Climate Change:
An Overview and its Impact on the Living Lakes

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"Climate change and governance: managing impacts on lakes"

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Tyndall°Centre
for Climate Change Research

Introduction

This report has been compiled for the 8th Living Lakes Conference to be held at the Zuckerman Institute at UEA from 7-12 September 2003. One of the twin themes of the Conference is climate change, most appropriate since the Zuckerman Institute hosts two leading centres for climate change research in the UK – the Climatic Research Unit and the Tyndall Centre for Climate Change Research.

The Tyndall Centre was approached by the organisers of the Conference and asked to make a presentation on our current understanding of climate change and to examine in some more details what climate change might imply for the 23 Living Lakes. This report summarises this work and is being distributed to all the Conference participants.

The report therefore comprises two elements – first, an overview of climate change (a 600 word abstract and a set of powerpoint slides to be used in the presentation) and, second, a series of analyses conducted for each of the 23 Living Lakes about the likely changes in climate expected over the century to come (focusing on changes in temperature and rainfall), together with a brief qualitative description of what this might mean for the hydrology of each lake system. This analysis uses the results and climate models used in the latest assessment (the 3rd Report published in 2001) of the Intergovernmental Panel on Climate Change – the IPCC – together with recent observed climate data. This analysis and interpretation only provides a preliminary investigation into climate change and how it will affect each lake system; more detailed hydro-climatic analysis, and an assessment of the impacts on the operations and functions of the lakes drawing upon the expertise of local managers, is truly required.

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Abstract

The climate of the Earth has never been stable, least of all during the history and evolution of life on Earth. Glacial periods, for example, have been (globally) 4°-5°C cooler than now, and some interglacials have been (perhaps) 1°-2°C warmer. These pre-historic changes in climate were clearly natural in origin and occurred on a planet inhabited by primitive societies with far smaller populations than at present. Ecosystems and species have moved, often freely, in response to such past changes and have evolved within this climatic history. Lake systems have risen and fallen many times during the Earth's climatic history.

The causes of contemporary and future changes in climate, the rate and potential significance of these changes for ecosystems and hydrological systems and for the human species, however, are all notably different from anything that has occurred previously in history or pre-history. The *causes* are now dominated by human perturbation of the atmosphere, the *rate* of warming already exceeds anything experienced in the last 10,000 years and, given the ecological imprint made by our current and growing population of 6 billion and more, the *significance* of this prospect for the natural world and for human society is qualitatively different from previously experienced changes in climate.

The atmosphere delivers both resources (e.g. rain, sun, wind) and hazards (e.g. hurricanes, blizzards, droughts) to ecosystems and societies. Ecosystems, hydrological systems and our human cultures and economies are 'tuned' to the climate in which they evolve. All societies have therefore evolved strategies to cope with some intrinsic level of climatic variability – for example, nomadic pastoralism, flood prevention, building design, weather forecasting, early warning systems and the weather-hedging industry are all forms of human response to the variability of climate or the extremes of weather. Consequently, there exists some level of variation in climate or some frequency or severity of weather extremes that can be 'accommodated' using existing strategies or behaviour. Exactly *what* can be accommodated, however, varies greatly within and between societies and between ecosystems, so that vulnerability to weather and climate change is strongly differentiated around the world.

So the central concern is *not* that humans are altering climate, but *whether* these changes in climate can be accommodated using our existing capacity to adapt, drawing upon our intellectual, regulatory, social or financial capital, and *whether* hydrological systems are resilient enough to survive these climatic perturbations given the other pressures they are subjected to by human development? Additional questions that flow from this perspective are: to what extent can we (need we?) predict future climates to assist this process of adaptation, and to what extent do we need (and desire) to reduce the size of the changes in climate facing us to allow our adaptive potential to sustain an acceptable dynamic equilibrium between climate, ecosystems and society?

We face certainly continuing, probably accelerating and possibly unprecedented changes in the Earth's climate over the coming years and decades. These changes in such a fundamental resource for society will introduce new challenges for the way we live with and influence climate. Some of these challenges may be broadly foreseeable, many of them may not. Some of the risks associated with a rapidly changing climate may be quantifiable, many of them may not. What should be our response?

As evidence is emerging that some hydrological and biological systems are already reacting to this human-induced change in climate, and as we know that at least for some regions and for some communities and ecosystems climate variability already imposes huge costs, doing nothing is unlikely to be the best option. Societies, including managers of valuable lake systems, need to develop and implement appropriate strategies to reduce the risks associated with a changing climate – to ensure that these changing climatic resources are appropriately exploited and that the adverse impacts of changing climatic hazards are minimised. Mitigation measures are required to reduce global greenhouse gas emissions with the intention of eventually stabilising atmospheric concentrations at some level at which an acceptable dynamic equilibrium could be sustained between climate, ecosystems and human society. On the other hand, due to the inertia of both the climate system and our energy structures, greenhouse gases accumulated and accumulating in the atmosphere since the pre-industrial era will continue to affect global climate long into the future. Together with the existing exposure of many communities and water resources to extremes of weather, adaptive measures become essential in order to enhance the coping abilities of valued lake systems, vulnerable communities and exposed infrastructures.

These crucial perspectives about climate change need to be integrated fundamentally into the full range of policy measures that are demanded by our drive towards sustainable development, an argument equally valid for the nations of the South as for the nations of the North, and for managers of lake systems as for other managed assets. We all need to come to terms with climate change.

Methodology

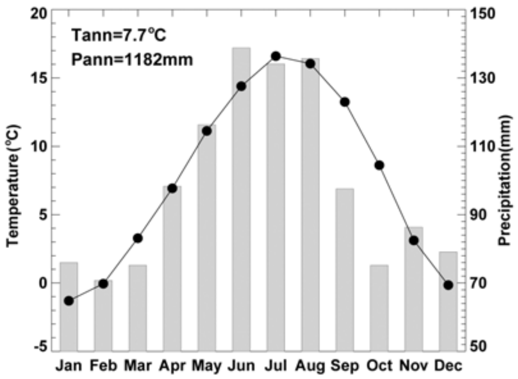
An identical analysis was performed for each of the 23 Living Lakes. This section describes the methodology, which data sets were used, and interprets the graphs included in each Living Lake section. We also point out the limitations of this analysis.

Lake "catchments"

For each lake, a rectangular "catchment" was defined in latitude and longitude based roughly on the true world catchment. In some cases we sought clarification on the most appropriate domains to use from local lake managers. The resulting "catchment" domains are defined on each page respectively.

Seasonality of present climate

Present-day seasonality of climate for each lake "catchment" was calculated using data from the CRU CL1.0 global 0.5° resolution monthly mean temperature and precipitation climatologies (www.cru.uea.ac.uk/cru/data/hrg.htm). We determined this seasonality from the 1961-1990 average climate. Monthly values for each lake "catchment" are the averages of values for all 0.5° by 0.5° (land) cells falling within the defined rectangular "catchments". CRU CL1.0 is described in New *et al.*, 1999. An example plot is shown below.



These graphs show average monthly climate for 1961-1990 for mean temperature (dots) and precipitation (bars). Data are averaged over the entire lake "catchment". Annual averages are listed in the top left portion of the panel.

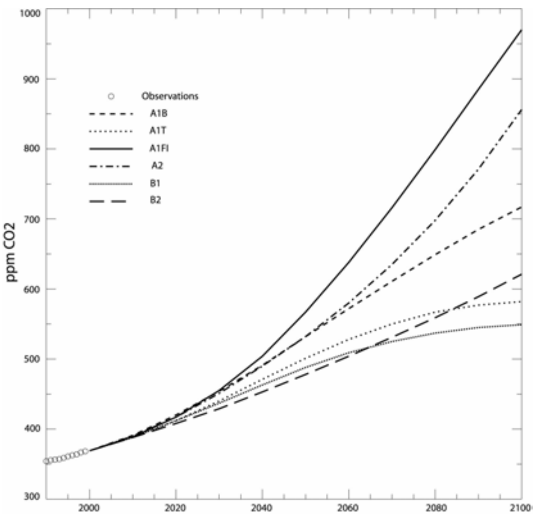
Emissions scenarios

Results are shown for only *one* emissions scenario – the SRES A2, which assumes a future world of fairly conventional energy development, i.e., continuing dependence on fossil carbon fuels. This is towards the upper end of the range of global warming rates published in the IPCC 2001 assessment and leads to a carbon dioxide concentration in the atmosphere by 2100 of about 850ppm (see Figure below).

It is certainly possible that climate may change more radically than suggested in our analysis, but if the world's development path is less carbon intensive than assumed by the SRES A2 scenario the changes in climate for the Living Lakes will be less than shown in this report. For example, a successful international regime for controlling and eventually reducing greenhouse gas emissions could keep carbon dioxide concentrations below 600ppm (the B1, B2 or A1T scenarios in the Figure below). In this case, global warming by the 2080s could be kept to about 2°C relative to the present, compared to the 3.2°C warming assumed by our analysis. Under such a successful climate mitigation regime, the changes in climate over the Living Lakes shown in this report would be reduced by about 30 to 40 per cent.

It is therefore important to keep three things in mind therefore when using this report:

- the changes in climate shown here assume no fundamental success in mitigating climate change worldwide (i.e., the SRES A2 scenario);
- large-scale mitigation of climate change is possible, although by no means assured;
- even under the most optimistic climate change mitigation scenario (e.g. the SRES B1 scenario), a substantial amount of climate change will still occur and needs to be planned for.



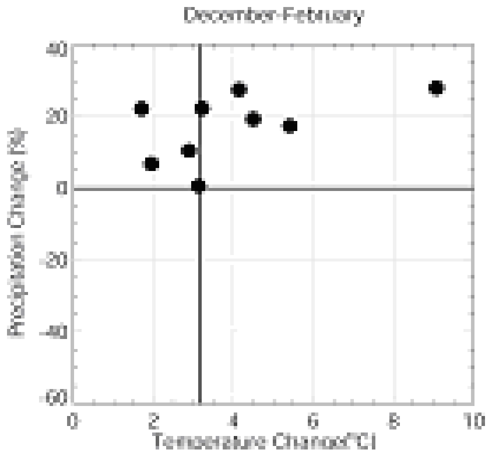
This graph shows the estimated atmospheric concentration of carbon dioxide for six different global greenhouse gas emissions scenarios, as constructed by the Special Report on Emissions Scenarios (SRES) of the IPCC Third Assessment Report. By 2100, these concentrations range from about 550ppm to over 950ppm. The present (2003) concentration is just over 370ppm. The scenario assumed in our report is the SRES A2 emissions, leading to a carbon dioxide concentration of about 850ppm by 2100.

Future climate scenarios

Changes in mean temperature and precipitation for the period around the 2080s (actually 2071-2100) were obtained from nine state-of-the-art global climate model (GCM) experiments. These changes are expressed relative to average 1961-1990 climate (see above), thus these changes represent climate change over 11 decades, i.e., from the 1970s to the 2080s. Results for two seasons are shown (December-January-February and June-July-August).

These nine GCM simulations are all reviewed by the IPCC Third Assessment Report (Cubasch *et al.*, 2001). The experiments analysed here are performed with the following nine models driven by the same emissions scenario – the IPCC SRES A2. The nine models are: CGCM2, CSIROmk2, CSM1.3, ECHam4, GFDL-R15b, MR12, CCSR/NIES 2, DOE PCM, and HadCM3 (three from the USA, one from UK, two from Japan, one from Germany, one from Australia and one from Canada). Details of these models are available in Table 9.1 of the Working Group 1 report of the Third Assessment Report of the IPCC (Cubasch *et al.*, 2001).

These nine model simulations originally generated outputs on a variety of latitude/longitude grids. They were processed onto a common 2.5° by 2.5° grid, used in this analysis, by Dr Richard Jones (Hadley Centre). All 2.5° grid cells falling inside our defined lake "catchments" (as above) were averaged to produce the climate scenario. For small catchments, the value of the nearest 2.5° grid cell was used. The results are plotted in the format shown below.



These graphs show change in average seasonal climate for the period around the 2080s, relative to 1961-1990 climate. Each dot represents the result from one global climate model experiment. Data are averaged over the entire lake "catchment". These changes assume the IPCC SRES A2 scenario – a mid-to-high range emissions scenario, assuming no rapid or widespread efforts to reduce carbon emissions. The vertical line marks the annual-mean global warming for the 2080s, and for the SRES A2 scenario, as calculated by the IPCC, a value of about 3.2°C. Results to the right of this line are more extreme than the global average; results to the left of the line are less extreme. The horizontal line at zero simply distinguishes between results in which climate getter wetter or drier.

Limitations of the analysis

As with all climate scenarios it is important to appreciate the limitations of the analysis:

- We are showing only changes in average climate over the whole lake "catchments" – for very large catchments, these average changes in climate may not represent more localised changes.
- Only changes in average seasonal climate for temperature and precipitation are shown. The variability of climate (i.e., the reliability) is also likely to alter and there are also likely to be changes in other climatic variables.
- There are some aspects of future climate change in which we have greater confidence than others. For example, we are more confident about increases in greenhouse gas concentrations and rises in sea-level, than we are about increases in storminess and the behaviour of El Niño. The scenarios presented here have been derived from climate models that include the best possible representation of processes in the atmosphere, ocean and land, given present scientific knowledge and computing technology. Nevertheless there is a varying degree of uncertainty associated with different climate variables which affects our confidence in the scenarios presented here (see Table1).

Climate variable	High Confidence
Atmospheric CO_2 concentration	
Global-mean sea-level	
Global-mean temperature	
Regional seasonal temperature	
Regional temperature extremes	
Regional seasonal precipitation	
Regional potential evapotranspiration	
Changes in climatic variability (e.g. El Niño, daily precipitation)	Low confidence
Climate surprises (e.g. disintegration of the West Antarctic Ice Sheet)	Very low or Unknown

Table 1: List of climate and associated scenario variables, ranked subjectively in decreasing order of confidence.

- Results are shown from only nine models. Although these are the world's leading climate models, we do not know whether this model sample captures the full range of future possibilities. All models have limitations. The real climate may change more or less rapidly than shown by these nine models, even for the same emissions scenario. Differences between models are associated with not knowing how the climate system reacts to unprecedented rates of greenhouse gas emissions or in knowing how clouds, forest, grasslands or, particularly, the world's oceans react to climate perturbations and how they feed back into the system. Table 3 (next section) summarises the climate changes and key climate sensitive features of the Living Lakes. The mean change in winter and summer temperature and precipitation is given, along with an assessment of the confidence associated with the precipitation change due to differences between climate models. The description of confidence follows the procedure for analysing inter-model differences adopted in the recent IPCC Third Scientific Assessment of Climate Change (IPCC, 2001), outlined in Table 2.

Change in precipitation	Explanation
Large increase	Agreement on increase with average change greater than +20%
Small increase	Agreement on increase with average change between +5 and +20%
No change	Agreement on change with average change between -5 and +5%
Small decrease	Agreement on decrease with average change of between -5 and -20%
Large decrease	Agreement on decrease with average change of less than -20%
Inconsistent sign	Disagreement - a consistent result from at least seven of the nine climate models is deemed necessary for agreement

Table 2: Criteria used in IPCC (2001) to classify the level of inter-climate model agreement for changes in climate variables.

Generic Impacts of Climate Change on Lakes

Climate change directly affects important characteristics of lake systems such as: lake levels; water temperature; thermal stratification; water quality; productivity; biodiversity. Indirect effects of climate change also affects lake systems through for example: changes in the characteristics of lake catchment (watershed) areas; climatic influence on socio-economic activity in and around lakes. In some cases current lack of understanding and limited availability of empirical case studies of lake processes and their interactions limits our ability to determine with confidence the impacts of climate change on lake hydrology and ecology. Nevertheless there are certain generic relationships between climate and lacustrine systems that will be common to most, if not all, the Living Lakes. The following section outlines some of these generic links between climate and lacustrine systems.

Climate variables likely to directly affect lakes

Rising average temperatures and changes in extremes.

- Rising air temperatures will increase surface water temperature and influence thermal stratification in lakes. Warmer winters may affect mixing and nutrient recycling rates in temperate lakes as reduced seasonal cooling, which causes breakdown in the thermal density contrast, may be reduced.
- Higher frequency of extreme temperatures in summer (with possible exceedence of critical thresholds) and reduced winter freezing in certain lakes are likely to affect thermal stratification and species composition.
- Higher surface air and water temperatures will increase open water evaporation rates and lead to a fall in lake levels unless offset by increases in precipitation or changes in other factors that affect evaporation rates (see below).

Changes in the temporal and spatial characteristics of precipitation.

- The impacts will vary according to the direction and magnitude of precipitation change and the hydrological characteristics of the lacustrine and any associated fluvial system.
- Endorheic (closed) and exorheic (open) lakes are very dependent on the balance of inflows and evaporation and may be very sensitive to change in either.
- Increases in precipitation, unless offset by higher evaporation, will increase lake inflows and lake levels, if extreme precipitation events increase in frequency this will lead to greater frequency of riparian flooding.
- The extent to which lake level fluctuations and change affect lake productivity and biodiversity varies according to local conditions of the lake and its catchment.
- Drier conditions, exacerbated by greater evaporation, will reduce lake inflows and lake levels. Water quality, productivity and biodiversity are likely to be reduced.
- Seasonal regimes may be reduced or enhanced, depending upon the nature and interaction of precipitation and evaporation change, with potentially significant effects on lake hydrology, ecology and management.
- Lakes fed by snowmelt rivers in spring are likely to see earlier and faster spring thaws leading to higher river flows and lake levels in this season.

- Changes in variability over longer timescales, e.g. decades, possibly associated with changes in behaviour of the El Niño - Southern Oscillation (ENSO) will also affect lake characteristics and management.

Changes in other climate variables, including radiation or cloud cover, relative humidity and windspeed.

- Data on factors affecting lake evaporation and catchment evapotranspiration other than temperature, namely relative humidity, cloud cover and wind speed over the lake and land cover in the contributing areas, were not available for this study.
- In some instances changes in these variables may cause marked changes in lake systems. Increased evaporation due to warmer temperatures may either be enhanced, for example by increases in windspeed and radiation, or offset (and sometimes even reduced) by increases in humidity and cloud cover.
- Changes in windspeed and prevailing wind direction will also influence mixing processes and thermal stratification in lakes. In tropical lakes mixing is more dependent upon evaporative cooling during the windy season.

Rise in sea-level.

- For low-lying lakes and those with tidal influences rising mean sea-level and increasing magnitude and possibly frequency of extremes will be important.
- By the 2080s, global-mean sea level rise is ~0.35m with emissions scenario A2 (the full range of possible sea-level rise by the 2080s as published by the IPCC is from ~0.08m to ~0.80m). The increase in mean sea-level combined with possible changes in storminess will have wide-ranging impacts upon lacustrine and associated fluvial systems.
- Flooding, saltwater incursion, rivers backing up and increases in lake levels will dramatically alter lake hydrology, ecology and management.

Interaction with non-climate factors

It is important to note that climate change will not occur in isolation - many other driving forces will operate on lake systems during this century and it may be the case that for many of the Living Lakes, particularly those with high population densities, climate change may play a relatively minor role in affecting future lake conditions. Lake hydrology, water quality and productivity are heavily dependent upon direct and indirect human activities. The way in which these activities evolve in the future will be influenced by climate change and will determine the extent and importance of climate impacts on lakes and society. Combining changes in climate and society into fully integrated assessments of the future state of lakes is beyond this analysis. Improving our ability to make such integrated assessments for lakes, and for ecosystems and society as a whole, is a major challenge for research during the next few decades.

Overview of Results for the Living Lakes

It is difficult to summarise the implications of climate change for the Living Lakes for three reasons which are discussed below: their diversity of characteristics; the range of possible future climate conditions projected for the Lakes; and the interaction between climate change and human activities.

Diversity of characteristics

The Living Lakes include lakes of very different sizes, from relatively small (Mono Lake) to extremely large (Lake Victoria); very different depths, from shallow (Milicz Ponds) to extremely deep (Lake Baikal); some with coastal influences (Lake St Lucia); diverse climate regimes, tropical (Laguna de Bay), temperate (the Broads), continental (Lake Tengiz) and Mediterranean (Nestos Lakes); whether closed, endorheic (Mono Lake) or open, exorheic (the Pantanal); nutrient status, eutrophic (the Broads) and oligotrophic (Lake Baikal); and their physical characteristics, open water lakes (Lake Bodensee), river valley wetlands (Columbia River wetlands), coastal marshes (Lake St Lucia), and so on.

The range of possible future climate conditions projected for the Living Lakes (see Table 3 for a summary)

- By the 2080s, all the Living Lakes are projected to be considerably warmer (>2°C) in “winter” (DJF) and “summer” (JJA) than the present day.
- In most of the Living Lakes, “summer” temperatures (JJA) increase at a faster rate than the rise in global-mean temperature.
- The rise in “winter” (DJF) temperatures is less homogeneous, with roughly equal numbers of lakes warming slightly faster or at a similar rate to the rise in global mean temperature, and a couple of lakes warming slightly more slowly.
- Three lakes, Lake St Lucia, Laguna de Bay and the Mahakam Lakes, have projected warming rates slightly lower than the rise in global mean temperature in both “winter” and “summer”.
- Only Lake Larache has precipitation projected to decrease in both seasons and only Lake Baikal has precipitation projected to increase in both seasons (a combination of small and large changes in both instances).
- Four lakes (Lake St Lucia, the Broads, Lake Bodensee and the Columbia River wetlands) have contrasting precipitation changes in “winter” and “summer”.
- None of the Living Lakes is projected to have large increases in precipitation in both “winter” and “summer”, nor large decreases in precipitation in both seasons.
- Ten lakes show an inconsistent pattern of precipitation change in “winter” and seven in “summer”. Three lakes, all located in the Americas, have inconsistent precipitation signals in both “winter” and “summer”.

Lake	Location	DJF Temperature change	JJA Temperature change	DJF Precipitation change	JJA Precipitation change
The Broads	Norfolk/Suffolk, UK	3.3	3.6	22 Large increase	-20 Large decrease
Bodensee	Germany, Austria, Switzerland	4.0	4.6	17 Small increase	-16 Small decrease
Lake La Nava	Castile-León, Spain	3.0	5.2	2 Inconsistent	-32 Large decrease
Milicz Ponds	Slask, Poland	5.0	3.8	19 Small increase	-3 No change
Nestos Lakes	Hrysoupolis, Greece	3.5	5.4	5 No change	-36 Large decrease
Uluabat Lake	Northwestern Turkey	3.2	5.2	-3 Inconsistent	-49 Large decrease
Lake Larache	Morocco	3.2	4.2	-18 Small decrease	-33 Large decrease
Lake Victoria	Uganda, Kenya, Tanzania	2.6	3.5	21 Large increase	0 Inconsistent
Lake St Lucia	KwaZulu Natal, South Africa	2.5	2.9	10 Small increase	-10 Small decrease
The Dead Sea	Israel, Jordan, Palestine	3.2	4.2	-13 Small decrease	63 Inconsistent
Lakes Peipsi and Vertsjarv	Baltic Sea, Estonia, Russia	6.7	3.8	23 Large increase	5 Inconsistant
Lake Tengiz	Kazakhstan	5.7	5.6	24 Large increase	-7 Inconsistent
Lake Baikal	Siberia, Russia	5.6	5.3	36 Large increase	8 Small increase
Poyang Lake	Yangtze River, China	4.4	3.3	-2 Inconsistent	13 Small increase
Lake Biwa	Shinga prefecture, Japan	3.3	3.2	-4 Small increase	14 No change
Mahakam Lakes	East Kalimantan, Indonesia	2.4	2.5	2 Inconsistent	7 Small increase
Laguna de Bay	The Philippines	2.2	2.4	-4 Inconsistent	9 Small increase
Columbia River Wetlands	British Columbia, Canada	4.4	4.9	12 Small increase	-7 Small decrease
Mono Lake	California, USA	3.6	4.7	16 Inconsistent	-19 Inconsistent
Laguna Chapal	Mexico	3.0	3.2	-18 Inconsistent	-8 Small decrease
Laguna Fuquene	Andes Mountains, Columbia	3.0	3.2	12 Inconsistent	-3 Inconsistent
Pantanal Wetland	Brazil, Bolivia, Paraguay	3.0	3.8	3 Inconsistent	-8 Inconsistent
Laguna Mar Chiquita	Argentina	3.2	2.4	5 Inconsistent	10 Small increase

Table 3: A summary of future temperature (°C) and precipitation (%) change for the Living Lakes case studies caused by greenhouse gas emissions assumed by the SRES A2 scenario. Results are summarised from nine climate model experiments.

- Ten lakes are projected to have either small or large increases in "winter" (DJF) precipitation, only five lakes are projected to have small increases in "summer" (JJA) precipitation and no lakes are projected to have large increases in "summer" precipitation.
- No change in "winter" or "summer" precipitation is projected to occur in only three instances.

- A considerable number of the Living Lakes are fed by tributaries draining mountainous regions and/or areas experiencing very cold winters which are likely to be affected by earlier and faster spring snowmelt due to warmer temperatures.
- A considerable number of the Living Lakes are located in coastal areas and to some degree are affected by tidal processes. These lakes are at risk from the effects of sea level rise, whereby increases in mean and flood water levels and increases in saltwater incursion are likely to have significant impacts on habitat conditions and water quality.

The interaction of human activities in the future

Some of the most important direct and indirect human activities that have significance for the future state of lakes include;

- Diversions/Abstractions
- Eutrophication
- Other water quality problems
- Navigation
- Inflows; quality, quantity, variability
- Productivity (livelihoods) - overexploitation
- Habitats and biodiversity
- Invasive species
- Land use change
- Tourism

These activities already pose challenges with varying degrees of importance to the Living Lakes and many of them will affect, and be affected by, climate change. This makes it extremely difficult to make precise judgements about the impacts and importance of climate change for the Living Lakes.

Having said this, certain key issues emerge collectively from the analysis of the 23 Living Lakes;

- There is high confidence that temperatures will rise in all the lakes with implications for water temperature (it will increase) and water quality. Higher temperatures are also likely to increase evaporation rates. Lakes which freeze over in winter and those fed by snowmelt rivers are likely to experience considerable disruption to the present temporal characteristics of these processes. Changes in extremes are likely to be particularly important (increasing spring floods, reduced frequencies of freezing events).
- Most of the Living Lakes are projected to experience some degree of precipitation change although there is less confidence in whether and how much change will occur for specific lakes. Changes in precipitation regime are likely to have important consequences for lakes with the precise detail depending upon the direction and magnitude of the changes. Some lakes, those with very large catchments, shallow lakes, those fed by major rivers, highly seasonal lakes and so on may exhibit quite pronounced responses to changes in precipitation regime. Some of the Living Lakes are affected by the influence of El Niño and will be exposed to the effects of changes in the frequency and intensity of El Niños that may occur as global climate changes.

- The present use and management of lakes and how this develops in future will greatly affect the consequences of climate change. Some lakes are already experiencing major stresses in terms of abstractions, fishing, pollution etc. It is difficult to determine precisely how these stresses will be affected by climate change for the reasons outlined above. In some cases climate change may exacerbate stresses (e.g. where precipitation declines in areas of limited water availability and high demand) and in other cases it may offer opportunities (e.g. warmer temperatures may increase productivity, increased precipitation may reduce water quality problems and increase supply). Some of the Living Lakes are at present relatively unaffected by human activities and will naturally respond to climate change as it occurs.
- Capacity to manage lakes now and in the future will determine how much a given change in climate affects lake systems and the people they support. Some of the Living Lakes have established procedures and institutions for effective management which puts them in a good position to plan and adapt to future climate change. Other Living Lakes have very little capacity to deal with rapid expansion and exploitation of their functions and in these cases climate change represents another incentive for building capacity in lake management.

Lake descriptions

The remainder of this report presents climate change scenarios for the 23 Living Lakes and a qualitative assessment of their implications for the future state of the lakes by the 2080s (i.e., the period 2070-2099). Unless otherwise acknowledged specific information on the Living Lakes has been obtained from the Living Lakes web site: http://www.livinglakes.org/lakesflash.htm

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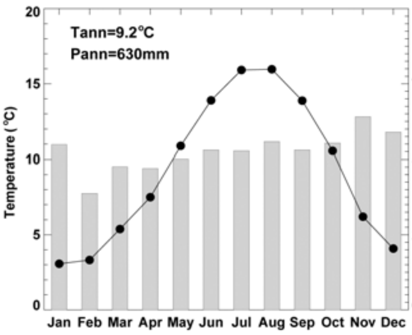
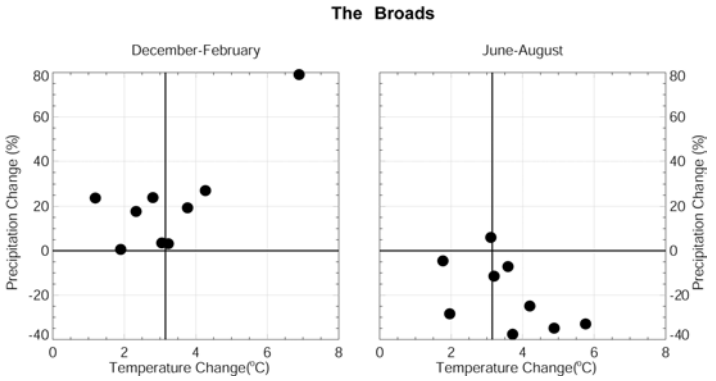
The 23 Living Lakes

The Broads

The Broads are a series of linked Man-made shallow lakes in the east of England, located between 52° and 53°N and 0° and 1.5°E. They provide an important habitat for migratory birds and have high amenity value. This region has warmed by over 1°C in the last century and is vulnerable to summer drought and saline intrusions. The climate in the region of the Broads is a typical mid-latitude temperature regime with quite pronounced differences between winter and summer temperatures which reach a maximum in August (16°C) and minimum in December (3°C). Annual precipitation is quite low at 630mm, with little seasonality. Seasonal differences in river flows and lake/wetland levels are driven primarily by seasonal variations in evaporation rates.



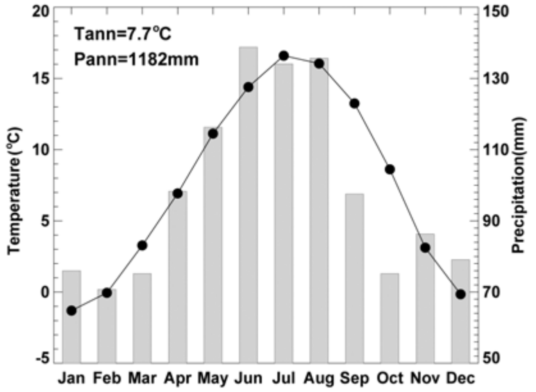


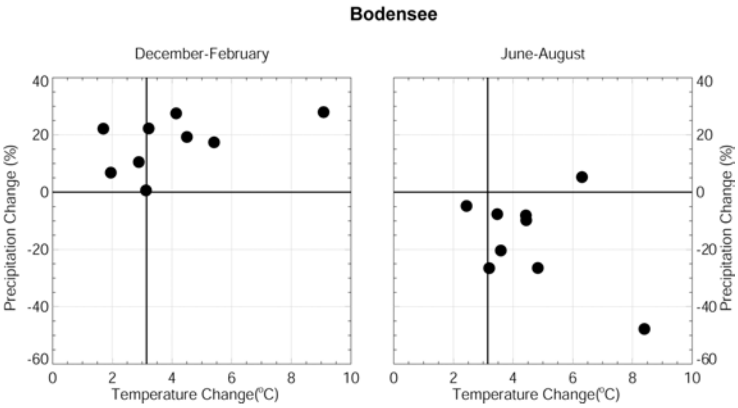
The Broads is a complex of around 50 small lakes, the result of peat digging during the 9th to 13th centuries, linked together by four rivers. The complex is low lying and located near to the East Anglian coastline and therefore strongly influenced by tidal processes and likely to be strongly affected by sea level rise. The area has small remnants of wetlands and some remaining undrained river floodplain and is recognised nationally and internationally for its beauty, flora and fauna (particularly bird life) and as a major tourist attraction.

Temperature increases in winter are clustered either side of the IPCC A2 global-mean and increases in summer are a little higher than the A2 global-mean. This would lead to a slight enhancement of the existing seasonal temperature contrast. The models show good agreement for precipitation in both seasons. Winter precipitation increases by marginal amounts up to 20 per cent or more and summer precipitation decreases in all but one case by between 4 and 38 per cent.

The precipitation changes described above suggest there will be a much more marked seasonality in rainfall and river flows, for example increased winter and spring flooding and higher frequency of summer low flow events. The complex mosaic of habitats will be affected and river and lake water quality in summer is likely to deteriorate. Rising sea levels during this century will affect the present tidal influence in the system with wide ranging implications for flood risk and present habitats distribution. The manner in which management practices in the river catchments and the lake system develop and change will form the backdrop against which climate changes will occur and how impacts will be manifest. Nevertheless, the marked changes in rainfall seasonality and resultant river flows and lake levels along with the significant effects of sea level rise mean that by the 2070s the water levels and water quality in the Broads system is likely to be very different to the present situation.

Bodensee



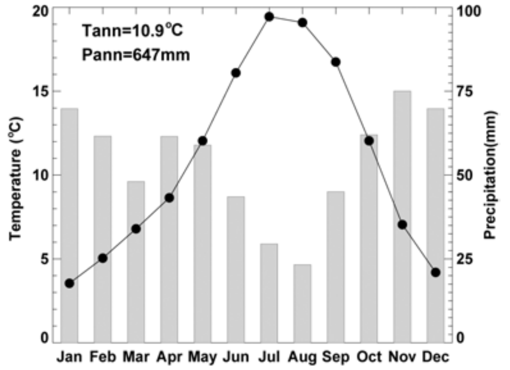


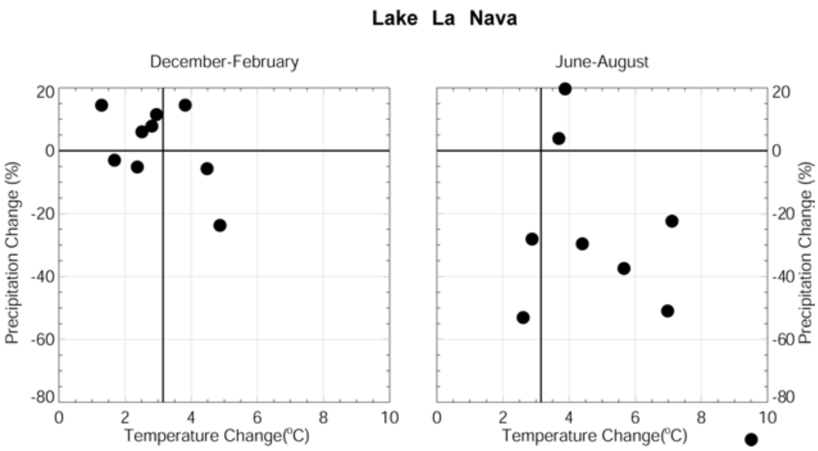
Formed where the Rhine River broadens and forms central Europe's second largest freshwater lake, 40 miles in length and 8.5 miles wide, Lake Bodensee (also known as Lake Constance) experiences a relatively cool and wet climate. Temperatures fall below freezing in the winter months and rise to about 16°C in summer. Annual precipitation is quite high, almost 1200mm, with summer precipitation (~130mm/month) almost twice as much as winter precipitation (~80mm/month).

Temperatures in winter increase at roughly the same rate as the global mean and in summer slightly higher than that (4.6°C). Precipitation changes in both seasons show good agreement between the climate models, with slight increases in winter and slight decreases in summer. These changes are unlikely to significantly affect the lake's seasonal regime, although earlier and faster spring snowmelt in tributaries draining the Swiss and Austrian Alps may alter established seasonal patterns and possibly lead to change in flood levels around the lake and downstream in the Rhine.

The lake experiences an annual drop in level which exposes the lake bottom in which ducks forage for food during autumn. This period of low lake level may be extended in the future with implications for lakeside activities and habitats. The lake is heavily utilised for recreation and provides drinking water for more than 4.5 million people. Due to the high population density around the lake and its high degree of utilisation it is already a major challenge to achieve sustainable management of the lake. It is difficult to predict with any accuracy how existing pressures on the lake will evolve and be affected by the combined effects of future changes in climate and socio-economic activities and policies in the lake catchment. Higher temperatures and lower precipitation in summer (plus less inputs from summer snowmelt) are certainly likely to exacerbate water quality problems caused by pollution. Higher temperatures in winter plus higher precipitation and the possibility that less will fall as snow will lead to increased river flows and higher lake levels.

Lake La Nava



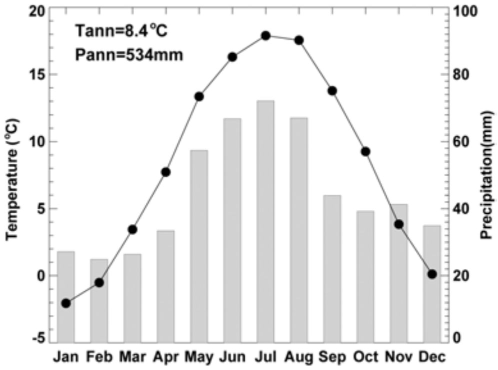


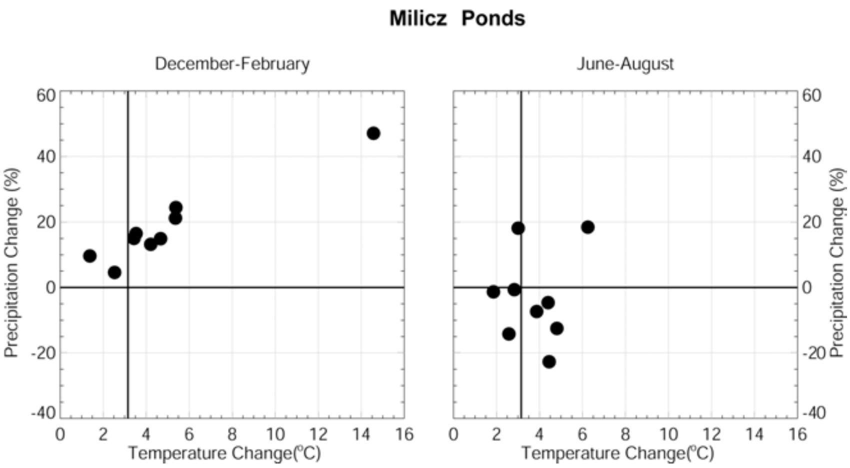
Lake La Nava in Spain, and its associated wetlands, experience a Mediterranean type climate, with cool wet winters and warm dry summers. The summer-winter temperature contrast is not very large with a minimum in January (3.5°C) and a maximum in July (19.5°C). Annual precipitation is quite low and although not strongly seasonal, the warm summer temperatures lead to drier conditions so that wetlands and the original lake dry out (the lake and wetlands are ephemeral).

Future climate in the lake region shows winter warming close to the global mean, whilst warming in summer is much more rapid, leading to temperatures projected to be 5.2°C above those of the present day. The pattern of precipitation change in the future is unclear in winter, with climate models all suggesting fairly small changes either above and below the present day conditions. In summer, however, agreement between climate models is better and precipitation is suggested to decline substantially by around 33 per cent.

The combined effects of a decrease in recharge due to constant precipitation and increased evaporation in winter, and lower precipitation and higher evaporation in summer, are likely to cause a much more pronounced and extended drying out of the lake and reclaimed wetlands in the La Nava catchment. The limited areas that are now seasonally inundated may be quite sensitive to changes of this magnitude with implications for habitat composition and the wetland reclamation programme that is currently underway. The effects may be compounded by increased demand for water for irrigation, particularly in the spring and autumn. Higher temperatures and reduced in flows may also adversely affect water temperature and quality.

Milicz Ponds





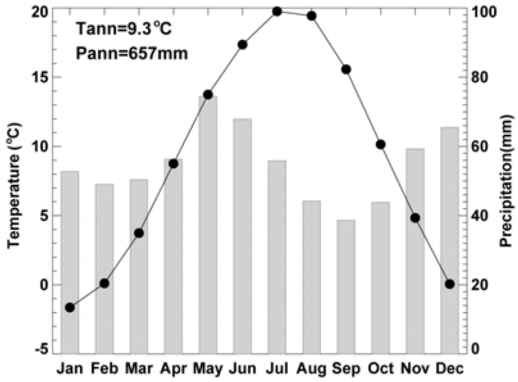
The Milicz Ponds area of Poland experiences a cool dry climate with warm summers, temperatures up to 18°C July, and cold winters, with temperatures falling to 2°C below freezing. Precipitation averages around or slightly below 40mm/month from September to April and increases to about 60mm/month from May to August.

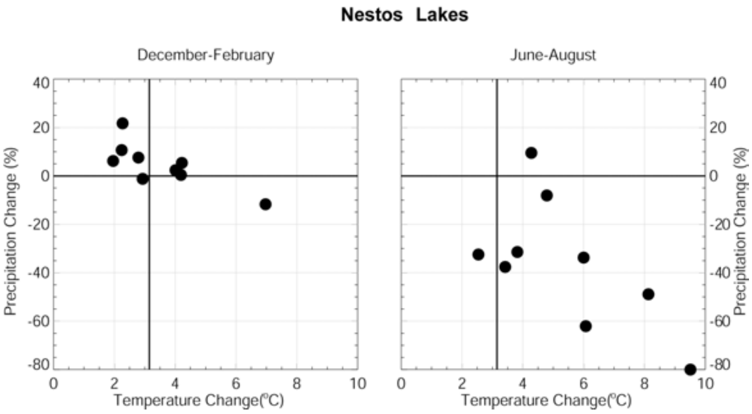
The Milicz Ponds are located near Breslaw in the Barycz River valley, a tributary of the Odra River, the second largest in Europe. The lakes originated as carp ponds excavated by monks in the middle ages and now support as many as 276 bird species in a biodiversity-rich mosaic of forest and waterbodies.

Warming occurs slightly faster than the global mean in winter (5.0°C) and at roughly the same rate in summer. There is good agreement between the climate models for future precipitation in the region, with increases of about 19 per cent in winter and slight decreases (-3 per cent) in summer.

The increase in winter precipitation coupled with an increase in evaporation in all months is unlikely to offset the decrease in summer precipitation which is likely to lead to reduced river flows in summer, lower groundwater levels and lower water levels in the ponds. The counteracting effects of increased evaporation in winter may cancel out or at least reduce the effects in higher precipitation so that the flood frequency and water levels in the ponds may not change substantially. Water quality and productivity will be heavily dependent upon future management regimes and processes of agricultural change which at present still use traditional methods in parts of the Barycz valley.

Nestos Lakes





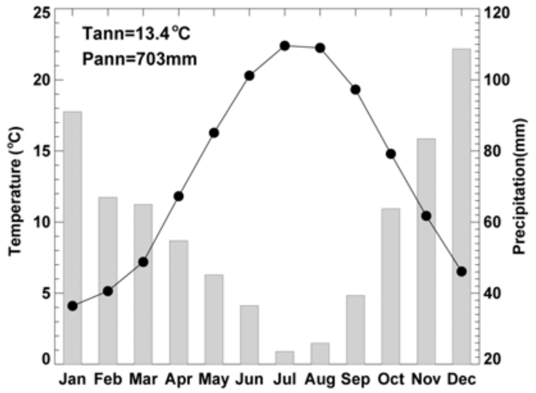
The Nestos Lakes are part of the Nestos River delta system in the eastern part of Greece, opposite the island of Thasos. The area experiences a Mediterranean climate modified by altitude, as much of the river catchment drains the Rhodopian Mountains of Bulgaria. Summer temperatures are moderately warm, reaching up to 20°C in July and cold in winter, falling to 0°C or below from December to February. The climate is quite dry and there is little seasonality in precipitation, with most months receiving between 40 and 70mm/month.

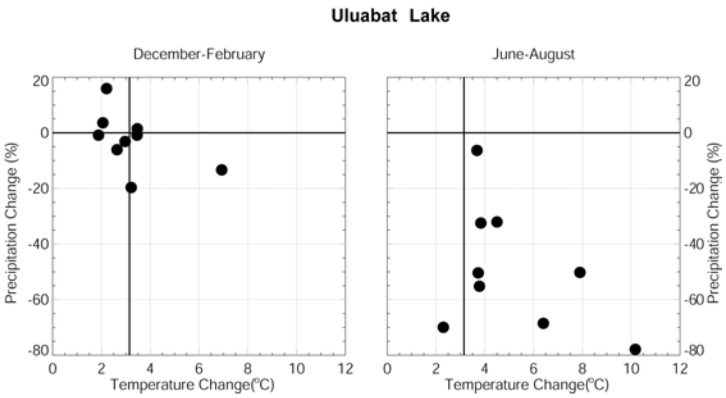
The rate of warming is much greater in summer than in winter, with mean temperatures rising by about 5.4°C in the summer season. Seasonal changes in precipitation show good agreement between the climate models and in opposing directions in winter and summer. Precipitation increases slightly in winter and decreases substantially in summer, by about 36 per cent.

The Nestos lakes system of seven lakes and eleven ponds lie in a complex mosaic of wetlands, dry meadows, hedges and small-scale agricultural fields. The effects of increased evaporation and substantially reduced precipitation in summer would likely lead to significant decline in summer river flows. As lake levels are determined largely by flows in the Nestos River they are likely to fall considerably in summer. There may also be effects on river flows related to earlier and faster spring snowmelt which could exacerbate low flows and lake levels in summer. The combined effects of these changes will magnify present problems related to expansion of intensive agriculture, wetland drainage and water abstractions which already lead to ponds draining entirely in summer. The coastal location of the lakes and ponds also means that the system will be vulnerable to rising sea level and its attendant impacts on freshwater systems. The impacts of climate and human activities on the complex mosaic of habitats which support a rich biodiversity will be considerable.

Uluabat Lake

Uluabat Lake, located in northwestern Turkey, experiences a strongly seasonal Mediterranean type climate. Summers are quite hot and dry with temperatures reaching 22°C in July and precipitation less than 40mm/month from June to September. Winters are warm and wet with minimum temperatures around 5°C in January and precipitation above 80mm per month from November to January.

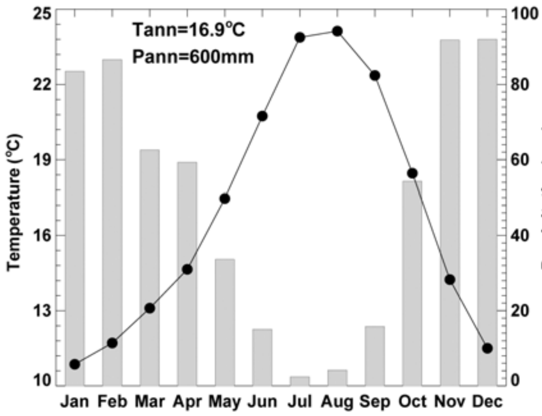




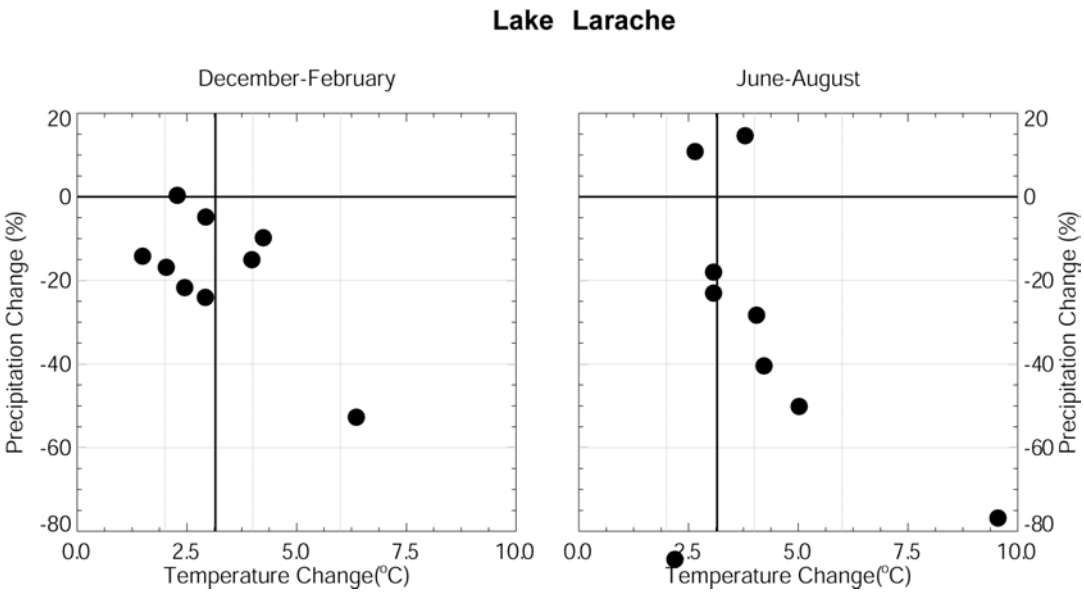
The future climate scenarios suggested by the climate models indicate warming in winter at a similar rate to the global mean and faster summer warming with mean temperatures reaching as high as 5.1°C above the present day conditions. For the winter wet season the climate models show a mixed pattern of change with no clear signal, whereas for the summer dry season the models converge showing a marked decrease (-49 per cent) in precipitation. In terms of absolute precipitation amounts these changes are small and on their own are unlikely to produce significant effects on lake behaviour. Combined with substantially higher evaporation, however, this could lead to a considerable decline in lake level.

Lake Uluabat lies in a large catchment fed largely by the Mustafa Kemalpasa Stream and has an outlet that flows into the Marmara Sea. The lake is large and shallow and therefore fluctuates in area so that the shore areas of the lake, which are almost all covered with submerged plants, may be vulnerable to significant and prolonged changes in lake level. The lake represents an important site in Turkey and Europe due to its rich biodiversity and valuable freshwater. The changes in climate suggested here are unlikely to cause major changes in the lake. Changes in spring and autumn climate, however, or changes in extreme weather phenomena (which have not been presented here), particularly in precipitation, might produce greater impacts on the lake.

Lake Larache



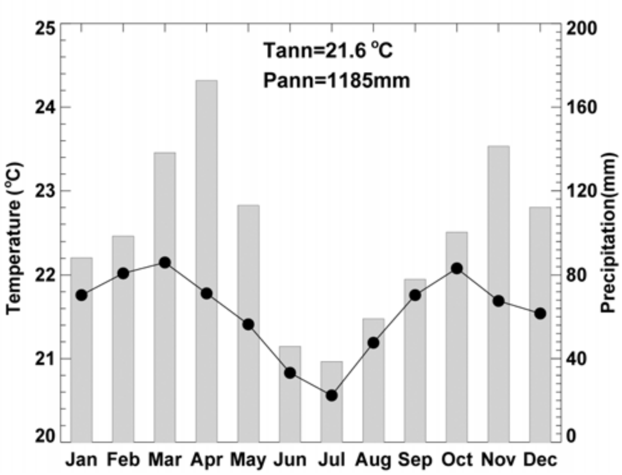
The Lake Larache river and coastal wetland system in Morocco experiences a typically Mediterranean climate with warm wet winters and hot dry summers. Maximum temperatures of around 23°C occur in July and August and minimum temperatures, which only fall to about 11°C, occur in January. There is a strong seasonal precipitation contrast with four months (June to September) receiving less than 20mm and six months (November to April) receiving over 60mm.

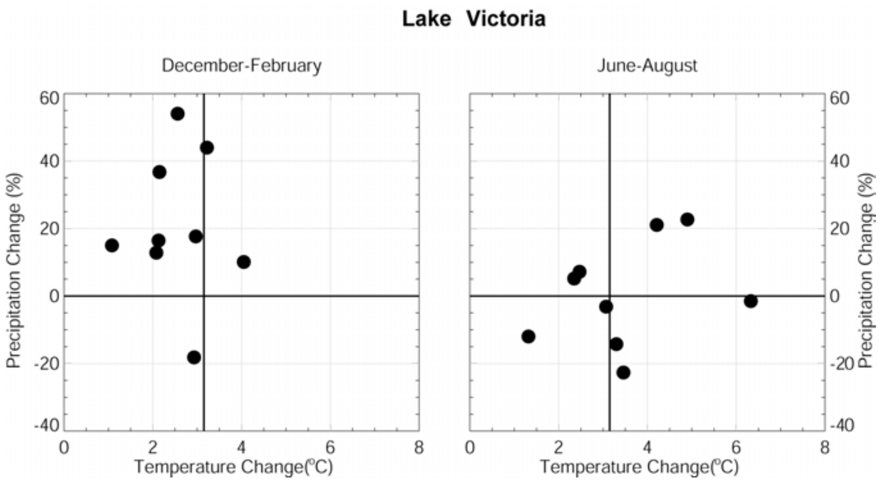


The rise in temperature over Lake Larache is close to the global mean in winter and slightly higher (4.2°C) in summer. There is good agreement between climate models in both seasons concerning the possible change in future precipitation in the region. Lake Larache is unusual compared to most other Living Lakes in that precipitation is projected to decrease in both seasons. In winter, the main season for precipitation, decreases of about 18 per cent are projected, along with decreases of 33 per cent in summer (although this change actually translates to very small absolute changes in precipitation because the summer months are effectively dry). The interaction of higher sea level and reduced river flows in summer and winter will affect estuarine processes and habitat composition throughout the wetland system. Saltwater incursion is likely to disrupt freshwater and inland habitats with potentially significant effects on migratory bird populations and also refuge for reptiles and amphibians.

Lake Victoria

The long-term climate regime in the Lake Victoria basin reflects its tropical equatorial location. Temperatures show low seasonal variation with maxima in March and October and minima in July and December. Precipitation is bimodal with maxima during March to May (main rains) and October to December and minima during June to August.



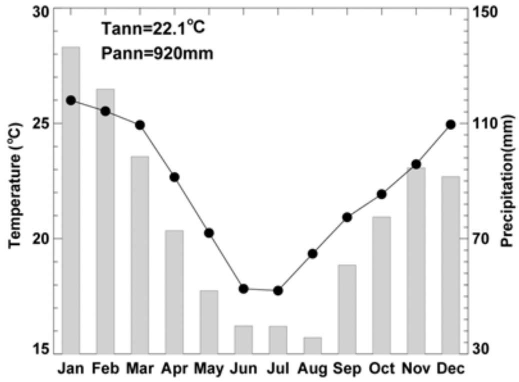


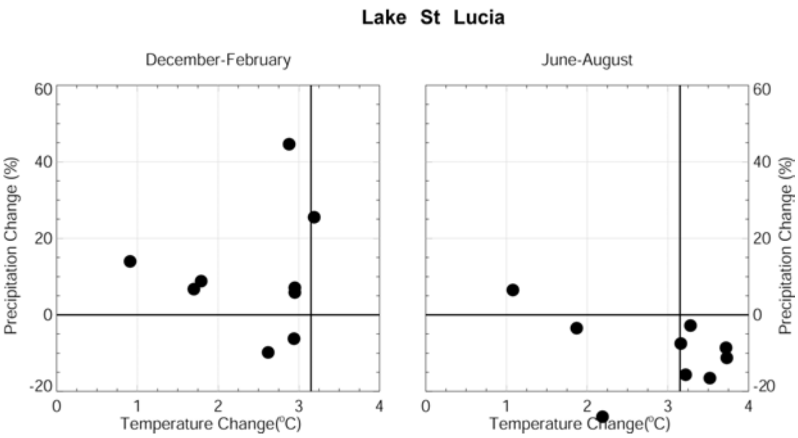
The lake basin climate models show for the 2080s increasing temperatures in “winter” and “summer” seasons, ranging from 1°C to 6.3°C, with an average slightly lower than the global mean (~3.2°C) and with greater warming in “summer” than “winter”. “Winter” precipitation increases by between 10 and 55 per cent in all but one model. Change in “summer” precipitation is more ambiguous, with the models split fairly equally between increases and decreases in rainfall.

Lake Victoria is exorheic and has recorded marked and prolonged variations in lake levels (up to 2.5°C) in response to precipitation extremes and trends during the 20th century. A close balance between lake evaporation and lake rainfall dominates the lake water budget so that modest changes in precipitation can cause marked changes in lake level and outflows. The effect of increased evaporation due to higher temperatures and possibly reduced “summer” rainfall in reducing future lake levels, is likely to be offset by the large increase in “winter” precipitation. This is likely to lead to increases in lake level (conditional upon future management policy of Owen Falls dam) and lake outflows into the White Nile system, with consequences for downstream flooding and lakeside activities.

The effects of increasing water temperature on water quality is complicated by its role in thermal stratification (also affected by windspeed). Recent evidence from Lake Tanganyika (Verburg *et al.*, 2003) highlights the ecological consequences of a century of observed regional warming in the lake. Warming is associated with a sharpened density gradient which has slowed vertical mixing and reduced primary productivity and further warming is hypothesised to continue these trends. These findings for Lake Tanganyika are supported by O'Reilly *et al.* (2003) who show that rise in surface-water temperature has increased the stability of the water column. This, combined with lower windspeeds, has reduced mixing in the lake and primary productivity may have decreased by about 20 per cent accounting for a roughly 30 per cent decrease in fish yields. The implications of climate change for current environmental challenges in Lake Victoria, such as biodiversity decline, eutrophication and management of water hyacinth, are difficult to assess. Changes in lake inflows, agricultural practice, and land use in the runoff contributing area together with management of pollution will also play an important role in determining water quality in Lake Victoria and the direct effects of climate change may be relatively small.

Lake St. Lucia



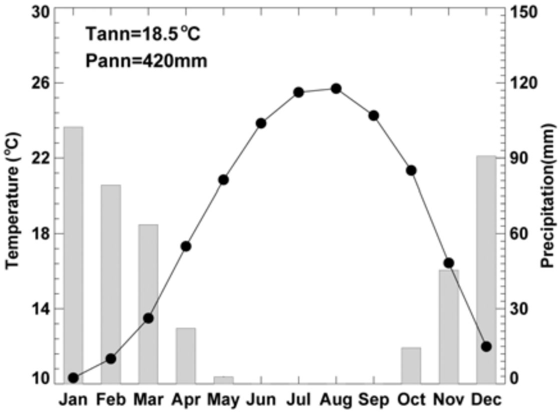


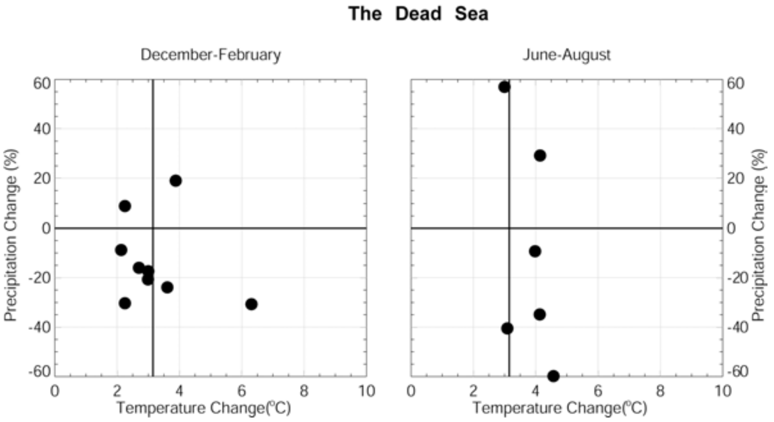
This Southern Hemisphere Lake in South Africa is part of an estuarine system. It displays moderate seasonal temperature variation of about 8.5°C between summer and winter. The precipitation regime is highly seasonal with seven months recording over 70mm (October to April) and three recording under 50mm (June to August).

In Southern Hemisphere summer (DJF), Lake St Lucia warms slightly less rapidly than the global average with an average increase of 2.4°C. In winter (JJA), the region warms at roughly the same rate (2.9°C) compared with the global average of about 3.2°C. Precipitation changes are consistent between models in both seasons, suggesting small increases of about 10 per cent in DJF (actually quite substantial in mm terms - about 9 to 14mm per month), and small decreases of about 10 per cent in JJA (much less substantial in mm terms as this is the dry season). Overall these changes would increase the seasonal precipitation regime causing river inflows and lake levels to increase in DJF and decline in JJA.

Increased river inflows and lake levels in DJF will lead to inundation of riparian wetlands and coastal areas and reduced JJA (dry) season flows may lead to lower lake levels, depending on sea-level rise and tidal interactions. This may lead to increased salinity which is already a problem in some years causing mass die-offs of aquatic plants and animals. St. Lucia supports more species of animal than the better-known Kruger National Park and the Okavango Delta and the area is considered critical to the survival of a large number of animal species. The combined effects of these changes in precipitation and sea-level rise will have significant implications for the functioning of this estuarine system with the danger that extreme storms might cause major and permanent disruption to the present ecology and hydrology.

The Dead Sea



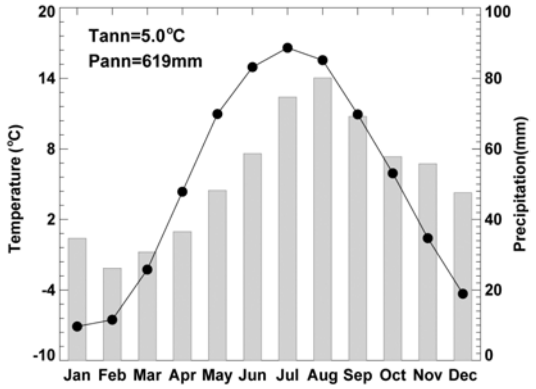


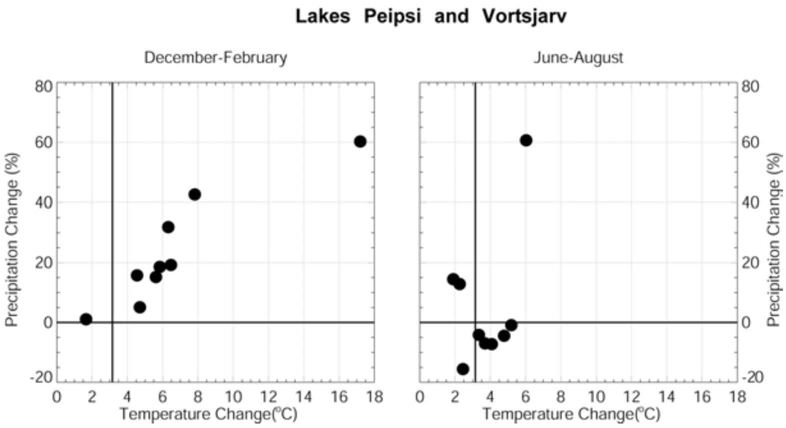
The Dead Sea lies at the terminus of the Jordan River, 417m below sea level and experiences a fairly hot and dry Mediterranean climate. Temperatures reach over 25°C in summer (July and August) and fall only to about 10°C in winter (January). Precipitation occurs mainly from November to March (>50mm/month), with June to September receiving very low precipitation amounts.

Projected warming in the Dead Sea region of Israel is similar to the global mean projections (between 3-4°C) and the precipitation change in absolute terms is small. A slight percentage decline in winter (13 per cent) translates to roughly 8-10mm/month and some very large percentage decreases in summer (63 per cent) translate to negligible amounts in mm. Increased evaporation (in a region where evaporative losses are already high and a major determinant of water availability), plus lower winter precipitation, will produce lower river flows, a fall in the level of the Dead Sea, and increases in salinity.

The Dead Sea is already ongoing transformation through human activities, manifest primarily in a fall in level (>20m since early this century) and surface area which has led to a fall in the level of water tables in surrounding areas. Climate change, particularly increased evaporation, is likely to exacerbate this trend by increasing agricultural and domestic water demand and abstractions (withdrawals from the Jordan River for irrigation are critical in this respect).

Lakes Peipsi and Vortsjarv





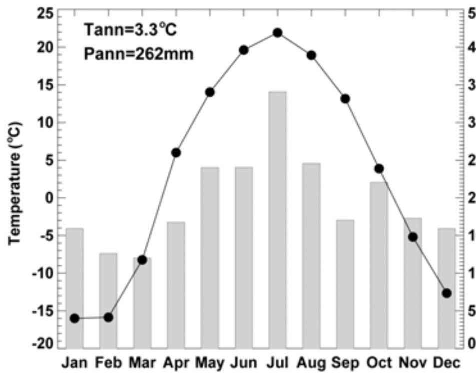
Lake Peipsi and Lake Vortsjärv are large shallow lakes located in Estonia and the Russian Federation and are part of the Baltic Sea basin. The climate regime is cool and fairly dry (annual precipitation is 619mm). Temperatures range from -7°C in January to 17°C in July. Precipitation is over 30mm/month in all months and July, August and September comprise the three wettest months.

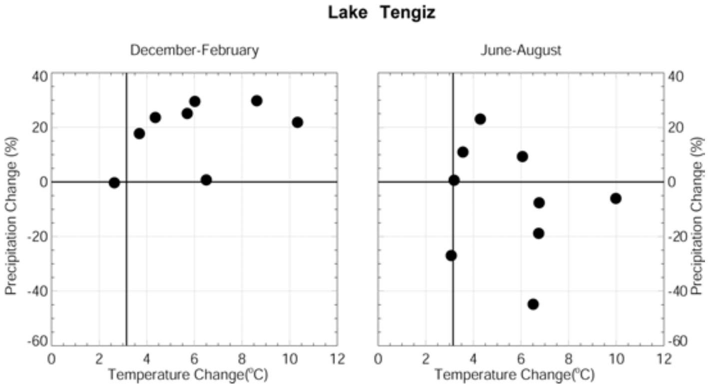
Warming in winter is the largest out of all the Living Lakes (climate models tend to project greater warming in higher latitudes), over double the global mean (6.7°C). Summer warming is far more in line with the global mean at about 3.8°C. Precipitation is projected to increase by 23 per cent in winter and has an inconsistent signal in summer. Lake Peipsi is the largest international lake in Europe (surface area 3,555km^2), whereas Lake Vortsjärv is much smaller (270km^2). They are joined by the Emajõgi River.

The much warmer temperatures projected for winter are likely to disrupt the present cycle of ice cover on Peipsi which usually forms around the end of November and reaches its thickest depth in the second half of March. Reduced thickness, extent and duration of ice cover, plus earlier spring snowmelt will affect the ecological functions of the lakes. Higher winter precipitation, if stored as snowfall, will increase the spring snowmelt contribution leading to a more rapid increase in lake level and the possibility of increased food frequencies. Eutrophication is currently the biggest problem facing both lakes due to phosphorous and nitrate loads from agriculture. Warmer temperatures may increase agricultural activity in the lake catchment and they will increase water temperature with consequences for eutrophication and productivity.

Lake Tengiz

Lake Tengiz is located in Kazakhstan, north of the Aral Sea. The lake catchment experiences a dry continental climate with very cold winters (minimum around -15°C from December to February) and fairly hot summers (maximum 22°C in July). Precipitation shows little seasonality and is below 40mm/month throughout the year.

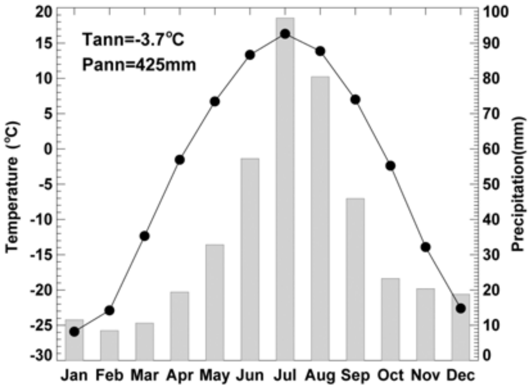


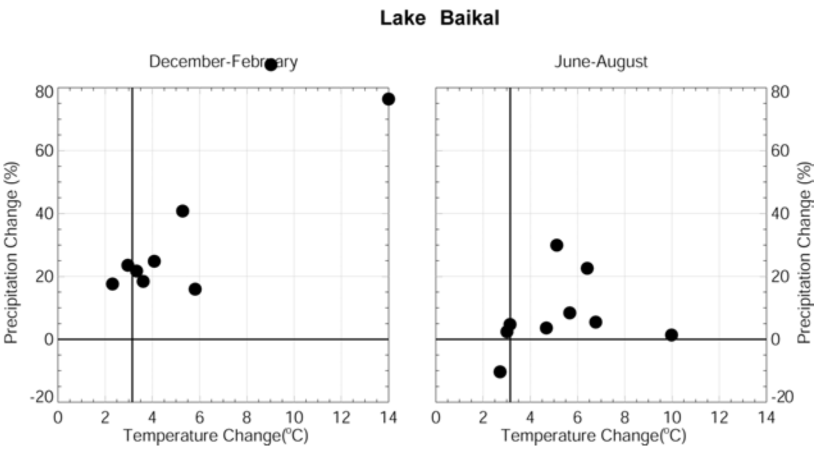


Climate models suggest faster rates of warming in winter and summer than the global mean, with temperatures increasing by over 5.5°C in both seasons. Precipitation increases in winter by about 24 per cent, whereas in summer there is no clear signal from the climate models which suggest changes ranging from a 45 per cent decrease to a 23 per cent increase in precipitation.

Lake Tengiz is a large (2000km^2) endorheic lake with high salinity in a region of steppe desert. Because winter precipitation is already low, increases of about 23 per cent do not amount to very much additional water to the system. Increased losses to evaporation (over a large lake surface area) in summer may well offset winter increases in precipitation. Warming of over 5.5°C in winter will not raise average monthly temperatures between December and February above 0°C. Warmer temperatures in spring and autumn, however, may change the established patterns of freezing and thawing in the region with implications for lake ice cover, surface runoff and habitats around the lake system.

Lake Baikal





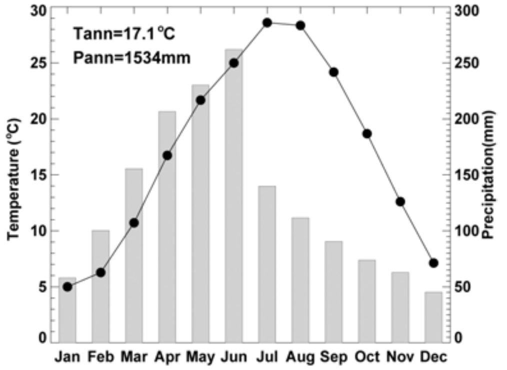
Lake Baikal is located in southeastern Siberia and is the world's largest lake in terms of surface freshwater volume. The lake's vast catchment, 540 000km^2, is comprised of boreal forest and bare rock and experiences a dry extreme continental climate. The mean annual temperature is below freezing (-3.7°C). Winters are very cold (minimum around -25°C from December to February) and summers are warm (maximum 15°C in July). Precipitation shows pronounced seasonality with dry conditions (<25mm/month) from October to April and wetter conditions from May to September (>30 to >90mm/month).

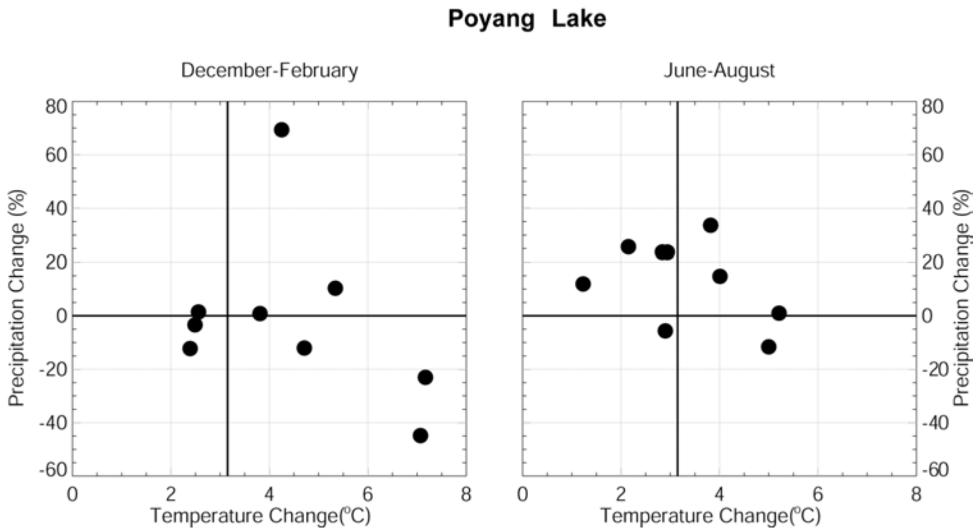
The climate models suggest warming in the region at a faster rate than the global mean in both winter and summer, with both seasons warming by more than 5°C above present conditions by the 2080s. Lake Baikal is unusual compared to other Living Lakes in that precipitation is projected to increase in both seasons, with good agreement between the climate models.

The level of water in Lake Baikal depends on river flows which fluctuate over periods of years. The original amplitude of fluctuation was about 2m, but is now regulated by Irkutsk hydroelectric power station. The lake has one outlet, is oligotrophic (low in nutrients) and the water is very clear. Most of the absolute increase in precipitation occurs in summer. The increases projected in both seasons, and their effects on inflows, are likely to be enough to offset losses to evaporation and cause an increase in lake level with implications for lakeside activities and hydropower generation. Industrial pollution has been a problem for water quality. During summer the vertical temperature gradient is positive throughout the entire water column. The surface freezes during the winter so that the lake becomes inversely stratified with respect to temperature (Ravens et al. 2000). Warmer temperatures are likely to reduce the period of surface freezing and inverse temperature stratification.

Poyang Lake

Poyang Lake in Jiangxi Province is the largest freshwater lake in China. The climate is warm and humid and the temperature and precipitation regimes are strongly seasonal. Temperatures range from 5°C in January to 28°C in July and August. Precipitation is highest from March to June (150-250mm/month) but remains close to or above 50mm/month through the rest of the year.

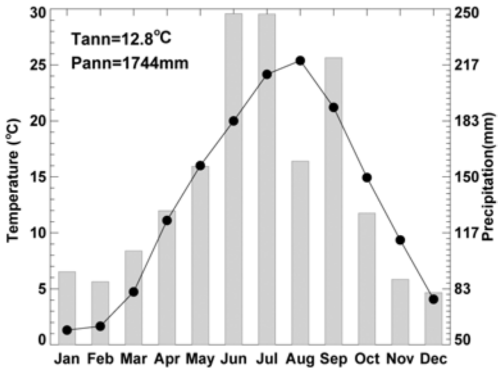


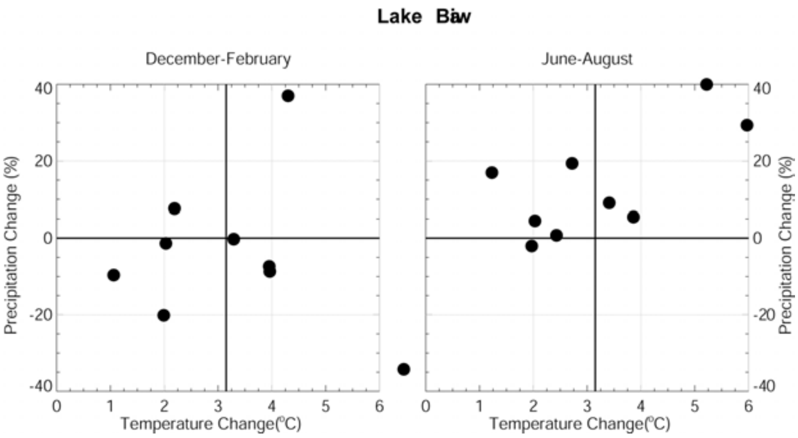


Warming in winter is considerably faster than the global mean (4.4°C) and in summer is about the same rate (3.3°C). Precipitation changes in winter are inconsistent and in summer the models suggest a small increase of about 13 per cent, which is quite large in mm terms since June, July and August all receive over 100mm, with June recording over 250mm.

The lake basin is subject to large changes in inundated area every year. In the dry season the lake contracts to <1000km^2 and in the wet it season grows up to 4000km^2. The lake is a natural overspill reservoir for the Yangtse River and therefore the effects of changes in climate described above will be strongly affected by what happens to the flows of the Yangtse River, water resources development and policies to deal with flooding, which is already a major problem. Increases in summer precipitation, particularly if they occur over the whole of the upper Yangtse basin, are likely to increase river flows and floods with massive implications for the inhabitants around Poyang Lake and elsewhere in the basin. Like many of the Living Lakes Poyang Lake faces threats to its ecology from human activities such as wetland drainage and bird poisoning from agricultural runoff, all of which are likely to increase in the future alongside a changing climate.

Lake Biwa



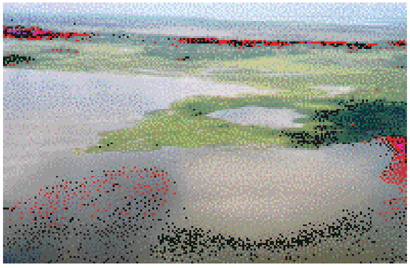


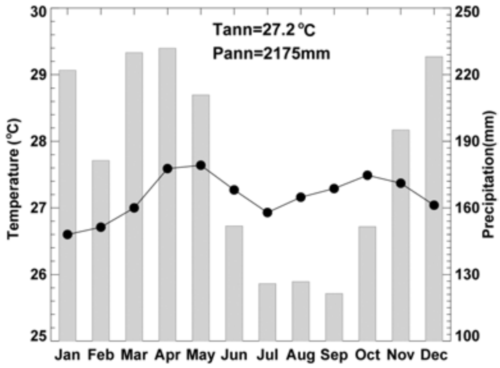
Lake Biwa in Japan experiences a humid warm climate with strong seasonality in both temperature and precipitation. Minimum temperatures occur in January (1.3°C) and maximum temperatures occur in August (25.1°C). Precipitation exceeds 80mm in all months, with drier months (~80mm) between November and March and wetter months (>100mm) between April and October.

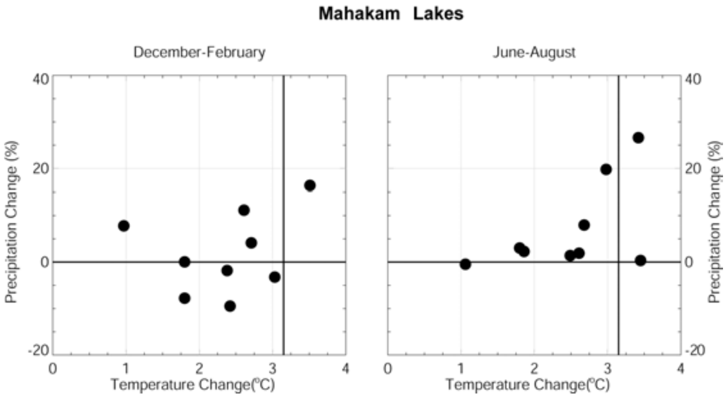
Lake Biwa warms slightly faster than the rate of global mean warming in both seasons. This has the potential to reduce lake inflows from over 500 tributaries draining the Ibuki, Suzuka and Hira mountains, leading to a reduction in lake levels which will also be affected by increased surface evaporation. Precipitation changes in winter are inconsistent (there are two opposing model outliers) with climate models suggesting significant increases and decreases in precipitation. Precipitation is suggested to increase moderately in summer (wet season) by about 14 per cent which in mm terms is quite a significant increase and likely to cause substantial increases in lake level and outflows.

Warmer spring temperatures may bring forward and quicken the rate of snowmelt in mountain streams leading to increased flood risk and earlier peak flows in spring. The seasonal cycle in lake levels and outflows would be enhanced by these changes in temperature and precipitation with implications for lakeside activities and loss of marshes and shallow lake habitats. It is difficult to assess the impacts of these changes on water quality in Lake Biwa which is currently affected by high nutrient loads from urban and agricultural practices.

Mahakam Lakes





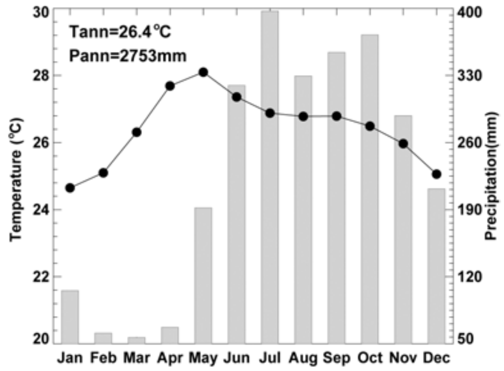


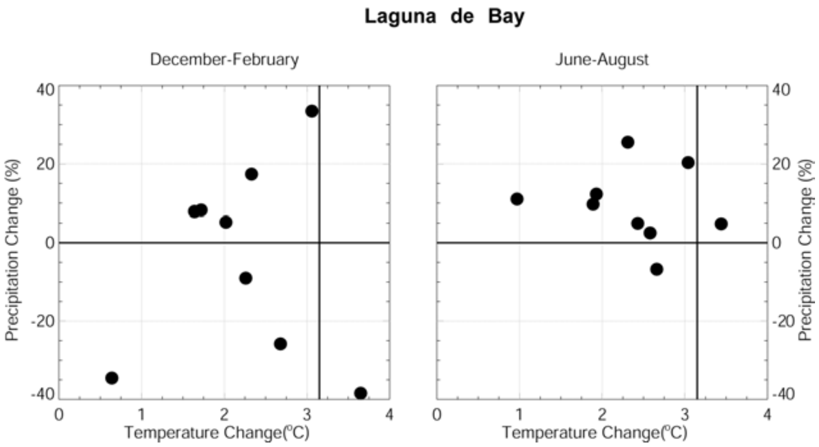
The Mahakam Lakes system is located in east Kalimantan, Indonesia, on the Mahakam River. The catchment area is about 77,000km^2 and experiences a tropical humid climate regime with high temperatures throughout the year and a weak bi-modal precipitation regime. The wet season stretches from October through to May with a slight break during February. The three driest months (July to September) all receive more than 100mm/month.

Winter and summer temperatures in the Mahakam Lakes region rise slightly slower than the global mean, reaching around 2.3°C above current temperatures by the 2080s. Changes in precipitation are quite modest in both seasons, with disagreement between climate models for winter precipitation and a slight increase projected for summer (7 per cent). Out of the two seasons with available data, winter is the critical one for river flows and lake levels so the changes outlined above are unlikely to cause major effects on the hydrology of the lake system.

The Mahakam Lake system is comprised of a complex of various size and shape lakes and makes an interesting case study of climate change impacts because they already exhibit large annual and interannual fluctuations in level and area. In extreme dry years, many coincident with El Niño events, some of the lakes dry out completely and where such conditions persist they will jeopardize flora and fauna and local livelihoods dependent on fishing. Water inputs from the upper Mahakam River and river overflows during the wet season drive the fluctuations in lake levels. The changes described here need to be considered alongside the possibility of larger scale changes in behaviour of the El Niño-Southern Oscillation that might occur leading to different patterns of longer term variability and extreme dry years in the region. These possible changes, in addition to the continuation of current pressures from siltation, eutrophication, overfishing and non-environmentally-friendly fish cage culture, will severely challenge the sustainable management of this biodiversity rich lake system.

Laguna de Bay



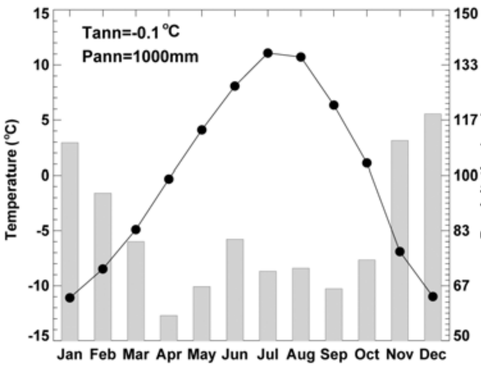


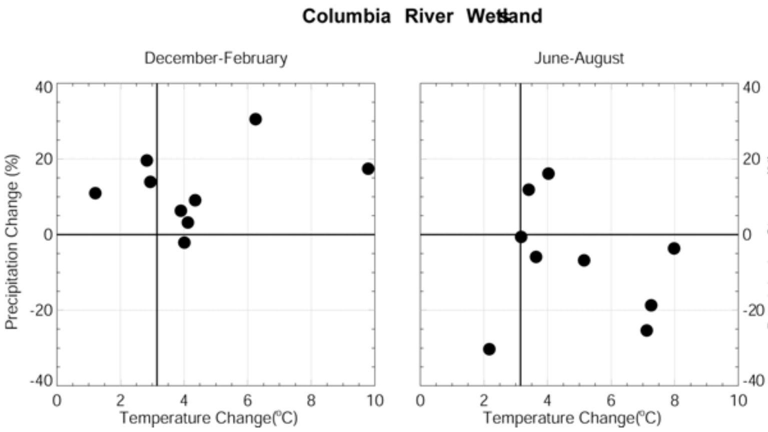
Laguna de Bay is located close to Manila in the Philippines with an area of 949km^2 and average depth of 2m. The lake experiences a tropical humid climate regime with high temperatures throughout the year and a strongly seasonal precipitation regime. The wet season stretches from May through to December and the mean annual precipitation is the highest of all the Living Lakes at 2753mm.

Winter and summer temperatures in the Laguna de Bay region rise slightly slower than the global mean reaching just over 2°C above current temperatures by the 2080s. Changes in precipitation are quite modest in both seasons, with wide disagreement between climate models for winter precipitation and a slight increase projected for summer (9 per cent). It would be useful to see climate model results for the autumn season (September to November, data not available) which brings a large proportion of the total annual precipitation.

Increases in precipitation of the order of 10 per cent (depending upon what happens in spring and especially autumn) are likely to cause increases in lake inflows, lake level and lake outflows. Higher temperatures may offset these increases, although increased cloudiness associated with higher precipitation may moderate the effects of temperature on evaporation. At present, the lake's most dominant use is fisheries, but it also serves as a waste sink for solid and liquid waste coming from households, cropland areas, industries, livestock and poultry and has been proposed as a major source of irrigation water. The effects of higher temperatures on productivity in this shallow lake may be important, but will occur alongside other pressures on water quality and productivity arising from changes in the levels of point and diffuse source pollutants.

Columbia River Wetlands



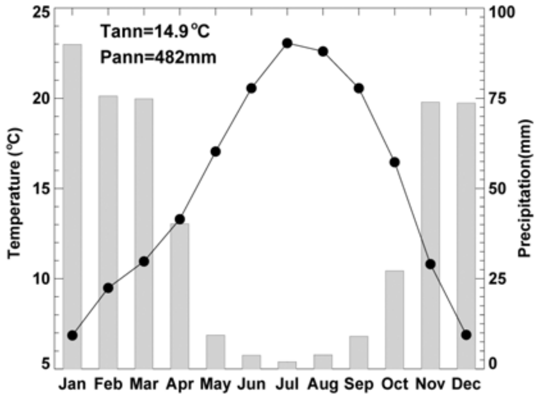


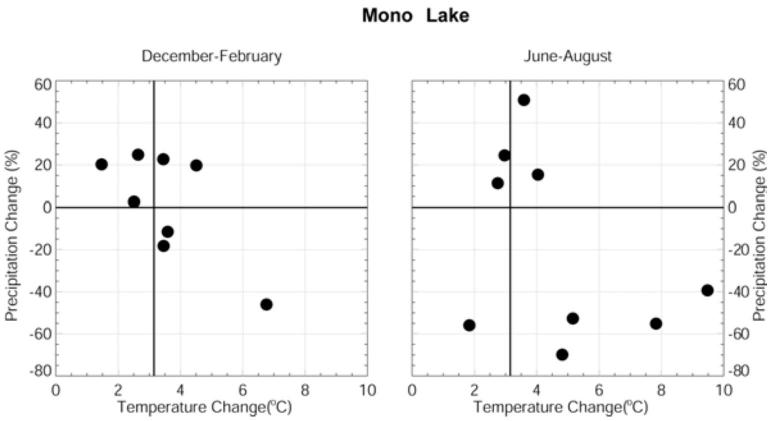
The Columbia Wetlands lie between the Purcell and Selkirk Mountains and the Canadian Rockies. The region experiences a cold and humid continental climate with mean annual temperature just below freezing (-0.1°C). Winters are very cold (below -5°C from November to February) and summers are cool (maximum 11°C in July). Precipitation is quite high and exhibits moderate seasonality with drier conditions (<80mm/month) from March to October and wetter conditions from November to February (>90mm/month).

The wetland has a forested upper catchment and a meandering main river channel which has created marshes and ponds that comprise an almost contiguous wetland. Warming occurs in both seasons at a faster rate than the global mean (4.4°C and 4.9°C, in winter and summer, respectively). Contrasting changes in precipitation are projected, with moderate increases in winter (12 per cent) and moderate decreases in summer (-7 per cent).

The combined effects of higher winter precipitation, less snowfall due to higher temperatures, earlier and faster spring snowmelt in the catchment is likely to produce substantially higher mean and peak flows in spring. The converse is likely to occur in summer; lower river flows and hence lower water levels in wetlands and lakes. Habitats and wildlife sensitive to water levels and inundation will be particularly affected by such changes. Extreme river floods may permanently alter channel patterns and wetland distribution. Low levels of human activity and interference in this relatively undisturbed system mean that it is one of the few Living Lakes (and, indeed, of any lakes or wetlands) for which climate change may be its major influence, rather than just one of many pressures, up to the 2080s.

Mono Lake





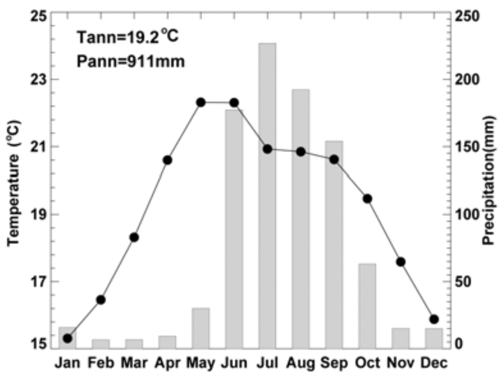
Mono Lake lies east of the Sierra Nevada in California. The region experiences cool winters with temperatures below 10°C from December to February and warm summers with temperatures above 20°C from June to September. Precipitation is strongly seasonal with a wet season that stretches from November to March, a dry season from May to September and transitional months in April and October.

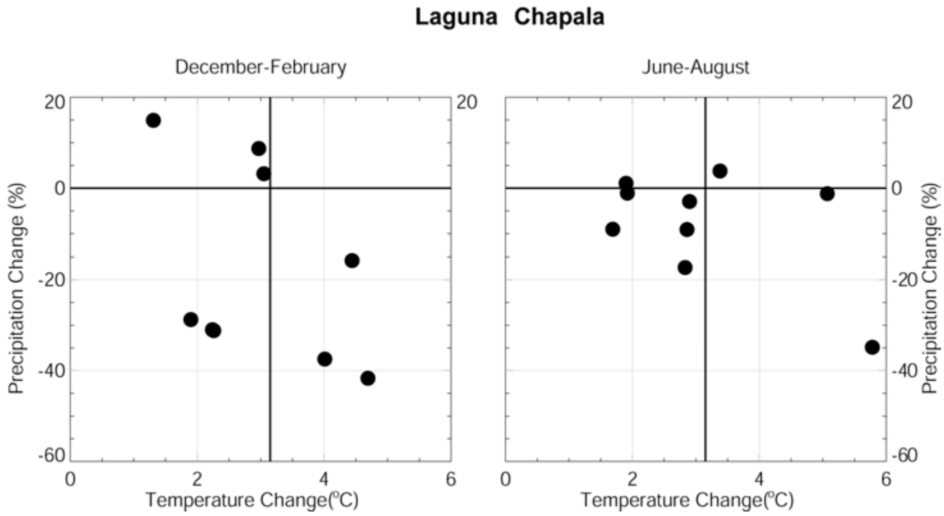
The climate models suggest warming in the region at a faster rate than the global mean in winter and summer, with winters warming by 3.6°C and summers warming by 4.7°C above present conditions by the 2070s. Projected change in precipitation shows a mixed signal in both seasons because of a wide range of results from the climate models.

Mono Lake is one of three lakes, all located in the Americas, which show no clear change in precipitation for either season by the 2080s. Whilst this makes it difficult to infer what the implications of climate change will be for the lake, it would be prudent to at least consider the effects of possible climate conditions in the future that include both moderate increases and decreases in precipitation. Mono Lake is endorheic with a relatively small catchment area compared to the other Living Lakes. It is therefore strongly influenced by evaporation and its water has high salt concentration. Diversion of lake inflows from the 1940s caused a substantial drop in lake level and doubling of salinity by 1981 which threatened the lake's specialised animals and plants. Higher rates of evaporation in the future are likely to cause similar, although much smaller, impacts on lake level and water quality.

Laguna Chapala

Laguna Chapal is the largest natural lake in Mexico located in the west at an elevation of 1524m. Temperatures are warmest in May and June (~22°C) and coolest in January (~15°C). Precipitation is very seasonal, with four months (June to September) receiving over 150mm and the rest less than 40mm, except for the transitional month of October (~60mm).

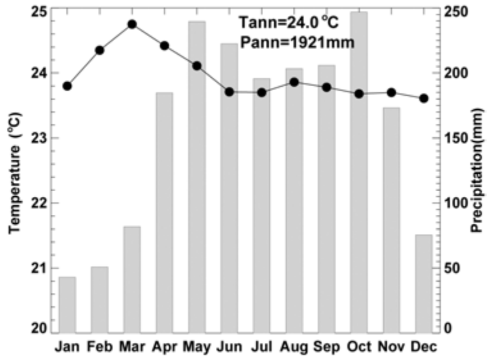


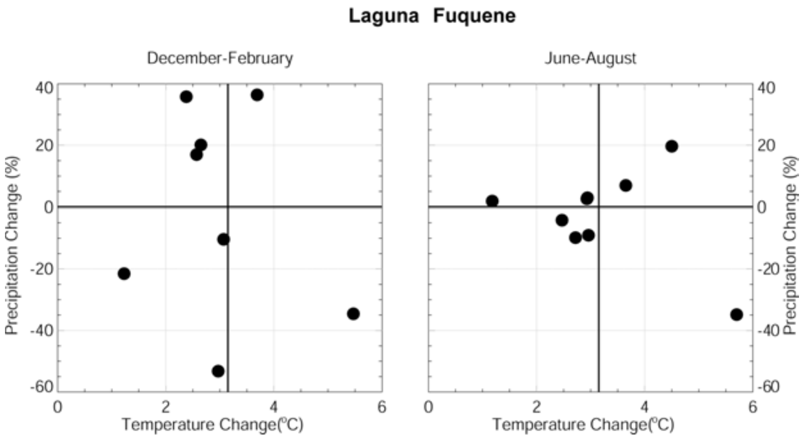


Future warming by the 2080s is slightly lower than the global mean in winter (3.0°C) and very close to it in summer (3.2°C). Precipitation changes in winter are inconsistent and in summer (the wet season) the models suggest a small decrease of about -8 per cent. Combined with higher rates of evaporation these changes could result in very substantial reductions in river flows and lake area and level.

River flows are generally quite sensitive to changes in precipitation due to the non-linear nature of the relationship between rainfall and runoff. This means that small changes in precipitation may result in quite large changes in river flows – so that changes in wet season precipitation of the order of 8 per cent may result in much larger percentage decreases in runoff with major consequences for river flows and lakes. It is not possible here to adequately review the functions of Laguna Chapal (it is Mexico's most important lake, with the region which surrounds its basin generating about 30 per cent of Mexico's GNP), nor is it possible to the explain the ongoing crisis that intense use of the lake and its catchment has caused (in the 1970s the lake had a volume of 8.1 billion m^3 whilst the volume in 2001/02 was just 1.3 billion m^3). Faced with a range of major problems that already beset Laguna Chapa l climate change represents another potential problem that will develop over the next few decades. Political will and capacity to implement water management are critical to resolving the current crisis and will be essential for developing policies for adapting to what could potentially be very significant changes in the Laguna Chapel system by the 2080s.

Laguna Fuquene





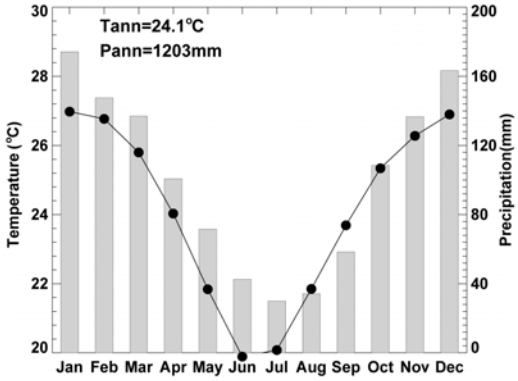
Laguna Fúquene is located n the Eastern Cordillera of Colombia close to the equator and at an elevation of 2539m it is the highest of the Living Lakes. The lake experiences a warm humid tropical climate regime moderated by its high elevation. The precipitation season extends from April to November and there are just four months with less than 100mm/month.

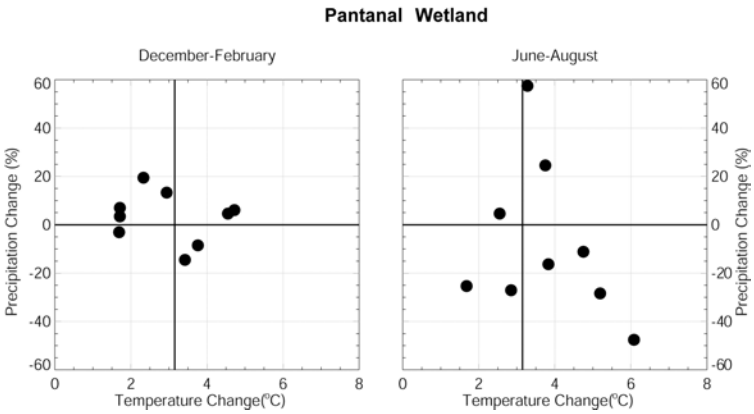
Projections of temperature increase and precipitation change show quite high divergence between the climate models. The average increase in temperature puts Laguna Fúquene close to the global mean warming in both seasons. As noted earlier, for precipitation, Laguna Fúquene is one of the three lakes in the Americas that does not show a clear precipitation signal in either season.

The lake is close to the Colombia capital Bogota and underpins regional economic activities, including a major dairy industry, 20,000 hectares of below-ground irrigated agricultural fields, and water supply facilities for at least 100,000 people. For these reasons, the significance of what is a very uncertain climate future may be relatively minor compared to future trends in utilisation and management of the lake.

Pantanal Wetland

In central South America, the Pantanal is the world's largest wetland, 140,000km^2 in surface area. The climate regime is warm and humid with modest seasonality in temperature and marked seasonality in precipitation. The cooler and drier months are in Southern Hemisphere winter. Warmer temperatures and higher precipitation occur through most of the rest of the year, with seven months receiving over 80mm/month.

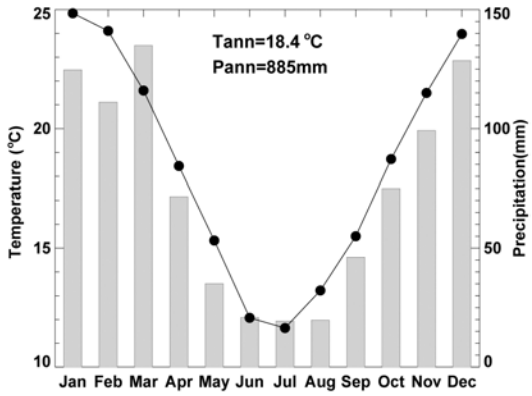


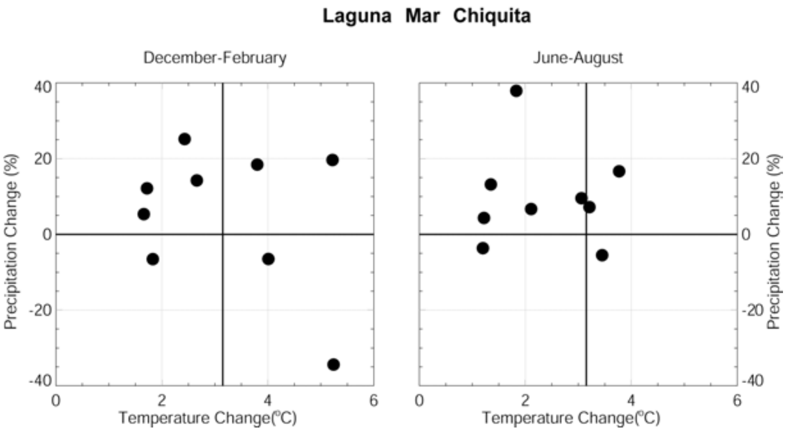


The Pantanal is one of the three lakes with the greatest divergence in climate model projections, particularly in terms of precipitation. Temperatures warm more in Southern Hemisphere winter (JJA) than in summer (DJF). The precipitation signal is divergent in both seasons.

Summarising what implications these uncertain climate change projections have for the Pantanal, and for the people and wildlife it supports, is difficult. In area alone the Pantanal is larger than Greece, is characterised by massive flooding fed by the waters of the Paraguay, and has vast areas of perennial and seasonal swamps. Assuming no change in precipitation the net effects of warmer temperatures will be to increase evaporation, possibly leading to smaller areas of swamps and periods of inundation, and to increase water temperature with implications for freshwater life. Any changes in precipitation, if they do occur, will also have major significance for the region, not just in the Pantanal, but in the vast upstream catchment of the Paraguay and its tributaries.

Laguna Mar Chiquita





Laguna Mar Chiquita is located in the Argentine provinces of Cordoba and Santiago del Estero. It displays moderate seasonal temperature variation of about 13°C between summer and winter. The precipitation regime is seasonal with seven months recording over 70mm (October to April) and five recording under 50mm (May to September).

In Southern Hemisphere summer (DJF), Laguna Mar Chiquita warms at a similar rate to the global average with an average increase of about 3.2°C. In winter (JJA), the region warms a little bit slower at about 2.4°C. Precipitation changes in summer are inconsistent and in winter they suggest small increases of about 10 per cent (actually quite small in mm terms – only about 2-3mm per month).

Overall these changes would slightly reduce the seasonal precipitation contrast and higher temperatures would increase water temperatures and evaporation from this endorheic lake. The Laguna Mar Chiquita has recorded large lake-level fluctuations in the recent past, in particular a 9m increase during the period 1972-1987 which led to a considerable decrease in salinity with a shift in the lake's limnology from a hypersaline stage to a mesosaline stage. Changes in evaporation rates over the lake in the future, unless offset by precipitation change, will have implications for the lake's salinity and ecology. The future behaviour of the El Niño - Southern Oscillation will also be important as it influences precipitation in the region. Other important rivers in Argentina such as the Parana are influenced by El Niño and have recorded long term fluctuations in river flows and major extremes associated with certain El Niño events, for example, widespread flooding in 1984. Pollution of the rivers that feed Laguna Mar Chiquita is a growing threat and capacity to manage the system is limited in terms of awareness about the importance of threats and lack of infrastructure and personnel to implement even minimal management strategies for the lake.

About the Tyndall Centre for Climate Change Research

The Tyndall Centre for Climate Change Research is a nationally distributed and trans-disciplinary research centre funded with a core grant of £10m for an initial 5-year term by three of the national UK research councils - NERC, ESRC and EPSRC - with additional support from the Department of Trade and Industry. It was launched in November 2000 and officially opened by the Environment Minister, Michael Meacher.

The Tyndall Centre is the UK's leading scientific research centre for undertaking integrated research that contributes to the development, evaluation and promotion of sustainable options for responding effectively to climate change. To accomplish our aims we recognise the importance of working across a range of scales in space and time, from household to global and from the present through the coming centuries. Integration across issues is essential and an interactive partnership approach with public and private sector organisations guides the programme and makes use of its findings.

The Tyndall Centre offers a UK-based, but globally active, climate change research organisation with a strong programme of scientifically-integrated and socially interactive research organised around four Research Themes:

- Integrative Frameworks
- Decarbonising modern societies
- Adapting to climate change
- Sustaining the coastal zone

The Centre is forging links with comparable centres and networks in Europe and is leading a bid to the EU Framework 6 Programme for a Network of Excellence. Tyndall also operates an international Visiting Fellowship programme, offers co-funded PhD studentships, maintains a co-ordinated external communications and outreach strategy, and is developing a short course programme for non-Annex I country professionals.

The Tyndall Centre draws together a substantial body of climate change research expertise resident in the UK's environmental, engineering and social science communities. Headquartered in the School of Environmental Sciences at UEA, the Centre also has regional offices at UMIST and University of Southampton and six further research institutions complete the Consortium - University of Cambridge (CIES), University of Leeds (ITS), University of Sussex (SPRU), Rutherford Appleton Laboratory (ERU), NERC's Centre for Ecology and Hydrology, and Cranfield University (CSMC). The Tyndall Centre HQ will move in June 2003 into a new £7m low energy building hosting the newly formed Zuckerman Institute for Connective Environmental Research.

Further information about the Tyndall Centre can be found at: www.tyndall.ac.uk

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