The Ramsar Convention on Wetlands

Ramsar COP8 DOC. 11: Climate Change and Wetlands

[English only]

"Wetlands: water, life, and culture"
8th Meeting of the Conference of the Contracting Parties
to the Convention on Wetlands (Ramsar, Iran, 1971)
Valencia, Spain, 18-26 November 2002

Ramsar COP8 DOC. 11
Information Paper
English only

Climate Change and Wetlands: Impacts, Adaptation and Mitigation

Note: This paper provides background information in support of draft resolution COP8 - DR 3, the Annex to which provides a summary of the key issues described in this paper. The six Figures referred to in this paper are available in Ramsar COP8 - DOC. 11 Annex. The draft text of this paper has been prepared Rick van Dam , Habiba Gitay and Max Finlayson1 on behalf of the Scientific and Technical Review Panel and its Expert Working Group on Climate Change and Wetlands, and edited and finalised by the Bureau's Deputy Secretary General.

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1 Introduction

1.1 Background

1. This paper has been prepared by the Scientific and Technical Review Panel (STRP) of the Convention on Wetlands (Ramsar, Iran, 1971) in response to Action 5.1.6 of the Convention's Work Plan 2000-2002, which requested the STRP to prepare for consideration at the 8th meeting of the Conference of the Parties (COP8) a comprehensive review of the potential impacts of climate change on wetlands and the roles that wetlands can potentially play in mitigating the effects of climate change and sea level rise.

2. The continuing loss and degradation of wetlands has attracted increasing worldwide concern, including through efforts made under the Ramsar Convention. Wetlands, as defined by the Convention, include coastal/marine habitats such as reefs, seagrass beds and mangroves, inland habitats such as lakes and marshes whether saline or fresh, temporary or permanent, and high altitude and latitude habitats such as bogs and fens.

3. The Convention seeks to achieve the conservation and wise (sustainable) use of wetlands by maintaining their ecological character through the promotion of effective management regimes that include monitoring and, where necessary, rehabilitation.

4. Currently, and in the future, wetlands are being and will be affected by pressures from global change such as climate change, sea level rise, pollution (including acid rain), and land use or land cover change. Successes in wetland conservation and wise use will need to be measured against the potential impacts of these pressures.

5. Human activities such as burning of fossil fuels and land use and land cover change have caused recent changes in the world's climate systems, and continued emissions of greenhouse gases is projected to result in further climate change (IPCC 2001a), which is a potentially large future pressure on wetlands. The projected changes in climate, including increasing mean global temperatures, changes in precipitation, sea level rise, and increased frequency and intensity of some extreme climatic events, will impact wetlands and their dependent species.

6. Adaptation measures could reduce some impacts, especially in the short term, and could also address some wetland degradation resulting from other pressures. Wetlands are considered to be vulnerable to climate change if adaptation options are limited and/or the wetlands are sensitive to climate change.

7. Full mitigation of climate change would require a substantial reduction of emission of greenhouse gases, although some impacts (e.g., sea level rise) will continue for centuries due to the emissions from the 19th and 20th centuries. However, mitigation options could not only include reducing greenhouse gas emission through the reduction of fossil fuel use, but also reducing the land-based emissions through conservation of existing large pools in wetlands. Changes in wetlands themselves may also affect at least the local and regional climate.

8. In addition to providing the analysis of climate change and wetlands called for in Action 5.1.6 of the Convention's Work Plan 2000-2002, this paper provides background information in support of the implementation of several other recent decisions made by Ramsar's Contracting Parties, including:

> i) Action 7.2.7 of the Ramsar Strategic Plan (1997-2002), which calls for the development of links with the UN Framework Convention on Climate Change (UNFCCC), in view of the potential impacts on wetlands of climate change;
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> ii) Resolution VII.4 on partnerships and cooperation with other Conventions, which called for a Memorandum of Cooperation with the UNFCCC; also endorsed through Recommendation 7.2 (see below);
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> iii) Recommendation 7.1 on the preparation of a global action plan for the wise use and management of peatlands, which noted the need to include wetland carbon sinks and sequestration initiatives as key issues in the Kyoto Protocol under the UNFCCC; and
>
> iv) Recommendation 7.2 on small island states, which noted the direct and urgent interests of Small Island Developing States in the impacts of climate change and the important role of wetlands in addressing these threats.

9. The findings of this paper are relevant also to implementation of a number of Resolutions being considered for adoption by COP8, including inter alia COP8 - DR 4 on wetlands and Integrated Coastal Zone Management, COP8 - DR 5 on partnerships and synergies with Multilateral Environmental Agreements and other institutions, and COP8 - DR 17 which provide guidelines for global action on peatlands.

1.2 Scope and sources of information

10. The focus of this paper is the impacts of climate change on wetlands, and adaptation and mitigation options. To set the context for this, the paper also provides a brief overview of the importance and global distribution of wetlands, as well as of recent and projected changes in global and regional climate and some other pressures (e.g., land use and land cover change). The paper also examines adaptive management options and reviews the extent to which the tools and guidelines contained in the Ramsar 'toolkit' of Wise Use Handbooks provides adequate guidance in support of management responses to climate change for wetlands. Climate change projections have a number of associated uncertainties due to the current state of knowledge and the complexity of the problem. These issues are addressed in the final section of the report in relation to how the uncertainties affect the robustness of projections of climate change and its impacts on wetlands.

11. It is beyond the current scope to address in detail the multiple pressures of global change and their overall impacts, and there is a need to examine further the effects of the multiple pressures on wetlands, which may be more important than the effects of climate change alone. Furthermore, as reflected in this paper, available information on adaptation and mitigation options for wetlands is limited, and more detailed regional or local work on this issue should be a priority for the future.

12. The major sources for information on climate change impacts on wetlands and adaptation and mitigation options were the results of the recent Intergovernmental Panel on Climate Change (IPCC) assessment reports (e.g., IPCC 1998, 2000, 2001a, 2001b, 2001c). These have been supplemented with more recent work on wetlands and climate change published since 2000. The section on adaptive management and vulnerability assessment draws on material from Kay & Waterman (1993), Harvey et al (1999), and van Dam et al (1999). Information on the global extent and distribution of wetlands is drawn from Finlayson & Spiers (1999) and Finlayson et al (1999).

2. The importance of wetlands and their values and functions

13. Wetlands are valuable resources that supply many goods and services (or products, functions and attributes) to people (Finlayson 1996). These goods and services include food, fibre (e.g., reeds), clean water, carbon and other nutrient stores/sinks, flood and storm control, ground water recharge and discharge, pollution control, organic matter or sediment export, routes for animal and plant migration, landscape and waterscape connectivity. Costanza et al. (1997) estimated the total global value of these goods and services provided by coastal areas and inland wetland ecosystems to be US$15.5 trillion or some 46% of the estimated total value of goods and services provided by all ecosystems worldwide.

14. Under the Ramsar Convention, ecological character of a wetland is defined as the sum of the many biological, physical, and chemical components of the wetland ecosystem, and their interactions (http://www.ramsar.org/key_res_vii.10e.htm). The goods and services provided by an individual wetland are the result of its ecological character and include important wetland functions, such as hydrological and biogeochemical cycling (described further below).

15. Other ecosystem functions are primary and secondary production, animal and plant interaction (e.g., pollination, herbivory), and carrier functions which include connectivity (landscape and waterscape), routes for animal migration, plant dispersal (including seeds), maintenance of biodiversity and aesthetic, spiritual, cultural and recreational services.

16. Wetland functions, and hence the goods and services provided by wetlands, will be impacted by climate change. For example, wetlands are critically important in global biogeochemical cycling (Sahagian & Melack 1998); but climate change will impact the biogeochemical cycling by affecting the hydrology, net primary production, respiration and decomposition rates and so also carbon and nitrogen cycling in wetlands.

17. Many wetlands contain large stores of carbon, so the release, maintenance or enhancement of these stores under a changing climate will in turn potentially affect future climate change (IPCC 2001c). Maintenance of the ecological character of a wetland (and thus its hydrological, biogeochemical, and ecological functions) will enable people to continue to enjoy the values and benefits derived from the wetland. Hence managing wetlands under climate change can support the delivery of the wise use principles of the Ramsar Convention (Davis 1994) and contribute to sustainable development of wetlands, both locally and further afield.

2.1 Hydrological functions

18. Many wetlands have inherently variable and rapidly reversible "states" driven by sometimes extremely variable water supply. Many of the goods and services provided by wetlands are dependent on their hydrological functions as well as the "state" they are in.

19. Water runoff, water flows, ground water recharge and discharge and flow systems, residence period of the water and turnover time ("flushing of wetlands" and their replenishment) are closely associated with the control of water quality, nutrient cycling, and the distribution and survival of certain plant and animals species (Hollis 1998, Mitsch et al 1994).

20. Many of these hydrological functions operate at the catchment level and thus management of the catchment hydrology will affect the overall functioning of wetlands and the goods and services they provide [(see also Ramsar's guidance on water allocations and management (COP8 - DR 1))].

2.2 Biogeochemical functions

21. Biogeochemical functions of wetlands include the transformation and cycling of elements, the retention and removal of dissolved substances from surface waters, and accumulation of peats and inorganic sediments. These functions retain nutrients and other elements, improve water quality, and affect aquatic and atmospheric chemistry (Sahagian & Melack 1998).

22. Wetlands play an important role in carbon and nitrogen storage, and they are also natural sources of greenhouse gases (GHG) such as methane (CH4) and sulphur dioxide (SO2) (Sahagian & Melack 1998). The general roles played by wetlands in the production, metabolism, storage and release of these compounds (particularly carbon dioxide, methane, nitrous oxide and sulphur dioxide) are briefly outlined below. However, the wide range of wetland types and their differing characteristics in cycling of for different GHGs makes it difficult to identify the specific role of each wetland (Patterson, 1999).

Carbon storage (carbon dioxide and methane)

23. Wetlands are important reservoirs of carbon, representing about 15% of the terrestrial biosphere carbon pools (Bolin & Sukumar 2000; Patterson 1999). When boreal forests and some tropical forested wetlands are included as wetlands, this figure comes to about 37% of the terrestrial carbon pool (Bolin & Sukamar 2000).

24. In terrestrial ecosystems (including wetlands), the majority of carbon is stored in the soil as organic matter, which may be released when the soil is disturbed, for example due to wetland drainage and destruction or fires (Bolin & Sukumar 2000; Gitay et al 2001). In general, carbon in soil is approximately five times higher than that in above-ground vegetation;, but this ratio is much higher in grasslands (~30:1) and wetlands (~15:1) (Bolin & Sukumar 2000). The ability of a wetland to store carbon is related to its hydrology and the associated level of the water table, geomorphology, and local climate (Patterson 1999; Sahagian & Melack 1998).

25. Wetlands and rice fields, when flooded, are among the largest sources of methane from the terrestrial systems to the atmosphere (Cao et al 1998; Dale 1997; Roulet 2000; Sahagian & Melack 1998). Wetland plants enhance methane emissions by acting as conduits of gas exchange, and through the production of root exudates and plant litter. Important factors controlling methane production include rates of primary productivity, salinity, water level, temperature, light, and soil properties (Cao et al 1998; Patterson 1999; Sahagian & Melack 1998). Vegetative biomass, including that of rice, is positively correlated with methane emissions in wetlands, i.e. the larger the biomass the higher the emission of methane.

26. About one quarter of the carbon sequestered by wetlands is subsequently emitted to the atmosphere as methane (Patterson 1999) and approximately one fifth to one third of the global wetland methane emissions are derived from rice paddies (Cao et al 1998). Tropical wetlands appear to be larger contributors of methane to the atmosphere than northern wetlands (north of 45° latitude).

27. As well as being sources of methane, wetlands may also act as sinks of methane although the dynamics of methane storage in relation to primary production and drying/inundation patterns is poorly understood and requires significant further investigation.

Nitrous oxide production

28. Microbiological processes in soils are the major source of atmospheric nitrous oxide (N2O), with fertilizer application and biomass burning probably being the largest anthropogenic sources (Bolin & Sukumar 2000; Watson et al 1992). Emissions from soils are greater under warm and wet conditions, for example in tropical forest environments. There is little information about N2O emissions from wetlands, but peatlands are thought to be neither a significant source or sink (Roulet 2000).

Sulfur production

29. Sulfur gases exist in the atmosphere mostly as sulfate aerosols (i.e., microscopic airborne particles; Carter & La Rovere 2000). Anthropogenic sources of sulfur, particularly sulfur dioxide (SO2) from industrial emissions, are the greatest contributors to atmospheric sulfate aerosols (Watson et al 1992). Sulfur compounds are commonly present in wetlands and are a minor source of atmospheric sulfur. The reduction of sulfate resulting from microbial oxidation of organic materials results in the formation of sulfide gases, including dimethyl sulfide (DMS) and hydrogen sulfide (H2S) (Sahagian & Melack 1998). Fluxes of sulfur gases from coastal wetlands are known to be 10-100 times greater than from the ocean, although their aerial extent is thought to be limited (Sahagian & Melack 1998).

Greenhouse gases

30. The naturally occurring greenhouse gases that exert a positive radiative forcing (i.e., they warm the atmosphere) are considered to be water vapour, CO2, methane, and nitrous oxide. Sulphur dioxide is also considered a greenhouse gas but, in contrast to the others, it has a cooling effect on the atmosphere (Watson et al 1992). Human activity (fossil fuel combustion and land use/land cover change) has affected the concentration of these greenhouse gases in the atmosphere (IPCC 2001a) and this has in turn affected the Earth's climate.

31. Given that a) wetlands store about a third of the terrestrial carbon; and b) the terrestrial biosphere, which at present is a sink, is projected to become a source by the 22nd century, wetlands may become a source for GHGs, either directly due to projected changes in climate or indirectly due to changes in their disturbance regimes.

32. Natural peat-accumulating wetlands (peatlands) are known to be an overall sink for carbon (Gitay et al 2001; Roulet 2000), although CH4 emissions from these ecosystems represent a considerable source of carbon to the atmosphere (Roulet 2000; see below). In a study of the Canadian peatlands, Roulet (2000) estimated that these peatlands are neither a net source or sink of GHGs. However, it was recognised that the calculations carried much uncertainty, due mostly to a lack of knowledge about temporal changes to the peatlands. Existing data on carbon storage in peatlands are highly variable (Gitay et al 2001), and very little is known about the carbon dynamics of non-peat-accumulating wetlands (Roulet 2000).

2.3 Consequences of wetland modification and changes in disturbance regimes

33. Past and present land use and land cover change are the main factors that affect terrestrial sources and sinks of carbon (Bolin & Sukumar 2000; Roulet 2000). Of particular importance is the fact that, during the 1980s, more than 90% of the net release of carbon from land use/land cover change was a result of land use changes in the tropical regions of the world (Bolin & Sukumar 2000).

34. Roulet (2000) identified six anthropogenic modifications that could alter the exchange of gases between wetlands and the atmosphere, in relation to Canadian wetlands: agricultural reclamation; urban and industrial land use; energy development; peat harvesting; forest harvesting; and wetland creation. These modifications are considered also relevant on a global scale, and their consequences are summarised below.

35. In addition, the impacts of climate change on wetlands will also directly and indirectly influence the fluxes of GHGs, either by increasing the respiration rates and primary production and/or by reducing the water table. With increased temperatures this would lead to increased frequency and intensity of fires (Bolin and Sukamar 2000; Gitay et al., 2001). However, while projections for CO2 and CH4 emissions can be made, there is insufficient information to project the fate of N2O emissions under land use change scenarios (Roulet 2000).

Agricultural reclamation

36. Agricultural reclamation includes activities such as drainage, in-filling, construction of dykes, and also cultivation. Lowering of water levels may result in an increase in CO2 emissions but a reduction or even cessation of CH4 emissions. However, CH4 emissions from drainage ditches can be significant (Roulet 2000).

37. Conversion of wetlands to agricultural lands can lead to increases in CO2 emissions, with cropping activities also potentially leading to increases in N2O emissions (Roulet 2000). Of importance here is that agricultural practices often replace diverse natural ecosystems with single species ecosystems, since recent research has shown that ecosystems with high plant diversity were better able to sequester CO2 and nitrogen than ecosystems with reduced biodiversity (Lazaroff 2001a).

38. Agricultural reclamation also results in wetland fragmentation, which can affect other wetland functions such as migration of some animals and plants.

Urban and industrial land use

39. Wetland destruction, through drainage or in-filling, is a common feature of urban and industrial development. The complete removal of a wetland should eliminate the sink for CO2 and the source of CH4 (Roulet 2000). Thus, the overall net effect on GHG emissions could range from negligible to a small increase in emissions (Roulet 2000). Following in-filling and compaction of the wetland soil, some carbon stock will most likely remain part of the soil carbon pool (Roulet 2000).

Energy development and water storage

40. The major modification to wetlands associated with energy development and water storage is the construction of reservoirs and dams. The flooding of former wetlands, and subsequent creation of new wetlands, can result in a number of changes to GHG fluxes.

41. Reservoirs are known to be significant sources of both CO2 and CH4, especially if a former carbon-rich land cover (e.g., forest or peatlands) is inundated. Although the proportion of GHG emissions derived from the former wetland's sediments is usually unknown, it is known that flooding of such systems increases both CO2 and CH4 emissions, and therefore net GHG emissions, significantly (Roulet 2000), and that this can continue over a long period of time.

Peat and forest harvesting

42. Peat harvesting requires the drainage of a peatland, and thus will most likely result in a reduction in CH4 emissions and an increase in CO2 emissions from peat soils. The impact on net GHG emissions could range from negligible to a large increase in emissions (Roulet 2000). In addition, there will be a net loss in the carbon stock due to that contained in the extracted peat.

43. Harvesting of wet forests also involves their drainage, resulting in a reduction in CH4 emissions and a small increase in CO2 loss from the soil. Loss of CO2 is partially offset by carbon uptake in the living biomass of the vegetation, although removal of the tree cover would be expected to minimise this effect. Apart from the impact on the GHG emissions, forestry activities are a threat to the viability of many forested peatlands, but particularly tropical forested wetlands (Gitay et al 2001).

Wetland creation

44. The creation of new, and the restoration of former, wetlands is becoming an increasingly common practice. Wetland creation involves the flooding of soils and the subsequent establishment of aquatic plant communities and formation of organic sediments (Roulet 2000). An increase in net primary productivity (NPP) will lead to the uptake of CO2, while the flooded soils will also contribute to increased CH4 emissions. The overall effect on net GHG emissions is difficult to determine but could range from a small negative effect to a small positive effect (Roulet 2000).

Changes in the frequency and intensity of fires

45. Fires are part of natural dynamics and management regimes of many wetlands. Fire as a disturbance is likely to be affected by climate change, with some regions, for example those experiencing El Niño-like phenomena and those in the higher latitude regions, likely to experience increased intensity and frequency of fires as a result of increased primary productivity and climatic conditions more favourable to fires (Gitay et al. 2001)

Climate change feedbacks

46. Most research on the impacts of climate change on the exchange of GHGs between wetlands and the atmosphere has focused on peatlands (e.g., Anisimov & Fitzharris 2001; Gitay et al 2001; Kundzewicz & Parry 2001; Lal et al 2001). The main points are summarised here, and further information is provided in sections 3 and 4 below:

> i) By altering the hydrology of wetlands, climate change will have significant consequences for CO2 and CH4 exchange between wetlands and the atmosphere. Drying of wetlands will probably reduce CH4 emissions and increase CO2 emissions. Overall, it is generally accepted that aspects of climate change, such as longer and more frequent droughts, increased incidence of fire, and thawing of permafrost, will have negative effects on the carbon balance of wetlands such as peatlands (Gitay et al 2001).
>
> ii). However, higher temperatures and atmospheric CO2 levels will also increase net primary productivity of wetlands in many regions, and thus increase CO2 uptake by the plant biomass.
>
> iii) Methane emissions could increase if the area under rice cultivation increases with climate change (Cao et al 1998), although it is uncertain whether this will occur on a global scale (Lal et al 2001).
>
> iv) Terrestrial ecosystems are currently a sink for carbon due to past land management practices, the fertilization effect of CO2 on plant photosynthesis (either directly via increased carbon assimilation, or indirectly through higher water use efficiency), nitrogen deposition (especially in the northern hemisphere), and climate change. This sink is projected to be maintained over the next few decades, but may then diminish and even become a source of carbon with increased warming towards the end of the 21st century. This be due to an increase in plant and soil respiration and changes in disturbance regimes (e.g., fire and insect outbreaks) mediated through climate change (IPCC 2001c).
>
> v) The GHG exchange characteristics of the resultant vegetation community structure (either wetland or terrestrial in nature) of a wetland following climate change-related impacts need to be better understood before the implications of climate change on the overall carbon balance can be more fully evaluated.

3. Global summary of impacts of climate change on wetlands

3.1 Global wetland distribution

47. Using a standard methodology to assess more than 500 regional and national inventory sources(Finlayson & Davidson 1999a), a global review of wetlands resources was undertaken in 1999 for the Ramsar Convention (Finlayson & Spiers 1999, Finlayson et al 1999a). This included an international/continental analysis (Spiers 1999) and regional analyses that addressed the extent and adequacy of the wetland inventory information base in Africa (Stevenson & Frazier 1999a), Asia (Watkins & Parish 1999), the Middle East (Frazier & Stevenson 1999), Eastern Europe (Stevenson & Frazier 1999b), Western Europe (Stevenson & Frazier 1999c), the Neotropics (Davidson et al 1999a), North America (Davidson et al 1999b), and Oceania (Watkins 1999).

48. Overall, the 1999 Ramsar review found that the extent of wetland inventory was patchy or incomplete and often unreliable, and that it was very difficult to establish standardised and reliable figures for many wetland types owing to inconsistencies in coverage of wetland types. Only 7% of countries examined at that time had adequate or comprehensive national wetland inventory. Regional and global estimates compiled from national sources are given in Table 1, and provide a global estimate of approximately 12.8 million km2..

49. Global estimates for some wetland types covered by the Ramsar Convention were also compiled as part of the global review, and include:

§ Natural freshwater wetlands 5.7 million km2
§ Rice paddy 1.3 million km2
§ Mangroves 0.18 million km2
§ Coral reefs 0.3-0.60 million km2

50. On these figures the area of wetlands worldwide ranges from 7.48-7.78 million km2, but that does not include many other wetland types, such as salt marshes, coastal flats and seagrass meadows, karst and caves, and reservoirs as recognised under the Ramsar Convention.

51. Despite the poor level of overall coverage of national wetland inventory, these estimates are considerably higher than previous estimates for wetland extent, derived largely from remote sensing, which vary from 5.6-9.7 million km2 (Spiers 1999). Darras et al (2000) also report that there are inconsistencies between global wetland datasets, partly due to incompatible classification of data. By combining a number of datasets they provided an estimate of 9.542 million km2 (excluding marine wetlands), but most likely still underestimated the global extent of wetlands, especially the extent of seasonally inundated wetlands.

Table 1. Estimated area of wetlands in each of the regions of the world recognised under the Ramsar Wetlands Convention, from Finlayson & Davidson (1999b); Finlayson et al (1999).

	Estimated area of wetlands	
Region	**Million km^2**	**Percentage of global estimated area**
Africa	1.21	9.5
Asia	2.04	16.0
Eastern Europe	2.29	17.9
Western Europe	0.29	2.3
Neotropics	4.15	32.5

North America	2.42	19.0
Oceania	0.36	2.8
Global (total)	**12.76**	**100**

52. As a visual representation, wetland groups as defined by Matthews & Fung (1987) are illustrated in **Figure 1** in the appendix, which provides a broad picture of the global distribution of commonly recognised inland wetlands. This representation suffers from many of the problems outlined above. Marine and possibly many coastal wetlands are not shown. Furthermore, it has been extremely difficult to map the distribution and extent of wetlands that are only inundated intermittently or episodically. It is unlikely that a valid representation of wetland types, particularly as defined under the Ramsar Convention, is available (Finlayson et al 1999a).

53. Uncertainty over the distribution and extent of wetlands makes any impact and vulnerability assessments difficult, particularly at regional and local levels. This is further complicated by the fact that the commonly used plant-based (or morphological/structural) wetland classifications do not reflect the functioning of wetlands in terms of their hydrology and biogeochemical cycling (Sahagian and Melack 1998). A functional characterization of wetlands reflecting these functions will be needed for the importance of wetlands, particularly in global biogeochemical cycling, to be fully determined.

3.2 Summary of observed and projected global climate change

54. Changes in climate occur as a result of internal variability of the climate system and external factors (both natural factors such as solar radiation, cloud formation, and rainfall and those resulting from human activities, including increased concentrations of greenhouse gases) in the atmosphere.

55. Since the 1750s, human activities (e.g., burning fossil fuel and land use/land cover change) have increased the atmospheric greenhouse gases (e.g., water vapour, carbon dioxide, methane, nitrous oxides, and sulphur dioxide). Increase in these greenhouse gases has and will continue to increase the mean global temperature, alter the precipitation patterns, and raise sea level. This will result in an enhanced global hydrological cycle and more extreme and heavier precipitation events in many areas. Atmospheric concentrations of carbon dioxide have increased by about 30% and methane by about 150% during this period (IPCC 2001c).

56. Other greenhouse gases and the associated biogeochemical cycles have also been affected. For example, nitrogen production, due largely to chemical fertilizer production, has doubled in the 20th century (Walker et al 1999), and atmospheric concentrations of nitrous oxide have increased by about 16% (IPCC 2001c).

57. Changes in anthropogenic sulphur dioxide emissions have been large, but regionally variable, and the gas is generally short-lived. In the late 1990s, the anthropogenic sulphur dioxide emissions decreased compared to the mid-1980s, due to structural changes in the energy system as well as concerns about local and regional air pollution (Albriton & Filho et al 2001). These emissions, or aerosols, cool the atmosphere (unlike the other greenhouse gases), but are still important in explaining the changes in climate observed in the 20th century and those projected for the 21st century and beyond

Observed climate change

58. In the latest IPCC assessment, a suite of changes consistent with a warming world have been documented (Folland & Karl 2001; IPCC 2001c, see also Table 2).

59. The global surface temperature is estimated to have increased by 0.4ºC to 0.8ºC, with the rate of warming in the 20th century being greater than that in the past 1000 years, with the 1990s being the warmest

decade of the millennium. Global land surface air temperatures have warmed faster than the global ocean surface temperatures. Night-time minimum temperatures have increased along with the lengthening of the freeze-free season, and thus, growing season (by about 4 to 16 days in the last four decades of the 20th century) in many middle and high latitude regions. There has been a reduction in the frequency of extreme low temperatures, without an equivalent increase in the frequency of extreme high temperatures.

60. Over the past 25 years, there has been an increase in precipitation in many parts of the northern hemisphere, with an increase in heavy and extreme precipitation events over land in the mid- and high latitudes, leading to an enhanced hydrological cycle. There has been an increase in the intensity and frequency of El Niño events that has affected drought and/or floods in many parts of the southern hemisphere. There has been a decline in the extent of Arctic sea ice, particularly in spring and summer, with about a 40% decrease in the average thickness of summer Arctic sea ice over the last three decades of the 20th century (Folland & Karl 2001; IPCC 2001c).

61. Table 2 provides further examples of observed changes in the biophysical system during the 20th century.

Table 2 Observed changes in the atmospheric greenhouse gases, climatic variables and associated changes in some biophysical systems during the 20th century (modified from IPCC 2001c).

Indicator	**Observed Changes**
Atmospheric concentration of CO2	From 280 ppm for 1000-1750 AD to 368 ppm in 2000 AD (31±4% increase)
Atmospheric concentration of CH4	From 700 ppb for 1000-1750 AD to 1750 ppb in 2000 AD (150±25% increase)
Atmospheric concentration of N2O	From 270 ppb for 1000-1750 AD to 316 ppb in 2000 AD(17±5% increase)
Global mean surface temperature	Increased by 0.6±0.2°C over the 20th century; land areas warmed more than the oceans
Northern Hemisphere surface temperature	Increased over the 20th century greater than during any other century in the last 1000 years; 1990s warmest decade of the millennium
Continental precipitation	Increased by 5-10% over the 20th century in the northern hemisphere; decreased in some regions, e.g., north and west Africa and parts of the Mediterranean
Heavy precipitation events	Increased at mid- and high northern latitudes
Global mean sea level	Increased at an average annual rate of 1 to 2 mm during the 20th century
Duration of ice cover of rivers and lakes	Decreased by about two weeks over the 20th century in mid- and high latitudes of the Northern Hemisphere
Arctic sea ice extent and thickness	Thinned by 40% in recent decades in late summer to early autumn and decreased in extent by 10-15% since the 1950s in spring and summer
Non-polar glaciers	Wide-spread retreat during the 20th century
Snow cover	Decreased in area by 10% since 1960s
Permafrost	Thawed, warmed and degraded in parts of the polar regions

El-Niño events	More frequent, persistent and intense during the last 20-30 years compared to the previous 100 years

Projected climate change

62. The Working Group I report of the IPCC Third Assessment (IPCC 2001a) has provided revised global, and to some extent regional, climate change projections based on a new series of emission scenarios from the IPCC Special Report of Emissions Scenarios (SRES).

63. The SRES scenarios consist of six scenario groups, based upon narrative storylines. They are all plausible and internally consistent, and no probabilities of occurrence are assigned. They encompass four combinations of demographic change, social and economic development, and broad economic developments (see Box 1). Each of these scenarios has its own greenhouse gas emission trajectories (Carter & La Rovere 2000). Parts of this report will refer to the A2 and B2 scenarios: A2 has high greenhouse gas emissions which continue to increase beyond 2100; and B2 scenarios have mid to low levels of greenhouse gas emissions with rates of increase showing signs of slowing by the end of 2100 (IPCC 2001a).

Box 1. The Emission Scenarios of the Special Report on Emission Scenarios (SRES)

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in the mid-21st century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies).

A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than in other storylines.

B1. The B1 storyline and scenario family describes a convergent world with the same global population (which peaks in mid-century and declines thereafter) as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, albeit at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

64. Using the full range of SRES scenarios, the mean atmospheric carbon dioxide (CO2) concentrations are

projected to increase from the 1990 level to 475 - 1100 ppm by 2100 (see Table 3). The mean global temperatures are projected to be 1.4°C to 5.8°C higher by 2100 with a great deal of variation in the regions, but generally the temperatures increasing most in the mid- to high latitudes of the northern hemisphere (see figure 2). The changes in precipitation are small (5% to 20% at regional scale) with generally an increase in year to year variation. There is generally an increase in the precipitation in the northern hemisphere and a decrease in the mid-latitudes with some increase in the tropics projected by 2100 (see Figure 3). Given the increases in temperature, the overall effect would be an increase in evapotranspiration in the tropics and a decrease in run-off affecting some wetlands. The sea level rise projections are 10-90cm by 2100 (Table 3), which could be due to thermal expansion of sea water and loss or decrease in glaciers and ice-sheets.

65. Many of the impacts on wetlands may be due not only to changes in the mean climatic variables described above but also to changes in the frequency and intensity of extreme climatic events. Examples of such projected changes include an increase in the number of hot days, fewer cold days, more heavy precipitation events, and increased frequency and intensity of floods and droughts (see Table 4).

Table 3 Climate change and greenhouse gas (GHG) concentration projections for the 21st century, if no climate policy interventions are made (modified from IPCC 2001c).

Indicators	2025	2050	2100
CO$_2$ Concentration	415–460 ppm	460–625 ppm	475–1100 ppm
Global Mean Temperature Change from 1990	0.4–1.1°C	0.8–2.6°C	1.4–5.8°C
Global Mean Sea-Level Rise from 1990	2–15 cm	5–30 cm	10–90 cm

Table 4 Examples of impacts resulting from projected changes in extreme climate events (modified from IPCC 2001b).

Projected Changes during the 21st Century in Extreme Climate Phenomena		Examples of Projected Impacts
Higher maximum temperatures, more hot days and heat waves over nearly all land areas		Increased heat stress in wildlife
Higher minimum temperatures, fewer cold days, frost days and cold waves over nearly all land areas		Extended range and activity of some pest and disease vectors
More intense precipitation events over many areas		Increased flood, landslide, avalanche, and mudslide damage Increased soil erosion Increased flood runoff could increase recharge of some floodplain aquifers
Increased summer drying over most mid-latitude continental interiors and associated risk of drought, Intensified droughts and floods associated with El Niño events in many different regions		Decreased water resource quantity and quality Increased risk of fires

Increase in tropical cyclone peak wind intensities, mean and peak precipitation intensities (over some areas)		Increased coastal erosion and damage to coastal buildings and infrastructure Increased damage to coastal ecosystems such as coral reefs and mangroves

3.3 Impacts of climate change on wetlands and wetland species

66. Impacts are covered, where the information exists, for all types of wetlands as defined by the Ramsar Convention (Davis 1994), including temporary and permanent inland and coastal aquatic habitats, including coral reefs.

67. Before summarising the potential impacts of climate change on wetlands, it is worth noting the following context-setting statement regarding climate change impacts on global water resources (Arnell & Chunzhen 2001):

> "The potential impacts of climate change must be seen in the context of other changes which affect water management. Few studies have explicitly compared climate change with other pressures, but in many environments it is likely that over a time horizon of less than 20 years, climate change impacts will be very small relative to other pressures."

68. Thus, whilst this paper makes only occasional reference to non-climate related pressures to wetlands, it must be recognised that climate change will act in conjunction with a range of other pressures, many of which, depending on the region, may pose far greater immediate concern for wetlands and their water resources in the short to medium term. However, as stated earlier, it is outside the scope of this report to integrate impacts of climate change with those of other components of global change, or indeed, the many pressures that affect wetlands locally. Analyses of the combined effect of all such pressures is required before an accurate analysis of effects on all wetland types due to climate change alone can be clearly identified. The exception in this regard may be coral reefs. These have already been recognised as undergoing increased degradation, and have been a focus of attention for the analysis of climate change impacts (Wilkinson 1999).

69. Despite the importance of multiple pressures, there is evidence to suggest that observed changes in the regional climate have already affected biological systems. Examples include polewards and upward altitudinal shift in animal (including geese, ducks and fish) ranges, extension of breeding seasons, and coral bleaching events associated with increase in the frequency of El Niño events (IPCC 2001b).

70. Walther et al (2002) also note the following:

> "Common changes in the timing of spring activities include earlier breeding or first singing of birds, earlier arrival of migrant birds, earlier appearances of butterflies, earlier choruses and spawning in amphibians and earlier shooting and flowering of plants."

71. It appears that climate change will have its most pronounced effect on wetlands through alterations in hydrological regimes: specifically, the nature and variability of the hydroperiod and the number and severity of extreme events.

72. However, other variables related to climate may play important roles in determining regional and local impacts, including increased temperature and altered evapotranspiration, altered biogeochemistry, altered amounts and patterns of suspended sediment loadings, fire, oxidation of organic sediments, and the physical effects of wave energy (IPCC 1998; Burkett & Kusler 2000; USGCRP 2000).

73. Some broad projected impacts of climate change to specific types of wetlands are outlined in Table 5. It is acknowledged from the outset that the effect of climate change on all elements of biodiversity requires further analysis. A first analysis is currently being undertaken by the IPCC following a request from the Subsidiary Body for Scientific, Technical and Technological Advice (SBSTTA) of the Convention on Biological Diversity (IPCC 2002).

74. The following global summary of potential effects on wetlands addresses the various wetland types as discussed by the relevant chapters within IPCC (2001b) and other relevant reports. These include the impact of climate change on: lakes and streams, other inland wetlands, and coastal wetlands which are described separately for beaches, deltaic, mangrove and salt marsh communities, and coral reefs.

75. Given the range of information sources, and the various approaches and/or scenarios used to predict impacts, in most cases it is not possible to assign levels of confidence to the majority of the projected impacts of climate change on wetlands. Thus, the information in the following sections should be seen as a review of the range of the documented possible impacts on wetlands due to climate change (including sea level rise) that may or may not occur depending on the eventual extent of climate change, as well as the ability of wetlands to adapt to it or for humans to implement adaptation options.

Table 5 Projected impacts in some key water-based systems and water resources under temperature and precipitation changes approximating those of the SRES scenarios (modified from IPCC 2001c)

Indicators	2025	2100
Corals	Increase in frequency of coral bleaching and death of corals	More extensive coral bleaching and death Reduced species biodiversity and fish yields from reefs
Coastal Wetlands and Shorelines	Loss of some coastal wetlands to sea level rise Increased erosion of shorelines	More extensive loss of coastal wetlands Further erosion of shorelines
Ice environments	Retreat of glaciers, decreased sea ice extent, thawing of some permafrost, longer ice free seasons on rivers and lakes	Extensive Arctic sea ice reduction, benefiting shipping but harming wildlife (e.g. seals, polar bears, walrus) Ground subsidence leading to changes in some ecosystems. Substantial loss of ice volume from glaciers, particularly tropical glaciers
Water supply	Peak river flow shifts from spring toward winter in basins where snowfall is an important source of water	Water supply decreased in many water-stressed countries, increased in some other water-stressed countries
Water quality	Water quality degraded by higher temperatures Water quality changes modified by changes in water flow volume Increase in salt-water intrusion into coastal aquifers due to sea level rise.	Water quality effects amplified
Water demand	Water demand for irrigation will respond to changes in climate; higher temperatures will tend to increase	Water demand effects amplified.

	demand	
Floods and droughts	Increased flood damage due to more intense precipitation events Increased drought frequency	Flood damage several fold higher than "no climate change scenarios" Further increase in drought events and their impacts

Lakes and streams

76. Unless otherwise acknowledged, the information presented for lakes and streams is summarised from Gitay et al (2001). Responses of lakes and streams to climate change include: warming of rivers and associated availability of thermal refuges, reductions in ice cover, reduction of dissolved oxygen in deep waters, altered mixing regimes, changes in the interaction between waters and their watersheds, alterations in flow regime, changes in biogeochemical cycling, greater frequencies of extreme events including flood and drought, changes in growth, reproduction and distribution of organisms, and poleward movement of climate zones for organisms (USGCRP 2000).

77. The only limnological properties measured or simulated at a global scale are lake and river ice phenologies. It is apparent that ice cover durations for inland waters are decreasing, and in some regions have most likely been doing so since the early 1700s. Climate change simulations (at 2× $CO2$ change) indicate further significant decreases in ice cover duration and ice thickness. Associated with these effects will be changes to the processes that ice cover and associated ice break-up flooding can influence. Some of these include gas exchange with the atmosphere, erosion and deposition, nutrient cycling, aquatic organism habitat availability through changes in pH and dissolved oxygen, seasonal succession, biodiversity, and primary production.

78. Changes in temperature and precipitation can impact fisheries through changes in abundance, distribution and species composition. Fisheries in small rivers and lakes are believed to be more susceptible to changes in temperature and precipitation than those in large rivers and lakes. Aquaculture activities will be affected in various ways, but will also probably adapt better than wild fisheries. Higher temperatures will probably result in higher growth rates of many species, but will also bring the threat of more disease. In addition, more food will be required to support the higher growth rates.

79. Warming will alter species abundance, distribution and composition. It is thought that the rate of migration of less mobile aquatic species, such as some fish and molluscs, will be unable to keep up with the rate of change in freshwater habitats. Distributions of fish are forecast to move poleward, with cold water fish being further restricted in their range, and cool and warm water fish expanding in range. Aquatic insects, which have an aerial life stage, will be less likely to be restricted.

80. The invasion of exotic species will become a bigger problem for lake and stream ecosystems under warmer conditions. In conjunction with current human activities (e.g., impoundment construction) the warmer, drier conditions will further threaten natural habitats and biodiversity. This could be manifested in greater temperature and dissolved oxygen stratification of inland lakes and subsequent death of some fish and macro-invertebrate species (Talling & Lamoalle 1998). At high latitudes warming is expected to increase biological productivity, whereas at low latitudes the boundaries between cold and cool-water species may change and possibly lead to extinctions (IPCC 1996).

81. Little is known about the combined effects of climate change with those human activities already influencing lakes and rivers. The influence of climate change on water quality issues such as eutrophication is unclear, particularly because many of the climate-influenced processes leading to eutrophication (e.g., precipitation, snow melt, ice cover, runoff, thermal stratification) have interacting and often opposing

effects. Thus, effects of climate change on nutrient recycling will most likely be site-specific and could lead to either a greater or reduced susceptibility to eutrophication. Impacts on other water quality problems, such as acidification and chemical contamination, are also uncertain, although it is apparent that they will be influenced by climate change to some degree.

82. Finally, some of these impacts of climate change on lakes and streams will have consequences for recreational, domestic and industrial uses of lake and river water resources. They will also be intertwined with adaptation and mitigation measures: for example the building of further dams to store water for domestic and irrigation purposes could further block migration routes for many fish species and change shallow water or semi-permanent aquatic habitats into permanent deepwater habitats. This would exacerbate the negative effects of large dams, as identified in the Report of the World Commission on Dams (World Commission on Dams 2000).

Other inland wetlands

83. Unless otherwise acknowledged, the information presented for other inland wetlands is summarised from Gitay et al (2001). This section covers inland wetland habitats defined as "any area of land where the water table is at or near the surface for some defined period of time, leading to unique physio-chemical and biological processes and conditions characteristic of shallow flooded systems". However, the majority of information presented relates to peatlands. This reflects the lack of work at a global scale on other inland wetlands, which are often controlled by local hydrology. Further information on such wetlands is provided, where available, in the regional summaries of climate change impacts (section 4).

84. The potential impacts of climate change on wetlands are based on studies assessing the effects on wetland plant communities of climate variability and overuse of water resources. The effects generally involve the replacement of original wetland species with other types of wetland species (e.g., succession of swamp and fen peatland communities to bog peatland communities) or forest or heathland species, and associated effects. Related to this, climate warming could promote the invasion of alien species and the range expansion of existing alien species.

85. It is thought that the response of wetland plant communities may greatly influence the species diversity of wetland ecosystems. However, the natural temporal and spatial variability of wetland communities due to variability in water supply is a key factor, and one that makes it difficult to predict impacts of climate change.

86. Sea level rise may affect a range of freshwater wetlands in low-lying regions. For example, in tropical regions low-lying floodplains and associated swamps could be displaced by salt water habitats due to the combined actions of sea level rise, more intense monsoonal rains, and larger tidal/storm surges (Bayliss et al 1997) (see Table 5). Such changes will result in dislocation, if not displacement, of many wetland species, both plants and animals. Plant species not tolerant to increased salinity or inundation could be eliminated whilst salt-tolerant mangrove species could expand from nearby coastal habitats.

87. Migratory and resident animals such as birds and fish may lose important staging, feeding and breeding grounds. These scenarios have been outlined for the low-lying floodplains in northern Australia (Eliot et al 1999). Large scale species changes in the Volga delta (Russia) over a number of decades may provide guidance on the extent of fluctuations in both plant and animal populations in response to rising sea levels. It is apparent that the distribution of many plant species, e.g., the lotus lily Nelumbo nucifera and the reed Phragmites australis, has changed enormously, as have bird and fish populations (Finlayson et al 1993).

88. Climate change may also affect the wetland carbon sink, although the direction of the effect is uncertain due to the number of climate-related contributing factors and the range of possible responses. Any major

change to the hydrology and vegetative community of a wetland will have the potential to affect the carbon sink. The impact of water level draw-down in northern latitude peatlands has been well studied and is thought to provide some insight for climate change impacts. Vegetation changes associated with the water draw-down resulted in increased primary production, biomass, and slower decomposition of litter, such that the net carbon accumulation rate remained unchanged or even increased. However, other aspects of climate change, such as longer and more frequent droughts and thawing of permafrost, will most likely have negative effects on peat carbon balance. In addition, human activities such as agriculture and forestry will also continue to transform wetlands and reduce overall wetland area, potentially resulting in losses of stored carbon.

89. The extent of biodiversity loss or dislocation from inland habitats as a consequence of climate change will be difficult to discern from other existing pressures. However, it can be assumed that large-scale change to these habitats will result in species changes. Vegetation zones, such as those in high latitudes and altitudes, and presence of species may change in response to temperature and inundation patterns. The extent of such change is unknown. White et al (1999) predict that boreal forests will extend northwards into the tundra, and also southwards in Asia. Similarly, fish migrations will be affected by both temperature and flow patterns.

90. The most apparent faunal changes may occur with migratory and nomadic bird species that use a network of wetland habitats across or within continents, respectively. The cross-continental migration of many birds is at risk of being disrupted due to changes in habitats (see references in Walther et al 2002).

91. Disruption of rainfall and flooding patterns across large areas of arid land will similarly adversely affect bird species that rely on a network of wetlands and lakes that are alternately or even episodically wet and fresh and drier and saline (Roshier et al 2001), or even a small number of wetlands such as those used by the banded stilt Cladorhynchus leucocephalus ,which breeds opportunistically in Australia's arid interior (Williams 1998).

92. Responses to these climate-induced changes may also be affected by adaptation and mitigation actions that cause further fragmentation of habitats or disruption or loss of migration corridors, or even by changes to other biota, such as increased exposure of wading birds to predators (Butler and Vennesland 2000).

Coastal wetlands

93. Unless otherwise acknowledged, the information presented for coastal wetlands is summarised from McLean & Tsyban et al (2001).

94. Potential impacts of climate change and sea level rise on coastal systems include: increased coastal erosion; more extensive coastal inundation; higher storm surge flooding; landward intrusion of seawater in estuaries and aquifers; changes in surface water and groundwater characteristics; changes in the distribution of pathogenic organisms; higher sea-surface temperatures; and reduced sea-ice cover (Table 5). These effects can also lead to associated socio-economic impacts, which, although often relevant in many ways to wetlands, are not discussed here.

95. Responses in species' distribution from such changes are not well known, although it is known that many species in coastal wetlands respond to even small changes in water levels. Warren & Niering (1993) project that rapid sea level rise will result in shifts in species' compositions, a reduction in productivity, and loss of other wetland functions. These changes will be manifest across many species and greatly influenced by interactions between the species.

96. Many coastal wetlands, for example coral reefs, beaches, salt marshes, and mangrove communities, provide significant coastal protection and thus contribute substantially to the resilience of coastal systems.

However, many of these are also identified as being sensitive to accelerated sea level rise. Areas identified as sensitive to accelerated sea level rise in the Second Assessment Report of the IPCC (Bijlsma et al 1996) included low-elevation coral atolls and reef islands, as well as low-lying deltaic, coastal plain and barrier coasts, and their associated wetland habitats (i.e. beaches, estuaries, lagoons, salt marshes, mangroves). Nichols et al (1999) project that coastal wetlands in the Mediterranean, the Baltic, and to a lesser extent along the Atlantic coast of Central and North America and the smaller islands of the Caribbean will be under threat if not lost due to future sea level rises.

Beaches

97. Climate change and sea level rise are expected to change prevailing ocean wave heights and directions, as well as the magnitude of storm waves and surges, such that seawater will reach higher elevations on land than at present and will extend further inland. Thus, erosion of sandy shorelines will be more likely given expected accelerated sea level rise over the coming decades. The possible loss of nesting habitat for marine turtles that are already under human pressure worldwide is one major consequence of such erosion or, indeed, of redeposition of sediments.

Deltaic coasts

98. Deltaic regions will be particularly susceptible to accelerated inundation, shoreline recession, wetland deterioration, and interior land loss. In addition, given that the characteristic sediment deposition in deltas results in natural dewatering and compaction, such areas are already prone to subsidence. The pressures of human activity on deltaic regions are also great, further increasing their susceptibility.

99. In situations where sediment delivery is greatly reduced (usually due to upstream river regulation/diversion), marine processes will begin to dominate, and substantial coastal land loss can result from wave and surge erosion. Another potential impact of sea level rise on deltaic regions is saltwater intrusion of freshwater aquifers and even surface waters (Li et al 1999).

100. The biodiversity loss from deltaic coasts is already high in many areas, and speicies diversity could decrease further with loss of habitat for breeding birds and fish (Li et al 1999). Such change will also exacerbate recent large loss of vegetation and habitat in many deltas, such as the Mekong delta (Hollis 1998; Mitsch et al 1998), and change in habitats alongside other deltas, for example the coastal lagoons of the Volta delta (Finlayson et al 1999b). Mitsch et al (1994) provides a summary of the status and biotic importance of deltaic wetlands.

Mangrove and salt marsh communities

101. Nicholls et al (1999) predicted that by the 2080s, 22% of the world's coastal wetlands, specifically salt marshes, mangrove forests, and inter-tidal habitats, could be lost due to sea level rise alone. Combined with other human-related pressures, coastal wetland loss could be as high as 70% (Nicholls et al 1999).

102. The current exploitation and destruction of mangrove forests is reducing the resilience needed to accommodate sea level rise and storm waves and surges. Predicted responses of mangroves to sea level rise vary from little adverse impact to collapse. It is likely that responses of mangroves to sea level rise will be influenced also by other factors, such as sediment supply/flux, presence of suitable substrate, stand composition and status, and tidal range.

103. Mangrove communities may be able to migrate in response to seal level rise, but only where there exists adequate sediment supply and substrate and if sea level rise is not too rapid. In addition, the extent of coastal development will also affect the ability of coastal wetland communities to migrate in response to sea level rise (Nicholls et al 1999).

104. Responses of salt marshes to sea level rise will also be influenced by factors such as sediment supply and the nature of the backshore environment. Sufficient sediment delivery is required for vertical accretion of salt marshes to protect them from inundation by seawater. Tidal marsh (vertical) accretion is known to track sea level rise, such that the inundation of the marsh surface is not likely to be a major concern. However, in some areas, sea level rise may be too fast for accretion to keep up.

Coral reefs

105. The major aspects of climate change that could affect coral reefs are sea level rise, increased sea surface temperature, and elevated levels of CO2 in the atmosphere subsequently affecting the CO2 levels in the water.

106. Recent coral reef bleaching events around the world have re-ignited the debate about the impacts of climate change on coral reefs (Hoegh-Guldberg 1999; Wilkinson 1999). According to Wilkinson (2000), approximately 27% of the world's coral reefs have been effectively lost, with over half of that loss being due to the massive climate-related coral bleaching event of 1998.

107. Some studies suggest that maximum vertical accretion rates of healthy coral reef flats will be sufficient to accommodate the expected rate of sea level rise. However, the adaptive ability of reefs that are already degraded and under continuous stress from many human activities is less clear, and it cannot be assumed that the threat of sea level rise to coral reefs is minor. In addition, the prospect of more frequent bleaching events due to higher sea surface temperatures (see below), as well as of reduced reef calcification due to doubling of CO2 concentrations in the atmosphere, suggests that vertical accretion rates may not be able to keep pace with sea level rise.

108. Of major concern for coral reefs is rising sea surface temperatures. With sea surface temperatures expected to rise by 1-2°C by 2100 (see section 3.1), coral reefs will be under greater threat from bleaching and possibly death. However, there remains some debate concerning whether recent coral bleaching events were attributable to global warming, particularly considering the range of other pressures coral reefs are already under (e.g., pollution, increased sedimentation, over-harvesting of aquatic life including corals, predation and disease, and extreme natural events).

109. Sea surface temperatures of >1°C above seasonal averages can result in bleaching events, although the magnitude of effects (ranging from reduced growth and reproductive capacity to death) vary depending on factors such as the magnitude and duration of the temperature anomaly and, in some cases, water depth. Bleaching events have also been related to major El Niño events, during which seasonal maximum temperatures are exceeded by at least 1°C (Hoegh-Guldberg 1999). The implications of this are obvious given the projection of a more El Niño-like mean state in the tropics and increased intensity of El Niño-like events.

110. Other climate change-related factors that could affect coral reefs include altered ocean circulation patterns influencing the dispersal and transport of coral larvae, and increased frequency and/or intensity of severe weather events further damaging coral reefs and disrupting recovery (Westmacott et al 2000).

111. Corals species display differential susceptibility to increased sea surface temperature and bleaching. Consequently, extensive coral bleaching will likely lead to reduced coral diversity, habitat diversity, and overall species diversity. Such impacts could also have adverse effects on fish populations and other marine and coastal resources that are important for human livelihood (Wilkinson 1999).

4. Regional impacts of climate change on wetlands

112. The IPCC uses eight regions for its regional assessments: 1) Africa, 2) Asia, 3) Australia and New Zealand, 4) Europe, 5) Latin America, 6) North America,, 7) Polar regions, and 8) Small Island States (figure 4a). These regions are used in this section, since much of the information presented is derived from IPCC reports. The IPCC regions are broadly but not wholly similar to those used by the Ramsar Convention (see **Figure 4**).

113. Section 4.1 provides an overview of key projections of regional climate change, based on the latest IPCC assessment reports. Following this, for each IPCC region the wetland distribution is summarised, and the impact of climate change on wetlands is reviewed (sections 4.2 to 4.9). As with the global assessments (section 3.3), the impact of climate change is described separately for lakes and streams, other inland wetlands, and coastal wetlands.

4.1 Summary of projected regional climate change

114. The SRES scenarios have only been available for a very short time, and thus it has not been possible to include regional impact assessments based upon these scenarios. The impacts assessments in the Third Assessment Report of the IPCC, described here, use climate projections which tend to be based on equilibrium climate change scenarios (e.g., 2xCO2) or the scenarios used in the Second Assessment Report (i.e., the IS92 series), which projected global mean surface temperature of about 2 to 3 °C.

115. The two SRES scenarios are used to illustrate the projected surface temperatures and precipitation changes in different regions (see Figures 2 and 3 in the appendix).

116. Except for the Arctic, the sea surface temperatures are projected to warm less than the land and this could result in the coastal areas warming less than the interiors of the continents (see Figure 2). Projected changes in global surface temperatures include:

> i) High latitudes of the northern hemisphere: temperature is projected to increase by about 6°C (much greater than the global average warming) in both summer and winter compared to the 1990s.
>
> ii) Mid-latitudes in the northern hemisphere: at least a warming greater than the global average warming (3 to 5°C) is projected, with the Mediterranean and central Asian region warming more in the summer (June, July, August) than the winter, North America equally in summer and winter, and east Asia more in the winter than summer.
>
> iii) Northern Africa: projected to experience greater than average warming throughout the year.
>
> iv) Central and southern Africa, most of Australia and southern America: projected to warm by 1 to 3 °C, with some inconsistencies in the magnitude of warming between the different global circulation models. For Africa, warming is projected to be greatest over the interior of the semi-arid margins of the Sahara and central southern Africa

117. Projected changes in precipitation (see **Figure 3**) by regions are:

> i) Mid- to high latitudes: precipitation is projected to increase by 0.5 to 1mm per day with some indication that the changes may be greater in the winter than the summer.
>
> ii) In the areas affected by the present El Niño events in the north Pacific, precipitation is projected to increase by 1 to 3 mm per day.
>
> iii) In the equatorial and southern parts of Africa, South America and Australia, precipitation is

projected to decrease by about 0.25 mm per day with some suggestion in Australia and southern Africa of a decrease in the precipitation in the winter rather than in the summer.

4.2 Africa

Wetland habitats and distribution

118. Wetland distribution and extent in Africa were reviewed by Stevenson & Frazier (1999a, see also Figure 1), who provide a figure of 121-125 million ha, about 4% of the land surface, which they considered to be an underestimate. More than 85% (~107 million ha) of this area was classed as inland wetland, with less than 10% being coastal/marine (~9-11 million ha) and 5% being artificial (~4.6 million ha). Large areas of inland wetlands are known to occur in Chad (~13 million ha), the Congo basin (~26 million ha), Nigeria (~5.5 million ha), Uganda (~4.5 million ha) and Sudan (~4.2 million ha). Nigeria also supports a large area of coastal wetlands (1.3 - 3.2 million ha).

Effects on wetlands and wetland species

119. Unless otherwise acknowledged, the information presented for the African region is summarised from chapter 2 of IPCC (1998) (Zinyowera et al 1998) and chapter 10 of IPCC (2001) (Desanker & Magadza, et al 2001).

Lakes and streams

120. Both the historical data and climate model simulations concur that water crises are imminent in large parts of Africa. The major impacts of climate change on African water systems will be through changes in the hydrological cycle, temperature, and rainfall.

121. Apart from the Zambezi/Congo Rivers, the major African rivers traverse semi-arid to arid lands before reaching the coast. Consequently, their discharge relative to catchment size is very small, with the water resource already under pressure from human activities. Elevated temperatures will enhance evaporative losses, and as precipitation is expected to decrease in the semi-arid to arid regions, runoff and discharge will most likely be further reduced. Many river systems already experience high evaporative losses, which in addition to infiltration/permeation, result in runoff to precipitation ratios of around 0.1.

122. Estimates of changes in precipitation and evaporation for 11 of Africa's major river basins indicate that eight of the systems could experience an overall decrease in runoff (Arnell 1999). These included the Volta in west Africa, the Shabeelle in northeast Africa, the Ogooue in west central Africa, the Rufiji, Ruvuma and Limpopo in east Africa, and the Zambezi and Orange in southern Africa (Arnell 1999). In the savanna regions, the frequency of seasonal flow cessation may be increasing, and periods of drought now represent critical water shortages for human use and biodiversity.

123. The impact of climate change on the Nile is highly uncertain, with predictions ranging from increased precipitation and flow to decreased precipitation and flow. Regardless of the precise impacts, the Nile is considered to be very sensitive to climate change, particularly climate warming, because of its low runoff efficiency and high dryness index. It is predicted that a reduction in flows of over 20% would exceed current transboundary management capabilities and result in major socio-economic impacts. The runoff and discharge of the River Gambia is also very sensitive to climate change variables, and discharge reductions are expected to result in increased saltwater intrusion. Sea level rise is expected to further exacerbate saline intrusion. The River Zambezi will probably experience the most extreme changes in precipitation (-10 to -20%), evaporative losses (+15 to +25%), and runoff (-26 to -40%), and combined with impoundment and land use change, impacts to this river system will probably be substantial.

124. Water storage in lakes and reservoirs is expected to be significantly affected by changes in precipitation and enhanced evaporation. Historical records indicate that many lakes and reservoirs have either ceased to have an outflow or have dried completely during drought conditions. Higher temperatures and less rainfall would further increase evaporative losses, while lake water temperatures will also increase. Even in the tropics, where temperatures are expected to rise less than in temperate regions, the changes may be sufficient to dramatically alter water levels, mixing regimes, and productivity.

125. Temperature increases may benefit lake and riverine fisheries, although the responses will vary spatially. In lakes, the responses will also be limited by carrying capacity and possibly influenced by eutrophication. However, reductions in precipitation and runoff may result in adverse effects on freshwater fisheries, as has been found during drought conditions in Lake Kariba, Zimbabwe. It should be noted that increases in fish production for fisheries do not necessarily equate to positive impacts for fish diversity, as the thermal tolerances of temperature-sensitive species are exceeded.

Other inland wetlands

126. There appears to be little information on climate change impacts to other inland wetlands in Africa. This is likely to be a reflection of the region's perspective of water availability as a resource and human health issue rather than a conservation and biodiversity issue. Nevertheless, it is recognised that a significant reduction in rainfall or increase in evapotranspiration in Angola would threaten the Okavango delta wetland in Botswana. This situation would almost certainly apply to most inland wetland habitats in semi-arid, arid, and southern Africa, and possibly also in the Sahel (northeast Africa). In addition to the Okavango delta, other major wetland systems such as the Kafue River floodplains, Lake Bangweulu, and the Caprivi Strip wetlands support a rich and diverse fauna, in particular avifauna, that may be threatened by climate change.

127. Although not specifically mentioned in relation to wetlands and their conservation, Desanker & Magadza et al (2001) identified a range of issues that are relevant to wetlands:

> i) The interaction between climate change and fire and burning regimes is important and will most likely have implications for ecosystem structure and biodiversity.
>
> i) A changing climate may alter or hamper animal migrations, including waterfowl, and reduce the effectiveness of the current system of reserves and Ramsar sites.
>
> iii) The incidence and distribution of vector-borne diseases will be affected by changes in temperature and precipitation. For example, in the highland area of Rwanda, a 337% increase in malaria incidence in 1987 was largely explained by rainfall and temperature, while the Sahel region has experienced a decline in malaria transmission following drought conditions over the past 30 years. In contrast, some diseases, such as meningitis, are apparently more prolific in semi-arid regions with low humidity and could be favoured by warming and reduced precipitation.
>
> iv) Wetlands and floodplains are often sites of dense urban and particularly rural development, and major flooding of these areas would result in major socio-economic consequences.
>
> v) Climate change projections of increased temperature and reduced precipitation could initiate or exacerbate desertification, particularly in the arid, semi-arid and dry sub-humid areas, which occupy 43% of the African land area and contain 40% of the population. Associated impacts of desertification on wetlands would revolve around biophysical changes towards a more dryland environment such as grassland and savanna.

Coastal wetlands

128. The coastal nations of west and central Africa, from Senegal to Angola, have low-lying lagoonal coasts that are susceptible to erosion, inundation, and extreme storm events. Consequently, these regions will be threatened by sea level rise and will have difficulties adapting due to rapid urban expansion along the coast. For example, in Senegal, a 1-m rise in sea level could inundate and erode more than 6,000 km2 of land, much of which is wetlands.

129. In addition, a number of African coastal areas that are threatened by sea level rise offer unique habitat for migratory bird species. It is anticipated that the Arctic breeding grounds for these species will be adversely affected by climate change (e.g., Lindstrom and Agrell 1999), but there is far less information available on the effect on waterbird populations using the wintering grounds across Africa. The absence of good quality monitoring data for many African wetland birds will constrain any further assessment.

130. Sea level rise may also lessen the protective function of reefs along the east coast of Africa, increasing the potential for coastal erosion. To the northeast, the coastal areas of Egypt, including around Cairo and the Nile, are also threatened by sea level rise, and substantial parts of the Nile delta could be lost as a result of increased inundation and erosion.

131. The anchovy fishery in the southwest of Africa may be impacted by climate change. Essentially, recruitment in the species is influenced by water temperature and upwelling of nutrient-rich waters, both of which are linked to global climatic conditions. Thus, changes to both factors would most likely have severe impacts on the fishery. In addition to being an important fishery species, the anchovy is also recognised as a key element in the food chain for many other fish species, aquatic mammals, and birds.

4.3 Asia

Wetland habitats and distribution

132. Wetland distribution and extent in Asia is not accurately known (Watkins & Parish 1999). There are an estimated 204 million hectares, excluding Russia but including some 7.4 million ha in the Middle East (Frazier & Stevenson 1999, see also Figure 1), but the reliability of these figures is unknown. Mangroves cover an estimated 7 5 million ha, with much of this occurring in Indonesia (~4.3 million ha). Peat swamps are also common, but as with much of the inventory available for Asia, differences in definition and delineation undermine the value of these estimates, which include 17-27 million ha in Indonesia, ~2.5 million ha in Malaysia and 1-3 million ha in China. Coral reefs cover around 2.7 million ha in the Philippines, and rice fields across all of Asia cover an estimated 133.6 million ha.

Impacts of climate change on wetlands and wetland species

133. Unless otherwise acknowledged, the information presented for the Asian region is summarised from chapters 7, 10 and 11 of IPCC (1998) (Gitay & Noble et al 1998; McLean et al 1998; Yoshino & Jilan et al 1998) and chapter 11 of IPCC (2001) (Lal et al 2001).

Lakes and streams

134. There is concern that climate change may accelerate the damage to lakes and rivers (and other wetlands) already caused by environmental pollutants, exploitation of natural resources, transformation of lands, and recreational activities. It is likely that changes to runoff and river discharge as a result of climate change will place further pressure on water resources that are already under increasing demand due to population growth, urbanisation, industrialisation, and, in particular, agriculture (McLean et al 1998).

135. Predicted changes in runoff modelled according to changes in precipitation and evapotranspiration by

2050 vary (Arnell 1999). Nevertheless, results suggest increased runoff in northern boreal Asia, temperate Asia and central tropical Asia, and decreased runoff in southern boreal Asia, arid and semi-arid Asia, western tropical Asia (i.e., India; high variability between model estimates), and southeastern tropical Asia (Arnell 1999). By 2050, increased runoff in Siberian river systems is expected to cause difficulties with seasonal inundation and flooding and associated management of these problems. Runoff in temperate Asia will vary spatially, with south China possibly experiencing reduced runoff.

136. A large number of perennial rivers in semi-arid Asia are fed by snow and glacial-melt from almost 1500 glaciers in the Himalayas. The past few decades have seen the retreat of almost two thirds of these glaciers due to a range of climate and non-climate related factors. Future global warming is expected to increase the rate of glacial melting, which will likely lead to higher summer flows in some rivers for a number of decades, beyond which flow will decrease as the glaciers disappear. For countries with very large glaciers, increased runoff may persist for a century or more, substantially increasing regional water resources.

137. The snow melting season coincides with the summer monsoon season, so any intensification of the monsoon could increase the likelihood and magnitude of floods. Such impacts are expected to be greater in the western Himalayas than the eastern Himalayas, due to the greater contribution of snow melt to runoff. An increase in surface runoff during autumn and a decrease during spring are forecast for the highland regions of South Asia (i.e., from Pakistan to Bangladesh), while rising temperatures will result in greater snow melt and a raising of the snow line. This situation will further increase the risk of flooding for countries in this region. On the east coast of Malaysia, and in the coastal areas of Sarawak and Sabah, flooding usually occurs on an annual basis during the rainy northeast monsoon season; increases in the intensity and frequency of heavy rainfall during this period are expected to increase the intensity and frequency of flooding in the region.

138. With predicted temperature increases, and associated reductions in snowfalls, some lakes, including Lake Biwa and Lake Kasumigaura in Japan, are expected to be more susceptible to eutrophication and other water quality problems (Kobori 2000). Related to this, the invasion of alien species and range expansion of existing alien species (e.g., water hyacinth, Eichhornia crassipes; banana plant, Nymphoides aquatica; and Salvinia molesta) may have major implications for native aquatic plant biodiversity (Kadono 2000).

139. Lakes in northern latitudes may change from a vertically homogeneous state to being stratified, while the opposite might occur in the southerly areas of temperate Asia, potentially resulting in impacts on biota. Lake levels will probably decline or fluctuate more widely due to changes in precipitation and evapotranspiration. As a result, the littoral zones of lakes may change significantly, possibly resulting in reduced productivity and biodiversity (particularly in the case of lakes with extensive bordering wetlands).

140. Warming in temperate Asia could result in local extinctions of cold and cool water fish and invertebrate species. Such impacts would be most pronounced in shallow lakes, streams and rivers in which appropriate thermal refugia are not accessible. Some aspects of this have been discussed for lakes in Japan, where it is thought that changing temperature and water quality could result in declines in cold water fish species such as salmonids and zooplankton invertebrates such as Daphnia spp., while favouring the growth of blue-green and other types of algae (Kobori 2000).

141. In tropical Asia, fisheries at higher elevations may be susceptible to lower dissolved oxygen concentrations due to warmer temperatures, while changes in the timing and amount of rainfall in the lowlands could affect fish migration, spawning, dispersal and growth.

142. Finally, in Japan, if the 0°C isotherm in mid-winter shifts northward, the wintering grounds of wild geese and their patterns of migration can be expected to alter accordingly (Takeshita & Kurechi 2000). The

effect on migratory waterbirds across the Asian flyways is unknown, with any assessments being constrained by an absence of long-term monitoring at many sites.

Other inland wetlands

143. **Peatlands**. Large scale melting and shrinkage of the area of permafrost in boreal Asia is expected, and this is likely to have major implications for the boreal peatlands overlying the permafrost. The worst case scenario could be the loss of these wetlands and the subsequent release to the atmosphere of large amounts of carbon dioxide and possibly methane. Permafrost in northeast China is expected to disappear if the temperature rises by ^{3}2°C, although deep-seated, ice-rich permafrost will be resistant to changes. In tropical Asia, projected increases in evapotranspiration and projected rainfall variability are likely to have negative impacts on the viability of tropical peatlands (McLean et al 1998). This could lead to species' extinctions.

144. **Rice paddies**. In general, increased carbon dioxide levels and longer frost-free periods are expected to enhance agricultural productivity in North Asia. Rice yields are expected to increase in northern and north-central Japan, but decrease in the southern regions of the country. In tropical Asia, rice crops may be vulnerable to increased minimum temperatures as the success in forming grains is sensitive to a threshold temperature of 26°C and grain yield falls by about 10% for every degree increase above 26°C during the flowering and pollination process.

145. Water shortages in India will probably outweigh the benefits of increased carbon dioxide for rice crops, and net declines in yield could be expected. In addition, two crop simulation models (ORYZA1 and SIMRIW) have predicted that increases in temperature of more than 2°C will offset the positive effects of elevated carbon dioxide to the point that potential rice yields start to decline. It can probably be expected that the area of rice under cultivation (i.e., the area of rice paddies) will reflect the influences of climate changes on potential yield, yield stability, and total production.

146. **Others**. Ephemeral wetlands in semi-arid and arid Asia are important culturally, economically, and biologically. Due to the currently limited rainfall in these regions, these wetlands may be among the most sensitive ecosystems to changes in the amount and seasonality of rainfall and evaporation. Such changes may lead to local extinction of some animal and plant populations. In eastern China, herbaceous wetlands could decline as a result of less rainfall and higher evapotranspiration.

147. A number of migratory waterbirds which breed in semi-arid regions of central and west Asia are in decline, including the globally threatened Sociable Plover Chettusia gregaria, a decline which Shevchenko (1998) suggests is occurring through the possible exacerbation of adverse effects of land use change by climate change and associated increasing aridity in central Asia.

Coastal wetlands

148. Coastal areas are likely to be at risk of geomorphological and ecological changes due to climate change-induced sea level rise. The major climate change processes include accelerated sea level rise, sea surface temperature rise and more frequent and intense severe storm events. In addition, tropical Asia is subjected to the climate variability associated with ENSO, which is known to have major impacts on coastal systems.

149. **Beaches**. Beach erosion due to sea level rise has been documented as a major threat to the Japanese coast. This could have implications for waterbirds such as shorebirds, which utilise tideland habitats as staging sites during their migration (Takeshita & Kurechi 2000), and also for sea turtles, which utilise the beaches as nesting grounds (Kamezaki 2000).

150. **Deltas and estuaries.** The major delta areas of Asia are likely to experience changes in water regimes,

saltwater intrusion of both fresh surface and ground waters, siltation and land loss.

151. The deltas of the interior seas in semi-arid and arid Asia have been severely affected by the changing water levels in recent history due to human activities, including building dams and the diversion of water for irrigation, thus reducing the in-flow into these seas. The Volga delta in the Caspian sea extended 17 km while the water level dropped 4 m between 1930 and 1977, but has since retreated up to 15 km as the water level has begun to rise. Deltas in the Aral Sea, which has reduced in area by over 50%, have become highly exposed and are subject to frequent dust and salt storms.

152. In regions where runoff is predicted to decrease, water and sediment discharge to deltas will probably decrease, resulting in delta progradation being slowed or even ceasing. River regulation and diversion for human activities are already resulting in such impacts to deltas in Asia (Li et al 1999). Decreased sedimentation, rising sea level, and more intense storm events could combine to further erode the low-lying muddy coastlines associated with large deltas.

153. In contrast, in regions where runoff and discharge are expected to increase (e.g., East China, boreal Asia), sea level rise and wave and storm surge could act to reduce the discharge rate, thus resulting in inundation and flooding of the low-lying deltaic plains (Li et al 1999). Li et al (1999) predicted that, further exacerbating inundation and flooding, a sea level rise of 48 cm by 2050 and a storm surge of 2-3 m would inundate approximately 40% of the area of the Yellow River Delta (301,300 ha), resulting in major ecological impacts and economic losses.

154. The marshes and tidal flats of many of the deltas in Asia, such as the Mekong, Yangtze, Huang He, and the Mai Po marshes in Hong Kong, are critically important stop-over sites for migratory waterbirds, particularly ducks, geese and shorebirds (Lal et al 2001; Li et al 1999). Habitat alteration through sea level rise could threaten the continued presence of these bird and other wildlife populations.

155. It has been suggested that increased surface runoff and nutrient loads in regions such as boreal Asia may actually benefit aquatic life and associated coastal fisheries, while fisheries in coastal tropical Asia would suffer due to more frequent El Niño events and associated declines in plankton biomass and fish larvae abundance. Seagrasses in Japanese coastal waters are also thought to be at risk, with predicted changes in distribution and abundance due largely to changes in water temperature (Aioi & Omori 2000).

156. Tidal rivers and estuaries will become more prone to saltwater intrusion as a result of projected sea level rise. In addition, rising water levels in estuaries will decrease the size and connectedness of small islands. Higher sea surface temperatures and nutrient loads in estuaries and deltas will support extended phytoplankton blooms, resulting in water quality problems. Associated with this, there will possibly be increased incidence of water borne diseases such as cholera, Giardia, Salmonella and Cryptosoridium in many countries of South Asia.

157. In tropical Asia, the Ganges-Brahmaputra (Bangladesh), Irrawaddy (Myanmar), Choo Phraya (Thailand), Mekong and Song Hong (Vietnam) deltas are amongst the most vulnerable to sea level rise. This is due to their geomorphology, large human populations, and the associated infrastructure which reduces the potential adaptation options. In temperate Asia, the Yangtze and Huang He (Yellow River) deltas are amongst the most vulnerable to sea level rise due mostly to the same reasons.

158. **Mangroves and salt marshes.** Large changes in species composition and zonation in mangrove forests in tropical Asia are expected due to sea level rise, changes in precipitation and therefore runoff, and the associated physico-chemical changes. Such changes could leave other coastal wetlands (e.g., salt marshes, lagoons) exposed to the impacts of sea level rise and wave and storm surges. Li et al (1999) identified salt marshes in the Yellow River Delta, China, as being at risk from climate change and sea level rise, primarily

due to coastal erosion and landward retreat.

159. Many mangrove and salt marsh communities support important biodiversity, which could be threatened by sea level rise. For example, the mangrove forests of the Sundarbans of Bangladesh, the largest continuous mangrove area in the world, which provides habitat for a large range of wildlife including Bengal tigers, Indian otters, spotted deer, estuarine crocodiles and marine lizards, could be destroyed by a 1m rise in sea level. In addition, loss of mangrove communities will result in major socio-economic impacts, due to effects on fisheries and other resource industries (e.g., woodcutting) that rely on the Sundarbans.

160. **Coral reefs**. Almost one third of the world's mapped coral reefs are found in southeast Asia, extending north to Japan. Reefs in Indonesia and the Philippines are noted for their high biodiversity and their ecological and economic importance. Recent coral bleaching events throughout Asia have resulted in changes to the species community structure, with faster growing branched species being severely affected and replaced by physically resilient hemispherical corals. Increased sea surface temperature and atmospheric carbon dioxide concentrations are likely to have serious damaging effects on reef accretion and biodiversity in tropical Asia, particularly as many of the reef ecosystems are already under enormous pressure from other human activities.

4.4 Australia and New Zealand

Wetland habitats and distribution

161. Wetland extent and distribution in Australia and New Zealand were reviewed by Watkins (1999, see also Figure 1). There was an estimated 0.25 million km2 of wetlands, of which 98% occurs in Australia. These figures are considered to be underestimates due to differences in definition and delineation of habitats in arid areas. Mangroves cover an estimated 0.115 million km2 in Australia and coral reefs 0.35 million km2 (see Spiers 1999).

Impacts of climate change on wetlands and wetland species

162. Unless otherwise acknowledged, the information presented for the Australia and New Zealand region is summarised from chapter 4 of IPCC (1998) (Basher & Pittock et al 1998) and chapter 12 of IPCC (2001) (Pittock & Wratt et al 2001).

163. Many of the region's wetlands, both inland and coastal, are sensitive to natural climate variations and changes. Several of the key regional concerns regarding vulnerability to climate change and impacts in Australia and New Zealand relate to wetlands. These include: drought, flood and water supply; ecosystem uniqueness and vulnerability; coral reefs; alpine areas; and increasing coastal and tropical exposure.

Lakes and streams

164. Current ranges of scenarios suggest significant reductions in the mean flow of many Australian rivers. Much of this is due to the increased tendency to an El Niño-like state, which results in drier conditions in Australia. Rainfall and river flow is known to be largely linked to ENSO (El Niño Southern Oscillation) in eastern Australia. Arnell (1999) predicted a 12-35% reduction in annual runoff by 2050 in the Murray-Darling Basin, as well as reductions in both maximum and minimum flows. Less severe increases in drought conditions have been predicted for Queensland.

165. Although rainfall and river flow in New Zealand is generally less linked to ENSO, more frequent or severe El Niño conditions still represent a concern for riverine systems and other wetlands. However, river and lake ecosystems in New Zealand are thought to have an existing resilience to hydrological variability

and temperature variability, so impacts may not be as large.

166. Snow cover duration and depth are also sensitive to climate variability and change. It is estimated that snow cover in the Australian Alps could decrease by 18-66% by 2030 and 39-96% by 2070. Combined with decreases in precipitation, this would have further major effects on river flows originating in the alpine regions. In contrast, warming has been predicted to have no significant impact on snow cover in New Zealand in the medium term.

167. Warming and potential reduced stream flow may lead to an increased risk of eutrophication and nuisance algal blooms in lakes and rivers. If the predicted fewer, but more intense, rainfall events do occur, rivers and lakes could be subjected to increased silt loads due to soil erosion, as well as to increased flash flooding risk.

168. All of these effects would have associated implications for aquatic biodiversity. For example, an increase in the magnitude and frequency of extreme events may lower the diversity of tropical lowland streams in northeastern Australia, but not necessarily the upland rainforest streams, which have a high diversity and appear to be relatively resilient. In addition, increased drought conditions in southeast Australia have been shown to favour native fish species over introduced species (e.g., trout). Increased flooding of inland lakes may favour those bird species that utilise these in a nomadic manner. Conversely, increased drying in inland areas could make conditions for nomadic species that use a network of lakes even more precarious. The extent of flooding and drying and the current use of many larger lakes by waterbirds has recently been assessed (Roshier et al 2001). Williams (1998) also points out that breeding areas for opportunistically breeding species such as the banded stilt Cladorhynchus leucocephalus could be lost.

Other inland wetlands

169. Climate change will probably add to the pressure on freshwater wetlands through changes in inflow (including saltwater intrusion) and increased water losses.

170. Many near-coastal freshwater floodplains (and other wetland habitats) in northern Australia could become saline, given projections of sea level rise and climate change (Bayliss et al 1997). Where saltwater intrusion has not occurred, freshwater wetlands in the wet-dry tropics could dry out faster or more extensively during the dry season due to higher temperatures and evapotranspiration, although this could be offset by increased wet season rainfall (Bayliss et al 1997). Higher temperatures may also result in more fires, which could have major implications for the vegetation structure of temporary wetlands such as paperbark (Melaleuca species) swamps and floodplains (Bayliss et al 1997). In southeastern Australia, the natural effects of drought may be exacerbated by climate change, and off-channel wetlands, including billabongs (cutoff meanders), may dry up for extended periods, resulting in negative impacts on biodiversity. The aquatic fauna of southwestern Australia, which is noted for its high endemism but low diversity, is thought to be potentially vulnerable to climate change due to the low probability of recolonisation of local species from elsewhere.

171. Many other inland wetlands in Australia that are subjected to fluctuations in filling, due to both natural and human-related factors, may also be seriously affected by predicted reductions in rainfall and higher temperatures due to climate change. Many of these large inland wetlands are important reproductive sites for migratory and resident waterbirds, and further stresses could threaten their populations. In addition, where saltwater intrusion is an issue, freshwater organisms, including fish, turtles, some frogs and snakes, and a range of invertebrate species could become restricted in their range (Bayliss et al 1997).

172. Wetlands in New Zealand are currently more threatened than those in Australia. Furthermore, more than half of the country's 73 'significant' wetland sites are located in coastal regions and will be susceptible

to sea level rise and its associated effects.

Coastal wetlands

173. **Estuaries**. Expansion of estuarine systems due to sea level rise will be at the expense of present-day freshwater dominated wetlands, and general inland expansion of tidally influenced terrain will result in establishment of saline marsh and mangrove plant communities (Bayliss et al 1997). Of major concern are possible loss of mudflats that are currently used by large numbers of wintering migratory shorebirds. Whilst data exist for some of these habitats, comprehensive nation-wide surveys are not conducted and there is uncertainty over the wider applicability of assessments based only upon individual sites.

174. **Mangroves and salt marshes.** Mangrove communities in Australia and New Zealands are considered to be susceptible to sea level rise, although there is debate about their adaptive capacity. Landward migration of mangroves will be inhibited in many locations by coastal development. However, in northern Australia, mangroves are often backed by extensive areas of undeveloped, low gradient hinterland, and given the usually high amounts of sediment supply, mangroves may well be able to adapt to sea level rise by migrating landward (Bayliss et al 1997).

175. The sub-coastal flats and salt marshes may be inundated more often and extensively under rising sea levels (Bayliss et al 1997), although the ability of salt marshes to adapt will depend on sediment supply and accretion. Many mangroves have undergone change in the past, but the reasons for this have often not been clearly understood.

176. The responses of mangrove, salt marsh and other coastal wetland communities to climate change and sea level rise will have a major effect on wildlife populations, particularly migratory waterbirds and mangrove-dwelling animals including prawns and fish such as the migratory barramundi Lates calcarifer (Bayliss et al 1997).

177. **Coral reefs.** Warming in Australia's coral reef region is expected to be about 2-3°C by 2100. Unless the coral reefs can adapt quickly to this, by that time they will be regularly exposed to temperatures above the current threshold for coral bleaching. Adaptation is thought to be possible, and even occurring to some extent in the more northerly parts of the Great Barrier Reef (Hoegh-Guldberg 1999). However, the rate of adaptation is not thought to be sufficient for the frequency and severity of high sea surface temperatures projected from 2050 onwards, and mass bleaching leading to death of corals will become more common in the region in the coming decades.

178. Sea level rise may not have a major impact on Australian coral reefs given their healthy state, and reef accretion may be able to keep pace with the rising water level unless decreased calcification rates inhibit such growth. Other impacts to coral reefs could occur due to increased intensity of tropical cyclones, and increased riverine discharge of freshwaters and sediment following more intense storm events. These impacts could reduce the biodiversity of the reef complex, and they could also weaken coral reefs' effectiveness in providing protection to coastal zones.

4.5 Europe

Wetland habitats and distribution

179. Wetland distribution and extent in Europe were reviewed by Stevenson & Frazier (1999b, c, see also figure 1). There are an estimated 258 million hectares (Stevenson & Frazier 1999b, 1999c), with the largest proportion of this (~217.6 million ha) occurring in Russia, and with large areas also in Sweden (~12.8 million ha), Latvia (~4.5 million ha), and Norway (~3.3 million ha) (Stevenson & Frazier 1999b). More than 95% of these are inland wetlands with less than 2% being coastal/marine. These figures, however, are

considered to be gross underestimates.

Impacts of climate change on wetlands and wetland species

180. Unless otherwise acknowledged, the information presented for the Europe region is summarised from chapter 5 of IPCC (1998) (Beniston & Tol et al 1998) and chapter 13 of IPCC (2001) (Kundzewics & Parry et al 2001).

Lakes and streams

181. On a broad scale, annual average streamflows are expected to increase in northern Europe and decrease in southern and central Europe (Arnell 1999). However, there are subregional differences in the extent of changes as well as in changes to the timing of flows. In the Mediterranean and maritime western Europe regions, climate change will increase the range between summer and winter flows. In areas where snowfall is a large component of precipitation (e.g., central and eastern Europe), a rise in temperature will result in more rain and increased runoff and flow during winter and less during spring. Such hydrological changes could lead to changes in the structure and possibly the function of lake and stream communities that could be more significant than temperature increase. Northern Europe is expected to experience little change in the timing of flows.

182. Increases in winter runoff and flows due to more rainfall will increase the risk of riverine flooding in winter. Decreases in summer flows, coupled with higher temperatures, are likely to lead to a deterioration in lake and stream water quality, including lowered dissolved oxygen. In addition, a reduction in the temporal and spatial extent of ice cover on lakes and streams will increase light penetration, further enhancing their primary production. This is of particular concern in boreal regions, where light attenuation due to ice cover is a major limiting factor for aquatic productivity. These impacts could lead to major biotic changes, with increased risk of toxic cyanobacterial blooms and subsequent, as well as independent, effects on primary and secondary consumers.

183. The risk of increased fire frequency, arising from changes in climate, in southern Europe could also have implications for lakes and streams, which will receive greater runoff immediately following fires. In addition, seasonal wetlands could be more at risk from fire and associated biophysical changes than previously. Climate change will probably have greater impacts on the littoral zones of lakes, where aquatic macrophytes will be able to make use of both the nutrients in sediments and the higher temperatures, than it will on the water bodies themselves.

184. Freshwater fish productivity could increase with higher temperatures. However, it is likely that a change in community structure may also be seen, with populations of cyprinid and percid fish dominating over cold water, salmonid, species. It is expected that the geographic distribution of cold water and temperate anadromous fish species (i.e. those migrating from the sea to breed in rivers, lakes and streams), including salmonids, sea trout, alewife, and sturgeon, will expand to the north while shrinking from the south. Populations of extreme cold water fish species, including Arctic charr, are expected to decrease, particularly in low-altitude, shallow lakes, where temperature increases will have the most impact.

Other inland wetlands

185. In Europe, many wetlands are highly influenced by the timing and duration of ice-cover and timing of ice break-up, particularly with regard to the supply and flux of nutrients, and the associated biological and ecological processes.

186. In arctic and sub-arctic regions, higher temperatures may lead to changes in permafrost extent and distribution. It has been reported that permafrost-underlain tussock tundra and patterned ground in the

Scandes (Scandinavian Mountains; bordering Norway and Sweden) may be replaced rapidly by low-alpine heath scrub as the permafrost thaws. The impact of climate change on average runoff in tundra regions is unclear, although Arnell (1999) indicated increases in average annual runoff in far northern Europe.

187. In boreal regions, warmer conditions (i.e., a shorter season of sub-zero temperatures) will change snow cover characteristics and affect wetlands as described above. Peatlands are the dominant wetland type in the boreal regions and have been well studied. Changes to the hydrological regime and water balance of peatlands could affect their abilities to sequester and store carbon. Recent studies suggest that in a warming climate, nutrient-poor peatlands may be able to increase their long-term carbon accumulation, while nutrient-rich peatlands could become potential sources of atmospheric carbon (as CO2). However, emissions of methane are also of importance, and both global warming and increased atmospheric carbon dioxide levels may facilitate methane emissions from peatlands.

188. With warming climate, it is likely that boreal peatlands will expand their distribution northwards, possibly displacing tundra and other permafrost-dependent habitats whose formation is controlled by the local topography. A rapid rate of climate change may cause degradation of the southern boundaries of the peatlands much faster than their northward expansion, further complicating predictions of overall consequent changes to the carbon cycle.

189. Freshwater wetlands in the temperate regions of central and eastern Europe are thought to be vulnerable to climate change, particularly given the land use pressures they face and are likely to continue to face. Similarly, freshwater wetlands in the Mediterranean region, particularly hydrologically isolated depressional wetlands, are considered vulnerable. The scattered and isolated nature of many wetland systems in southern and central Europe may hinder the migration of wetland species to more suitable climatic conditions. In addition, drier conditions in the Mediterranean region may adversely affect the trans-Saharan migrant bird populations that rely on suitable foraging habitat whilst en-route. These birds are also likely to suffer loss of their breeding habitats in northern Europe (Lindstrom and Agrell 1999; Zöckler and Lysenko 2000).

Coastal wetlands

190. Sea level rise will result in inundation and displacement of coastal wetlands and lowlands. The most threatened coastal wetlands within Europe are tidal deltas, estuaries, beaches, and salt marshes. The Mediterranean and Baltic coasts, with their low tidal ranges (<1 m), will be more susceptible to sea level rise than the Atlantic Ocean and North Sea coasts, which experience much higher tidal ranges. In addition, the extent of urban, industrial and agricultural development along coastal Europe has reduced the resilience and adaptation options for the coastal zone to respond to the impacts of to climate variability and change.

191. Deltas and estuaries. The Rhône, Po, and Ebro deltas are thought to be susceptible to climate change. There has already been considerable subsidence and reduced sediment delivery to these regions as a result of natural and human factors. In Venice, a 30 cm rise in sea level this century has already exacerbated flooding and consequent damage to infrastructure.

192. Austin & Rehfisch (2002) report on the implications of climate change of nine common species of waders (shorebirds) that over-winter on estuaries in the United Kingdom. As minimum temperatures on the east coast have become more similar to those on the west coast, there has been an eastward shift in the distribution of these birds. Further analysis of population estimates and distributions may provide further evidence of such responses.

193. **Salt marshes and intertidal flats.** Europe is estimated to have almost 3,000 km2 of salt marshes and over 6,500 km2 of other unvegetated intertidal habitat, much of which is contained within Ramsar sites. The

loss of mangroves, salt marshes and/or intertidal habitat by 2080 due to sea level rise alone has been estimated at 31-100% for the Mediterranean coast, 84-98% for the Baltic coast, and 0-17% for the Atlantic coast. The variability reflects the range of SRES sea level rise scenarios as well as uncertainty about coastal wetland responses to sea level rise.

194. Losses of these habitat types will reduce available habitat for wildlife, including fish (Nicholls et al 1999) and migratory bird species (Lindstrom and Agrell 1999; Zöckler and Lysenko 2000). The combined pressures of sea level rise and coastal development (resulting in "coastal squeeze") could reduce the availability of intertidal areas, resulting in loss of feeding habitat for, and causing population declines in, wintering shorebirds.

194. **Other coastal wetlands.** Rising air and sea temperatures may decrease the incidence of sea ice during winter and increase the incidence of algal blooms in coastal areas.

4.6 Latin America

Wetland habitats and distribution

195. Wetland distribution and extent in Latin America, including Mexico, were reviewed by Davidson et al (1999a, b, see also Figure 1). There are an estimated 417 million hectares, although this figure is not considered to be accurate. Based on existing figures most of this occurs in Brazil (~111.7 million ha), although figures for many countries were not available. Data on specific wetland types is available, for example freshwater swamps (~13.7 million ha), mangroves (~11.2 million ha), and peatlands (~9 million ha), but again these are certainly underestimates of the total areas. The inland wetlands of the Pantanal of Brazil, Bolivia and Paraguay cover between 14-20 million ha.

Impacts of climate change on wetlands and wetland species

196. Unless otherwise acknowledged, the information presented for the Latin America region is summarised from chapter 6 of IPCC (1998) (Canziani & Diaz et al 1998) and chapter 14 of IPCC (2001) (Mata & Campos et al 2001).

Lakes and streams

197. A number of regions and types of aquatic ecosystems have been identified as being most vulnerable to impact from climate change. These include: semi-arid and arid areas, lakes and streams in high evaporative drainages, basins with small catchments and short retention times, and shallow lakes and rivers where appropriate thermal refugia are not available. In general, it is thought that increased climate variability will have greater ecological impacts than changes in average conditions, such that flood and drought events will reduce the biological diversity and productivity of stream ecosystems.

198. In Latin America there have been few specific water resource studies using climate change scenarios. Those that have been undertaken vary in their predictions, often as a result of which scenario was used. A shift of seasonality and decreased runoff during low-flow periods was predicted for the Uruguay River basin. An increase in discharge during the low water period in December and January was predicted for the Choquepayu River in Bolivia. Under an increased precipitation scenario, greater runoff was predicted for the Pirai River, which is located in the humid environment of Bolivia.

199. In the humid tropics, extreme precipitation events could increase the siltation rate and decrease the effective life of many reservoirs. Changes in mixing regimes of lakes in temperate zones are also projected as a result of increased winter air temperatures. Impacts on biota are expected to be greatest in isolated systems, such as high-elevation Andean lakes, areas in the south of Argentina and Chile, or where species

are close to their geographical distribution limits. Species in large, north-south flowing drainage systems will probably have greater flexibility to migrate to compatible conditions.

200. The cryosphere in Latin America, represented by glaciers in the Andes, Patagonia's ice fields, and the Darwin ice field in Tiera del Fuego, may be affected by climate change, resulting in subsequent changes to timing and amplitude of runoff. Glaciers are already melting at accelerated rates in the Venezuelan and Peruvian Andes and in the southern extreme of the region. Arid regions downstream of these areas will probably benefit from additional runoff, although adverse consequences such as erosion, flooding and sedimentation could also occur.

Other inland wetlands

201. Little information is available on the impacts of climate change on other inland wetlands in Latin America. These impacts are anticipated to be more extensive the tropics and subtropics, but it is thought that human activities may cause greater impacts than climate change.

Coastal wetlands

202. The coastal wetlands in central America are amongst the most productive in the world, but many are also vulnerable to sea level rise.. Coastal erosion is likely to occur due to a combination of sea level rise and reduced sediment delivery from rivers caused by lower stream flows.

203. **Deltas and estuaries.** Flat areas, such as the Amazon, Orinoco and Paraná river deltas, and the mouths of other rivers, such as the Magdalena in Columbia and Salado in Argentina, are projected to be affected by sea level rise. In addition, estuaries, such as the Rio de Plata in Argentina, will experience salt water intrusion as a result of sea level rise, reducing the supply of freshwater.

204. **Mangroves.** Mangrove forests will be affected by sea level rise. In the tropical Americas, mangrove habitats are already being lost at the rate of about 1% per year due to human activities, and this may increase with the added pressure of sea level rise and possibly reduced sediment delivery from rivers. Fisheries that rely on mangrove habitats are also declining and will suffer further if coastal wetlands are lost as a consequence of sea level rise.

205. **Coral reefs.** Accretion rates of coral reefs in Latin America appear to be sufficient to keep pace with projected sea level rise, assuming other factors do not affect growth conditions. Mata & Campos et al (2001) did not discuss potential impacts of elevated sea surface temperature, although they would be expected to be similar to those described for other regions and globally.

4.7 North America

Wetland habitats and distribution

206. Wetland area in North America amounts to about 191 million ha, comprising about 41 million ha in the conterminous USA and 150 million ha in Canada (Davidson et al 1999b, see also Figure 1). Some 173.5 million ha of this total is peatland, of which about 111.3 million ha is in Canada. Estimates for boreal wetlands in Alaska (25-60 million ha) suggest, however, that such figures may be greatly affected by differences in wetland definition and classification. Some 18.9 million ha of peatland in the USA is forested. Mangroves cover an estimated 0.66 million ha and seagrasses 1.2 million ha.

Impacts of climate change on wetlands and wetland species

207. Unless otherwise acknowledged, the information presented for the North America region was

summarised from chapter 8 of IPCC (1998) (Shriner & Street et al 1998), chapter 15 of IPCC (2001) (Cohen & Miller et al 2001), and USGCRP (2000).

Lakes and streams

208. In general, there is greater confidence in projections of seasonal shifts in runoff and related hydrological characteristics than there is in projections of annual runoff. Projections of shorter snow accumulation periods appear to be even more robust, with a seasonal shift to greater winter runoff and reduced summer flow expected. This will be due to earlier snowmelt and also possibly increased precipitation in winter, and may result in increases in the risk of winter and early spring floods in mountainous western and northern Canadian watersheds. However, reductions in snow packs and river ice are predicted in southeastern Canadian and northeastern U.S. watersheds, which will most likely reduce the risk of winter and spring floods.

209. Many areas of Canada could experience a decrease in total flow, lower minimum flow, lower average annual peak flow, and lower lake levels. The latter is of particular importance for the Great Lakes region, where warmer temperatures are expected to result in lower lake levels and outflows, and for high latitude lakes (e.g., in the Mackenzie Basin).

210. Stream flows in the arid and semi-arid western parts of North America will be highly sensitive to changes in temperature and precipitation. Those rivers originating in mountainous regions will be sensitive to winter precipitation in the headwaters. Where these rivers pass through the dry semi-arid or arid regions, damage from severe flood events may be greater due to the presence of soils more vulnerable to erosion. Increased erosion will result in deposition downstream, although such impacts of climate change have not been well studied.

211. Changes to the hydrology of lakes and rivers can alter the physico-chemical characteristics and quality of the water. For example, where drier spring and summer seasons are projected, such as the Great Lakes region, concentrations of dissolved organic matter from soils will decrease, increasing the water clarity and resulting in a range of associated effects (e.g., increased primary production, altering thermocline depths). Earlier ice cover break-up in the Great Lakes has led to earlier spring algal blooms and altered the dynamics of nutrient cycling processes. Lower stream flows and lake levels will also serve to concentrate nutrients and chemical contaminants, further deteriorating water quality. Projected reductions in outflow of up to 50% from Lake Ontario may result in the saltwater wedge in the St Lawrence River intruding further upstream, with associated ecosystem impacts.

212. An increase in the incidence of severe rainfall events, as projected for the southeast, may increase the load of suspended sediment and associated non-point source pollutants (e.g., nitrogen) in rivers and lakes. Climate warming may also result in substantial changes in the thermal regimes and mixing properties of many mid- and high latitude lakes. Many of the above conditions will also favour the outbreak of water-borne diseases such as Giardia and Cryptosporidium.

213. The retreat of mountain glaciers is also occurring in North America, and the continuation of this in a warming climate will affect stream flow and lake levels. As expected elsewhere, glacial melt may initially increase summer flows until the glacier reservoir becomes depleted and flow decreases. However, the retreat of glaciers will probably result in the formation of lakes in exposed basins. A steady pattern of glacial retreat is already observed in the southern Rocky Mountains, below central British Columbia and Alberta. Permafrost thaw will also result in impacts to rivers and lakes; increased erosion and mud/landslides will result in increased sediment loads to rivers and lakes, increased infiltration of surface water will reduce overland flow; while lakes and ponds may drain laterally or to groundwater aquifers.

214. All these impacts of climate change may affect fish populations and other aquatic species. In general, the lack of thermal refugia and migratory routes in lakes, streams and rivers may cause contraction of the distributions of many fish species. For example, warmer lake water temperature will reduce dissolved oxygen concentration and lower the level of the thermocline, most likely resulting in a loss of habitat for coldwater fish species in areas such as Wisconsin and Minnesota (western Great Lakes). In addition, reduced summer flows and increased temperatures will cause a loss of suitable habitat for cool water fish species in riverine environments in the Rocky Mountain region (British Columbia, western Canada).

215. Other impacts to freshwater biota could be caused by a range of climate related factors. For example, lower lake levels could result in reduced fish productivity due to loss of breeding and nursery habitats, while more intense storm events could reduce biomass, productivity and abundance of some species or populations through severe erosion and scouring. However, more frequent flooding of floodplain habitats could increase productivity of many aquatic organisms. Finally, anadromous fish species (e.g., salmonids), which rely on marine and freshwater aquatic systems at different points in their life cycles, are more likely to be impacted than many other fish species.

Other inland wetlands

216. Climate change will impact the structure and function of wetlands, primarily through alterations in hydrology, particularly the water table level, to which many wetland flora and fauna respond dramatically.

217. For example, forecast increased incidences of drought conditions in the Prairie Pothole Region of the Great Northern Plains (bordering northern central U.S. and southern central Canada, and already under great pressure from human activities) will significantly reduce breeding duck populations in the U.S. The Prairie Pothole Region is thought to produce 50 to 80% of the continent's ducks, despite the fact that it represents only 10% of the total wetland area of the continent (Hulme & Sheard 1999). In addition, lower water levels in small alpine lakes in Oregon's Cascade Mountains due to less rainfall increases the exposure of western toad eggs to ultraviolet light, making them susceptible to disease outbreaks and related mortality (Lazaroff 2001b). Altered flooding patterns and sediment loadings will have impacts on other Ramsar-listed wetland areas such as the Queen Maud Gulf lowlands, which is renowned for being a major breeding and nesting ground for a variety of migratory waterbirds.

218. The extent of semi-permanent and seasonal wetlands may be reduced by general increases in evapotranspiration and reduced summer soil moisture, particularly in the prairie regions of North America. Mid-continental wetlands that depend on precipitation as a primary water source will be especially vulnerable to climate variation and change (Winter 2000).

219. Changes to the water table could affect the vast peatlands on northern Canada, with associated changes to their carbon sequestering ability, although the direction and extent of the effect is highly uncertain. Based on a 2×CO_2 scenario, it is predicted that the southern limit of peatlands in Canada will retreat 200-300 km northwards, towards the Arctic coast (Anisimov & Fitzharris et al 2001), probably being displaced by boreal forest. The combination of permafrost thaw and extreme events (fire, storm surges) may accelerate erosion, cause landslides in coastal areas, and influence peatland development in the Mackenzie Basin in northwest Canada.

220. Climate warming will also reduce the extent of alpine tundra in North America, potentially causing species loss and ecosystem degradation through increased fragmentation. A major reduction in northern peatlands may result in a shift from a net sink to a net source of carbon dioxide for the tundra region, while methane emissions may decrease due to drying and increased oxidation at the surface.

Coastal wetlands

221. Sea level rise will result in the loss of coastal wetlands in many areas due to erosion, flooding and saltwater intrusion. The combined forces of both sea level rise and other risks such as storm surge are of particular concern. It is estimated that a 50 cm rise in sea level would inundate approximately 50% of North American coastal wetlands.

222. The U.S. coastal regions expected to be most vulnerable to sea level rise are concentrated along the Atlantic coast and the Gulf coast, and they include the coastlines of Florida, Louisiana, North Carolina, and Texas. Louisiana is expected to experience the greatest wetland loss due to rising sea level. Vulnerable coastlines in Canada include those of Nova Scotia, the Beaufort Sea region, and the Fraser River Delta. In the near term, however, it is thought that coastal ecosystems will be more vulnerable to changes in river and groundwater flows due to shifts in inland precipitation, evapotranspiration, and river ecosystem dynamics.

223. Climate change may also impact coastal and marine bird populations. For marine birds, responses are expected to centre around changes to the distribution of prey species, which will be influenced by shifts in the distribution of water masses of different temperature and salinity. For arctic nesting birds, including geese and shorebirds, the timing of snowmelt will influence breeding timing and success. In addition, the loss of coastal wetlands and beaches may impact upon marine mammals, such as tropical seals and sea lions, coastal whales and dolphins, and manatees in estuarine habitats, due to the loss of calving and pupping areas. Sea turtles may also be affected by the loss of beaches.

224. **Deltas and estuaries.** Increased influx of freshwater in estuaries due to severe rainfall events may affect estuary-dependent species, such as oysters. Combined with higher temperatures, high runoff and associated nutrient (e.g., nitrogen) loads from watersheds could provide favourable conditions for harmful algal blooms and result in hypoxic conditions in estuaries, as has occurred in coastal regions of the Gulf of Mexico. Contaminant loads to deltas and estuaries could also increase. However, the range of factors involved are not fully understood, making it difficult to predict the impacts.

225. Altered flooding patterns and sediment loadings will have impacts on some internationally recognised wetlands, including the Peace-Athabasca-Slave delta, the Mackenzie delta, and intertidal wetland areas of Hudson Bay. In estuaries, sandy beaches may be more vulnerable than vegetated wetlands due to an inability to migrate landward because of coastal development.

226. Rising sea level will enable saltwater to intrude further inland, and this will impact upon aquatic communities. Increased salinity has already reduced oyster harvests in Delaware Bay and Chesapeake Bay, while cypress swamps in Louisiana have become open lakes. As an example of projected impacts, sea level rise could result in increased erosion of mudflats and salt marshes and complete inundation of tidal marshes in parts of San Francisco Bay and the Sacramento-San Joaquin River delta in northern California.

227. **Mangroves and salt marshes.** It is thought that tidelands and coastal marshes in bay shores may be particularly vulnerable to coastal erosion and inundation due to sea level rise, where development limits implementation of potential adaptation options. Coastal wetland habitat loss will be exacerbated by the fact that such habitats will not be able to migrate inland because of coastal development of the adjacent lands. Loss of shallow marshes in coastal regions, particularly in southeastern United States, could affect waterbirds, although there is insufficient information upon which to make confident predictions (Butler & Vennesland 2000). Although many waterbirds are adapted to cope with spatial variability in wetlands, it is less clear how they will cope with temporal climate variability.

228. **Coral reefs**. Coral reefs occur in the vicinity of the U.S.-Caribbean border. They may experience severe coral bleaching due to warmer water temperatures.

4.8 Polar Regions

Wetland habitats and distribution

230. Wetlands in the polar regions are vast, although at times it is difficult to separate the data for truly polar regions from that for sub-polar regions. With this limitation in mind there are some 70.7 million ha of wetlands in Alaska, most of which are within the tundra and taiga regions (Hall et al 1994). In northern Canada there are 80.4 million ha of wetland, including the extensive peatlands of the taiga and the wetlands of the Hudson plain (Ecological Stratification Working Group 1996). In northern Russia, including Siberia, there is an estimated 6 million ha of peatlands (Botch 1999).

Impacts of climate change on wetlands and wetland species

231. Unless otherwise acknowledged, the information presented for the Polar Regions is summarised from chapter 3 of IPCC (1998) (Everett & Fitzharris et al 1998) and chapter 16 of IPCC (2001) (Anisimov & Fitzharris et al 2001). Impacts of climate change on snow and ice processes and permafrost will dictate the nature and extent of changes to wetlands in the Polar Regions.

Lakes and streams

232. Run-off in the Arctic is expected to decrease, primarily due to reductions in snow melt at intermediate and high elevation zones and increased water storage capacity of the ground due to loss of permafrost. However, summer base flows will increase due to increased summer storminess, resulting in an overall reduction in seasonal fluctuations in runoff. Changes to precipitation may modify the sediment loads in Arctic rivers.

233. In addition, thawing of ice-rich permafrost can be accompanied by surface mass movements and land subsidence, possibly increasing the input of sediment to watercourses. Such increases in sediment and associated nutrient loads will alter aquatic biological productivity considerably. Also, temperature changes will affect species in rivers and lakes, with their ranges likely to shift polewards by about 150 km for every 1°C increase in air temperature.

234. Many streams that normally freeze to their beds will retain a layer of water beneath the ice, due to higher temperatures and some enhancement of winter flow. This may benefit aquatic invertebrates and fish. Ice-jamming and associated flooding of rivers could be enhanced, although a shorter ice season, thinner ice, and reduced snowmelt magnitude could reduce the severity of ice jamming in the large northward-flowing rivers. This would have severe impact on northern riparian ecosystems, particularly the many lakes and ponds adjacent to the river deltas, which rely on periodic flooding for their survival.

235. Ice cover and break-up are known to exert a major influence on the aquatic ecology of northern rivers, lakes and ponds in the Arctic, affecting various bio-physical processes and ecosystem biodiversity and productivity. Primary production is expected to increase in all Arctic lakes and ponds as a result of extended and warmer ice-free seasons, increased solar radiation penetration, and a larger input of organic matter and nutrients from the terrestrial landscape.

Other inland wetlands

236. The major impact of climate change in the vast tundra wetlands in the Polar Regions will be due to changes in permafrost temperature, leading to changes in the morphology and distribution of the permafrost. Permafrost currently underlies almost a quarter of the exposed land area of the Northern Hemisphere. While this area is expected to diminish over the next century, the extent of change is uncertain. Nevertheless, on a broad scale, it appears that tundra habitat will retreat northwards, being replaced by boreal forest. Some estimates predict that two-thirds of the tundra habitat will be lost.

237. Depending on changes in rainfall and drainage conditions, degradation of permafrost may result in over-saturation or desiccation of the surface, and this will have major implications for some wetlands. It is expected that lichens and mosses, which dominate the tundra regions, will be replaced by a denser cover of vascular plants. This, combined with higher evaporation rates, is likely to reduce the amount of ponded water and run-off. Furthermore, loss of permafrost will create a link between the surface and groundwater aquifers, potentially leading to the drainage of wetlands.

238. The regions thought to be sensitive to climate change include patchy Arctic wetlands on continuous permafrost and those along the southern limit of permafrost. However, land subsidence due to permafrost thawing (i.e., the development of thermokarst terrain) may lead to the development of new wetlands and drainage networks, particularly in areas of ice-rich permafrost. This has already been reported in areas of relatively warm, discontinuous permafrost in central Alaska.

239. As has been described in previous sections, the impact of climate change on the ability of peatlands to act as greenhouse gas (GHG) sinks or sources is a major issue. Estimates suggest that reductions in the water stored in northern peatlands due to warming and increased evaporation could be sufficient to convert them from a source to a sink of atmospheric methane. However, soil carbon in subarctic wetlands may be released by a reduction in permafrost due to climate change (Bolin & Sukumar 2000; Lazaroff 2001c). There is evidence that recent warming in Alaska has converted tundra from a net carbon sink to a source, although the direction and magnitude of responses may be regionally variable, depending on climate, topography and warming regime. For example, the development of thermokarst (warm water melting the permafrost below) may increase soil moisture and water impoundment in lowland areas, resulting in increased emissions of methane.

240. The effects of climate change on arctic-breeding shorebirds was investigated by Lindström & Agrell (1999) and Zöckler and Lysenko (2000). Approximately 50 species depend on the circumpolar tundra as breeding grounds during the Arctic summer. In the short term, climate change may have positive effects on breeding success, particularly due to warmer conditions and associated effects, such as increases in insect abundance. However, in the long term, northward vegetation community shifts may result in the loss of preferred breeding habitat and crucial coastal stopover sites.

241. Zöckler & Lysenko (2000) also attempted to predict the impact of climate change on arctic breeding water bird populations. Despite uncertainties relating to the small number of species assessed and the inclusion of appropriate variables into a future scenario, they concluded that all arctic water bird populations breeding in areas projected to have cooler spring and summer temperatures (under a moderate climate scenario), between northeastern Canada and west Greenland, are of special concern. Changing vegetation patterns in association with altered temperatures and rainfall, particularly the replacement of tundra by forest, were predicted to have major effects on bird populations. Species likely to be affected include the Tundra Bean Goose (Anser fabalis rossicus/serrirotris), Red-breasted Goose (Branta ruficollis), Spoon-billed Sandpiper (Eurynorhynchos pygmeus), and Emperor Goose (Anser canagicus). However, both the above studies recognised that the prediction of impacts is highly problematic, particularly because the birds spend only a few months per year in the Arctic, in between being subjected to a range of changing conditions (including natural predation, hunting, and climate change) elsewhere in the world.

Coastal wetlands

242. As described above, river deltas are thought to be sensitive to changes in the frequency and severity of ice-jams and associated flooding.

4.9 Small Island States

Wetland habitats and distribution

243. Most Small Island States are located in four major regions of the world: the Pacific Ocean, the Atlantic Ocean/Caribbean, the Indian Ocean, and the Mediterranean Sea.

244. Combined data on the Small Island States has been derived from information collated by Davidson et al (1999b) and Watkins (1999, see also Figure 1). Wetlands in the Oceania islands cover about 10.4 million ha, most of which occurs in Papua New Guinea (~10.1 million ha). Mangroves cover around 0.6 million ha, including 0.5 million ha in Papua New Guinea. In the Caribbean islands wetland areas are available for some islands, such as Cuba (~1.7 million ha), Haiti (~0.5 million ha), and the Dominican Republic (~0.04 million ha), although the accuracy of these figures is uncertain. Many of these wetlands are mangroves (e.g., Cuba ~0.5 million ha and Dominican Republic ~0.4 million ha) or peatlands (Cuba ~0.7 million ha and Haiti ~0.05 million ha). Some 2 million ha of coral reef also occurs in the Caribbean and 4 million ha in Papua New Guinea. Coral reefs and mangroves are also widely distributed in Pacific Island States.

Impacts of climate change on wetlands and wetland species

245. Unless otherwise acknowledged, the information presented for the Small Island States is summarised from chapter 9 of IPCC (1998) (Nurse et al 1998) and chapter 17 of IPCC (2001) (Nurse & Sem et al 2001). The most significant impacts of climate change to Small Island States will be due to changes in sea level (and associated coastal erosion and saltwater intrusion; Environment News Service 2001a), rainfall regimes, soil moisture budgets, prevailing winds, and wave action. Many of the impacts of climate change, in association with human pressures, probably will result in loss of biodiversity on small islands.

Inland wetlands

246. Due to the global distribution of the Small Island States, impacts of climate change on freshwater wetlands will depend on local climatological changes. The presence and availability of freshwater is a limiting factor for socio-economic development in Small Island States. Therefore, impacts of climate change on the presence and availability of freshwater will be of great importance. The general prediction of decreased rainfall in summer for three of the four major small island regions (the Atlantic Ocean/Caribbean, Indian Ocean, and Mediterranean region) suggests the possibility of reduced water availability.

Coastal wetlands

247. Beaches. In general, beaches will be vulnerable to further erosion due to sea level rise, increased intensity of storms, and alterations to prevailing winds and wave directions. Significant beach erosion has been reported for small islands where sea level rise has been recorded for over a decade. At Negril in Jamaica, about 10m of the world famous white sand beach was eroded between 1995 and 1998 due to increased storm surge and human activities such as coastal development (Environment News Service 2001a). In many cases, coastal development prevents beaches from adapting by shifting landward.

248. **Mangroves, tidal flats and seagrasses.** The debate about the ability of mangrove forests to adapt to sea level rise was summarised above in the global summary of impacts to wetlands (see section 3.3). Mangrove communities in many small islands have a limited ability to migrate landward in response to sea level rise, due to a range of factors, including coastal development and lack of substrate suitability (Mapalo 1999), the latter being typical in microtidal, sediment-starved environments such as in the Caribbean.

249. Consequently, substantial mangrove forest losses due to sea level rise have been predicted for a number of small island regions. For example, a 1 m sea level rise in Cuba would result in over 300,000 ha of mangrove forest being at risk, while the Port Royal mangrove wetland in Jamaica could completely collapse. The situation is similar for other small islands in the Caribbean and elsewhere (e.g., the

Philippines; Mapalo 1999). Mapalo (1999) noted that an implication of reduced mangrove habitat on Olango Island in the Philippines was the loss of roosting sites for migratory birds. Fish nursery habitats will also be lost. The coastal biodiversity in Cuba is considered to be the most vulnerable to sea level rise.

250. Mangroves may also be affected by changes in precipitation, because they require large amounts of freshwater for optimal growth. Less rainfall would reduce this freshwater input, while sediment delivery would also be reduced. The loss of mangrove and other intertidal habitats could have impacts on coastal fisheries, on which many small island regions can be highly dependent.

251. Tidal and mud flats will be affected by sea level rise, resulting in the loss of habitat of many shorebird species, including the endangered Tuamoto Sandpiper (Prosobonia cancellata) and Bristle-thighed Curlew (Numenius tahitiensis). Other possibly vulnerable areas for shorebirds and seabirds include Laysan Island (Hawaii), the Kerguelen and Crozet Islands (southern Indian Ocean), and the Galapagos Islands (Pacific Ocean). Climate warming may affect sea turtles, which usually nest in summer, when they are close to their upper thermal tolerance. As sea turtle sex ratio is determined by temperature, warmer conditions may result in a higher ratio of females to males.

252. Seagrass communities are also thought to be at risk from climate change and sea level rise. They will be particularly sensitive to increased sea surface temperature, probably affecting their growth and other physiological functions, and altering their distribution (Short & Neckles 1999). In addition, increased freshwater input to shallow waters surrounding small islands, and more intense storm events, could also affect seagrass distribution (Mapalo 1999).

253. **Coral reefs.** Potential effects of climate change on coral reefs in Small Island State regions are essentially those described in the global summary (see section 3.3), and in various of the other regional summaries in this section. Nurse & Sem et al (2001) only provided a few specific comments concerning coral reefs and Small Island States.

254. Coral reefs serve a range of important functions for tropical islands. In particular, they are a source of food and they function as natural breakwaters along the coastlines. The protective function of coral reefs has been reported to have been compromised throughout the Caribbean Sea due to coral bleaching and death (Environment News Service 2001a). The current degradation of many coral reefs in Small Island State regions and small island countries due to human activities places them under greater pressure from sea level rise. This is in contrast to currently healthy coral reefs in Australia, which are expected to be able to keep pace with sea level rise (Pittock & Wratt 2001). Mapalo (1999) also identified any increase in the intensity and frequency of typhoons as posing a significant hazard to coral reefs around Olango Island and other coral reef islands in the region.

255. The impact of climate change that may be the most significant to coral reefs is increased surface water temperature, particularly because around some island regions, corals currently live at or near their temperature tolerance. Highlighting this, at Rangiroa Island in French Polynesia, high sea surface temperatures (~ 32°C) during 1998 resulted in the mass bleaching and death of corals that will take an estimated 100 years to recover (Environment News Service 2001b).

5. Adaptation options

257. Adaptation here is taken to be a human intervention to address the effects of climate change, and does not include the autonomous response of the ecosystems themselves, for example an increased net primary productivity in many species due to the increased levels of atmospheric concentrations of carbon dioxide (IPCC 2001b).

258. Adaptation options and their implementation are thus strongly dependent on institutional capacity in the region or country. Specifically, institutional capacity includes both financial and human resources as well as the political will to address the adaptation options for climate change. Such political will can often be related to the national current and future socio-economic development and the current extent of the country's exposure to climate change. The potential for adaptation is more limited for developing countries, which are projected to be the most adversely affected.

259. Adaptation appears to be easier if the climate changes are modest and/or gradual rather than large and/or abrupt. Many of the adaptation options can not only address climate change impacts but could also provide "win-win" option for other problems, such as wetland degradation (IPCC 2001b). Adaptation options are often limited by our state of scientific knowledge. However, implementing these options, especially the "win-win" options, is often a function of political and governance decisions rather than of the state of scientific knowledge (Finlayson 1999).

260. Adaptation options should be considered within overall frameworks for sustainable development and should not conflict with the wise use of wetlands. However, given the inertia in some wetland species and functions, the development of adaptation options may not result in rapid responses (Gitay et al 2001). In addition, there is also likely to be institutional inertia. For example, implementation of management plans may be on a ten-year cycle, and that could affect the planning and implementation of adaptation options.

261. Monitoring of adaptation options should be considered to be an essential feature so that the overall adaptive framework, which should be responsive to the changes being observed either as a result of the adaptation measures or some other factors, can be modified as needed. In this sense the framework for adaptation and mitigation options (**Figure 5**) illustrates the extent of connections that exist between wetlands, their goods and services, and various pressures, including that of climate change.

262. Most wetland processes are dependent upon catchment-level hydrology, which can prove extremely difficult to manage. Thus, adaptations for the projected climate change may be practically impossible or very limited (Gitay et al 2001; USGCRP 2000).

263. Potential adaptation options are also limited by the geomorphology of the system: the evolutionary time frame of the dynamics of the system can limit some options. For example, a coastal low-lying wetland system that is relatively young and has a dynamic substrate and channeling system has fewer adaptation options than an older and more stable system. In addition, adaptation options for wetlands subject to climate change and sea level rise have on the whole not been extensively addressed in the IPCC Third Assessment Report (see Table 6).

264. A major component of adaptation that needs further attention is assessment of the actual vulnerability of wetlands and wetland species and functions to climate change and sea level rise.

265. Where adaptation options have been addressed they have usually been linked to established socio-economic imperatives, such as the locations of settlements, infrastructure, and economically important production. In many cases the adaptation options include protection of the coast by physical structures, accommodation of change, retreating from vulnerable areas, or simply doing nothing. In some cases, however, it may become necessary to take active steps to protect wetlands. This could occur where large numbers of people rely directly on non-marine wetlands in the coastal zone or where the wetlands provide goods and services required by people in urban areas. Foremost amongst such services are fish products and fresh water. However, as these goods and services are often uncosted or not in the possession of powerful vested interests or otherwise influential groups, it is likely that little active intervention will occur.

266. In some instances, the wetland habitats could be relocated or become re-established, although it is

likely that in many cases this option will be limited by major natural and infrastructural physical constraints.

267. The recent IPCC reports suggest a small number of generic potential adaptation options that can contribute to the conservation and sustainable use of wetlands (Arnell & Chunzen 2001; Gitay et al. 2001, Mata and Campos 2001, McLean and Tsyban et al 2001, Nurse and Sem et al 2001, Scott and Gupta et al 2001, Desanker and Magadza et al 2001, USGCRP 2000, Burkett and Kusler 2000). Examples, some of which have been mentioned in the regional sections above, include:

> i) Design of multiple-use reserves and protected areas which incorporate corridors that would allow for migration of organisms as a response to climate change. The response of some wetland species (both animals and plants) to climate change could be a range expansion or poleward movement of the species. Some of these may be invasive species (both native and alien) and could impact on the system especially through changes in the hydrology. Adaptation options in this case would have to include truncation of potential corridors or control of invasive species to limit the expansion of more competitive native or alien species, especially into wetlands that may be small and have high endemism.
>
> ii) Expansion of aquaculture to relieve stress on natural fisheries, despite the fact that much past aquaculture has led to the loss of wetlands and wetland species. Such options should be implemented only if they could demonstrate a reduction in pressure on existing wetlands.
>
> iii) Poleward transportation of less mobile aquatic species across watershed boundaries to cooler waters.
>
> iv) Specific management in some ecosystems which could reduce pressures on wetlands. For example, in the wetlands in the Arctic, economic diversification could reduce the pressure on wildlife. Rotational and decreased use of marginal wetlands, especially in semi-arid areas, could reduce wetland and wetland biodiversity loss.
>
> v) Integration of land, water and marine area management with the aim of reducing non-climate stresses upon wetlands, for example through reduction of fragmentation of water systems, reduction of land-based pollution into marine systems such as coral reefs, or reduction of invasive species.
>
> vi) Use of water control structures for some wetlands, in order to enhance particular wetland functions and address water management issues, such as securing long-term water resources for wetland conservation. It is unlikely that such steps could be taken independently of other water management decisions, such as those that will affect irrigation and potable water supplies, and they should form part of integrated river basin and water resource management.
>
> vii) Development of 'setbacks' for coastal and estuarine wetlands, perhaps linked with moves to direct sediment to specific places.
>
> viii) High priority management actions in wetlands that are valuable and likely to be lost or degraded, including the implementation of wetland rehabilitation and restoration projects. Wetland creation could also be usefully undertaken, but possibly not in many cases where existing infrastructure limits both the area and processes that support particular wetland types or functions.

Other adaptation options which could benefit wetlands concern the more efficient use of natural resources and the removal of policies and financial measures that work against the maintenance, and even the creation, of wetlands.

268. There are likely to be negative repercussions to specific adaptation options (Gitay et al. 2001). Examples include:

> i) The active transportation of aquatic species or "better-adapted" warm water species poleward - historical evidence suggests that this could result in the extinction of local wetland species and large changes in ecosystem processes and structure, all with economic consequences;
>
> ii) Interactions resulting from increased stocking and relocation of recreational and aquacultural endeavours;
>
> iii) Other negative effects related to secondary pressures from new hydrologic engineering structures.

269. There also may be co-benefits of adaptation measures. For example, the development of infrastructure against sea level rise in a low-lying coastal system could result in economic gains, although the relative expense of structures such as ports and trading centres that arise are unlikely to have been costed within the context of climate change.

Table 6 Examples of adaptation options for selected sectors (Modified from IPCC 2001c, Tables 3-6).

Sector/System dependent on wetlands	Adaptation Options
Water	· Increase water-use efficiency with "demand-side" management (e.g., pricing incentives, regulations, technology standards). · Increase water supply, or reliability of water supply, with "supply-side" management (e.g., construct new water storage and diversion infrastructure). · Change institutional and legal framework to facilitate transfer of water among users (e.g., establish water markets). · Reduce nutrient loadings of rivers and protect/augment streamside vegetation to offset eutrophying effects of higher water temperatures. · Reform flood management plans to reduce downstream flood peaks; reduce paved surfaces and use vegetation to reduce storm runoff and increase water infiltration. · Re-evaluate design criteria of dams, levees and other infrastructure for flood protection.
Food and Fiber	· Change timing of planting, harvesting, and other management activities.
Coastal Areas, Marine Fisheries	· Prevent or phase-out development in coastal areas vulnerable to erosion, inundation, and storm-surge flooding. · Use "hard" (dikes, levees, seawalls) or "soft" (beach nourishment, dune and wetland restoration, afforestation) structures to protect coasts. · Implement storm warning systems and evacuation plans. · Protect and restore wetlands, estuaries, and floodplains to preserve essential habitat for fisheries. · Modify and strengthen fisheries management institutions and policies to promote conservation of fisheries. · Conduct research and monitoring to better support integrated management of fisheries.

270. Analyses on specific wetlands suggests that adaptation options are limited in terms of their migration,especially inland, often due to the geology and/or the human settlement and infrastructure or the cost of the operation (Bayliss et al 1998, Mapalo 1999, Turner and Streever 2001).

271. In Kakadu National Park in northern Australia, freshwater habitats are likely to be lost to rising sea

level with little likelihood of adaptation, except for retreat and a vastly changed landscape, because of the low-lying, relatively young and extensive wetland (Bayliss et al 1997; Eliot et al 1999). On the Olango Island, in the Philippines, major habitat loss and a decline in tourism potential is likely to occur (Mapalo 1999) as a result of sea level rise, with few adaptation options available because of the size of the island and the human population/infrastructure. In the Yellow River delta, China, major infrastructure and settlement constraints are likely to impede further movement of the delta system, which has often changed course in the past (Li et al. 1999).

272. Various restoration, remediation and prevention actions are currently used in wetland management, especially to address salt water intrusion or degradation of wetlands (see for example Applegate 1998, Turner and Streever 2001, USGCRP 2000). The cost of this often long-term management action is such that it would be an unlikely option for future widespread application. An illustrative example is that of inland wetlands in floodplain systems adjacent to Kakadu National Park in northern Australia. In these wetlands, human activities have led to changes in hydrology and physical structure of the creeks (or channels) which could be interpreted as similar to those projected for climate change, including changes in storm activities and sea level rise (Bayliss et al. 1997). The result has been salt-water intrusion and thus degradation of 17,000 ha of formerly freshwater wetlands (Woodroffe & Mulrennan 1993). The institutional response was to implement a long-term (15 year) and costly (estimated to be millions of dollars) remediation and prevention works (Applegate 1999) with little or no ongoing success. This implies that such interventions are not generally a viable adaptation option in developing or developed countries, given the likely magnitude of changes in the future.

6. Mitigation options

273. Human activities such as fossil fuel use and land use/land cover change have resulted in substantial amounts of carbon being added to the atmosphere in the past 200 years. The total annual emissions of carbon to the atmosphere from human activities is about 7.9 Gigatonnes (Gt). About 1.6 Gt (17%) of this is from the land use and land cover change and the rest (6.3 Gt C) from burning fossil fuels. The atmosphere retains about 3.3Gt of this and the rest, by present estimates, is absorbed by the oceans and the terrestrial biosphere in equal quantities (Bolin and Sukamar 2000). Substantial reduction of the greenhouse gas would be required for the CO2 concentrations in the atmosphere to stabilise during the 21st century to less than twice the pre-industrial level (IPCC 2001c)

274. The effect of the greenhouse gases already emitted through human activity will persist for centuries due to the lag in the response, particularly of the oceans and the ice sheets (IPCC 2001c). Given the role of the land-based activities in the carbon being emitted, mitigation options can not only include the reduction of the greenhouse gas emission through the reduction of fossil fuel use, but must also reduce the land-based emissions through conservation of existing carbon pools, sequestration of carbon into the terrestrial biosphere, and substitution of biological products for fossil fuels or energy-intensive products (IPCC 2001c). Under the Kyoto Protocol, there is a provision for the Annex 1 countries (mostly developed countries) to use land use and land use change and forestry activities (afforestation, reforestation and avoided deforestation and other land-management activities) to meet their emission reduction targets (which overall is approximately 0.1Gt C to the atmosphere annually) (IPCC 2000).

275. About 28% of the carbon since the 18th century has been retained in the atmosphere and the remainder is estimated to have been taken up, in approximately equal amounts, by oceans and the terrestrial ecosystems. Between 1980 and 1998, the terrestrial ecosystems have been a small net sink for carbon dioxide, probably as a result of land use practices and natural regrowth, the indirect effects of human activities, including the CO2 fertilization effect and nitrogen deposition, and changing climate. Projections suggest that the additional terrestrial uptake of atmospheric CO2 on a global scale may continue for a number of decades (and thus the land-based sinks are a temporary measure), but may then gradually

diminish and could even become a source by the end of the 21st century. However, this conclusion does not consider the effect of future land use and land cover change or of any actions to enhance the terrestrial sinks (IPCC 2000).

276. Mitigation activities permitted under the Kyoto Protocol and Marrakesh Accords can affect wetlands. Afforestation could allow forested wetlands to be planted on land that has been without forest cover for a significant period of time (e.g., 20 to 50 years). Reforestation will convert back to forest land which was formerly forested but has then been cleared for other land uses. Although these mitigation activities may be minimal for forested wetlands, they can nevertheless have benefits to the wetlands as well as posing risks of negative impacts. Consistency with national and/or international sustainable development goals could reduce the risk of the negative impacts.

277. Impacts include (IPCC 2000, Noble et al 2000):

> i) reforestation or afforestation: possible benefits including an increase in the diversity of flora and fauna, except in cases where biologically diverse non-forest ecosystems (e.g., grasslands) are replaced by forests consisting of single or few species. Afforestation can also have various positive or negative impacts on ecosystem functions, such as water run-off and nutrient cycling;
>
> ii) deforestation: avoiding deforestation can provide potentially large co-benefits, including conservation of biodiversity and soil resources and maintenance of forest products;
>
> iii) tree cover: increasing tree cover, or protecting it from being decreased, can improve and protect soil quality in areas that are vulnerable, stabilise river flows, and thus potentially indirectly benefit wetland functions;
>
> iv) potentially harmful effects of planting tree species with high water demand in locations where this may lead to increased water stress and reduction of water availability to wetlands.

278. Peatland-dominated wetlands are one of the major sources of greenhouse gases (as methane and CO2). Due to the large size of some of these wetlands, for example the northern hemisphere tundra and taiga zones, changes in these wetlands can modify energy, water, and gas fluxes and affect atmospheric composition, which can create changes in local and regional climate. In the tundra, this could lead to enhanced warming of the region and potentially change the disturbance regime (e.g, fires), which could act as further feedback to climate change (Gitay et al 2001). Any actions that would avoid degradation of these wetlands and thus the potential release of the greenhouse gases would be an extremely beneficial mitigation option.

279. Patterson (1999) proposed that measures to increase carbon sequestration should include measures to retard decomposition in forests and agricultural systems, conservation and extension of wetlands to maintain anaerobic conditions and protect resistant organic residues, and management of agricultural environments to enhance primary production and increase soil organic matter.

280. However, it is unlikely that these steps could be readily undertaken without taking note of the many interactions that exist between wetlands and their goods and services and various pressures and socio-economic drivers, as shown in Figure 5.

7. Assessment of vulnerable wetlands

280. Human and natural systems are defined as vulnerable to climate change either because they have few or no adaptation options to reduce the impacts of climate change and/or because they are naturally sensitive to climate change, for example due to their geographic or socio-political location (IPCC 2001b). As a result

of limited or lack of adaptation options for wetlands and/or sensitivity to climate change, many wetlands can be considered to be vulnerable to climate change.

281. Such vulnerability can have further impacts on the human societies dependent on these wetlands. The case in Kakadu National Park in northern Australia highlights this: it is a socially complex situation where indigenous landowners who have only resumed ownership of their traditional lands in recent decades are likely to face major changes if not the loss of the wetland areas they value and upon which they depend (Bayliss et al 1997).

282. Certain types of wetlands have been identified as particularly sensitive to climate change and thus likely to be impacted earliest and most severely. These are notably high latitude and high altitude wetlands, including arctic and sub-arctic ombotrophic bog communities, alpine streams and lakes (Gitay et al 2001), and coral reefs (Nurse and Sem et al 2001).

283. Any wetland that is affected by one or more of the global changes (see figure 5) and/or introduction or invasion by alien species resulting in changes in hydrology can also be considered to be vulnerable to climate change. Wetlands that are isolated and experience species loss would have a low chance of recolonisation by species and thus are also considered vulnerable (Pittock, Wratt et al. 2001).

284. Given the various pressures on wetlands, there is a need to assess the impacts of these pressures on the wetlands, seeking options for reducing these impacts, and identifying wetlands that are vulnerable to one or more of the pressures. Various methods have been identified for vulnerability assessment (see below), although no one particular method has been agreed or, indeed, is necessarily practicable (Kay & Waterman 1993). Methods are related to definitions of vulnerability, defined by IPCC (1992) as "a nation's ability to cope with the consequences of an acceleration in sea level rise and other coastal impacts of global climate change."

285. Carter et al (1994) included socio-economic factors in their definition of vulnerability - "the degree to which an exposure unit is disrupted or adversely affected as a result of climatic factors. Both socio-economic and physical factors are important in determining vulnerability."

286. Starting with the IPCC Common Methodology (IPCC 1992), a number of assessment procedures have been proposed and used in case studies around the world. The approaches have some common elements, but Harvey et al (1999) point out differences between these, especially in relation to their emphasis on quantitative analyses and the attention paid to broader socio-economic needs, including traditional aesthetic and cultural values such as those of subsistence economies and traditional land tenure systems. An outline of three assessment methods is given in Table 7.

Table 7 Summary of various vulnerability assessment methods

IPCC (1992)
1. Delineate case study area and specify accelerated sea-level rise and climate change conditions
2. Produce inventory of study area characteristics
3. Identify relevant socio-economic development factors
4. Assess physical changes
5. Formulate response strategies
6. Assess the vulnerability profile
7. Identify future needs

Kay & Waterman (1993)
1. Delineation of a climatic change and sea-level rise impact zone
2. Analysis of the vulnerable and resilient components of the systems within the zone
3. Analysis of the links between the systems within the impact zone and the systems within the connected areas
4. Formulation of management strategies within the impact zone and connected areas

Harvey et al. (1999)
1. Definition of the spatial scale of the entire study area using biophysical and socio-economic boundaries

2. Definition of the temporal scale that incorporates current human-induced hazards and potential climate change hazards
3. Collection of the data on the relevant biophysical characteristics of the study area
4. Collection of data on the socio-economic, cultural and heritage characteristics of the study area
5. Reiteration of stages 1 to 4 for selected study sites
6. Identification of the relevant legislation, jurisdictions, plans and polices for the study area for different level of governance
7. Assessment of coastal vulnerability in both qualitative and quantitative terms on the basis of the various techniques utilised within the assessment
8. Setting priorities for current management and further long-term objectives according to the problems identified

287. The Kay & Waterman (1993) method has been used for specific wetland vulnerability assessments in Kakadu National Park, Australia (Bayliss et al. 1997), Yellow River delta, China (Li et al 1999), and Olango Island, the Philippines (Mapalo 1999). The Harvey et al (1999) method was developed from that proposed by Waterman & Kay (1993) with a more specific emphasis on a holistic view of climate change and current human-induced changes, and it also particularly identifies a need for spatial and temporal scales in the assessment. It has been used for assessing coastal change, but not specifically for wetlands.

288. The specific details of each method have been compared by Harvey et al (1999) using four broad headings (Table 8). This comparison was undertaken to illustrate the specific differences between each method, but most differences appear to be related to terminology and emphases within broad categories of information, rather than fundamental differences. In essence, each method requires much the same information, even if this has not been specifically illustrated in relevant case studies. Each method requires spatial and temporal delineation of the case study and the incorporation of socio-economic and cultural information, as emphasised by Harvey et al (1999). Thus, it is recommended that the applicability of each method be assessed by interested parties based on the particular needs and inputs available for their specific purposes.

289. In the Ramsar Convention context, although the terminology is different, the four categories of Harvey et al (1999) are the same as the first four steps outlined in the wetland risk assessment procedure (**Figure 6**) developed by van Dam et al (1999) and adopted by the Ramsar Convention (Resolution VII.10). Based on the comparison provided by Harvey et al (1999) and the detailed description provided by van Dam et al (1999), the specific detail outlined in Table 8 can be encompassed within the Ramsar wetland risk assessment procedure, although the two procedures have different emphases.

Table 8 Comparison of the IPCC (1992), Kay and Waterman (1993) and Harvey et al (1999) vulnerability assessment procedures, using standard categories of information (adopted from Harvey et al 1999), and the wetland risk assessment procedure of van Dam et al (1999).

	IPCC	**Kay & Waterman**	**Harvey et al**	**van Dam et al**
Definition of study area	Step 1	Step 1	Steps 1 & 2	Step 1
Data collection	Steps 2 & 3	Steps 2 & 3	Steps 3-6	Steps 2 & 3
Assessment	Steps 4 & 6	-	Step 7	Steps 2 & 3
Responses	Steps 5 & 7	Step 4	Step 8	Step 4

8. Key uncertainties and robust conclusions

290. There is a continuing lack of detailed information about the distribution, extent and use of wetlands which makes it difficult to predict the impacts of climate change. Lack of consistent wetland classification exacerbates this problem. In addition, changes in wetlands are dominated by changes in catchment hydrology which are poorly understood.

291. Climate change has certainly already affected some wetlands (e.g., Arctic wetlands, coral reefs) and will continue to do so. However, lack of regionally specific wetland data and regional climate change scenarios, let alone catchment level climate change scenarios, make it difficult to predict the impacts of

climate change on many wetlands.

292. Many pressures (e.g., land use change, pollution, extraction of water for urban or agricultural use) act on wetlands simultaneously, but may be with different time lags: for example, the run-off changes due to deforestation can be slow compared with those due to local temperature changes caused by changes in the frequency and intensity of El Niño-like phenomena. This complexity adds to the problems of considering not only climate change impacts but the adaptation options as well.

293. Any increase in the additional pressures due to human activity (e.g., drainage of wetlands or changes in their uses, including introduction of exotic species for recreational purposes) is likely to increase the impacts and limit the adaptation options. The overall adaptation options would be to minimise changes in hydrological regimes.

294. However, adaptation is no longer an option: it is a necessity, given that climate changes and related impacts are already occurring. Adaptation options will vary with location and wetland types but have the potential to reduce many of the adverse impacts of climate change and to enhance beneficial impacts.

295. The capacity of different regions to adapt to climate change will depend greatly on their current and future states of socio-economic development and their exposure to climate stress. The potential for adaptation is more limited for developing countries, which are projected to be the most adversely affected. Adaptation appears to be easier if the climate changes are modest and/or gradual rather than large and/or abrupt.

296. A major component of adaptation that needs further attention is assessment of the vulnerability of wetlands to climate change and sea level rise. Many wetlands are vulnerable to climate change either because of their sensitivity to changes in moisture and temperature regimes and/or as a result of the other pressures from human activities and limited or lack of adaptation options. Future management for these wetlands will need to take these multiple pressures and the added stress of climate change into account.

297. Monitoring programs aimed at gauging the effectiveness of these adaptation or management options and the steps to rectify any adverse effects should be part of the adaptive management strategy. There is a danger of implementing adaptation options that have only local or short-term benefits (e.g., stocking of fish for recreational fishing in a warming lake; infrastructure development to control floods) but which could result in longer term damage (e.g., extinction of local species and thus loss in local biodiversity; more damage from a large flood following artificial restriction of water flow capacity).

298. Some uncertainties concerning climate change and wetlands arise from a lack of data and a lack of understanding of key processes, and also from disagreement about what is known or even could be known. Other uncertainties are associated with predicting social and personal behaviour in response to information and events.

299. These uncertainties tend to escalate with the complexity of the problem (e.g., changes due to the multiple pressures), but also due to elements being introduced to include a more comprehensive range of physical, technical, social, and political impacts and policy responses. Such uncertainties can never be fully resolved, but they can often be bounded by more evidence and understanding, particularly in the search for consistent outcomes or robust conclusions (IPCC 2001c).

300. Our understanding of wetland hydrology, and its effects on chemical and biological functions, is very limited. This is a key uncertainty in the prediction of any impacts due to any of the single and/or multiple pressures from human activities, as well as in developing adaptation options. The feedbacks, the lag times, and the inertia in the response of wetlands and their functions add to the uncertainties.

301. For many wetlands, detailed local knowledge is required in terms of their distribution, their processes, their uses and their past and present management as the basis for prediction. In many regions this knowledge is lacking or very limited. Thus it is difficult to predict the impacts of climate change on wetlands beyond a generic level for many regions, let alone to suggest adaptation options.

302. Developing an integrated framework can encompass all the pressures due to human activities on wetlands. Such a framework can emphasise the linkages between the systems, the main drivers of the global change, the impact of these changes on the wetland function, and thus the goods and services upon which people depend. Adaptation and mitigation options, for example reduction in the greenhouse gas emissions, can then be sought which reduce the impacts or reduce the actual changes due to the drivers.

9. References

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Figures

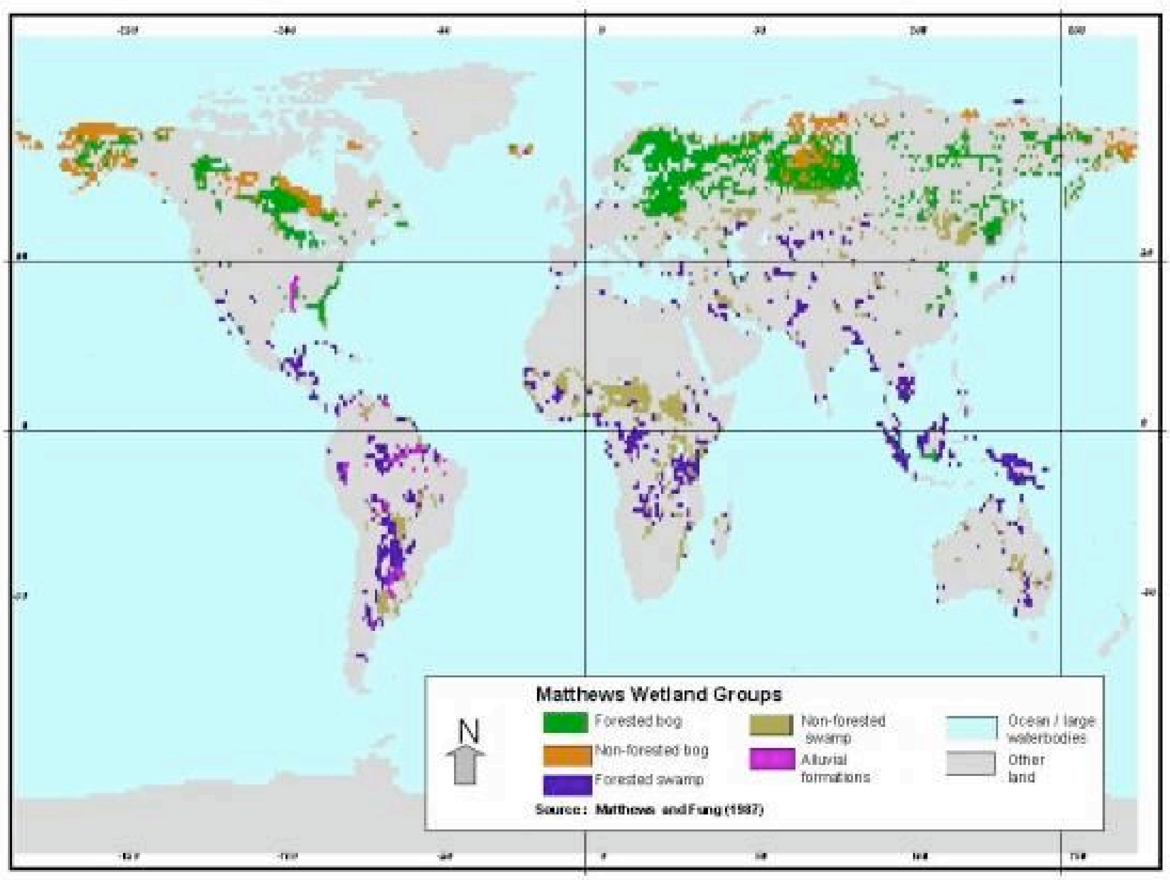

Figure 1 – Global wetland distribution using wetland groups as defined by Matthews & Fung (1987). Note that this representation does not include marine/coastal wetlands or some inland wetland types covered by the Ramsar Convention (see text).

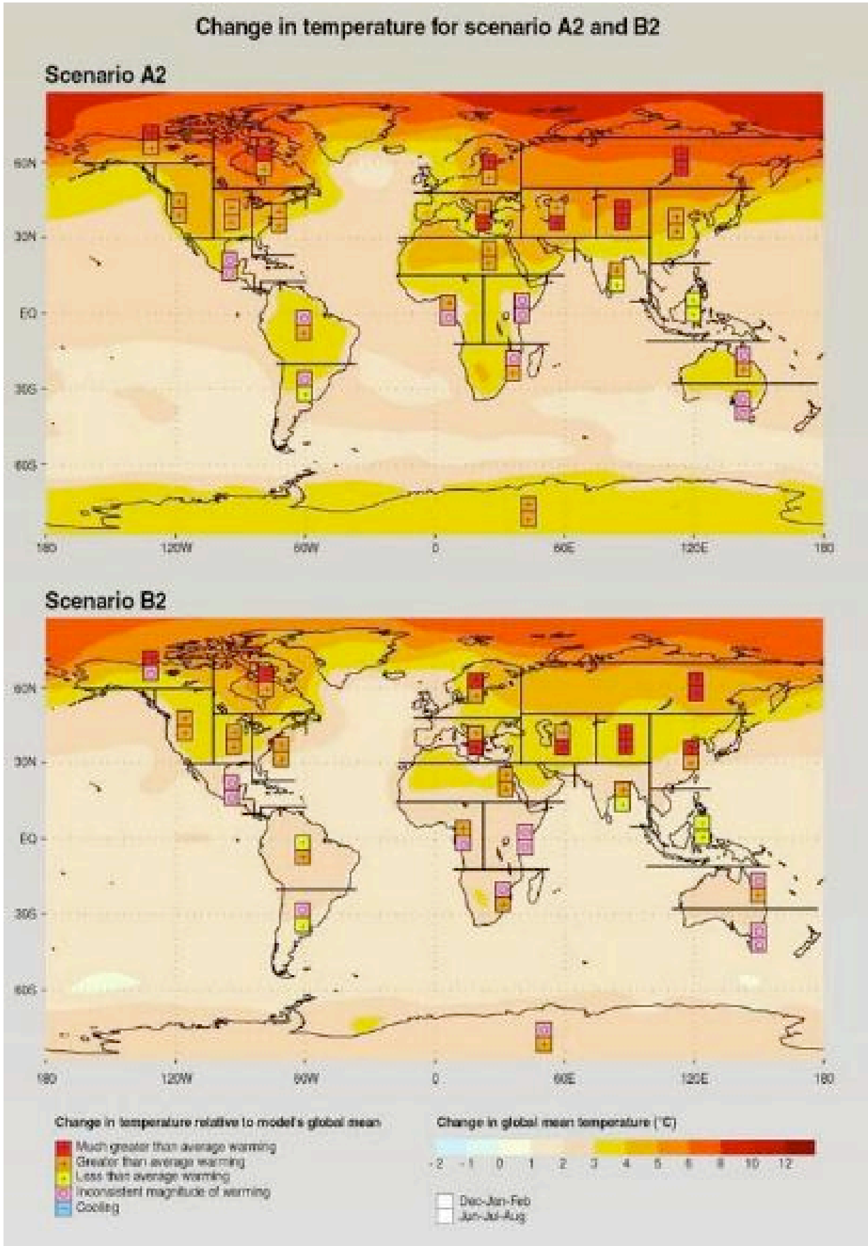

Figure 2 – Projected changes in surface temperatures (page 3)

The background shows the annual mean change of temperature (color shading) and its range (isolines) for (a) the SRES scenario A2 and (b) the SRES scenario B2. Both SRES scenarios show the period 2071 to 2100 relative to the period 1961 to 1990, and were performed using nine Atmospheric Ocean Global Circulation Models (AOGCMs). Scenarios A2 and B2 are shown as no AOGCM runs were available for the other SRES scenarios. The boxes show an analysis of inter-model consistency in regional relative warming (i.e., warming relative to each model's global average warming) for (a) the A2 and (b) the B2 scenario. Regions are classified as showing either agreement on warming in excess of 40% above the global mean annual average (*much greater than average warming*), agreement on warming greater than the global mean annual average (*greater than average warming*), agreement on warming less than the global mean annual average (*less than average warming*), or disagreement amongst models on the magnitude of regional relative warming (*inconsistent magnitude of warming*). Cooling never occurs. A consistent result from at least seven of the nine models is defined as being necessary for agreement. The global mean annual average warming of the models used span 1.2 to 4.5°C for A2 and 0.9 to 3.4°C for B2, and therefore a regional 40% amplification represents warming ranges of 1.7 to 6.3°C for A2 and 1.3 to 4.7°C for B2. Reproduced, with permission, from IPCC (2001a).

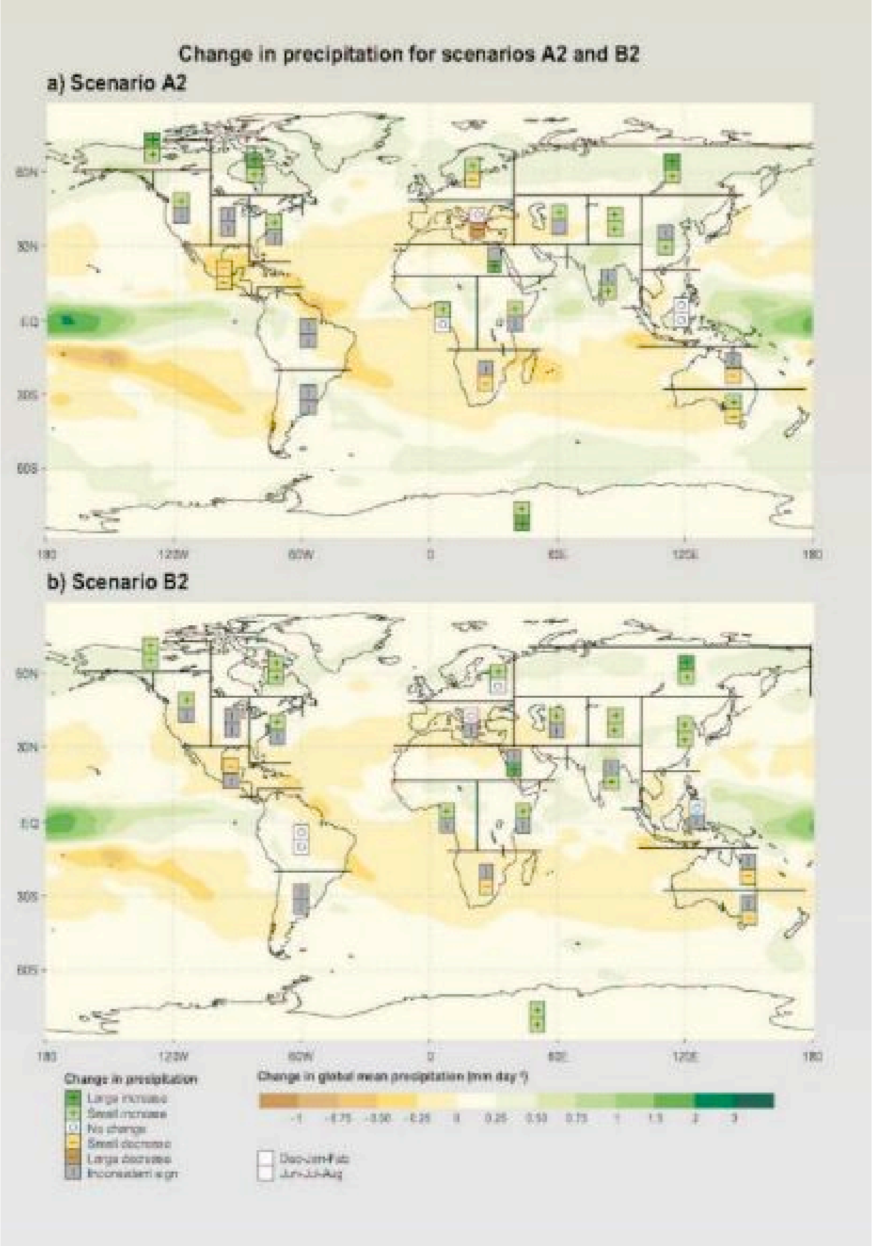

Figure 3 Projected changes in precipitation (page 4)

The background shows the annual mean change of rainfall (colour shading) for (a) the SRES scenario A2 and (b) the SRES scenario B2. Both SRES scenarios show the period 2071 to 2100 relative to the period 1961 to 1990, and were performed using nine AOGCMs. Scenarios A2 and B2 are shown as no AOGCM runs were available for the other SRES scenarios. The boxes show an analysis of inter-model consistency in regional precipitation change. Regions are classified as showing either agreement on increase with an average change of greater than 20% (*large increase*), agreement on increase with an average change between 5 and 20% (*small increase*), agreement on a change between -5 and +5% or agreement with an average change between -5 and +5% (*no change*), agreement on decrease with an average change between -5 and -20% (*small decrease*), agreement on decrease with an average change of more than -20% (*large decrease*), or disagreement (*inconsistent sign*). A consistent result from at least seven of the nine models is defined as being necessary for agreement. Reproduced, with permission, from IPCC (2001a).

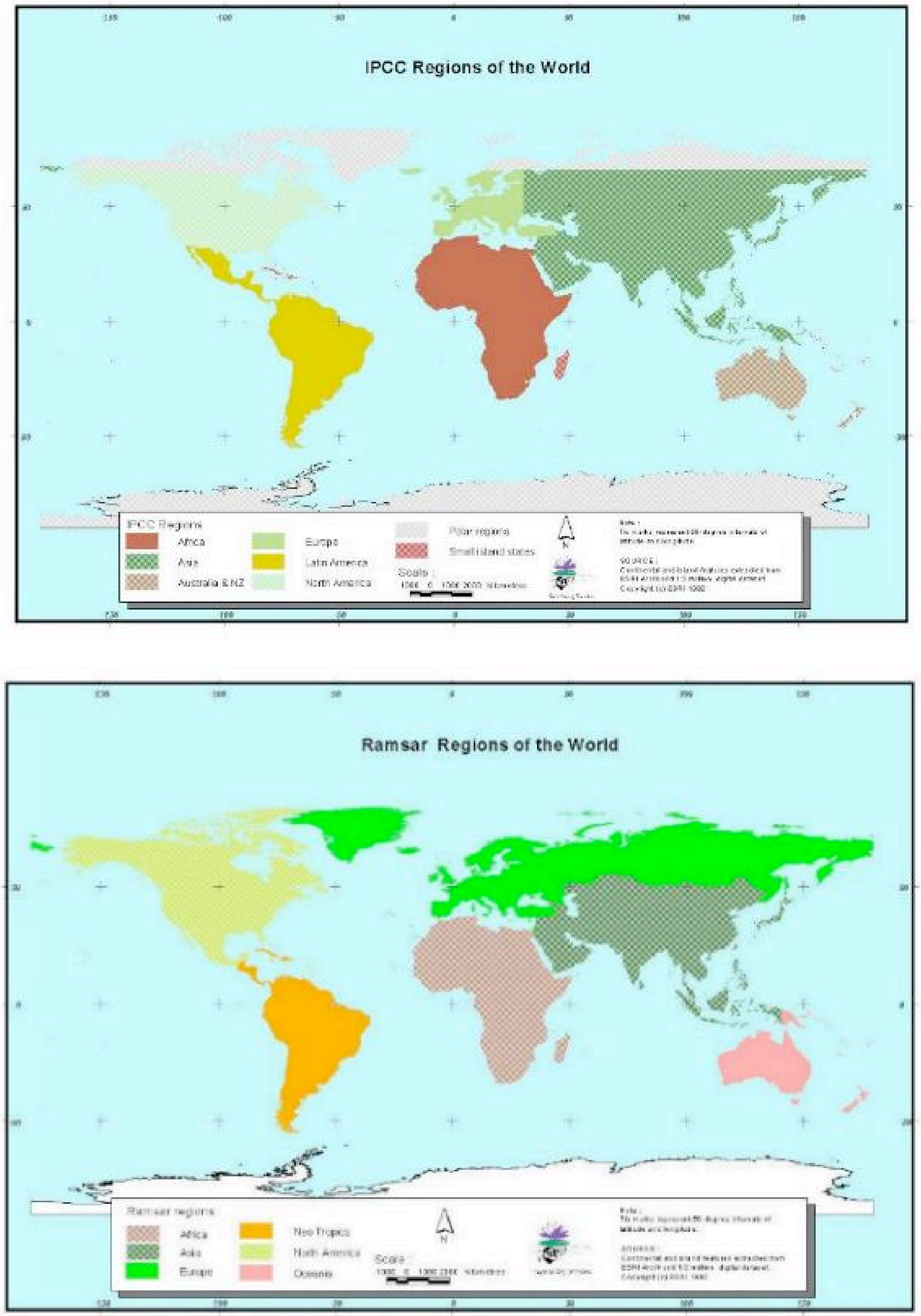

Figure 4 – Maps showing the generalised boundaries of the global regions used by: **A)** the IPCC in the Third Assessment Report; and **B)** the Ramsar Convention. The maps are indicative only and do represent an accurate analysis of the many countries/territories considered by the IPCC or the Convention.

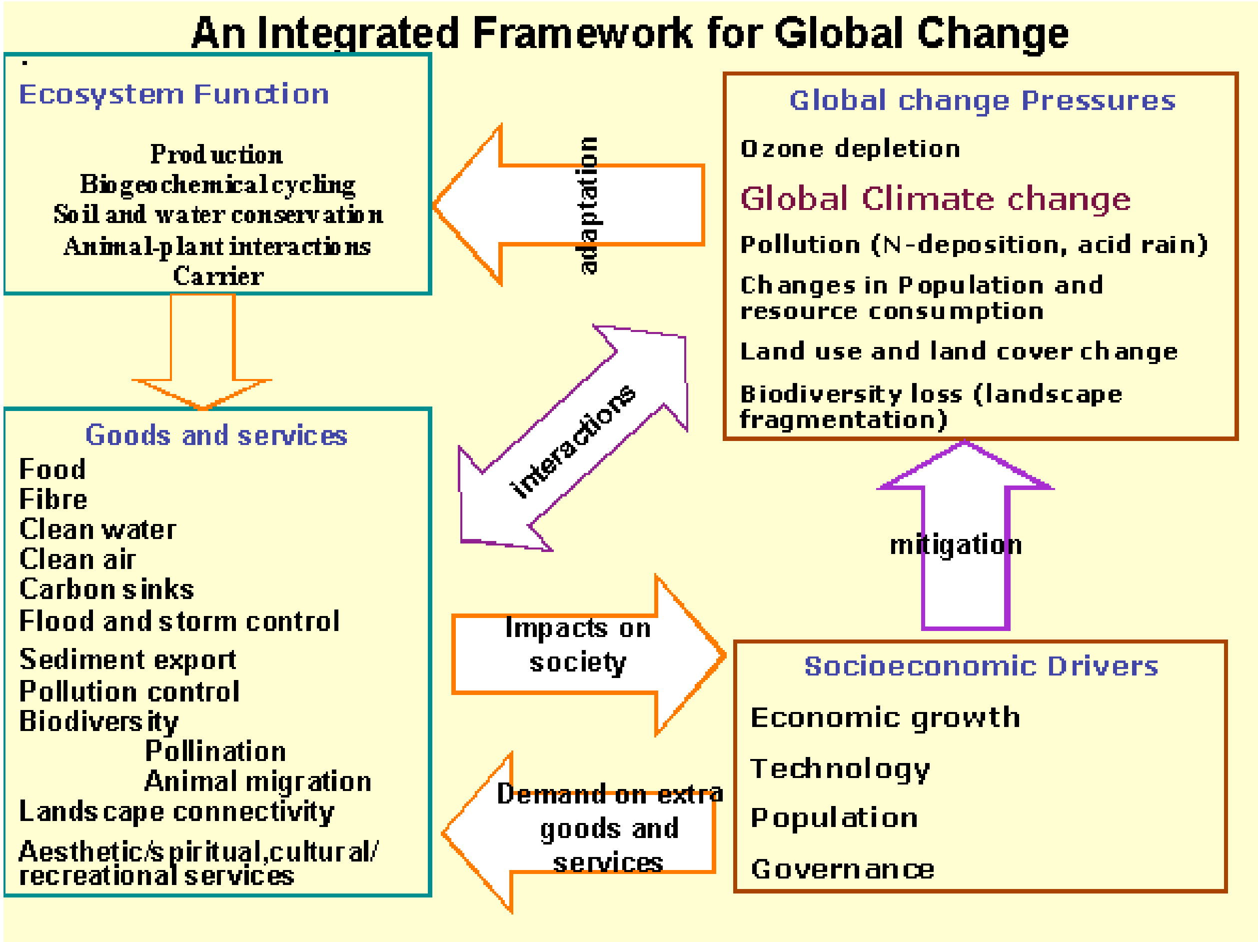

Figure 5 – Climate change in the context of global change and the interaction between these changes, their drivers (socio-economic pathways), and the ecosystem functions and the goods and services that ecosystems provide (modified from IPCC 2001c, Gitay et al 2001)

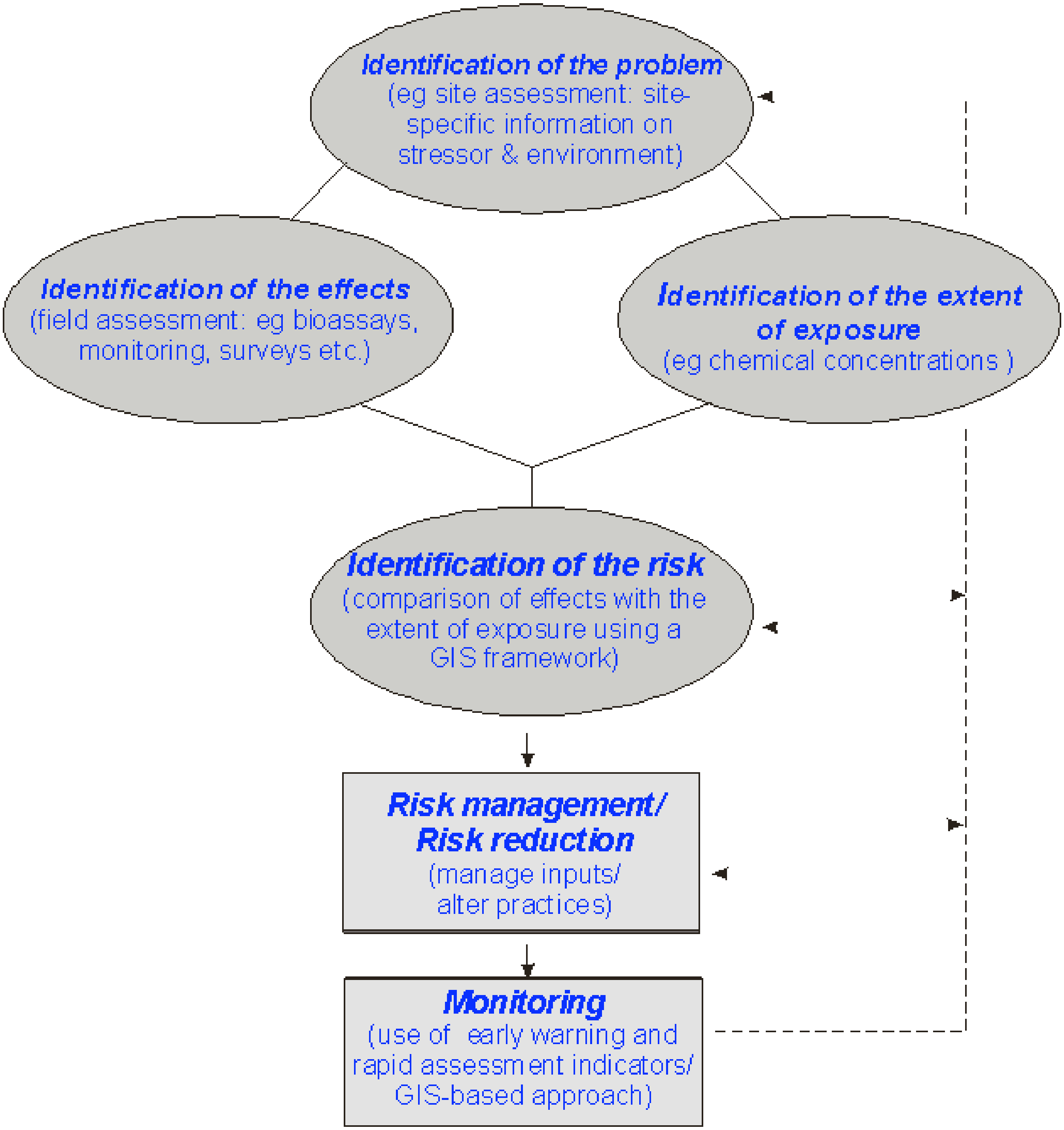

Figure 6 – The wetland risk assessment procedure adopted by the Ramsar Convention in Resolution VII.10 (from van Dam et al 1999).

For further information about the Ramsar Convention on Wetlands, please contact the **Ramsar Convention Bureau**, Rue Mauverney 28, CH-1196 Gland, Switzerland (tel +41 22 999 0170, fax +41 22 999 0169, e-mail ramsar@ramsar.org). Posted 14 August 2002, Dwight Peck, Ramsar.

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