.panda.org/about_wwf/where_we_work/ecoregions/about/habitat_types/selecting_terrestrial_ecoregions/) and provide the core source of information for the summaries of characteristics and sensitivities to disturbance given below.

Figure 4.7 Terrestrial biomes within the four ESPA regions



based on Olson et al. (2001)

Tropical/subtropical moist broadleaf forests (ESPA regions: All) form large, discontinuous patches around the equatorial belt in areas characterized by low variability, warm annual temperature and high annual rainfall (>2000 mm). These forests are dominated by semi-evergreen and evergreen deciduous tree species, exhibiting the highest levels of plant species diversity in any terrestrial major habitat type and supporting more species than any other terrestrial ecosystem. This biome contains 35% of terrestrial ecoregions, of which the most diverse occur in Amazonia. These habitats are highly sensitive to ploughing, overgrazing, and excessive burning.
Tropical/subtropical dry broadleaf forests (ESPA regions: Amazonia, S Africa, S Asia) occur in areas with warm temperatures throughout the year, high annual rainfall but a marked dry season. Deciduous trees predominate and shed their leaves during the dry season to control moisture loss, opening the canopy to support growth of a thick understorey. Though less biologically diverse than rainforests, they support a wide variety of wildlife. The retention of water sources and riparian forests is critical for many dry forest species. These forests are highly sensitive to excessive burning and deforestation.
Tropical/subtropical grasslands, savanna, shrubland (ESPA regions: Amazonia, S Africa, S Asia) occur in areas with warm annual temperatures where there is insufficient rainfall to support extensive tree cover. They are characterized by seasonally variable rainfall with annual totals between 900 and 1500 mm. Wide variability in soil moisture through the year leads to a vegetation cover dominated by grasses, although scattered trees can be common. Animals require large areas to

track seasonal water sources, which are critical for many species. Ploughing, overgrazing and excessive burning can cause rapid degradation, although restoration potential is high.

Flooded grasslands and savanna (ESPA regions: Amazonia, S Africa, S Asia) are large expanses or complexes of highly productive flooded grasslands, supporting numerous plants and animals adapted to the unique hydrological regimes and soil conditions. Maintaining hydrogrological integrity is critical to these habitats because many species track flooding patterns and seasonal abundance of resources, and utilize riparian habitats. These habitats are highly sensitive to diversion and channelization of water flow, water quality changes (e.g. pollution, eutrophication), and alteration of natural fire regimes.

Deserts and xeric shrublands (ESPA regions: Amazonia, China, S Africa) vary greatly in the amount of annual rainfall they receive, but generally evaporation exceeds rainfall, which is <250mm annually. Seasonal temperatures vary widely, with many being hot throughout the year and others experiencing cold winters, but diurnal temperature ranges are always large. Many habitats are ephemeral, reflecting the limited and often seasonal availability of water, and many species track seasonally variable and patchy resources, particularly water. Landscapes are highly sensitive to grazing, soil disturbance, burning, ploughing, and other land cover alterations. Restoration potential is low and regeneration is slow.

Montane grasslands and shrublands (ESPA regions: All) occur in tropical, subtropical, and temperate areas. Plants and animals often display strong adaptations to cool, sometimes moist, conditions and intense sunlight. Large areas are required for animals to track widely distributed seasonal or patchy resources; water sources and riparian vegetation are important for wildlife in drier regions. These fragile habitats are highly sensitive to ploughing, overgrazing, and excessive burning.

Mediterranean forest, woodland, scrub (ESPA regions: S Africa) are characterized by warm, dry summers and cool, moist winters. Regional and local endemism is common and some species have highly restricted ranges. Natural communities are highly sensitive to habitat fragmentation, grazing, and alteration of fire regimes. Restoration of communities is feasible but fire regimes must be restored and exotics controlled.

Temperate coniferous forest (ESPA regions: China) are found predominantly in areas with warm summers and cool winters. They vary enormously in the nature of the plants they support. In some, needle-leaf trees dominate, while others are home primarily to broadleaf evergreen trees or a mix of both tree types. Most tree species have relatively widespread distributions and are highly sensitive to logging and fragmentation because late-successional species and features typically regenerate slowly.

Temperate broadleaf and mixed forests (ESPA regions: S Asia, China) experience wide variability in temperature and precipitation. Most dominant species have widespread distributions, although many ecoregions support local endemics. Certain species are highly sensitive to habitat fragmentation but restoration potential is high. Exotic species can have significant impacts on native communities.

Temperate grasslands, savanna, shrubland (ESPA regions: China) differ from tropical grasslands in their cooler annual temperature regime. There are few trees apart from riparian / gallery forests along streams and rivers. Many animals require large areas to track seasonal or patchy resources including water, and to escape from fire. Ploughing, overgrazing and excessive burning can drastically alter species composition and restoration potential and can lead to severe degradation. Loss and degradation of riparian or gallery forest habitats and water sources (from overexploitation of water resources or land cover modification) has significant impacts on wildlife and can result in severe land degradation.

Mangroves (ESPA regions: All) occur in the waterlogged, salty soils of sheltered tropical and subtropical shores. Mangroves stretch from the intertidal zone up to the high-tide mark and thrive in areas of soft, waterlogged, oxygen-poor soil. A wide variety of aquatic and salt-tolerant plants are associated with mangroves, providing important nursery habitats for numerous aquatic animal species. Mangroves require relatively intact hydrographic and salinity regimes. Alterations to these regimes and also to substrate (e.g. as a result of freshwater and sediment inputs from terrestrial biomes) have considerable impact, and mangroves are susceptible to pollution, particularly from oil and petroleum compounds.

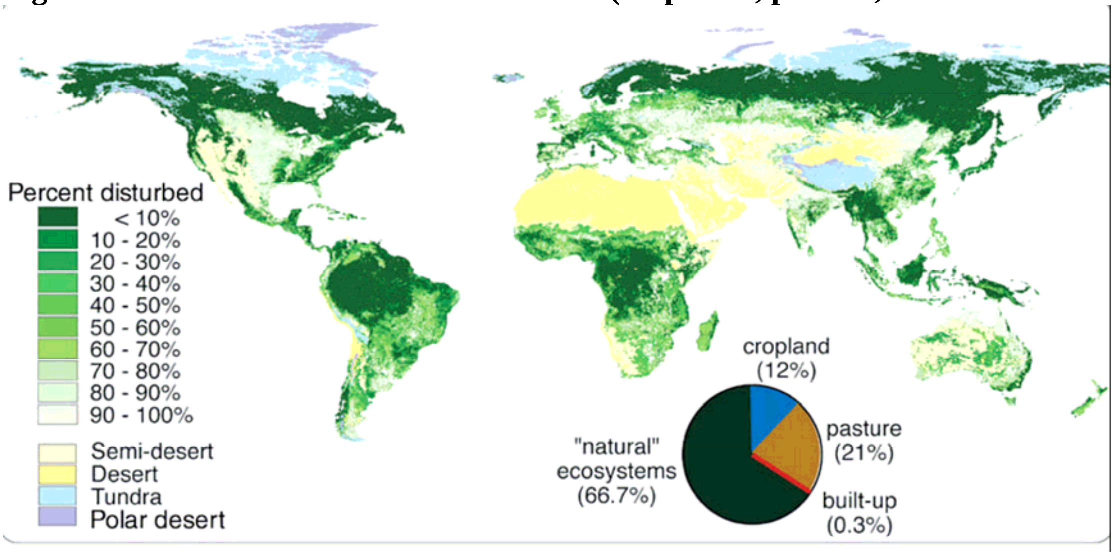
4.4.2 Biome sensitivity to environmental change

Changes in climate affect vegetation through mechanisms of plant physiology and competition and these mechanisms, in turn, can have significant impacts on the water cycle at a range of spatial scales (Scheffer et al., 2005). Also changes in photosynthesis, plant respiration and organic matter decomposition induced by climate change influence the land-atmosphere carbon flux (Scholze et al., 2006) and thus directly affect levels of atmospheric carbon. Such interactions are accentuated by human-induced changes in land and water use to the extent that Piao et al. (2007) argue that, despite important potential interactions between CO_2 and vegetation, land use change (especially in the tropics) has had a larger influence on runoff than climate change over the last century and both have disguised trends attributable to direct interactions between vegetation and CO_2.

Interactions between climate and vegetation can lead to important adjustments within and between biomes, including large potential changes in biodiversity (e.g. Van Vuuren et al., 2006) as well as physical structure (e.g. Dale et al., 2001) and spatial extent, that may have crucial implications for water-related ecosystem services within the ESPA regions. Foley et al. (2000, 2003) explain the crucial importance of incorporating a dynamic vegetation cover into global climate models (see also Cramer et al., 2001). Changes in vegetation imply changes in the physical properties of the land surface (albedo, roughness, leaf-area index, rooting depth, available moisture), which induce changes in physical (fluxes of energy and momentum) and biophysical feedbacks (fluxes of matter, mainly carbon and water) in association with climate changes. Foley et al. (2000) suggest that these interactions between atmosphere and biosphere operate in characteristic ways across three timescales: (i) seconds to hours – exchanges of energy, water, CO_2 and momentum induced by biophysical and physiological processes; (ii) days to months – changes in budburst, senescence, dormancy induced by changes in soil moisture, carbon allocation, vegetation phenology; (iii) seasons, years, decades – changes in stand growth, disturbance, land use as a result of fundamental changes in the nature of the vegetation cover. Foley et al. (2003) demonstrate the high level of clearance of natural vegetation that has occurred across the globe, noting that apart from desert and polar regions, the two zones that still retain significant areas of relatively low exploitation are the tropical rain forests of S. America, Africa, SE Asia and boreal forests of Russia and Canada (Figure 4.8). The former are particularly relevant to ESPA.

These dynamics between vegetation and climate are extremely complex, but their consequences have been explored at both global and regional scales. For example, Piao et al. (2007) focussed on the impact of rising CO_2 on vegetation and the consequences for runoff. They noted that rising CO_2 induces (i) stomatal closure, implying a decrease in evapotranspiration per unit leaf area and thus a potential to increase runoff, but also because CO_2 is a plant fertiliser (ii) increased plant productivity, changing plant structure, including an increase in the leaf area index with a potential to increase evapotranspiration and thus decrease runoff. Through comparison of the outcomes of several simulations using a process-based terrestrial biosphere model, they concluded that the net impact of rising CO_2 on vegetation during the 20^{th} century would have been a reduction

Figure 4.8 Global extent of human land use (croplands, pasture, urban settlements)



source: Foley et al. (2003)

in runoff, but that direct hydrological impacts of changing climate coupled with the effects of land use change (particularly deforestation and an increase in cropland) explain the observed increase in runoff. In relation to the ESPA regions, a major increases in precipitation (Figure 4.9 E) was observed in eastern Amazonia and the southeastern quadrant of Africa and a substantial decrease in precipitation was observed in western Amazonia, sub-Saharan Africa and southern China. There was a marked expansion in croplands (F) in southern Asia. In relation to the runoff simulations, increases were attributable to land use change across all of the ESPA regions (D), but this was moderated by climate change to induce increases in runoff in some areas (notably north-central Amazonia) but major decreases elsewhere (notably southern China and much of central and southern Africa).

There are many case studies which demonstrate that climate change can trigger major changes in vegetation (e.g. drought-induced trigger for tree die-off and plant disease, Breshears et al., 2005), that can in turn have enormous effects on the hydrological cycle (e.g. vegetation cover impacts on groundwater recharge in deserts, Scanlon et al., 2005). An emerging area in plant ecology is the investigation of interactions between vegetation and the water cycle at different spatial scales (Scheffer et al., 2005) and the expression of these interactions in self-organised patchiness and catastrophic shifts in ecosystems (Rieterk et al., 2004). Both Scheffer et al. (2005) and Rieterk et al. (2004) demonstrate hysteretic relationships between water-related variables (e.g. precipitation, soil moisture) and the cover of one or more vegetation types as threshold conditions are approached.

Scheffer et al. (2005) considered the impact of variations in precipitation on the extent of forests, savannas and deserts, citing changes in vegetation in the Sahel/Sahara and Amazon basins during the Holocene as examples. They noted two important factors which affect interactions between precipitation and vegetation: (i) vegetation may have large effects on regional climate - this positive feedback could potentially lead to large-scale hysteresis between climate and vegetation change; (ii) plants have a local interaction with microclimate and soils. This local positive feedback implies that critical precipitation conditions for colonization of a site may differ from those for disappearance from that site (Figure 4.10). Rietkerk et al. (2004) review the more general case where resource scarcity leads to spatial reorganisation of consumers and resources until resource scarcity reaches a threshold (Figure 4.11). At the threshold, consumers can no longer act as ecosystem engineers and the system moves to a homogenous state in which the consumer-engineers are absent. They note positive feedback between water availability and plant growth in arid areas to support this hysteresis model. Vegetation shades the ground reducing surface evaporation and root systems encourage water infiltration into the soil such that vegetation persists once it is present but once vegetation disappears the bare soil is too hostile for recolonisation. Similarly in waterlogged peatland ecosystems, there is a positive feedback between groundwater depth and plant productivity, such that patches of highly productive plants tend to be present on locally elevated drier sites. In both arid and peatland examples, the patches of consumers harvest resources (water, nutrients) from their surroundings. As resource availability decreases, vegetation goes through a predictable sequence of increasing patchiness until it disappears and bare soil or a different vegetation type replaces it. Greater inputs of resources are required to reverse this transition.

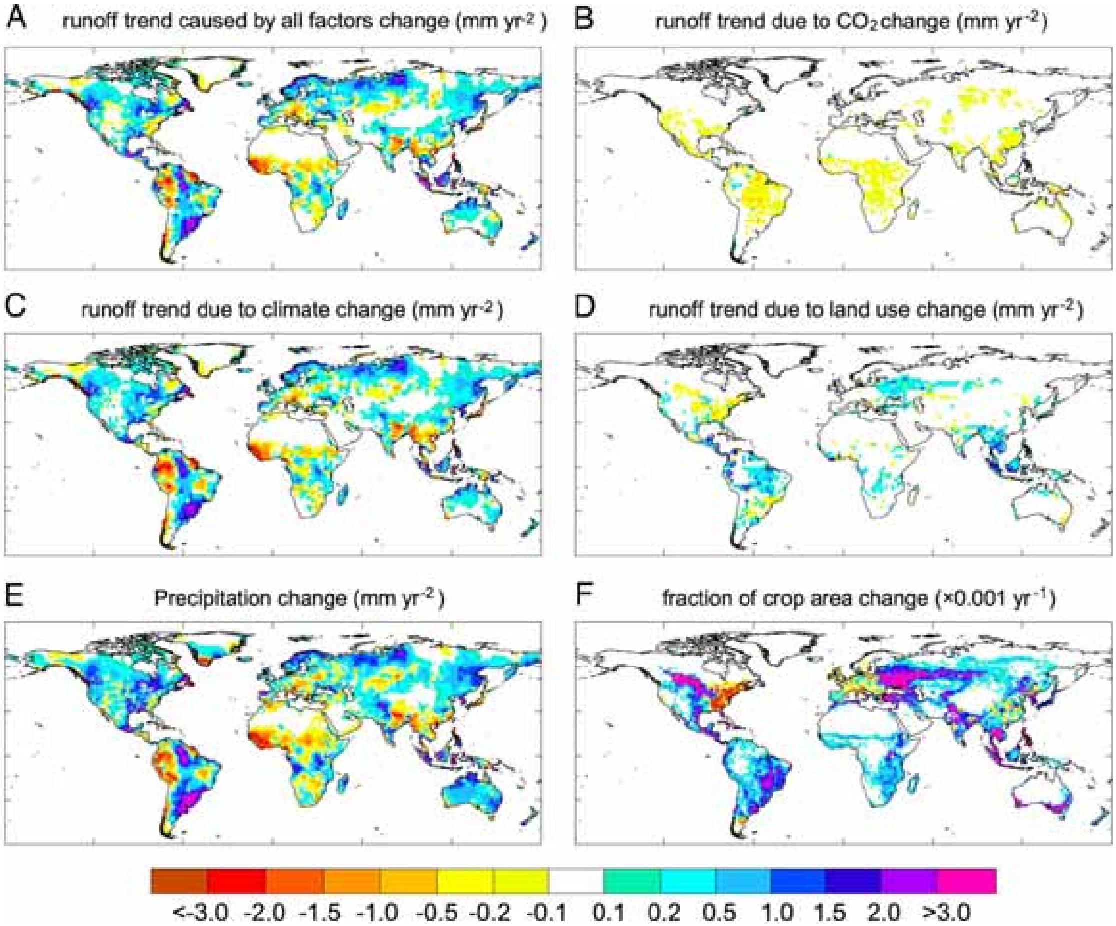
Furthermore, direct interference with vegetation can have impacts on climate as well as on carbon storage and land degradation (e.g. Laurance, 2004), all of which may induce ecoregion or biome margin shifts as well as shifts in areas suitable to support croplands (e.g. Ramankutty et al., 2002).

4.4.3 Changes in biome extent in the ESPA regions

Expected climate changes (section 4.2) can be combined with biome distributions and sensitivities to climate change to highlight major pressures that are likely to be induced with and without intensification of direct human impacts. Although many attempts have been made to model such changes, there exists enormous room for improvement in the modelling of vegetation-climate interactions, particularly in the representation of detailed processes close to the threshold for biome change and also the impacts of human activities.

China: Impacts of temperature changes on the length of the growing season between 1982 and 1993, indicate an extension of between 1.4 and 3.6 days per year across eastern China (Chen et al., 2005). At a finer spatial scale, dendrochronological investigations in north-west China, indicate a positive correlation between tree ring width and tree recruitment close to the tree line and both temperature and spring precipitation (Wang et al., 2006). These changes in the vegetation growing season may also be associated with biome shifts. Yu et al. (2006) summarise previous modelling results and present one of the most recent attempts to understand likely climate-induced vegetation pattern changes across China over the 21st century. They model the distribution of 12 vegetation types and then group them into 4 types (forest, shrubland, grassland and desert) that broadly follow composites of the biomes depicted in Figure 4.7. Based on the Hadley RCM A2 scenario, which gave an annual mean temperature increase of 4.4^{o}C and a precipitation change of between –330 and 780mm compared with 1961-1990, the main spatial changes in vegetation are forecast in the Tibetan Plateau, Yun-Gui Plateau and the north and northeastern plain of China (Figure 4.12). In general, forest and shrub biomes are forecast to increase at the expense of grassland, desert and barren areas, with a total extension in vegetated area of 19%. Similar results were obtained by Ni et al. (2000).

Figure 4.9 Spatial distribution of the trend in modeled runoff (A–D), precipitation (E), and fraction of agriculture area (F) over the 20th century.
Runoff trends (A to D) resulting from: A. the combined effects of climate, land use, and atmospheric CO2; B. increase in atmospheric CO2 (allowing LAI changes); C. climate change; D. land use change.



source: Piao et al., 2007.

Figure 4.10 (Left) Microclimatic moisture conditions not only depend on precipitation, but are also enhanced by the presence of vegetation. This implies that in dry regions the critical moisture level may be too low to allow colonization by plants, whereas once vegetation is present, microsite moisture at the same precipitation level may be sufficiently enhanced to allow growth and rejuvenation (Right) If microscale hysteresis of vegetation is taken into account, critical climatic conditions for collapse and recovery are much further apart than would be predicted if no microscale feedback would exist
(source: Scheffer et al., 2005)

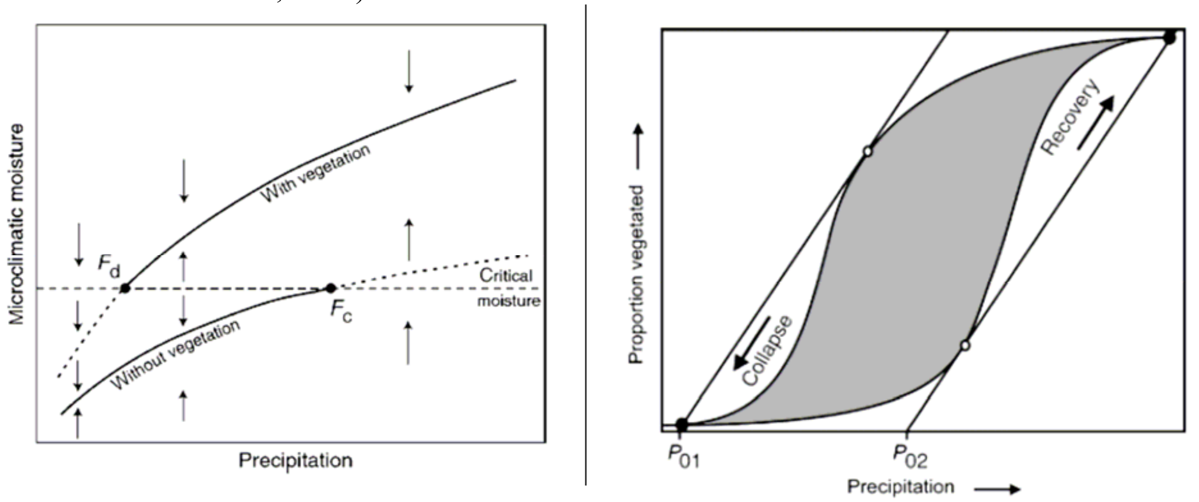


Figure 4.11. Ecosystems may undergo a predictable sequence of emerging self-organized patchiness as resource input decreases or increases. Thick solid lines represent mean equilibrium densities of consumers functioning as ecosystem engineers. Dotted arrows represent catastrophic shifts between selforganized patchy and homogeneous states, and vice versa. Dark colors in the insets represent high density. The range of resource input for which global bistability and hysteresis exists is between these dotted arrows. Solid arrows represent development of the system toward the coexisting self-organized patchy state or homogeneous state, depending on initial ecosystem engineer densities.
(source: Rietkerk et al., 2004)

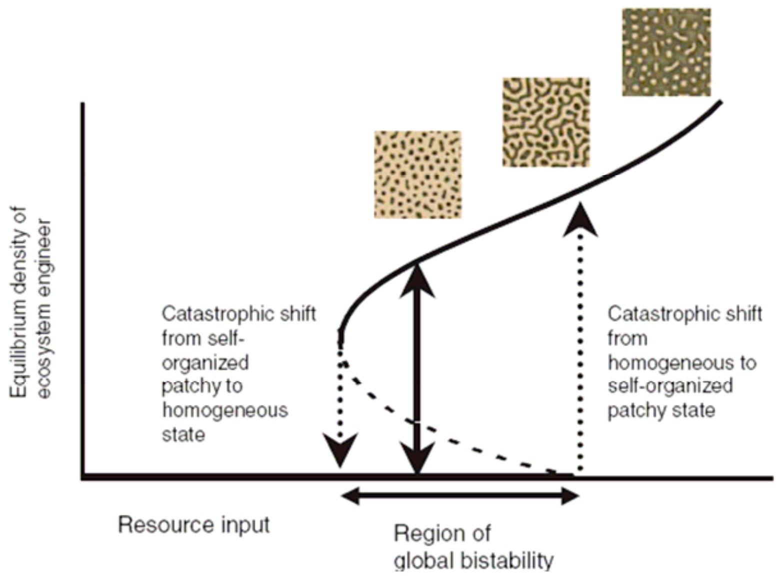
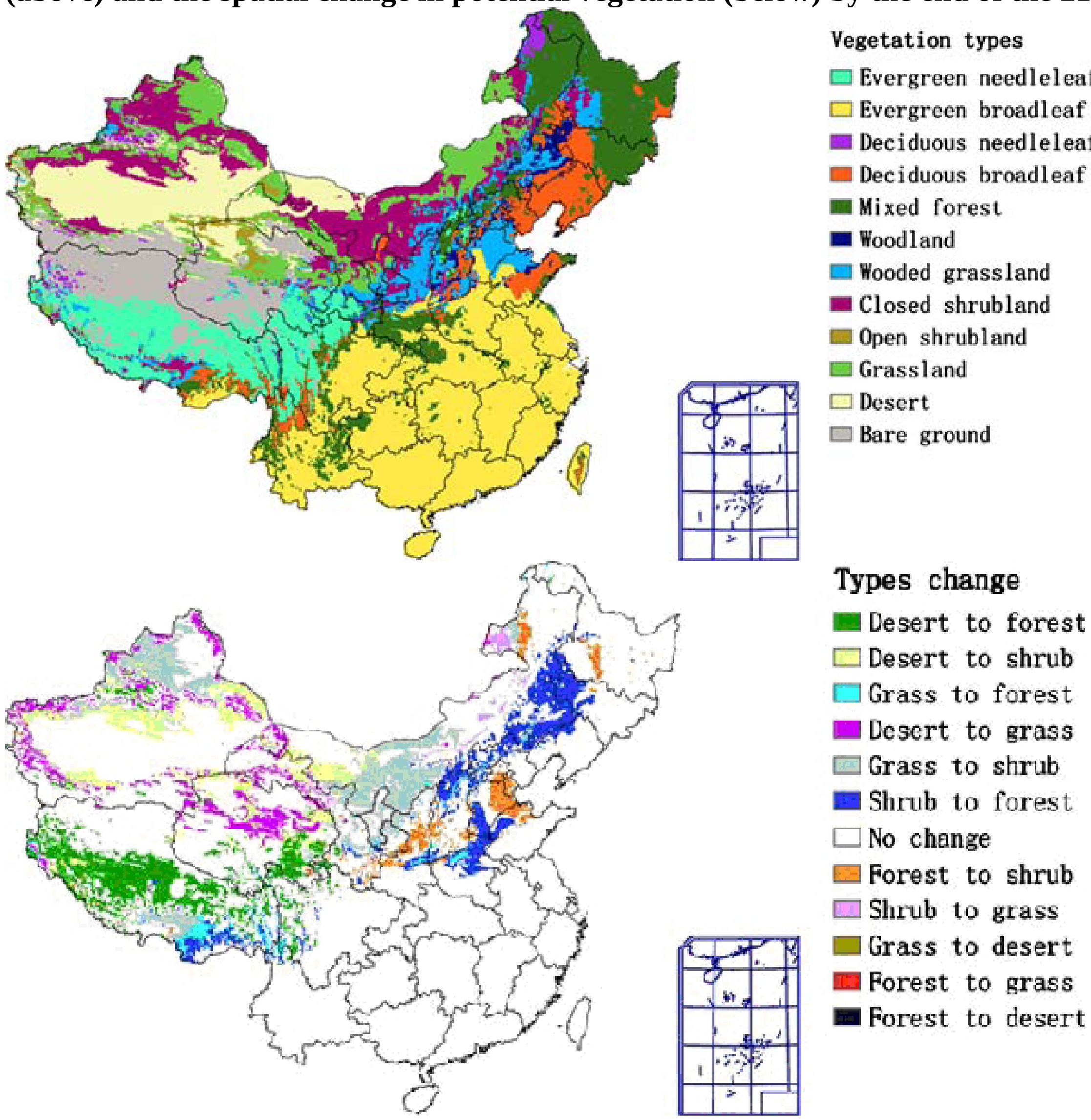


Figure 4.12 The distribution of potential vegetation under the Hadley RCM A2 scenario (above) and the spatial change in potential vegetation (below) by the end of the 21st Century



source: Yu et al. (2006)

Despite the apparently beneficial impact of forecast climate change for ‘potential’ (climate-induced) vegetation cover within China, human activities heavily disrupt the vegetation pattern and feedbacks on the changing vegetation and on climate have already been noted. Du et al (2004) note the statistically significant warming of 0.04°C/yr on the Tibetan Plateau, with a particularly large increase in winter of 0.13°C/yr, since 1978. This warming of air temperature is the highest in China and east Asia and has been associated with >200% increase in cattle numbers and 100% increase in sheep. The increase in livestock is interpreted to be a response to an increase in the spatial extent and productivity of the plateau grasslands. However, grazing reduces vegetation biomass, which may in turn affect climate through a reduction in evapotranspiration and thus an increase in temperature. The authors suggest that the very high temperature increases on the Tibetan Plateau may reflect not only global warming due to greenhouse gases but also overgrazing of vegetation due to increased livestock production, population increases and economic development.

Kang et al. (2004) demonstrate the heavy impact of agricultural expansion and irrigation in an area of Mongolia. Here there was no perceptible change in precipitation in the second half of the 20th century, but land use changes have induced a 15m drop in the water table, an increase in soil salinity in many areas, a massive decrease in the natural bush forest and the death of extensive areas of planted woodland. The decrease in vegetation cover, particularly shrubs, has resulted in land degradation and a change to desert across much of the area. Here human activities are causing the biome boundary to shift.

Rosenweig et al. (2004) model changes in crop demand and irrigation water availability in the context of competing municipal and industrial demands (i.e. desakota pressures) in northeastern China and conclude that lack of water for agriculture and ecosystem services is more marked here at present and in the future than their other study regions (Argentina, Brazil, Hungary, Romania, US).

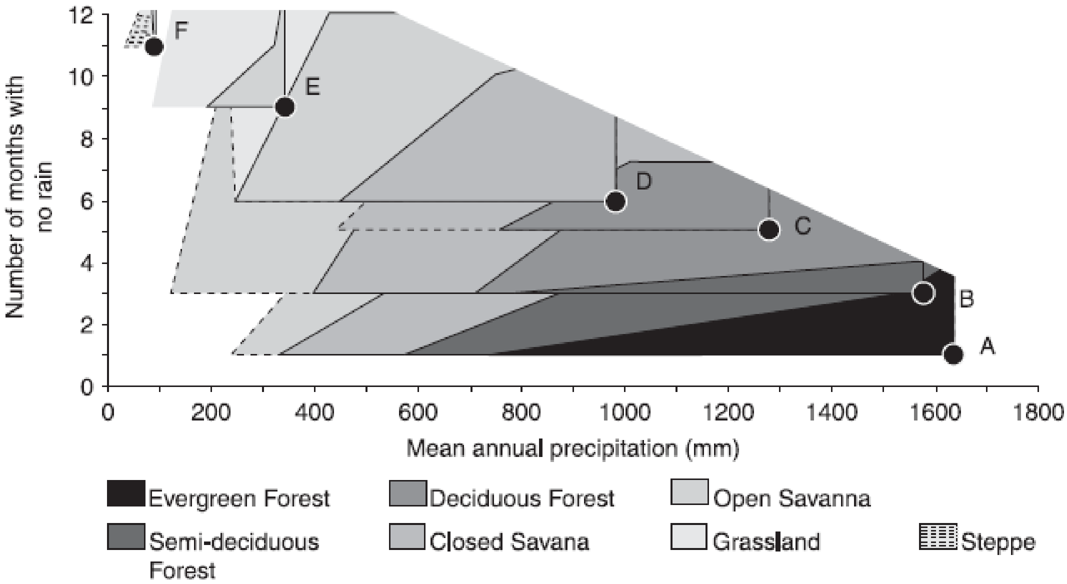
Sub-Saharan Africa: According to Hely et al (2006), the IPCC consider Africa to be the least-studied continent in terms of ecosystem dynamics and climate variability. Vanacker et al (2005) found significant changes in land cover in relation to short term (intra and inter-annual) variability in rainfall. These changes were particularly marked in grass and shrub savannas, showing that such short-term variability needs to be accommodated before longer-term responses to climate change can be identified, and also indicating that these environments may be particularly susceptible to longer-term changes. Hely et al (2006) also assessed the sensitivity of biomes to precipitation change, focussing on sites (A to F, Figure 4.13) along a transect extending from equatorial evergreen forests through savannas and steppes to desert. By considering changes in total precipitation and its distribution, they assessed the aggregate sensitivity of biomes to changes in precipitation and conclude that

> 'none of the ecosystems would shift towards a new type under the range of precipitation increases suggested by the IPCC (increases from 5 to 20%). However, deciduous and semi-deciduous forests may be very sensitive to small reductions in both the amount and seasonality of precipitation'.

Thomas et al. (2005) considered climate change impacts on drier areas, simulating likely effects of global warming on dune fields using three different climate models. Dune surface erodibility is governed by vegetation and moisture conditions whereas the ability of the atmosphere to erode these systems is governed by wind energy. They concluded that currently inactive dune-fields, which are used for pastoral and other agricultural activity from northern South Africa to Angola and Zambia, are likely to be reactivated and may be highly dynamic by 2099.

Whilst climate change will undoubtedly have very significant impacts within and between biomes, sensitivity to climate change needs to incorporate the impact of direct human activities. A number of studies focus on such issues at scales from biome to ecoregion to patch, but results are inconsistent and numerous questions remain unanswered. For example, Scheffer et al. (2005) describe interactions between natural fires that reduce woody cover, and excessive grazing of grasses by livestock that inhibits the spread of natural fires, as having an important effect on landscape dynamics and broader hydrological changes; whilst Sullivan (1999) concludes that fears of environmental degradation in response to livestock herding pressures in Namibia are not supported by scientific evidence; and Schreckenberger (1999) stresses the sustainable use of non-timber forest products as a key factor in maintaining the characteristic parkland landscape in Benin, which may be threatened by changing agricultural systems.

Figure 4.13 Sensitivity of African biomes (represented by sites A to F) to changes in precipitation

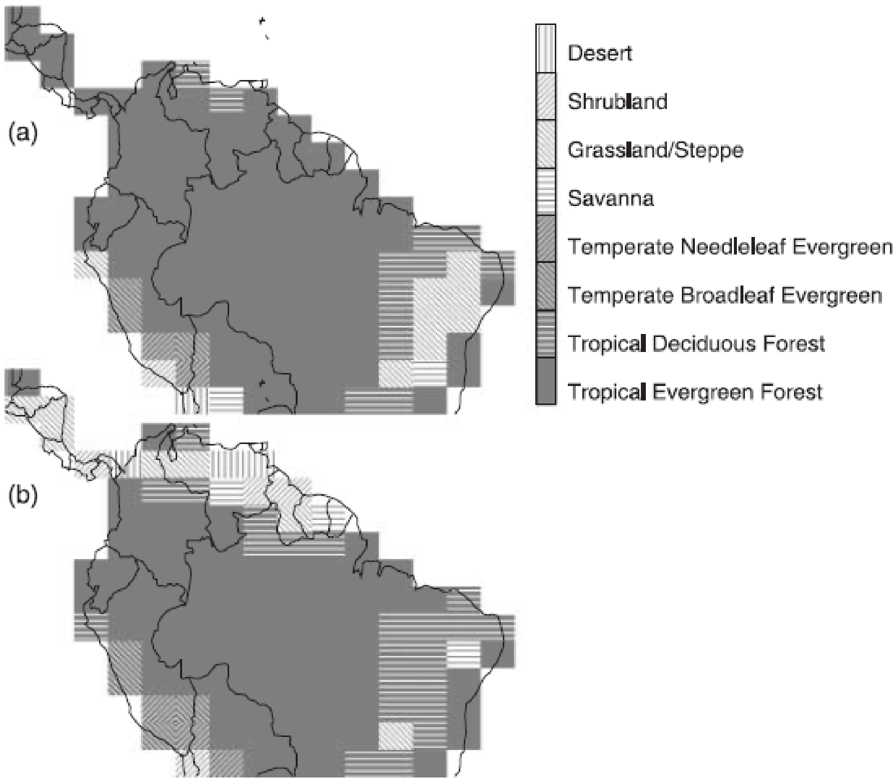


source: Hely et al. (2006)

Focusing specifically on African savannas, two recent studies investigate interactions between climate, environmental properties and human / animal pressures and the ways in which they appear to control tree cover. Sankaran et al. (2008) found that mean annual precipitation, soil properties, fire regime and herbivory accounted for 71% of the variance in woody cover. Mean annual precipitation was most important but its influence was confined largely to sites where precipitation was less than 700 mm. Fires were also important, particularly when their return interval was less than 15 years. Bucini and Hanan (2007) found a sigmoidal response of tree cover to mean annual precipitation that varied to a small degree with soil texture and was strongly modified by disturbances (fire, domestic livestock, human population density and cultivation intensity). The impact of the various disturbances on tree cover are relatively small in arid savannas (mean annual precipitation < 400mm), but can induce between 2% and 23% reductions of tree cover in semi-arid to mesic savannas (mean annual precipitation 400 to 1600mm) with cattle and human population densities being particularly influential. In wet savannas, where mean annual precipitation exceeds 1600mm, woody cover is controlled by disturbances that actively prevent canopy closure or reduce tree cover such as population density effects. These studies illustrate the important, direct impact of human activities on the landscape, and the high degree of variability in landscape sensitivity to both climate change and human modifications and pressure. They also demonstrate that much research is needed to develop our understanding of these interactions and of the sensitivity of different landscape types.

Amazonia: Modelling results vary but all indicate major potential changes in the landscapes within this region. Betts et al. (2004) compared simulations of precipitation and forest dieback from six different models. The HadCM3LC model gave the most extreme forecast changes, which they attributed to its fully-coupled climate-carbon cycle structure. They stressed the potential importance of the sensitivity of Amazonian forest to regional and global climate change, and the importance of direct human impacts on this sensitivity. Higgins (2006) investigated biodiversity loss under existing land use and potential climate change. He concluded that climate changes could shift the distribution of vegetation biomes and net primary production (NPP) such that conditions favourable for species richness in the Guiana Shield region (i.e. high precipitation and light land use) would disappear. Climate conditions may improve in eastern Brazil (Figure 4.14), compensating for the deterioration in the Guiana Shield region, but existing land use pressures are too high to support a biodiverse vegetation cover, so Higgins projected an overall collapse in species richness. Sternberg (2001) modelled hysteresis in the extent of savanna and forest accompanying biome shifts that are primarily a response to changes in dry season precipitation and deforestation (Figure 4.15). Laurance and Williamson (2001) highlighted positive feedbacks between human-induced forest fragmentation, climate and forest patch susceptibility to drought and wildfire damage, leading to what they described as a 'deforestation threshold'. This explicitly demonstrates the way in which human activities can enhance and accelerate changes and threshold conditions at biome, ecoregion and patch scales.

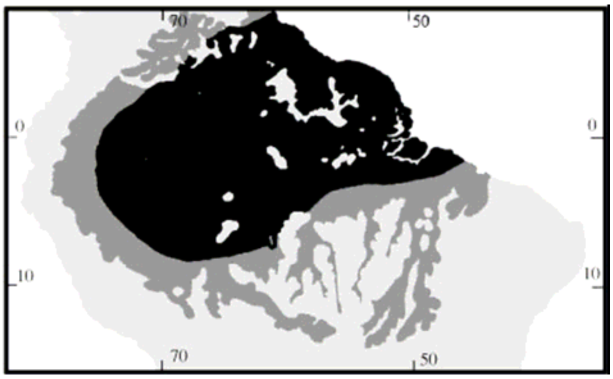
Figure 4.14 Biome distribution under current climate conditions (above) and following a southward shift in precipitation (below)



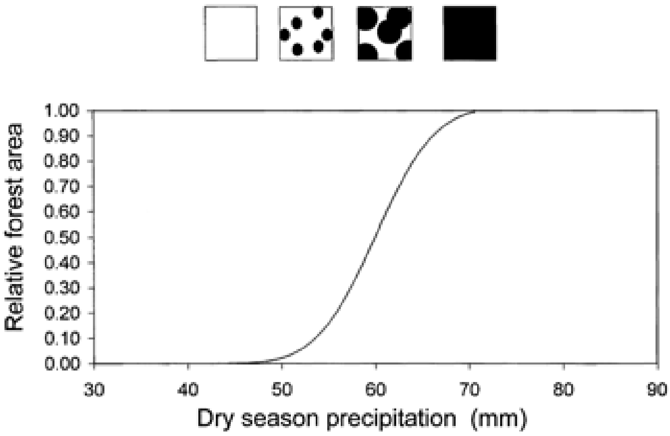
source: Higgins (2007)

Southern Asia:
Broad warming of climate, with an intensification northwards will undoubtedly have major effects on biome boundaries to the north of this region, including increasing elevation of montane grasslands, shrublands and forests (following trends noted in

A



B



C

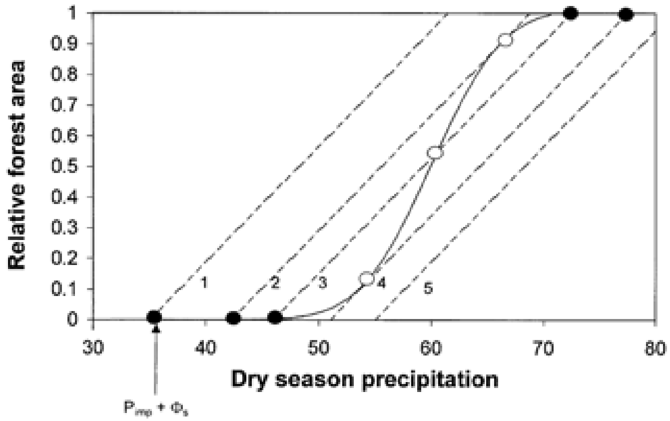


Figure 4.15

A. **Black regions have tropical forest and a dry season precipitation > 100 mm; dark grey regions have tropical forest with a dry season precipitation <100 mm – a region that could convert to savanna, given enough deforestation. Light grey regions represent other types of vegetation, mainly savannas, with precipitation during the dry season <100 mm.**

B. **relative forest area within savanna in relation to dry season precipitation.**

C. **different vegetation equilibrium points as a function of dry season precipitation**.

Source: Sternberg (2001).

China). Precipitation trends are less certain but are likely to reinforce biome shifts, reflecting increased variability in areas of monsoon rainfall and drought intensification in drier areas, which will place pressure on native vegetation-climate
interactions and also on land use. Human pressures including intensified land use, land use change, population growth and resettlement (particularly around cities and along transport corridors) are having intense impacts across all biomes (e.g. UNEP & IUCN, 2004). However, because of the high intensity of these pressures, which are particularly well-expressed in relation to water resources (quantity and quality) and water flows, they are probably best explored in a catchment rather than a biome context in the following section (4.5).

4.5 LAND USE, WATER STORES, FLUXES AND FLOW REGIMES

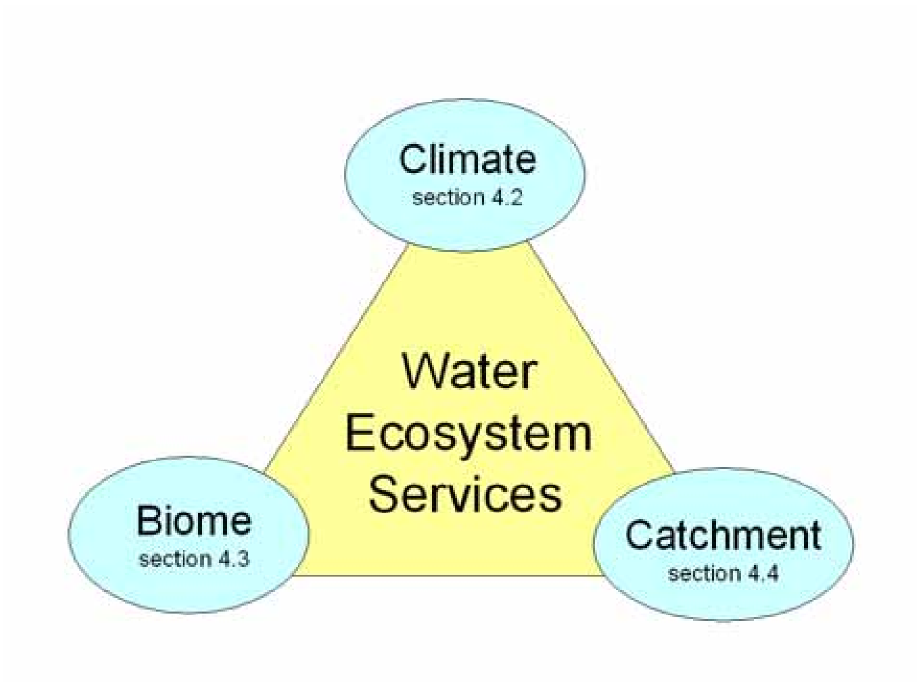
4.5.1 Introduction

In section 4.2, we considered likely climate changes within the ESPA regions, and in sections 4.3 and 4.4 we assessed the likely impact of these changes on snow and ice storage and melt, and on biome boundaries, with some assessment of additional adjustments induced by intensification / change of land use. Although climate and biome changes influence water-related ecosystem services, the most appropriate unit within which to assess direct human influences on water-related ecosystem services, particularly as a result of desakota activity, is the river catchment area. As we pass along the gradient from climate to biome to catchment, the relative importance of human influences on water-related ecosystem services changes from indirect impacts on climate to direct impacts on water quantity, quality, fluxes etc. (Figure 4.16). In section 2, water-related ecosystem services were listed (Table 2.1) and broad linkages between state changes in the freshwater environment, environmental and human impacts were tabulated (Table 2.2). In this section, we present evidence on changes in water storage, fluxes and flow regimes that are relevant to the ESPA regions and will provide a context to some catchment-based meso-scale case studies in section 5. Figure 4.17 provides a framework for these considerations. Figure 4.17A illustrates the groups of processes that affect water-related ecosystem structure and function at the catchment scale and Figure 4.17B indicates some of the ways in which the desakota phenomenon might affect these groups of processes.

4.5.2 Land use: human impacts across the rural-urban continuum

Changes in land use transform the hydrological response of catchments and also the routing of water through different hydrological pathways. Major land use changes such as clearance of forests (e.g. Costa et al., 2003), extension of urban cover (e.g. Gurnell et al., 2007) and intensification of grazing (e.g. Du et al., 2004) or cultivation all have major effects on catchment hydrology and have resulted in a marked increase in runoff worldwide (Piao et al., 2007). Increases in the proportion of rainfall running off and decreases in infiltration/percolation to soil moisture and groundwater stores are well-known hydrological consequences of land use changes that involve reduction of vegetation biomass, compaction or reduction of the fertility of soils, or the imposition of impervious surfaces, as are the accompanying increases in soil erosion and sediment yields. However, there is much to be learnt about how such effects can be ameliorated and also how climate-driven land-cover modifications interact with direct land-use changes, amplifying them to induce even more dramatic changes (Lambin et al., 2003) in hydrology and other resources at the catchment scale.

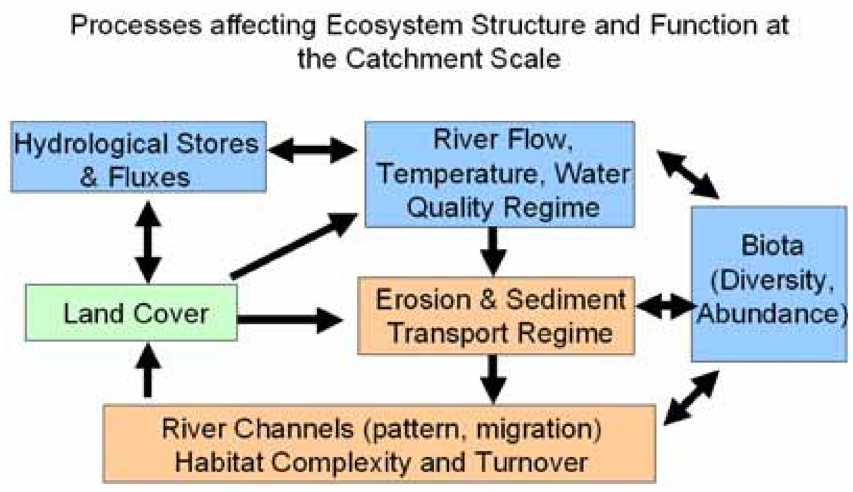
Figure 4.16 The climate - biome – catchment context for water related ecosystem services.



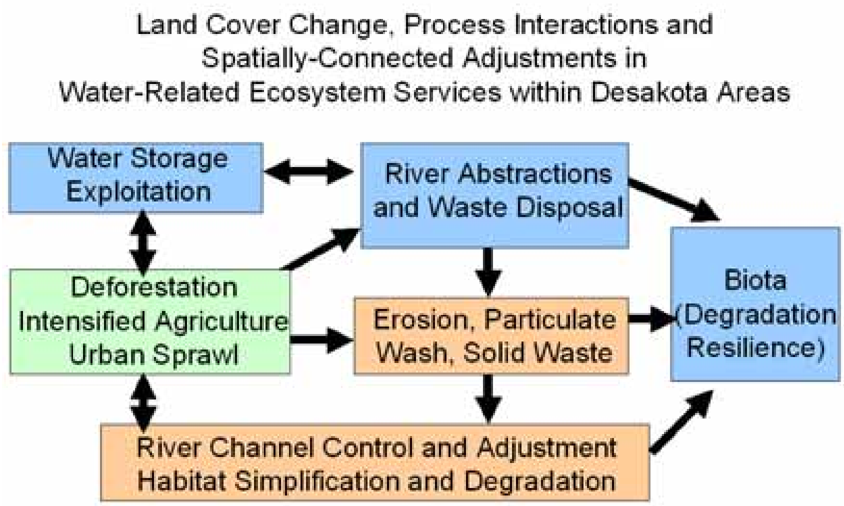
Because of the sensitivity of land cover to climate change, land use changes can have the most dramatic effects on catchment hydrology close to biome or ecoregion boundaries. Thus the hydrology of mountain grasslands and shrublands close to their elevational limits is highly sensitive to the development of grazing or cultivation. Du et al. (2004) suggest a positive feedback from degradation of grassland by overgrazing on the Tibetan plateau, which results in an increase in potential evapotranspiration promoting climate warming and the degradation process. Buytaert et al. (2006) describe the important hydrological role of the páramo (neotropical alpine grassland ecosystems) covering the higher elevations of the northern Andes. Many of the largest tributaries of the Amazon basin have their headwaters in the páramo and it is also an important source of water for domestic, agricultural and industrial consumption, and hydropower in the Andean highlands and arid and semi-arid lowlands. The authors note recent trends for intensive cattle grazing and cultivation within the páramo, which may adversely affect the hydrological regime and water resources across large downstream areas.

In transition zones between woodland and grassland, acute hydrological and other changes accompany expansion of grazing, cultivation and woodland clearance. This is demonstrated by research in the Tigray Highlands by Descheemaeker et al. (2006 a, b, c). They showed through plot experiments that vegetation cover is the most important variable influencing runoff, explaining about 80% of the variation in plot runoff coefficients. The threshold for runoff generation was positively correlated with vegetation cover and runoff was negligible when cover exceeded 65%. Other factors affecting runoff production were soil properties (organic matter, bulk density, litter cover) and slope gradient. Soil properties were also controlled primarily by

Figure 4.17 Desakota impacts on processes that affect ecosystem structure and function
A. Within catchments subject to relatively light human impacts, land cover affects hydrological and sediment stores and fluxes, which affect river channel characteristics and river water quality and flow regime, which in turn influence the biota. The biota, particularly plants in turn influence water quality, sediment dynamics and river channel characteristics, leading to localised impacts on land cover, particularly across river margins and floodplains.



B. Intensification of catchment use associated with the desakota phenomenon can lead to direct and adverse impacts on (i) river channel and floodplain forms and complexity, (ii) hydrological stores and fluxes and (iii) the quality of both water and sediment. These lead to reduced river-floodplain connectivity and reduced vigour of the biota, so reducing the beneficial impacts of the biota on water-related ecosystem services. In most cases, degradation of the biota also reduces their impact on river channel characteristics and so induces further habitat simplification and degradation.



vegetation cover but grazing exclusion led to massive increases in litter retention within shrub-covered areas. Where cattle were excluded and shrubby vegetation was able to recover, these exclusion areas also acted as important sediment traps for soils eroded upslope. Vegetation cover was the key explanatory variable for accumulated sediment thickness, with rich organic sedimentation increasing towards the upslope edge of exclusion zones and mean sediment deposition rates ranging between 26 and 123 Mg ha^{-1} yr^{-1}. These results demonstrate the sensitivity of water, organic matter and sediment dynamics to changes in vegetation cover and intensification of grazing or other land uses in these delicate, transition environments.

Geist and Lambin (2004) considered the complex causes and trajectories of desertification that accompanies some land cover and management changes and has major hydrological effects at the basin scale. In particular, they noted positive feedbacks in many case studies from Asia and Africa. In central Asia, they noted two major pathways of partly irreversible desertification: (i) the extension of grain farming into steppe grazing land, which triggers soil degradation and overstocking on the shrinking area remaining for grazing; and (ii) the development of large-scale water resource exploitation (e.g. deep wells) in desert ecosystems that historically supported only localized, traditional oasis farming. A common pathway of desertification found in Africa is the spatial concentration of farmers and pastoralists, as they shift from a nomadic to a sedentary life style, resulting in local overgrazing, high cropping intensities, intensive fuel wood gathering, and thus degradation of vegetation and deterioration of soil productivity, particularly during periods of drought.

In addition to changes in hydrological and sediment flows and pathways, agricultural land cover change can also adversely affect water quality through tillage exposure of fresh soil to weathering and inputs of fertilizer (Collins and Jenkins, 1996). Water quality impacts can be particularly extreme in arid environments where land cover changes are accompanied by extensive water resource exploitation. Thus, Kang et al. (2004) describe how inappropriate water-related human activities in the Shiyang River basin in the arid northwest of China have resulted in soil salinization, serious loss of vegetation, and desertification. In the same basin, Ma et al. (2005) explain how excessive groundwater exploitation of largely palaeo-groundwater has led to serious falls in the water table (up to 35m) and salinisation by evaporation of already saline groundwaters. Sustainable use of water resources, maintenance of the balance between land and water resources, and development of water-saving agriculture are required if desertification is to be arrested or reversed.

In relation to catchment land use change, an important finding that emerges from many studies is that land use change impacts vary with spatial scale, pattern and intensity and that there are thresholds of change above which major hydrological impacts occur. Thus, Li et al (2007) show, through numerical simulations of deforestation and overgrazing for the Niger and Lake Chad basins of West Africa, that the hydrological response to progressive land cover change is non-linear and exhibits a threshold effect. They found no significant impact on water yield and river discharge of deforestation (thinning) below 50% or overgrazing below 70% for savanna and 80% for grassland areas. Water yield increased dramatically when land cover change exceeded these thresholds. Pandey and Devota (2006), working on two Indian ecosystems, also stressed that forest or grassland vegetation in any region regulates the hydrological cycle, such that any change in land-use will have significant hydrological effects. Whilst selective removal of trees (<25%) does not lead to significant hydrological alteration, if a major area of forests is cleared, then spatio-temporal changes in the water balance are enormous. They suggested that land cover, particularly tree, management (plantations, re- and de-forestation) needs to incorporate these hydrological and ecological consequences. A general conclusion is that patchy land use, maintaining areas of semi-natural woodland or grassland not only supports varied, sustainable livelihoods but also minimizes adverse hydrological and ecological effects and sustains water-related ecosystem services. Gavin (2004) demonstrates a valuation approach to balancing such land management decisions.

Hydrological management through mixed and balanced land use approaches may still be feasible across rural parts of the ESPA regions and could be greatly aided by further fundamental research on hydrological trends and threshold conditions induced by particular mosaics of land uses and livelihoods. However, Zhao et al. (2006) and UNEP & IUCN (2004) note the severity of land transformations that have occurred in different parts of S Asia, resulting in enormous negative ecological consequences. Understanding the negative environmental impacts of land use change and developing landscape management approaches that sustain water-related ecosystem services and maintain economic viability and social acceptability is a major research challenge.

The most extreme impacts of land use change are associated with urban and peri-urban development. Gurnell et al. (2007) review the hydrological, geomorphological and ecological impacts of 'urbanisation' which show remarkable consistency in type and direction if not in magnitude across the Globe. Urban river and riparian ecosystems are impacted by changes in (i) the flashiness of the flow regime and associated flash flooding and hydraulic stresses; (ii) frequent depression of groundwater tables and river baseflows as a result of abstractions and reduced recharge through impervious surfaces; (iii) deterioration in water and sediment quality as a result of pollutant inputs from both diffuse and point sources; (iii) in many cases channel bed incision and armouring, which is often accompanied by the infiltration of contaminated fine sediment into the gaps in the coarser bed sediment matrix, (iv) building development up to the river edge with complete removal of riparian habitat and food sources, (v) resultant degradation of the aquatic and riparian ecosystems with only the most tolerant species surviving and serious consequences for water ecosystem goods and services (Chadwick, 2006). These effects have been termed the 'urban river syndrome' (Walsh et al., 2005). In the ESPA regions, these effects can be dramatic around urban areas. Severe increases in urban flooding are occurring as urban areas expand (e.g. Gupta, 2006) and enormous pressures on water supply coupled with negligible waste water treatment are leading to extremely heavy water pollution and the destruction of the riparian zone. For example, Karn and Harada (2001) note that river pollution in Nepal, India and Bangladesh is critical near urban areas, with BOD in the range 20-30 mg/l. Karn and Harada (2001) attribute 'rampant discharge of pollutants' to unplanned urbanization and industrialization (i.e. the Desakota phenomenon). In Australasia, N America and Europe, three management approaches are being developed to reverse the adverse effects of urban and suburban development: (i) improved water treatment; (ii) disconnection of urban impervious surfaces from river networks through the use of 'sustainable urban drainage' approaches; (iii) creation of vegetated riparian 'buffer' zones between the river network and urban building development (Gurnell et al., 2007). Components (ii) and (iii) could be seen as an urban approach to the landscape patchiness that is believe to moderate human impacts in more rural areas.

The Desakota phenomenon found in the ESPA regions, represents a spectrum from intensification of rural land uses to support burgeoning cities, through land use supporting highly mixed 'rural-urban' economies to unplanned, often high-density 'urban' development around the fringes of cities, although in some areas, a positive effect of the Desakota phenomenon is forest recovery as economic development creates enough non-farm jobs to reduce agricultural pressures (e.g Rudel et al., 2005). Whilst the Desakota phenomenon can be seen in many types of location and across many spatial scales, a core component is peri-urban development and particularly the intensification of this type of development in recent decades (e.g. Kombe, 2005; Kannel et al., 2007, Simon et al., 2004), which has placed great pressures on water ecosystem services (Moretto, 2007). 'From an environmental perspective, the peri-urban interface can be characterized as a heterogeneous mosaic of "natural" ecosystems, "productive" or "agro-" ecosystems, and "urban" ecosystems affected by the material and energy flows demanded by urban and rural systems' (p136, Allen, 2003). In relation to the concept of Desakota, this heterogeneous mosaic can be seen as being both intensive and patchy, with adverse consequences for water resources and quality, sediment yield, and river ecosystems. A key issue in peri-urban areas is access to water and facilities for waste-water disposal. Allen et al. (2006) note that water use and amount of water consumed in peri-urban areas is determined more by what is available than by human needs. Availability is governed by factors such as distance, the degree of facility sharing, and the regularity, price, safety and quality of the supply. Since many people gain income from water-intensive activities, such as food production (e.g. Ellis, 1998) including animal husbandry and horticulture, brick and block making (e.g. Haack and Khatiwada, 2007), tanning and dyeing, and food vending, enormous pressure is placed on water supplies, which therefore become heavily exploited. In peri-urban areas household and surface drainage systems are usually combined, industrial wastewater is rarely treated, and, when water resources are limited, farmers may use untreated wastewater for irrigation (e.g. Rutowski et al., 2007). These practices lead to massive deterioration in water quality (e.g. Kannel et al., 2007) and high exposure of peri-urban dwellers to disease, particularly since many of the poorest people inhabit low-lying areas that are susceptible to flooding by contaminated water (Allen et al., 2006). Overall, the water cycle, water quality and riparian areas come under enormous pressure in peri-urban areas, placing even higher pressure on water ecosystem services than occurs in fully-developed urban areas where infrastructure is planned and managed more effectively. Amelioration of all these effects from a water ecosystem services perspective, depends upon similar actions to those for more developed urban watersheds. These actions essentially 'making space for water' by ensuring the heterogeneous landscape contains sufficient 'buffer' patches to moderate hydrological connectivity to and from river and groundwater systems, encourage self-purification of water quality, and preserve/promote ecosystem complexity.

Human land use pressures along the rural to urban continuum can have extremely adverse impacts on catchment water ecosystem services. This review has described research from many environmental contexts and across many spatial scales that demonstrate the impressive ability of the catchment system to absorb such human impacts up to certain threshold conditions that relate to degree, patchiness and spatial layout of land use activities in the context of 'natural landscape' sensitivity. There is need for research in defining landscape sensitivity and thresholds in relation to water quantity, quality, sediment dynamics and consequences for river networks and in building these into management approaches that support ecosystem resilience and provision of water ecosystem services.

4.5.3 Water stores, flow regulation and regimes

In addition to the far-reaching effects of land use on runoff quantity, quality and pathways, direct human manipulations of hydrological stores through groundwater exploitation, dam construction and water diversion (including inter-catchment transfers) have enormous effects on the hydrological, geomorphological and ecological functioning of catchments and, in aggregate, have very significant effects at the regional and global scales.

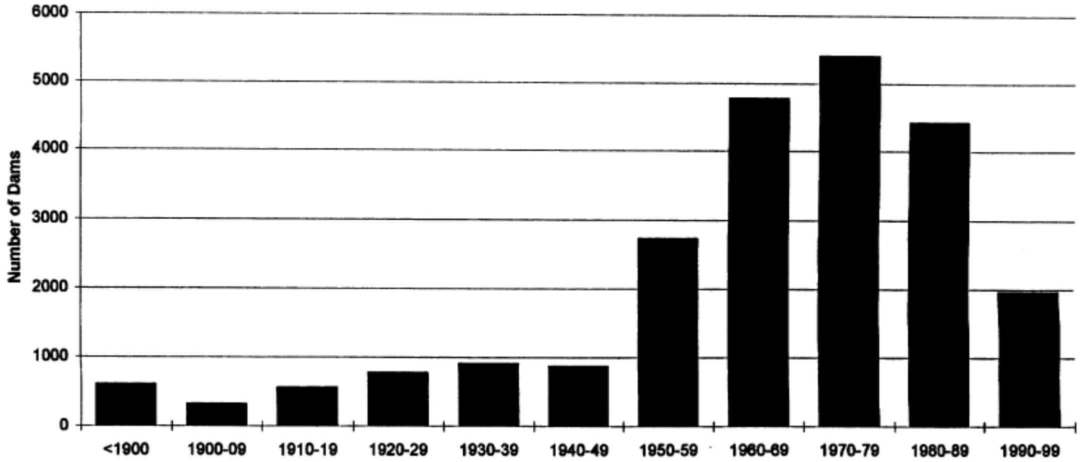
Vörösmarty and Sahagian (2000) review many of the ways in which expanding water use has stabilized and diverted continental runoff from one part of the hydrologic cycle to another including dam building, groundwater exploitation (aquifer mining), surface water diversion, changes in water storage in naturally-occurring lakes (e.g. Aral and Caspian seas; Ethiopian rift lakes - Alemayehu et al. 2007, Ayenew and Legesse, 2007), desertification and wetland drainage in addition to land use changes. They note that most of these changes involve increasing evapotranspiration losses, in essence enhancing land-atmosphere water fluxes as well as manipulating the passage of water across catchments. They conclude that these human water manipulations are very significant at a global scale, impacting on the scale of surface and subsurface water storage, exchanges of water between surface and atmosphere, temporal patterns of runoff (flow regimes) and also of sediment.

In relation to surface water impoundments, Rosenberg et al. (2000, Figure 4.18) suggest that large dams currently store 5500 km^3 water of which 3500 km^3 are used in regulating river flows, and Vörösmarty and Sahagian (2000) demonstrate the cumulative impact of large dam construction over the 20th century on the volume of water stored, the volume of river flow retained, and the consequent aging of water passing through the hydrological system (Figure 4.19).

Snoussi et al. (2007) attempt to disaggregate environmental pressures resulting from dam building in relation to other pressures such as land-use change and climate change within six catchments in Africa. Impoundment of water for power generation and irrigation has supported urban, industrial, and agricultural growth and also the control of floodwaters, reducing damage and loss of life and livelihood. In addition, there has been a significant increase in direct water abstraction for irrigation. However, these activities have also caused major long-term changes in the natural flows of water and sediment within the catchments that have negative downstream and coastal impacts. These include reductions in the quantities of water and sediment transported to the coast, leading to salinisation of the lower reaches of rivers, reduced siltation and consequent impoverishment of downstream floodplains, river channel adjustment and coastal erosion caused by reduced sediment discharge. They conclude that urgent research is needed to develop management models capable of coping with extreme climatic events, satisfying human water demands and maintaining the ecological functions of coastal wetlands (see also Petts and Gurnell, 2005). Management needs to encompass environmental water discharges and sediment bypass facilities around dams to improve downstream and coastal conditions, whilst maintaining flood protection and catchment management needs to reduce soil mobility and delivery to the river network (Snoussi et al., 2007).

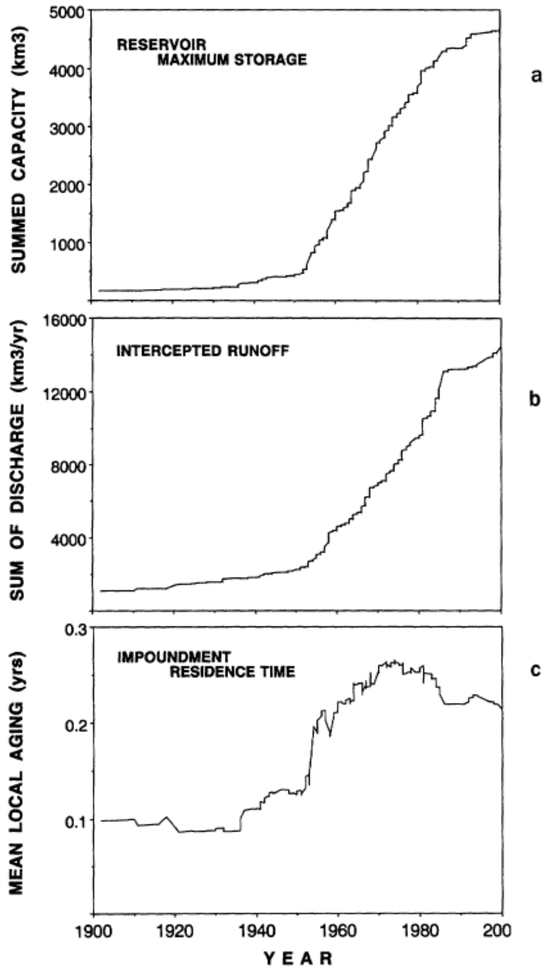
'Aquifer mining' (Vörösmarty and Sahagian, 2000) has similarly deleterious impacts on catchment hydrology and river networks. In a global synthesis of groundwater recharge in arid and semi-arid regions, Scanlon et al. (2006) note that groundwater pumping for irrigation usually greatly exceeds recharge rates, resulting in groundwater mining, and that increased recharge from irrigated agriculture has mobilized salts that have accumulated in the unsaturated zone over millennia, resulting in widespread ground and surface water contamination. Overexploitation of groundwater in northern China has induced large falls in water table levels (unconfined aquifers) and water pressures (confined aquifers) causing a range of environmental problems including the drying up of wells, land subsidence, pollution from waste-water contamination and seawater intrusion, and salinisation of the land (Han, 2003). In the Balochistan province of Pakistan, groundwater resources are being exploited beyond sustainable levels, causing rapid depletion of the water table in many aquifers. At the same time the disposal of untreated industrial, domestic, and municipal wastes into open water bodies and extensive use of insecticides, pesticides, herbicides, and chemical fertilizers on agricultural lands are polluting aquifers that are used for drinking water (Majeed, 2004). Since groundwater often feeds surface water, changes in the size and quality of the groundwater store have major implications for the quantity and quality of river flows (e.g. Smith et al., 2008). For example, in the North China Plain, a semiarid climate and heavy exploitation of water resources has resulted in severe river desiccation since the late 1950s (Xu, 2001).

Figure 4.18 Global construction of large dams during the 20th century



Source Rosenberg et al. (2000)

Figure 4.19 Global time series based on 600 large reservoirs, representing approximately 60% of global water storage behind large dams of (a) accumulated potential volume storage, (b) intercepted continental runofi and (c) mean age of impounded river discharge.



Source Vorosmarty et al (2000)

Even where groundwater quantity has not been overexploited, nutrients and other chemicals applied to the land can be readily discharged into rivers via groundwater, demonstrating the need for interdisciplinary research to better manage hydrological and biogeochemical linkages across catchments and along flow pathways (Smith et al., 2008), particularly where groundwater has become overexploited and polluted. Moreover, exploitation of surface waters may impact on groundwater as in the case of the reduction of surface water flows to the Gorai River, Bangladesh, through surface water diversion, which has resulted in saline intrusion into downstream soil and groundwaters (Mirza, 1998).

Manipulations of both surface and subsurface water stores have important effects on river flows, which in turn impact on aquatic and riparian ecosystems (Nilsson and Svedmark, 2002, Pinay et al., 2002). Functioning, biologically complex aquatic ecosystems provide many economically valuable services including food, flood control, purification of wastes, and habitat for biota. However, these ecosystem services depend upon maintenance of aquatic and riparian ecosystem integrity, which depend upon the quantity, quality, timing, and temporal variability of water flow and are, therefore, strongly linked to processes within the catchment (Baron et al., 2002, Naiman et al., 2002). In particular, the flow regime is thought to be the fundamental driver of both aquatic and riparian ecosystems (e.g. Petts, 1996), acting as a transport and dispersal mechanism, habitat regulator, process modulator and disturbance (Doyle et al., 2005), although as noted by Bunn and Arthington (2002) 'evidence about how rivers function in relation to flow regime and the flows that aquatic organisms need exists largely as a series of untested hypotheses'.

Much research has focused upon quantifying properties of river flow regimes that might be of ecological importance (e.g. Olden and Poff, 2003), whilst evidence on the adverse impacts of changed flow regimes on fisheries is accumulating (e.g. Sultana and Thompson, 1997, Xenopoulos et al., 2005) but as Bunn and Arthington (2002) suggest 'aquatic science needs to move quickly into a manipulative or experimental phase, preferably with the aims of restoration and measuring ecosystem response'.

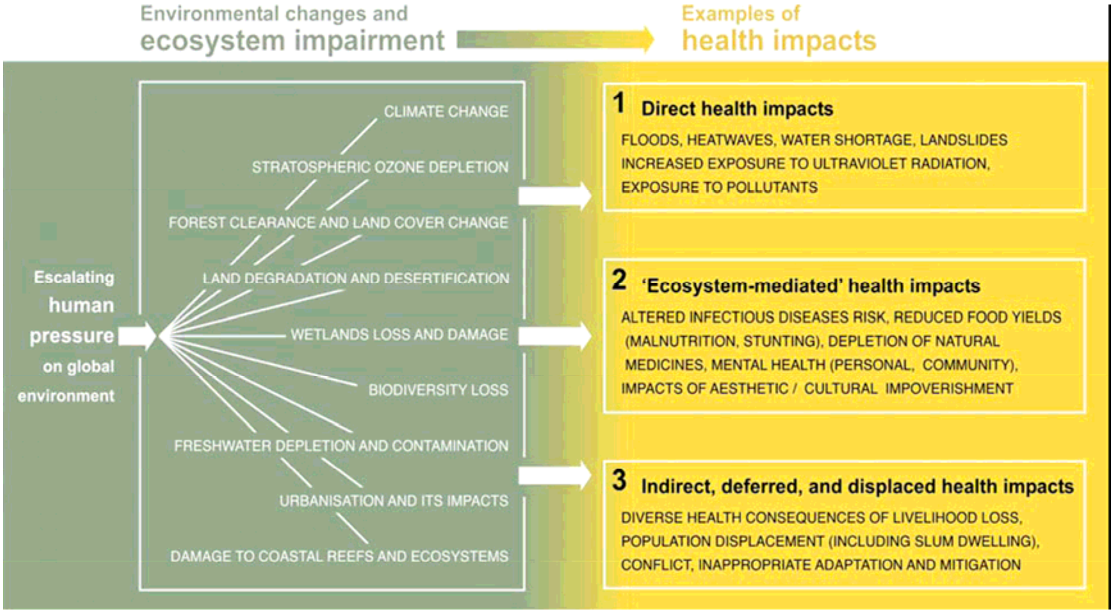
4.6 WATER-RELATED DISEASES

Human interventions in drainage basins include deforestation, agriculture, urban and industrial development, extension of infrastructure and the manipulation and development of both surface and groundwater resources. As discussed in section 4.5, these interventions become particularly intense and are often completely unplanned within Desakota areas, leading to far reaching consequences for both water quantity and quality. They also have major implications for the extent and changing pattern in the distribution of infectious diseases, which according to MEA (2005) depend on changes in the ecosystem(s) that support each disease, its transmission pathways and dynamics, and also socio-cultural changes that may affect relevant ecosystems, transmission pathways and the susceptibility of humans to the disease. Figure 4.20 illustrates how the Millenium Ecosystem Assessment (MEA, 2005) conceptualised the consequences of increasing human pressures on the global environment for human health.

Deterioration in the quantity and quality of available water impacts severely and in many ways on both humans and ecosystems, but a particularly serious impact is on human health. According to MEA (2005) water-associated infectious diseases claim up to 3.2 million lives each year, approximately 6% of all deaths globally. In this section, we focus on water-related diseases, considering their causes and possible interventions within the context of Desakota and environmental change.

Table 4.2 has been produced using fact sheets that are available from the World Health Organisation website. It groups water-related diseases according to whether they are induced primarily by bacteria, chemicals, fungi, parasites or viruses and it illustrates that key factors support the incidence and spread of each disease including changes in the distribution, availability and quality of water; the scale and methods of sewage disposal; any resistance to the pesticide chemicals that are used to control certain disease vectors; and climate variability and change.

Figure 4.20 Harmful effects of ecosystem change on human health



source: MEA (2005)

Table 4.2 Nature, Interventions and Geographical Extents of Water-Related Diseases (based on World Health Organisation fact sheets, available at http://www.who.int/water_sanitation_health/diseases/en/index.html)

Disease	Association with Water	Water-related Intervention	Geographical Extent
MULTIPLE CAUSES			
Anaemia	Caused by nutritional deficiency, but often associated with parasitic infections, including malaria, schistosomiasis and hookworm which are related to hygiene, sanitation, safe water and water management.	Improve hygiene, sanitation and water supply; improve water resource management to contribute to control of schistosomiasis and malaria	Worldwide but particularly in areas where malnutrition is prevalent and the risk of water-related infection is high
Diarrhoea	Diarrhoea is a symptom of infection caused by bacterial, viral and parasitic organisms most of which can be spread by contaminated water (particularly contaminated with human faeces).	Access to safe drinking water, improved sanitation, good personal and food hygiene.	Common where sanitation is poor
BACTERIAL			
Campylobacteriosis	Campylobacteriosis is caused by bacteria (usually *Campylobacter jejuni* or *C. coli*) found in most warm-blooded animals. People are exposed after consuming contaminated water or food.	Provision of safe (continuously disinfected, i.e. chlorinated) drinking-water supply, sewage-disposal systems coupled with protection of the water supply from contamination; adequate personal hygiene.	Campylobacter are one of the most common bacterial causes of gastroenteritis worldwide.
Cholera	Cholera is caused by the bacterium *Vibrio cholerae*. People become infected after consuming water or food contaminated by the faeces of infected persons. Vegetables and fruit that have been washed with water contaminated by sewage may also transmit the infection.	Provision of adequate safe drinking-water, adequate personal and food hygiene,·hygienic disposal of human excreta.	Cholera cases and deaths occur widely throughout all of the ESPA regions.
Leptospirosis	Leptospirosis is a bacterial disease caused by spirochaetes of the genus Leptospira. It affects many animals as well as humans. The infection is often transmitted to humans when water that has been contaminated by animal urine comes into contact with cuts in the skin, eyes or with the mucous membranes. In endemic areas the number of leptospirosis cases may peak during the rainy season and may reach epidemic proportions during flooding.	Control the infection source (e.g. rodent control, animal vaccination); interrupt the transmission route (e.g. wear protective clothing, avoid contact with infected animals and contaminated water)	Worldwide in both rural and urban areas and in temperate and tropical climates.
Trachoma	Trachoma is an infection of the eyes, caused by the bacterium Chlamydia trachomatis, that may result eventually in blindness. It is spread by contact with eye, nose, and throat secretions from affected individuals, or contact with objects such as towels or clothing, that have been in contact with these secretions. It is the world's leading cause of preventable blindness and occurs where people live in overcrowded conditions with limited access to water and health care.	Good personal and environmental hygiene has been proven to be successful in combating trachoma. Encouraging the washing of children's faces, improved access to water, and proper disposal of human and animal waste has been shown to decrease the number of trachoma infections.	Worldwide but most often in poor rural communities in developing countries

Typhoid and paratyphoid enteric fevers	Typhoid fever is a bacterial infection of the intestinal tract and bloodstream. Typhoid and paratyphoid germs are passed in the faeces and urine of infected people. People become infected after eating food or drinking beverages that have been handled by a person who is infected or by drinking water that has been contaminated by sewage containing the bacteria.	Good personal hygiene, especially regarding hand-washing after toilet use and before food preparation; provision of a safe water supply; proper sanitation systems	Typhoid and paratyphoid fevers are common in less-industrialized countries.
CHEMICAL			
Arsenicosis	Caused by exposure to arsenic, mainly ingested from drinking water but also from food or air. WHO's Guideline Value for arsenic in drinking water is 0.01 mg /litre.	Provision of safe drinking-water by employing deeper wells; rain water harvesting; arsenic removal systems; routine water testing.	Natural arsenic contamination occurs in many countries. Within the ESPA regions, Bangladesh, China and India are notable.
Toxins from Cyanobacteria	Cyanobacteria or blue-green algae can grow rapidly in calm, nutrient-rich water bodies in warm climates or during the late summer months in cooler climates. Some species of cyanobacteria produce toxins that affect humans.	Reduce eutrophication in lakes and reservoirs by careful management of wastewater disposal and control of fertilizer use including manure; educate about risks of drinking, bathing or water sports in water likely to contain high densities of cyanobacteria; treat water to remove the organisms and their toxins from drinking-water.	Associated with water bodies world wide.
Fluorosis	Acute high-level exposure to fluoride is rare. Moderate-level chronic exposure (above 1.5 mg/litre of water) is more common and drinking water is the most significant source. Fluoride in water is mostly of geological origin.	Where possible, find a supply of drinking-water with safe fluoride levels. Where access to safe water is already limited, de-fluoridation may be the only solution.	In the ESPA regions, water with high levels of fluoride is found in South Asia and China.
Methaemoglobinemia	Methaemoglobinaemia is associated with reduced levels of normal haemoglobinis that decrease the ability of blood to carry oxygen. The most common cause is high levels of nitrates in drinking-water resulting from the intensive use of manure and fertilizers on agricultural land.	Control nitrate levels in drinking water to below 50mg/litre, which is readily achieved in large, piped supplies, but more difficult in rural and small piped distribution systems.	World wide
FUNGAL			
Ringworm (Tinea)	Ringworm is a contagious skin disease caused by a fungus and spread by contact with infected persons, animals, soil or by indirect contact with fungus-contaminated items (e.g. clothing, towels, bedclothes, chairs, toilet articles). The link with water is via poor personal domestic hygiene and shortage of water for cleaning and washing.	Adequate supply of water for personal washing and hygiene; regular, thorough bathing with soap and water and careful drying of moist areas.	World wide

PARASITIC			
Guinea-Worm Disease (Dracunculiasis)	Humans are the reservoirs for guinea-worm disease. Infection is through the use of contaminated water. Guinea worm disease is caused by a large nematode, *Dracunculus medinensis*. The disease begins with a blister. Infected persons try to relieve the pain by immersing the infected part in water (e.g. ponds), which stimulates the worm to emerge and release thousands of larvae into the water. The larva is ingested by a water flea, where it develops and becomes infective in two weeks. When a person drinks the water, the cyclops is dissolved by the acidity of the stomach, and the larva is activated and penetrates the gut wall. It develops and migrates through the subcutaneous tissue, a blister forms and the mature worm tries to emerge, repeating the life cycle.	Interventions include case containment; community-based surveillance systems; provision of safe water (use of filtering and chemical treatment).	Africa
Malaria	Malaria is caused by four species of Plasmodium parasites (*P. falciparum, P. vivax, P. ovale, P. malariae*) When a mosquito bites an infected person, it ingests malaria parasites with blood and the parasite develops in the mosquito. The infective form (sporozoite) ends up in the salivary glands and is injected into new human hosts at subsequent blood-meals. The disease is closely associated with water, as the larval stages of mosquitoes develop in different kinds of water bodies according to their habitat requirements, (sun-lit / shaded, with / without aquatic vegetation, stagnant / slow flow, fresh / brackish).	Reduce mosquito breeding sites by filling in and draining water bodies and through other environmental management schemes.	Today, malaria occurs mostly in tropical and subtropical countries, particularly in Africa south of the Sahara, South-East Asia, and the forest fringe zones in South America. Climate change appears to be moving the altitude limits of malaria to higher elevations (e.g. East African Highlands).
Onchocerciasis	Onchocerciasis or river blindness is a parasitic disease caused by *Onchocerca volvulus*, a parasitic worm. The disease is transmitted between people through blackfly (Simulium) bites. The blackfly lay their eggs in fast-flowing rivers. The female blackfly typically seeks a bloodmeal after mating and, upon biting a person who is infected with onchocerciasis, may ingest worm larvae, which can then be passed on to the next person bitten by the blackfly. Eventually, the transmitted worm larvae develop into adult worms and settle into fibrous nodules in the human body, where they can result in hanging groins and elephantiasis of the genitals, and also serious visual impairment or blindness when they reach the eye.	Application of larvicides by aerial spraying of breeding sites in fast-flowing rivers so that blackflies capable of transmitting the parasite do not develop.	World wide but particularly prevalent in West Africa.

Scabies	Scabies infestation is caused by the microscopic mite *Sarcoptes scabei*. The fertilized female mite burrows into the skin, depositing eggs in the tunnel behind her. After the eggs are hatched, larvae migrate to the skin surface and eventually change into the adult form. Mating occurs on the skin surface. The characteristic itchy rash is an allergic response to the mite. Epidemics have been linked to poverty, poor water-supply, sanitation and overcrowding.	Personal hygiene is an important preventive measure and access to adequate water supply is important in control.	Scabies mites are found worldwide, affecting all socioeconomic classes and in all climates.
Schistosomiasis	Schistosomiasis is a water-based disease which is considered the second most important parasitic infection after malaria in terms of public health and economic impact. Schistosomiasis infection in humans is caused by three main species of flatworm (Schistosoma haematobium, S. japonicum, and S. mansoni). In Asia, cattle and water buffalo can also be important reservoir hosts. Infection occurs when free-swimming larvae penetrate human skin. The larvae develop in fresh-water snails. Humans are infected when they enter larvae-infested water for domestic, occupational and recreational purposes.	Improved sanitation and potable water minimizes contamination of and reduces contact with fresh water, thus limiting transmission. Environmental modification preventing snail vectors and limiting human water contact offers long-term control of schistosomiasis. Health impact assessment of new irrigation schemes and other water resources projects provides a basis for incorporating health safeguards in design and construction.	In the ESPA regions, Schistosomiasis is endemic in much of Africa, but is also found in parts of S America and China.
VIRAL			
Dengue and Dengue Haemorrhagic Fever	Four closely related viruses cause dengue and are transmitted to humans through the bites of infective female Aedes mosquitos. Typically a disease of urbanized areas, where the mosquitoes breed in small water bodies (e.g. drinking water containers, discarded car tyres, flower vases etc.). Mosquitos acquire the virus while feeding on the blood of infected people and may then also transmit the virus to the next generation of mosquitos.	Removing mosquito breeding-sites by proper disposal of solid waste that tend to collect water. Apply insecticide to decrease the mosquito population in epidemic areas.	Tropical and subtropical regions, predominately in urban and periurban areas, where Aedes mosquitos are prevalent.
Hepatitis	Hepatitis A and E viruses are both transmitted via the faecal-oral route, most often through contaminated water.	Good sanitation and waste disposal; good personal hygiene, especially hand-washing; adequate, clean water supply.	Both hepatitis A and E are found worldwide. Hepatitis A is particularly frequent in countries with poor sanitary and hygienic conditions.
Japanese Encephalitis	The virus causing Japanese encephalitis is transmitted by mosquitoes of the *Culex tritaeniorhynchus* and *Culex vishnui* groups, which breed particularly in flooded rice fields. The virus spills into humans when infected mosquito populations explode and the human biting rate increases (blood meals from animals, particularly pigs, are normally preferred).	Chemical vector control is not a solution, as the breeding sites (irrigated rice fields) are extensive. In some rice production systems, alternate wetting and drying may reduce vector populations. The introduction of pig rearing as a secondary source of income for rice-growing farmers in receptive areas should be discouraged.	Japanese encephalitis is a leading cause of viral encephalitis in Asia

4.6.1 Climate Change

The World Health Organisation estimates that warming and precipitation trends over the past 30 years have already claimed more than 150,000 lives annually (Patz et al., 2005). Such effects can be complex. For example, Magadza (1994) suggests that aridification in Southern Africa will encompass biome shifts, with major implications for food security and thus human disease susceptibility, and a multiplication and extended range of disease vectors. However, there are three main groups of ways in which climate can affect health:

(i) Climate change can directly affect human health through (Patz et al., 2000): temperature- related morbidity and mortality (Hajat et al., 2005, Gosling et al., 2007); health effects of extreme weather events (storms, tornadoes, hurricanes, and precipitation extremes) (Hunter, 2003) and floods (Magadza, 2000); and also air-pollution-related health effects.

(ii) Climate change can aggravate pre-existing health conditions such as the adverse effect of heatwaves on people suffering cardiovascular or respiratory illnesses; and can increase susceptibility to disease through malnutrition effects of drought or flood-induced crop failure.

(iii) Climate change can increase exposure to infectious diseases by supporting their transmission (Martens et al., 1999, Patz et al., 2005), and extending their spatial and seasonal ranges.

Group (iii) climate impacts are particularly complex and, in some cases controversial. Thus, Magadza (2000) suggests that the latitudinal and altitudinal range of malaria and schistosomiasis are likely to increase as stream flows are reduced to a series of pools, which reduce mosquito larvae mortality, for much longer periods than at present and that onchocerciasis (river blindness) could establish further south within Africa. The prevalence of waterborne disease agents, such as *Giardia* and *Cryposporidium* cysts have been correlated with rainfall, and malaria epidemics have been correlated with El Niño-related extreme weather conditions (Patz, 2001). Also Lama et al. (2004) associate environmental temperature, particularly in relation to El Nino, and the incidence and extent of cholera, noting that such associations are supported by cholera data from Bangladesh as well as in their study area in Peru, and Olago et al. (2007) show that cholera epidemics in the Lake Victoria Basin, Africa, are closely associated with El Nino years, and that sustained above-normal temperatures in two consecutive seasons, followed by a slight cooling in the second season, trigger cholera epidemics. However, Patz et al. (2005) note that there is still uncertainty in directly attributing the intensification or reappearance of diseases to climate change because of the lack of long-term, high-quality data sets and the variable influence of confounding factors such as socio-economic and immunity / drug resistance changes.

Uncertainty and scientific controversy are particularly notable in relation to associations between climate trends and the occurrence of malaria. For example, there are conflicting results in relation to increases in the incidence of malaria in the East African Highlands, where it has become a serious health problem. Bouma (2003) noted that although there seemed to be more support for non-climatic explanations, such as the deterioration of malaria control and the development of drug resistance, in explaining malaria occurrence, this could also reflect the use of inappropriate parameters and time periods (i.e. the transmission season) in climate-based epidemic forecasting. Whilst Hay et al. (2002) found no significant trends in temperature, rainfall, vapour pressure or the number of months suitable for transmission, Patz et al. (2002) criticised the analytical approach adopted by Hay et al., and Pascual et al. (2006) identified a significant warming trend. Pascual et al. then modelled the impact of this temperature change to show that it was amplified by at least an order of magnitude in the biological response of the mosquito population. In addition, Zhou et al.

(2004) suggested that climate variability as well as trend may be influential in initiating malaria epidemics.

4.6.2 Population Pressure and Land Use Change

Increasing human population pressures also impact directly and indirectly on human health as a result of intensified encroachment on natural environments; reductions in biodiversity, particularly reductions in natural predators of vector organisms; increased, close proximity to particular livestock, crops, and production methods that support disease transmission; and direct pressures on water resources imposed by uncontrolled urbanization or urban sprawl (MEA, 2005) and thus associated with the desakota phenomenon.

Under increasing population pressure and water demand, naturally-occurring water-quality problems can have severe health consequences that are independent of land use change. For example, the occurrence of fluorosis and arsenicosis as a result of chemically contaminated groundwater supplies (e.g. Chinoy et al. 1992, 1994, Dhiman and Keshari 2006).

Deforestation and associated changes in land use, irrigation, human settlement, industry and road construction have been accompanied by an increase or emergence of malaria, and schistosomiasis in some areas of Africa and Latin America (Patz, 2001). Although malaria is endemic in the Amazon region, Takken et al. (2005) describe a dramatic increase in malaria cases, which peaked at over 500,000 cases per year in the 1990s. They argue that deforestation has favoured the main malaria vector *Anopheles darlingi* by creating numerous sunlit larval habitats and also bringing many potential blood hosts (workers in forestry, agriculture and animal husbandry), into close contact with mosquitoes. .Vittor et al. (2006) confirm that in Peru *A. darlingi* demonstrates significantly higher human-biting intensities in areas that have undergone deforestation and road development. Takken et al. (2005) note that although malaria clinics and control programmes are now reducing the number of malaria cases in Amazonia, risks remain high in rural and peri-urban (i.e. desakota) areas where humans and mosquitoes are in close contact.

4.6.3 Inadequate Sanitation

In relation to unplanned urban expansion (desakota), Senzia et al. (2003) suggest that 90% of sewage from cities located in developing countries is discharged untreated into receiving waters; Merz et al. (2004) note increasing microbial and nutrient contamination of domestic water supply in rural areas of Nepal as a result of increasing settlement and intensification of agriculture; and Gupta and Deshpande (1999) describe mounting water resource pressures coupled with pollution of both surface and groundwater around towns and cities and increasing incidence of water borne diseases such as malaria, filaria, falciparum and cholera in Gujurat, NW India.

A lack of waste-water treatment facilities coupled with contamination of domestic water supplies is the prime cause of deterioration in human health within desakota areas in the ESPA regions. Of the 20 diseases listed in table 4.2, the intervention measures for 6 require improved sanitation and prevention of faecal / urine contamination of water supplies, whilst interventions for a further 4 require the provision of safe water to maintain personal hygiene.

Inadequate sanitation and unsafe water supplies are associated with a variety of diarrhoeal diseases, which Pokhrel and Viraraghavan (2004) estimate lead to 3.3 episodes of diarrhoea per child and 30,000 deaths annually in Nepal. In the Terai region of Nepal, Atreya (2006) found that, according to the Total Coliform count, the drinking water supply to 61% houses surveyed was contaminated, and estimated that the number of working days lost per household as a result of water-borne diseases each year was between 8 and 10. In Peru. Checkley et al (2204) found that children subject to the worst water supply, water storage and sanitation measures suffered more diarrhoea episodes than those living in the best conditions, and lack of adequate sewage disposal explained a 0.9 cm height deficit at 24 months.

Whilst direct contamination of surface water with inadequately treated sewage is the most widespread cause of contaminated drinking water, shallow groundwater can also become contaminated, particularly when population densities are high. Water supplies from shallow hand-dug wells are often closely linked to surface waters, leading to both microbial and nutrient contamination (e.g. Dongol et al., 2005).

4.7 SUMMARY AND RESEARCH NEEDS

This Regional Scale review has demonstrated important interrelationships both over the 20th century and in projections for the 21st century.

1. Changes in climate will have major consequences for ice and snow cover and melt-driven catchment systems within the ESPA regions. Whilst broad trends have been estimated, the broader implications of these changes across the entire hydrological cycle (e.g. including groundwater) and across large catchments needs further research.
2. Changes in climate also have the potential to cause shifts in biomes and/or their contained ecoregions and changes in the landcover within biomes or ecoregions can induce climate feedbacks
3. Relationships between vegetation, whether native or planted, and climate are complex and non-linear. In particular, biome and ecoregion boundaries may be particularly sensitive to changes in climate and *vice versa*. Self-organised patchiness in vegetation cover indicates a landscape close to threshold conditions that is highly sensitive to small changes in resource availability (e.g. climate drying or warming, groundwater extraction) and also small changes in landcover particularly with respect to engineering vegetation patches (e.g. overgrazing, burning, clearance of shrub and tree patches for fuel). These interactions need further research to identify the sensitivity of different landscapes to changes in vegetation and the resources (particularly water) that support vegetation growth.
4. Land use and management can strongly impact on climate-vegetation interactions across space and time scales, with the potential to induce marked changes in climate and water-related ecosystem services that may be extremely difficult to reverse. Whilst broad interactions between vegetation, land use and climate that impact on water-related ecosystem services have been defined, many research gaps remain. Particular research needs include (i) definition of responses to particular types of human land surface manipulation, (ii) the threshold conditions beyond which ecosystem impacts of particular land uses and management become severe, and (iii) the degree to which the spatial layout of human land use and management can moderate these threshold conditions.
5. Land use and management along the rural-urban continuum, and particularly within ‘peri-urban’ areas is central to the desakota phenomenon. Peri-urban areas are characterised by a patchwork of intensive land uses. Understanding the impact of mosaics of these land uses is crucial to developing approaches that balance human and ecosystem needs in a sustainable way. It is highly likely that adjustments in the current land use mosaic coupled with the introduction of patches of lower-intensity land uses to buffer the impacts of intense land use could yield dramatic improvements in water-related ecosystem services.
6. Direct manipulations of the hydrological system (particularly the over-development of groundwater and the imposition of large surface reservoirs) form the second major group of

human impacts on water-related ecosystem services. Much research has been conducted on the exploitation of groundwater and surface water stores, but a greater understanding is needed of how these manipulations fit within their broader environmental setting. Manipulation of both of these stores affects river flow, sediment transport and water quality regimes, yielding adverse effects on river and riparian ecosystems and thus on their ecosystem services. Moreover, the exploitation of both of these types of water store depends upon the spatial and temporal hydrological functioning of the catchments within which they are located. Conceptual, generic and case-study research is needed to investigate ways in which ground and surface water stores can be managed in greater sympathy with their catchment setting and the needs of humans and ecosystems within the catchment.

7. Population pressure, climate and land use change combine to have dramatic effects on water-related diseases and human health. Whilst major advances have been achieved in understanding intricate interactions between these factors, many controversies remain, particularly where climate and environmental change interact with disease vector organisms at different stages in their life cycles. Thus research gaps remain at the regional and sub-regional scales in understanding how climate change and human / land use pressures interact to create or remove vector habitats and to increase or reduce transmission seasons and pathways.
8. All of the above research needs can be summarised as new approaches to understanding catchments and integrating their management. The ESPA regions include very large catchments and rivers, where integrated understanding is limited but where integrated management, at least at the subcatchment scale based on sound integrated science, could yield enormous benefits.

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