1. WRA

China – UK, WRDMAP
Integrated Water Resources Management Document Series

Thematic Paper 1.9: Climate Change and Water Resources

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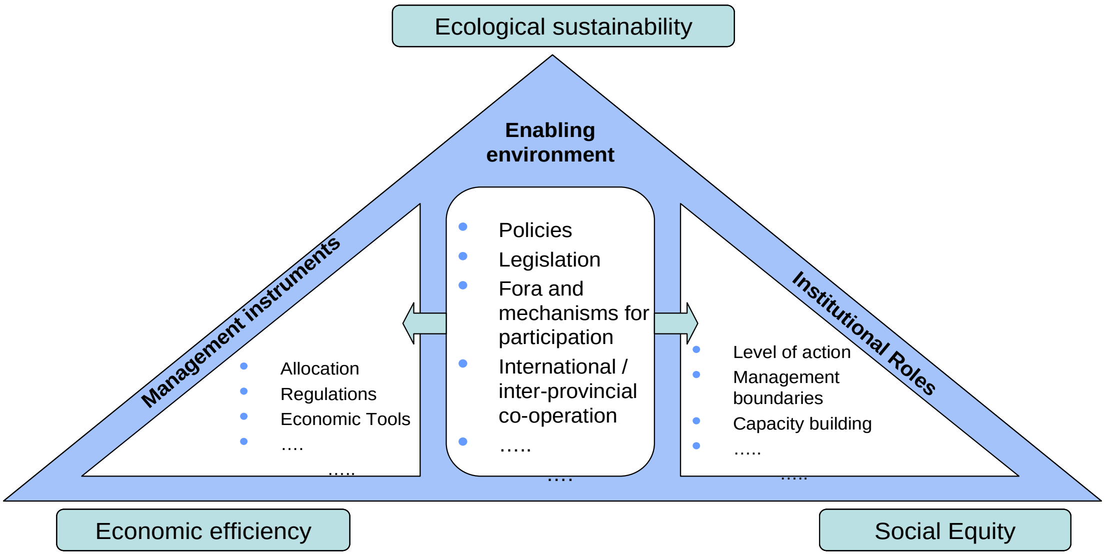
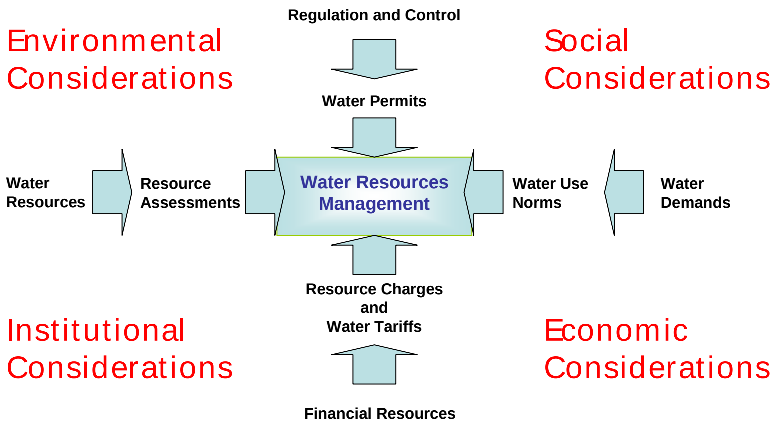
Integrated Water Resources Management (IWRM)

(Basics after Global Water Partnership)



Driving Elements of Integrated Water Resources Management



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Summary: This Thematic Paper outlines the latest thinking on potential climate change impacts on water resources and possible ways in which societies can modify or adapt their use of water resources to accommodate the forecast changes.

The paper is intended to summarise key points from what is a very extensive literature on climate modelling and climate change forecasting. Adaptation strategies are less researched but most feature methods already developed for use in water resource management. By summarising the literature it is hoped to assist water resources planners to develop their understanding of this increasingly important subject.

The paper provides an extended list of references and web sites to guide the interested reader to sources of more detailed information.

The paper covers the following topics:

- Introduction to climate change, modelling, forecasts and scaling issues
- Dealing with uncertainty
- Assessing climate change impacts on agriculture
- Impacts in non-irrigation use
- Assessing climate change impacts on water resources
- Adapting to climate change

This document is one of a series covering topics on sustainable water resources planning, allocation and management. Details are given in the bibliography.

The Ministry of Water Resources have supported the Water Resources Demand Management Assistance Project (WRDMAP) to develop this series to support WRD/WAB at provincial, municipal and county levels in their efforts to achieve sustainable water use.

1 Introduction

1.1 General

There is general consensus within the international scientific community that the global climate is changing. The **Intergovernmental Panel on Climate Change** (IPCC) was established in 1988 to investigate global climate change, and has produced assessment reports in 1990, 1995, 2001 and 2007. These reports are referred to as Assessment Reports 1 to 4 (AR1-AR4) respectively. Climate change can be the result of natural variability or the result of human activity.

Climate change resulting from human activity is often referred to as **anthropogenically** induced climate change. With each IPCC assessment report the evidence of global warming has become stronger, as has the evidence that the current warming is anthropogenically induced.

In Assessment Report Four (AR4), the IPCC has demonstrated clearly that warming of the global climate system is occurring. Observations indicate that global temperatures are rising. Consensus is that this warming is the result of changes in atmospheric composition brought about by human activities. Greenhouse gases (GHGs) released through the burning of fossil fuels and other activities, result in changes in the balance between incoming and outgoing radiation through the atmosphere.

The IPCC now considers it very likely that global warming has been anthropogenically induced by the emission of increasing quantities of CO_2, CH_2, and N_2O to the atmosphere. Some of the greenhouse gases have long residence times in the atmosphere, and even were emissions to be cut or halted immediately, there is still a commitment to future global warming because of the gases that are already there. The China Climate Change Info-Net (http://www.ccchina.gov.cn) provides an excellent source of information on all aspects of climate change. It provides links to both national and international networks and activities, as well as up to date news on policy initiatives and developments.

A wide range of impacts is associated with global warming and climate change. Climate change affects global earth systems, including the atmosphere, the biosphere and the hydrosphere; systems that are inter-linked in very complex ways. With respect to water resources, climate change directly affects precipitation and the component processes and energy inputs that influence potential evapotranspiration (temperature, solar radiation, relative humidity or vapour pressure, and wind speeds). Climate change thus affects water resources availability, and will affect natural vegetation systems, as well as the demand for water in agriculture.

Climate change will have a significant impact on glacial water storage, and on the timing of seasonal releases from that storage. In the short term this may result in increased water availability in areas supplied with water from glacial melt, but in the longer term resource availability is likely to reduce and the variability in availability will increase.

In some parts of China, water frozen in the soil horizons during winter months is important source of soil water for agriculture in spring, and the availability of this could decrease also. Demands for water outside of the agricultural sector will also be affected but to a much lesser extent, and changes in vegetation and land cover will influence hydrological response. In coastal regions, rising sea levels will also impact on water resources systems through saline intrusion, impeded drainage and damage from intensified storm surge.

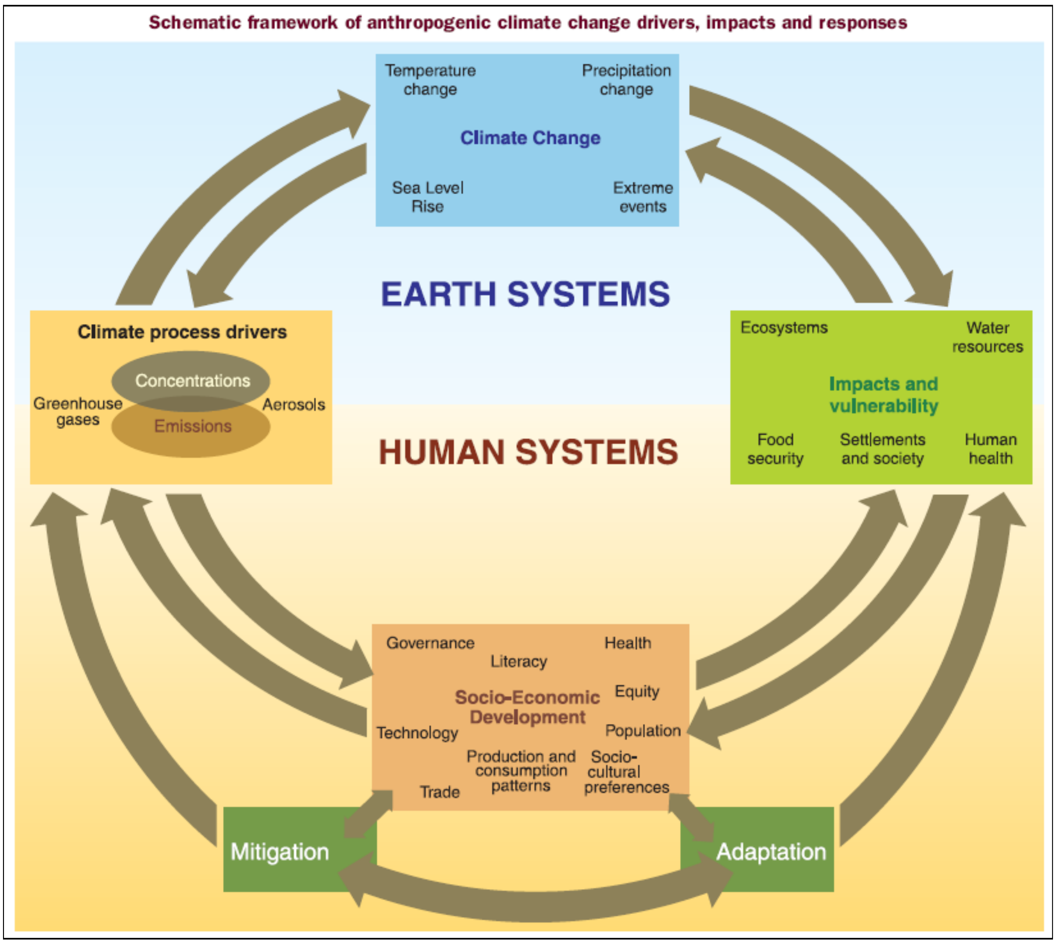
Climate Change Adaptation
Adaptation to climate change is the process by which adjustments are made to our activities, permitting us to exist with a changed set of climate attributes. These adjustments may be planned through government policy initiatives, or may be autonomous, taking place without specific policy initiatives. Planned adaptation could for example involve constructing fluvial or coastal flood defences, while autonomous adaptation could be in the choices that farmers make in their planting practices.
Climate Change Mitigation
Climate change mitigation refers to actions that are taken to reduce greenhouse gas emissions, and thereby to reduce the rate of future global warming, and stabilise atmospheric CO_2. Mitigation strategies include the introduction of renewable energy sources – e.g. wind, wave, tidal and solar energy, improving efficiency in energy use, etc.
Climate Change Vulnerability
Vulnerability to climate or environmental change describes how sensitive and individual or system is to a particular hazard. Many factors influence vulnerability, including geographical location, age, livelihood, access to resources etc.

With AR4, better understanding is being developed of the interactions and linkages between climate change divers, climate change impacts and potential adaptation responses. Figure 1 presents the schematic framework of climate change drivers, impacts and responses developed and presented by the IPCC in the AR4 Synthesis Report (http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf).

There are many complexities to be addressed, and of course this must be done within a framework of uncertainty. There are uncertainties associated with natural climate variability, with climate sensitivity to increasing CO_2, with the path that future greenhouse gas emissions might follow, and uncertainties in the true physical nature of all interacting processes and feedbacks that make up the climate system. There are also uncertainties in our ability to model these processes, interactions and feedbacks satisfactorily. In assessing potential future climate change impacts and appropriate adaptation strategies, it is therefore necessary to consider a range of plausible scenarios, and to model the impact of these on the climate system.

The science is improving continuously, as are the tools that provide a means of understanding complex impacts and feedbacks. Through modelling, an understanding of past changes can be developed and projections made of possible future climate changes. Mitigation strategies can be developed that will limit future GHG emissions, as well adaptation strategies that will reduce future vulnerability to climate change. Such strategies must be flexible and capable of adapting to unfolding circumstances.

Figure 1 IPCC framework for climate change impact assessment



Source: IPCC, 2007

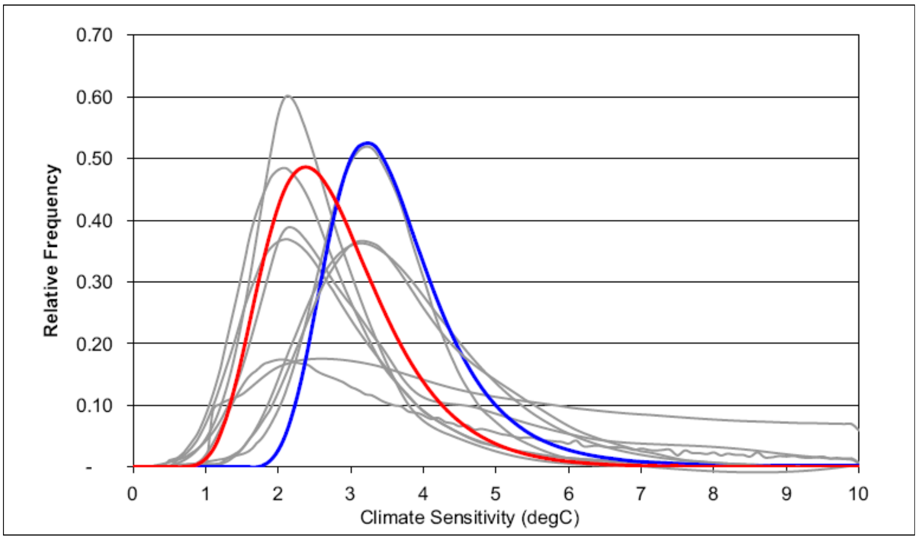
1.2 Climate sensitivity

Climate sensitivity is a measure of the sensitivity of global mean surface air temperatures to greenhouse gas concentrations. Climate sensitivity is generally expressed as the change in equilibrium mean global surface air temperature to a doubling of atmospheric CO_2 from pre-industrial levels (280 ppm to 560 ppm). In the IPCC Third Assessment Report (AR3, 2001), a comparison was made of temperature predictions from a range of state of the art climate models, and it was concluded that the likely range of climate sensitivity is 1.5 ℃ – 4.5℃.

In AR4 the IPCC indicate that *"climate sensitivity is likely to be in the range of 2 to 4.5℃ with a best estimate of about 3 ℃, and is very unlikely to be less than 1.5 ℃".* Different models produce different results, partly as a result of uncertainties in the physical description of some atmospheric process, and partly because of different parameterizations. A probabilistic approach to future climate change assessments is therefore most appropriate at the present time. A recent study (Meinhausen, 2006) has presented the results of eleven ensemble studies in which the parameters of individual climate models were systematically changed within plausible ranges. These results are shown in Figure 2.

Each grey line in Figure 2 represents the frequency distribution of climate sensitivity for a particular model when model parameters are adjusted within the plausible range. Temperature is considered to be the most reliably modelled climate parameter. Figure 2 thus gives a clear indication of underlying inter-model variability – emissions uncertainty is excluded. Clearly significant variability exists within any particular model, as a result of parameter choices. Mean values of climate sensitivity for the models considered is in the range of 2-3℃, Climate sensitivity is used in the parameterization of simple climate models.

Figure 2 Probability density functions for climate sensitivity



Source: Grey lines – Stern Review, 2007. (http://www.hm-treasury.gov.uk/sternreview_index.htm)
Red line – IPCC AR3 (Wigley and Raper, 2001)
Blue line – Ensemble studies at the UK Met Office Hadley Centre (Murphy et al., 2004)

1.3 Climate models

Projections of future climate change are made on the basis of climate models. Models of the global climate system exist at different scales and different levels of complexity. A good summary of climate model hierarchy is given in the IPCC AR4 Working Group 1 Technical Summary (Solomon et al., 2007).

There are “Simple Climate Models” (SCMs), “Earth System Models of Intermediate Complexity” (EMICs), and “Atmosphere Ocean Global Circulation Models” (AOGCMs).

SCMs can be used to project global temperatures and make use of energy balance equations operating between a lumped representation of the hemispheric and ocean systems. Their value is in being to evaluate multiple scenarios very quickly, but only at a global scale.

EMICs include some representation of the dynamics of atmospheric and ocean systems, and may include biogeochemical cycles also. They operate at a coarse spatial representation, but can be used to investigate climate change effects at continental scales. They can also be used to investigate long term multi-century effects using large ensembles, and can thus assist in making long term probabilistic projections.

AOGCMs have the most comprehensive physics base, although there are still some processes for which a complete physical description is not yet available (e.g. formation of clouds and precipitation) and because of this different models may have different parametric representations.

In the preparation of AR4, the IPCC co-ordinated the activities of 14 modelling groups in 10 countries using 23 models. Models were run for a set of standard experiments, thus producing a large database of results. This database has permitted multi-model ensemble analysis to be carried out, from which multi-model means for various parameters can be defined, and inter-model variability assessed. AOGCMs can have different spatial resolutions as well as different parameterizations, and it is this that results in inter-model variability, or uncertainty. Some modelling centres have also carried “multi-member” ensembles in which model parameters are adjusted to investigate their sensitivity.

AOGCMs are capable of simulating natural climate variability and climate changes resulting from anthropogenic forcings such as increases in greenhouse gases and land use changes. However, the horizontal scales of current AOGCMs are too coarse (150-300 km) to resolve the climatic features necessary for hydrological and other impact studies at a more regional or local level. The recent development and advances in regional climate models (RCMs) provide an excellent tool for studying climate changes at the basin-scale because of the relatively high resolution (~50 km) which permits the simulation of regional small-scale processes such as orographic forcing. RCMs can be run using boundary conditions created by AOGCMs, and may be considered as double nested in this regard. Generally they have the same physics base as the AOGCM used to drive it.

In AR4 the IPCC demonstrate that AOGCMs reproduce observed features of recent climate quite well, and that they also can reproduce past climate changes. They express confidence in the ability of AOGCMs to *“provide credible quantitative estimates of future* *climate change, particularly at continental and larger scales"*, and indicate that confidence in temperature projections is higher than confidence in precipitation projections. The representation of clouds and cloud feedback is considered to be the primary source of the inter-model differences that exist, and it is to be expected that inter-model variability will reduce as the cloud process understanding and description improves.

Volcanic Dust Veiling

Santa Maria, Agung, El Chichon and Pinatubo were significant volcanic eruptions that resulted in dust veiling and global cooling in the years immediately following the eruptions. This natural forcing is represented in the models.

Figure 3 shows the observed global mean temperatures (in black) and AOGCM simulated global mean temperatures by different climate models a) with anthropogenic forcing, and b) without anthropogenic forcing. The red line in a) is the inter-model mean, and the blue line in b) is the inter-model mean. In the inter-model mean temperature is close to the observed temperature throughout the simulation period when anthropogenic forcing is included. Without anthropogenic forcing the post 1960s trend in observed temperature cannot be reproduced. This is a clear demonstration of the influence of GHG emissions on global climate.

While the ability of AOGCMs to model past global temperatures changes is of course of fundamental importance, it is the representation of regional climate and regional change that is important in the development of adaptation responses. Representation of regional climate has improved in AOGCMs as the uncertainties in various process representations improves. Figure 4 shows observed and multi-model mean simulated precipitation rates for the 1979-1993 period, for the DJF and JJA seasons. Also shown are the projected multi-model mean simulated changes by the 2090-2099 period under the A1B emissions scenario. The multi-model mean simulation of seasonal precipitation for the 1979-1993 period is on the whole apparently very good, although clearly at the scale shown, only a general appreciation of global pattern reproduction can be deduced. The projected changes in seasonal precipitation are relative to the 1980-1999 period. Shading is provided only where 66% of models agree on the sign of changes, and stippling where 90% of models agree on the sign of changes. The indication is that much of China will get wetter (northern China in particular), although at there is clearly less agreement between models in mountainous areas (Solomon et al., 2007).

Figure 3 Influence of anthropogenic forcing on global temperature simulation

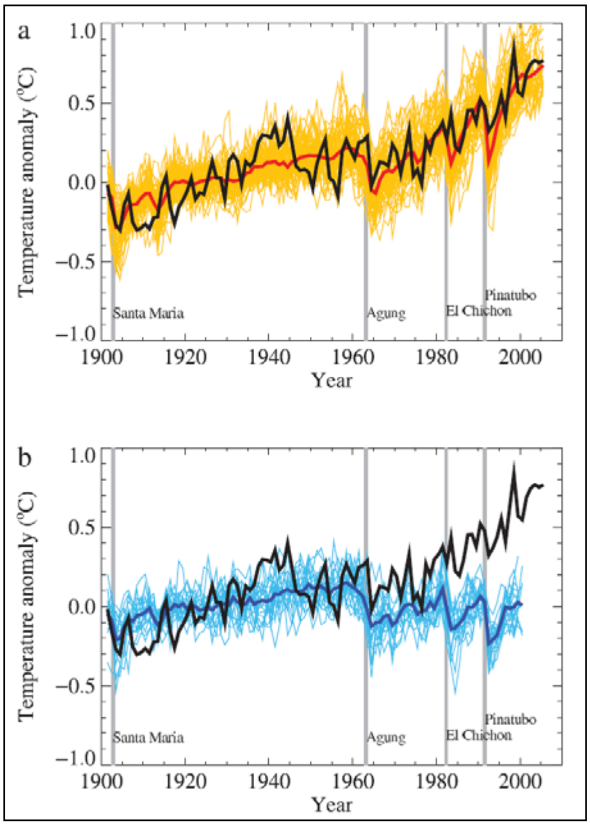
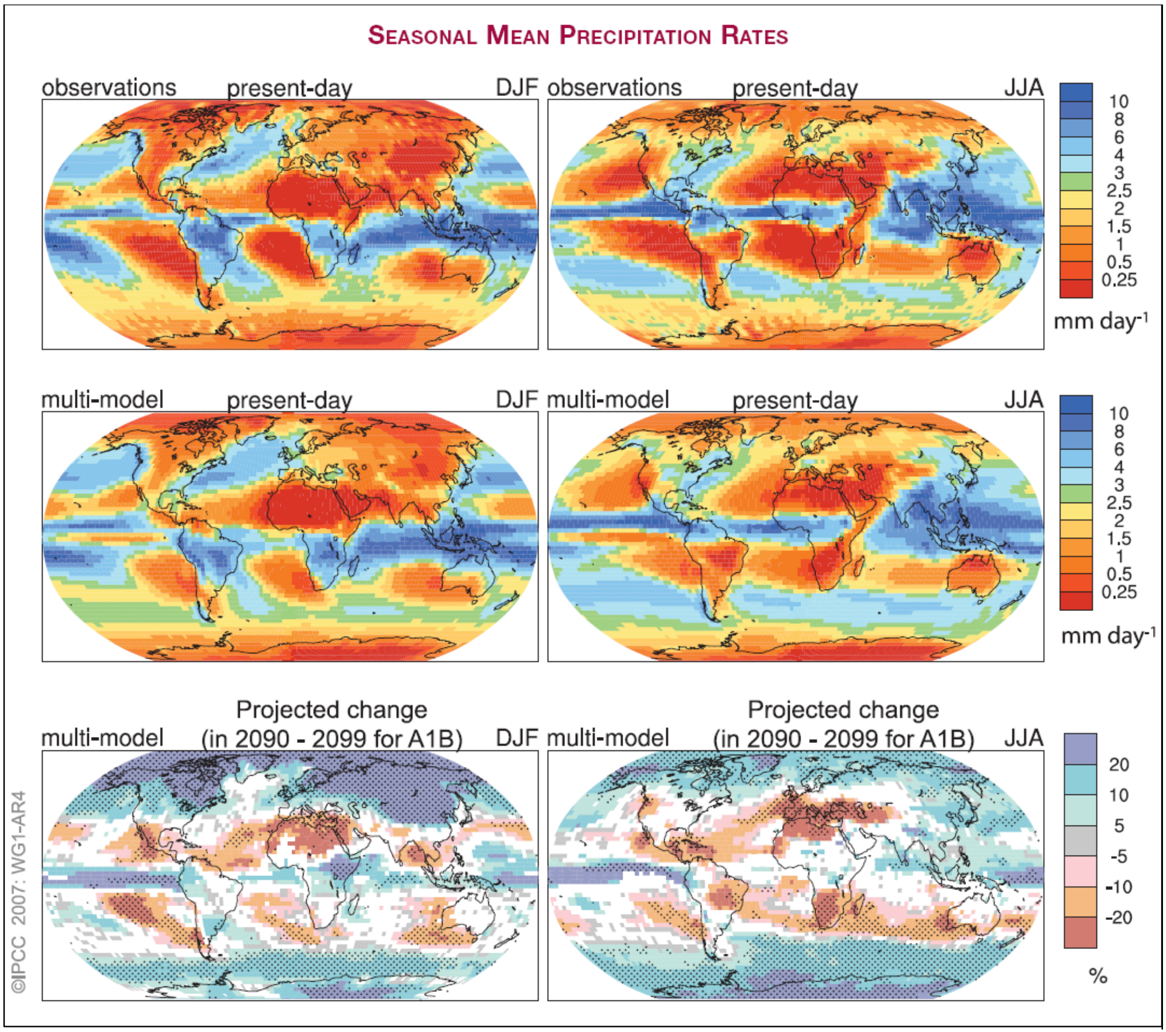


Figure 4 Multi-model mean simulations of seasonal precipitation



Source: IPCC, 2007. AR4, WG1.

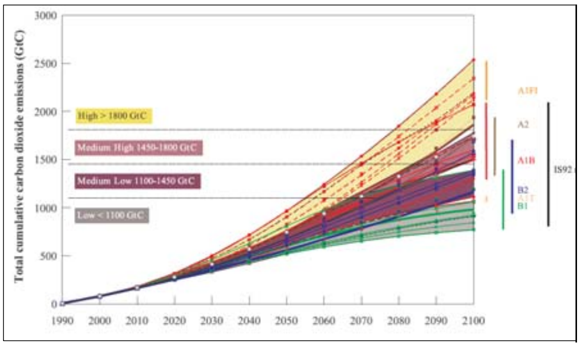
1.4 Emissions scenarios

The IPCC produced a "Special Report on Emissions Scenarios" in 2001 (IPCC, 2001). The scenarios that were developed are now generally referred to as the SRES scenarios. The full and summary reports are available from the IPCC web pages (http://www.ipcc.ch). Useful summaries are also available in the AR4 reports. The SRES developed scenarios on the basis of narrative storylines that describe possible development paths that the world may take in the coming decades. In total, 40 SRES scenarios were created, and for each there is a time series of GHC and sulphur emissions. Emissions are provided in terms of global totals and also totals and regional aggregates for individual constituent greenhouse gases. The time series for cumulative CO_2 emissions from all scenarios are presented in Figure 5 and are indicative of the range of emissions that SRES includes. In climate change impact studies, it is common to use selected "marker" scenarios.

Over the next few years a new generation of climate change projections will be performed with state-of-the-art GCMs participating in CMIP5, the Coupled Model Inter-comparison

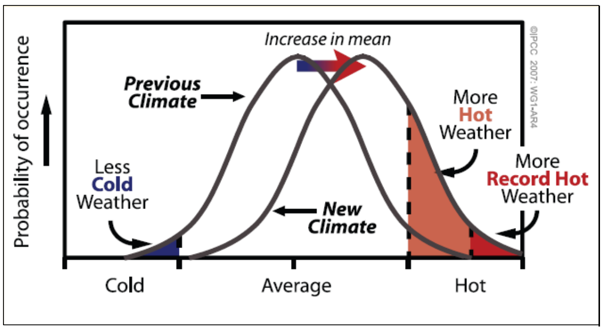
Project (http://cmip-pcmdi.llnl.gov/cmip5) as part of the World Climate Research Programme. About 20 global models worldwide will complete future climate projections up to 2100 for two reference concentration pathways (RCP), RCP4.5 and RCP8.5, i.e. a low and a high GHG concentration pathway. It is planned that a subset of these models will make available 6-hourly fields for regional model nesting, and many of these simulations are planned to be completed by late 2010.

Figure 5 Forecast total cumulative CO_2 emissions from full range of SRES scenarios



Source: IPCC, 2001.

Figure 6 Influence of a change in mean temperature on extremes



Source: IPCC, WG1, AR4

1.5 Impact of climate change on extremes

There is a general expectation that with climate change will come more extremes in weather conditions. Figure 6 shows diagrammatically how the frequency distribution of temperatures might be expected to change. Assuming that the variance of the distribution remains unchanged, and that the mean is increased, then extremes have to become more extreme. The distribution simply moves to the right. The incidence of very hot days becomes more frequent and the incidence of very cold days less frequent. Also, the magnitude of extremely high temperatures increases. A similar argument may be put forward for other extremes, such as droughts, flood producing rainfall events, and destructive wind / storm events. There is, however, also some indication that the variance of future weather patterns will increase, and this would lead to further increasing magnitude of extremes as the shape of the distribution changes.

In the context of water resources and water resources management, extreme conditions are generally the basis for design (either in the form of flood or drought), and the development of appropriate adaptation measures will in many cases require that assessments of changes in flood and drought conditions be made. Simulation of extreme events by AOGCMs is generally considered to have improved in AR4, but AOGCMs are at too coarse a spatial scale to properly model extreme precipitation. They under-estimate this on the whole. Drought sequences may be reasonably represented, but not high intensity flood producing precipitation events that often occur over localised areas. Modelling extremes, and indeed gaining better understanding and representation of more localised impacts requires that AOGCM results be downscaled.

1.6 Downscaling techniques

AOGCMs represent global circulation systems, and because of their complexity and computational requirements, are limited in their spatial resolution. The grid resolution is generally in the range of 1.5℃-3.0℃, and a single grid square could be representing an area in the range 20,000 to 90,000 km^2, within which there could be significant variations in topography, land use, etc. Generating data at the sub-grid scale is referred to as downscaling. There are two approaches to downscaling: dynamical downscaling and statistical downscaling.

Dynamical downscaling is based on high resolution climate models that are based on similar physical principles to AOGCMs. There are two types of dynamical downscaling models:

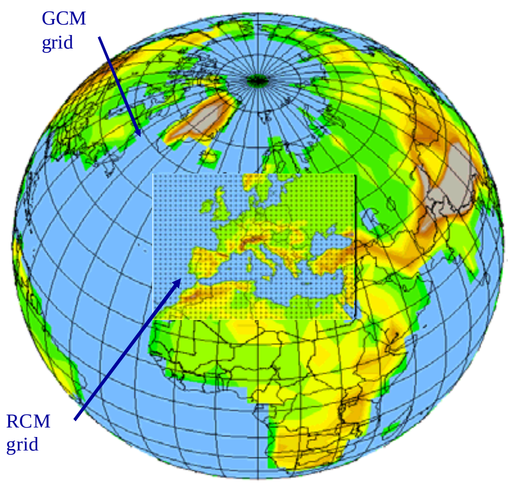
1. Atmosphere-only GCMs (AGCMs);

2. Nested Regional Climate Models (RCMs).

AGCMs can operate with a much finer grid resolution than AOGCMs. They model land surface processes in the same way as an AOGCM, and take ocean boundary condition data (sea surface temperature and sea ice) from an AOGCM model run. It is thought that for short simulation periods, this approach can lead to improved simulations of climate, but because of the disconnect between the atmospheric simulation and the ocean simulation, there is a risk of inconsistency in climate projections. It has been shown, however, that simulations of historic climate with high resolution AGCMs agree much better with observations than do AOGCM simulations.

Nested RCMs are set up to run with boundary conditions derived from an AOGCM, and therefore are generally consistent with AOGCM simulations. Spatial resolution on an RCM is typically about 0.5°, and some models are now being run at spatial resolutions of 0.25° and less. Some difficulties can arise through representation of the lower boundary condition, which comes from the AOGCM. There can be some distortion. In AR4, the IPCC report that RCMs can represent inter-annual variations in precipitation and temperature, and that they add value at small scales to climate statistics when driven by AOGCMs that are accurate at large scales (Christensen et al., 2007). Figure 7 conceptualises the double nesting approach.

Figure 7 Nested RCM concept



Statistical downscaling approaches are based on derived empirical relationships between observed data at different scales, and rely on the assumption that these relationships do not change and remain valid under perturbed climate conditions. In AR4, the IPCC report that they cannot accommodate regional feedbacks and may lack coherency among multiple climate variables

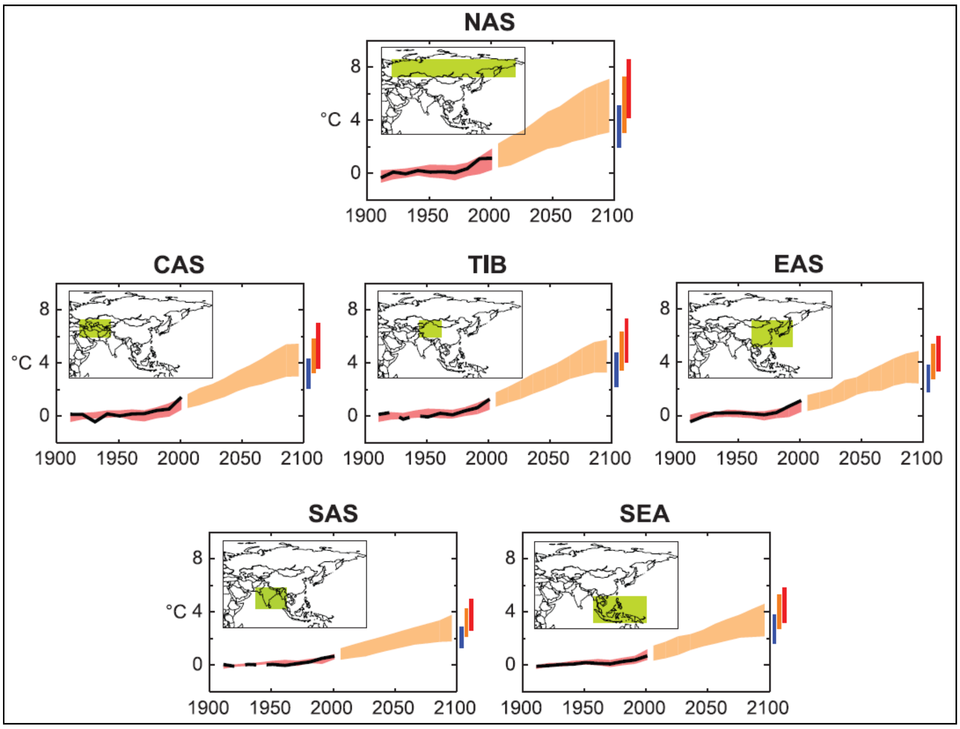
(Christensen et al., 2007). However, a wide range of statistical-dynamical downscaling approaches exist, and for certain types of analysis they may provide the most suitable approach.

1.7 AR4 climate change projections for East Asia

The IPCC have presented regional climate projections in AR4 based on the multi-model data sets (MMDs) for the A1B emissions scenario which is a mid-range scenario in terms of global temperature rise. For reporting purposes, Asia was divided into six sub-regions, as shown in Figure 8, which shows the projected temperature rises from the MMDs relative to the 1901-1950 period. For the period 1901-2005, known forcings were used in the models, and for the period 2001 to 2100 the A1B scenario was used. The bars at the right hand side of the plots represent the range of projected changes for the A1 scenario (blue), the A1B scenario (orange), and the A2 scenario (red).

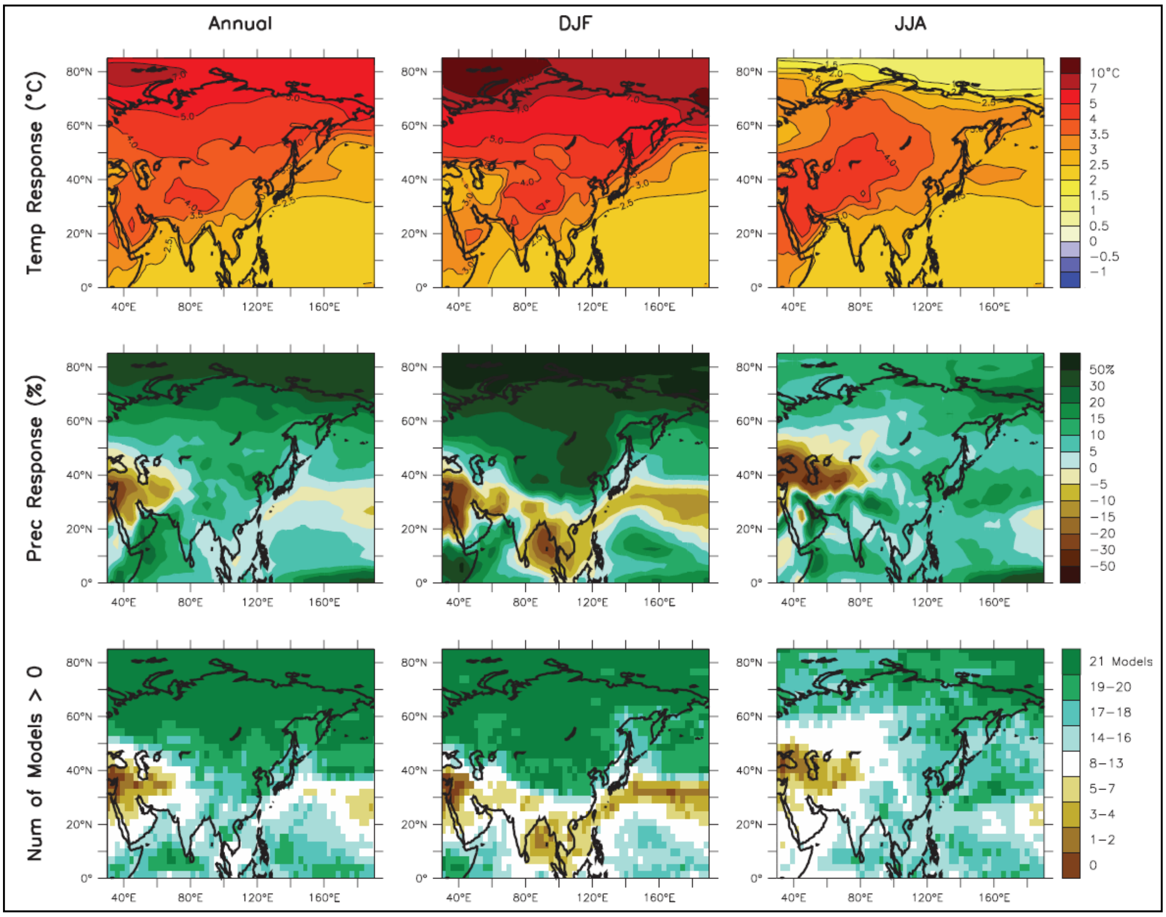
The indications of the MMD model results are that precipitation in East Asia is likely to increase, and that an increase in the frequency and intensity of extreme rainfall events in East Asia is very likely. The MMD models show a negative bias in temperature simulation and a positive bias in precipitation simulation for East Asia (average of +23%), with the mid-latitude rain band being shifted northwards except in summer. Forecast temperature and precipitation changes for Asia as a whole are shown in Figure 9. These changes are between the 1980-1999 period, and the 2080-2099 period for the MMD A1B simulations. There is an indication that much of East Asia will become wetter, with most models showing an increase in annual precipitation. However, there is notably less agreement on the sign of precipitation changes in the summer season. Regional climate modelling by Xu et al. (2005) has indicated more extreme rainfall events over China.

Figure 8 MMD A1B projected temperature increases for Asia



Source: IPCC, AR4, WG1, Christensen et al., 2007

Figure 9 MMD A1B projected temperature and precipitation changes for Asia



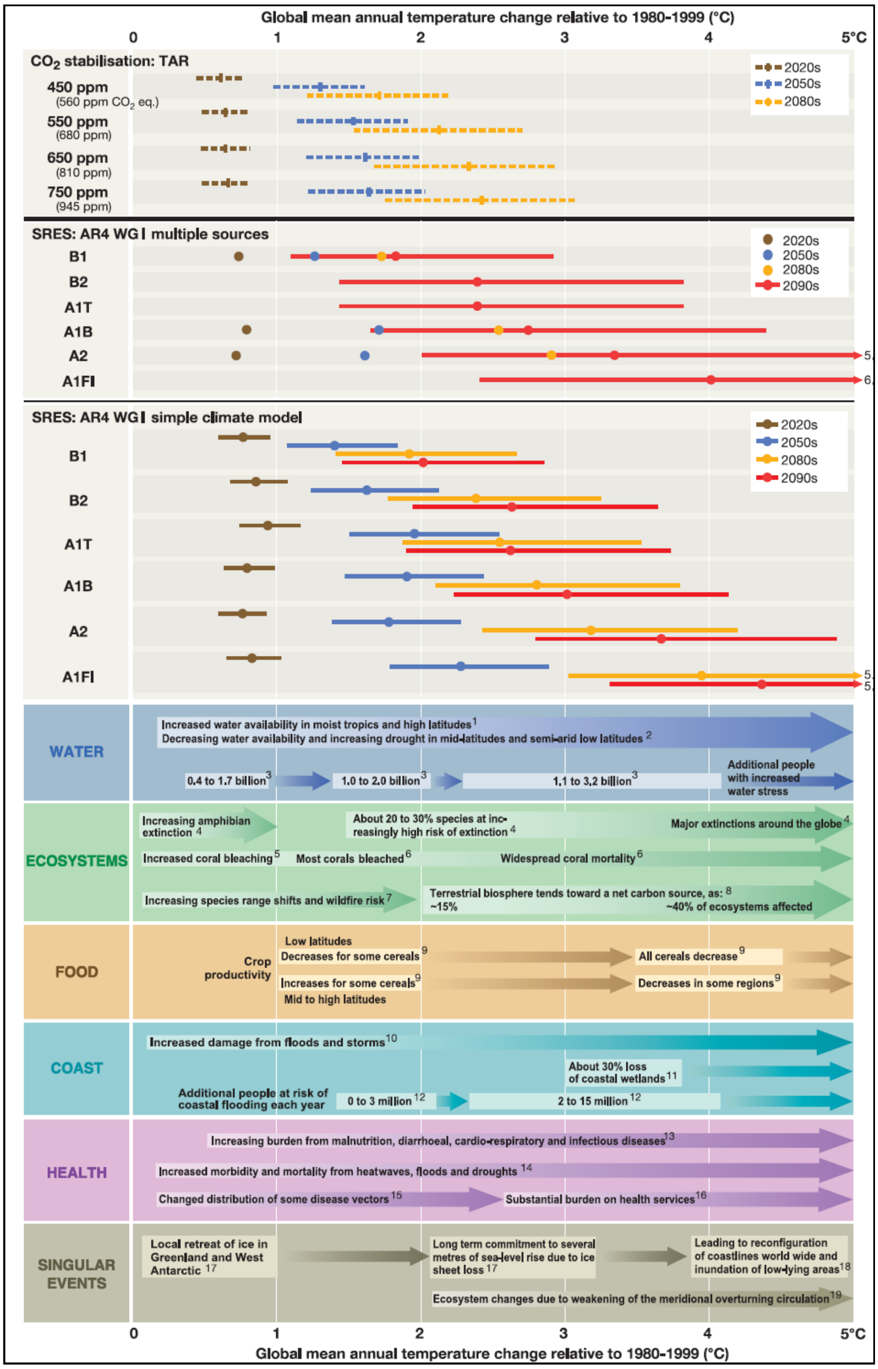
Source: IPCC, AR4, WGI, Christensen et al., 2007

1.8 Climate change impacts

The report of Working Group II of the IPCC AR4 addressed the projected impacts of climate change, and considers adaptation and vulnerability to climate change. The sectors considered were: freshwater resources and their management; ecosystems, food fibre and forest products; coastal systems and low lying areas; industry, settlement and society; and health. Regional impacts were also considered. A summary of the generic impacts globally is presented in Figure 10. In relation to water resources in China, impacts may vary quite significantly from one region of the country to another. The Himalayan regions will see a shift in runoff response as glaciers melt and spring snow melt occurs earlier. Parts of southern China may experience a reduction in runoff, while parts of northern China may experience increased runoff. All parts of China are likely to be exposed to increased flood risk. Coastal regions will be at risk from increased saline intrusion to estuaries and to coastal aquifers, and to increased storm surge damage. Drainage systems for agricultural and urban areas will be affected also.

AR4 presents summaries of recent extreme events in different regions of the world. Relevant data for China has been extracted and is presented in Table 1.

Figure 10 Projected generic sector impacts of global warming



Source: IPCC, AR4, WG2, Parry et al., 2007

Table 1 Summary of observed changes in extreme events in China

Event	Trend	References
Heatwaves	Increase in frequency of short duration heatwaves in recent decade, increasing warmer days and nights in recent decades.	Zhai et al., 1999; Zhai and Pan, 2003
Intense Rains and Floods	Increasing frequency of extreme rains in western and southern parts including Changjiang river, and decrease in northern regions; more floods in Changjiang river in past decade; more frequent floods in North-East China since 1990s; more intense summer rains in East China; severe flood in 1999; seven-fold increase in frequency of floods since 1950s.	Zhai et al., 1999; Ding and Pan, 2002; Zhai and Pan, 2003; Zhai, 2004
Droughts	Increase in area affected by drought has exceeded 6.7 Mha since 2000 in Beijing, Hebei Province, Shanxi Province, Inner Mongolia and North China; increase in dust storm affected area.	Chen et al., 2001; Yoshino, 2000, 2002; Zhou, 2003
Cyclones / Typhoons	Number and intensity of strong cyclones increased since 1950s; 21 extreme storm surges in 1950 to 2004 of which 14 occurred during 1986 to 2004.	Fan and Li, 2005

Source: IPCC, AR4, WG2, Cruz et al., 2007

2 Dealing with Uncertainty

2.1 Introduction

The climate system is subject to natural variability [1] that in the water cycle translates into floods and droughts. Statistical distributions are used to describe variability as it occurs in precipitation and in streamflow. Annual total precipitation or monthly or seasonal precipitation, for example, is often considered to fit to a normal distribution, while annual maximum short duration events would be fitted to an extreme value distribution, such as Gumbel or general logistic. By fitting a statistical distribution to observations of historic data, it is possible to forecast the magnitude of events at specified probabilities of non-exceedance. In water resources, general practice is to work with cumulative distribution functions and exceedance or non-exceedance probabilities, rather than probability density functions. Historically there has been an underlying assumption that although there is natural variability in the climate system, that variability was stationary and derived statistics from historically observed data would be representative of the future conditions. We now know this not to be the case, but the challenge is how to firstly quantify the non-stationarity that exists, and secondly how to incorporate that into

[1] Natural variability arises from natural external influences on the climate, including dust veiling following volcanic eruptions, changes in solar energy, and changes in ocean-atmospheric interactions resulting in long term variability.

water resources design and management practices.

Running an individual climate model, with a single GHG emissions scenario, will produce a time series of future climate. Model integrations or simulations might be carried out over a forecast period of 100 years. This record could be split up into blocks of 25 or 30 years, that are representative of particular planning horizons, and statistical analysis carried out on the simulated records for the particular variable in question. The assumption would be that the rate of change in the observed parameter is relatively low, and that in any particular 25 or 30 year block, stationarity can be assumed. The problem with this approach is that the quality or local accuracy of the climate model simulation of the parameter of interest may not be good. An alternative approach would be to determine the trend in the parameter of interest from the climate model simulation over the 100 year integration (linear or non-linear), and then to use this information to stochastically generate data from the observed historic data at particular planning horizons. Any such trends fitted to simulated forecast data need to consider the trend in the variance of the data as well as underlying trend in a mean value. This approach overcomes issues of modelling inaccuracy at particular locations, but there is an assumption that the simulated changes in the parameter being investigated are properly representative.

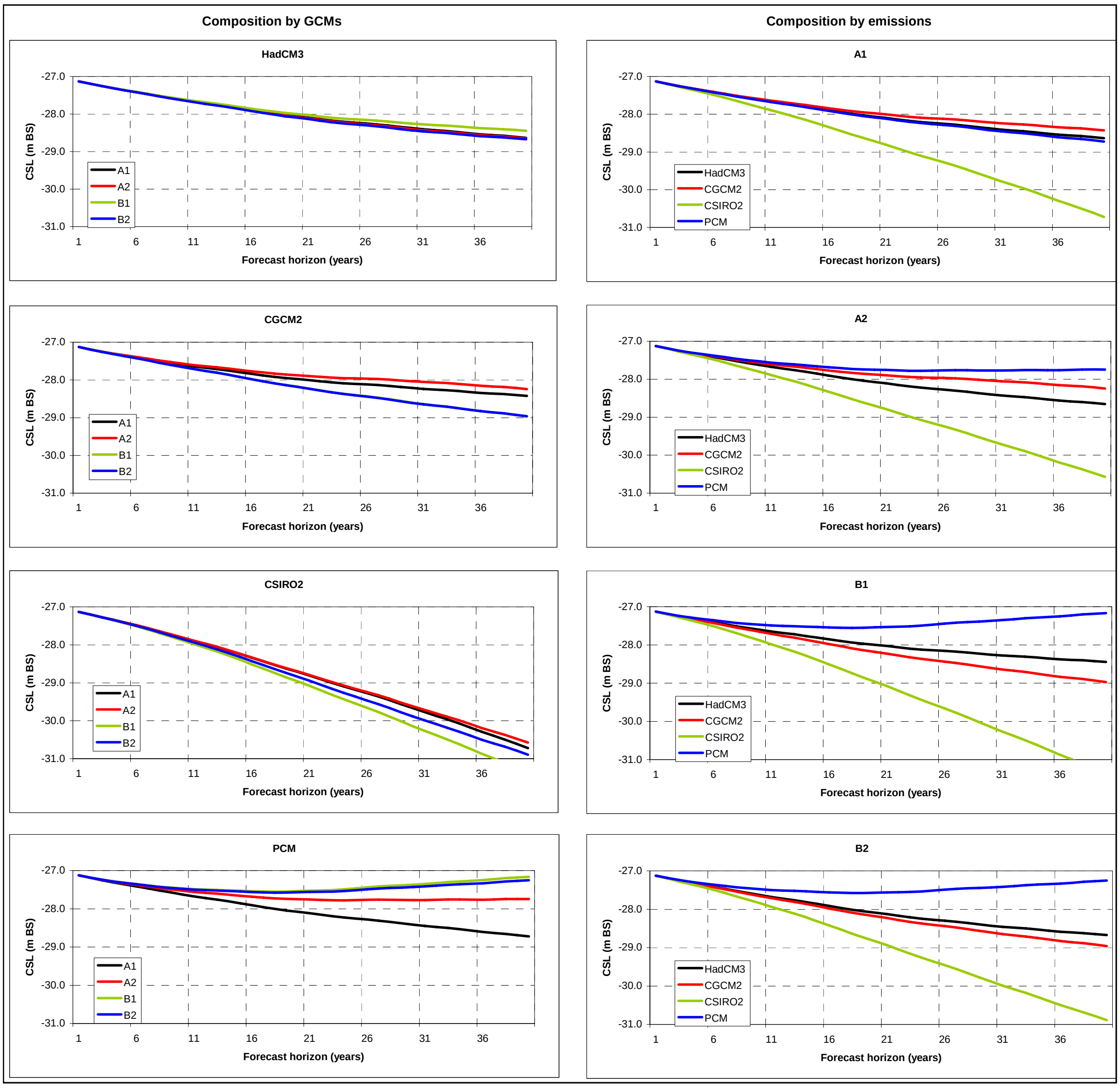
The IPCC AR4 modelling evaluations demonstrates that at present there is significant inter-model variability. Some models might show an increasing trend in precipitation at a particular location, while others show a decreasing trend. Inter-model variability is, at the present time, greater than inter-emissions scenario variability. Figure 11 shows a comparison of forecasts of future Caspian Sea levels produced from the results of climate change forecasts from four different GCMs and four different emissions scenarios. It is very clear that in this case inter-model variability is much larger than inter-emissions scenario variability.

Inter-model Variability
The plots on the left show the range in sea levels produced by each model for four emissions scenarios. The maximum range over the 40 year period is about 1.5 m with the PCM model. The plots on the right show the results for each emissions scenarios by the four models. The maximum range in the B scenarios over the 40 year period approaches 5 m.

An approach to dealing with inter-model variability, is to carry out climate projections for any particular emissions scenario, using an ensemble of models that are considered to be reliable in their process representation. If each of the ensemble member projections is considered to be equally plausible, then the results can combined. Results may be combined for particular time slices of say 25 or 30 years, and analysed statistically for that period, or a more sophisticated analysis carried out to determine average trends and variances across the models.

There are uncertainties and inaccuracies associated with model scales and resolution also. In a GCM variables may be considered to be grid averaged, perhaps representing an area of as much as 90,000 km^2, and thus missing the influence of local features and topography which can be significant. This can be overcome to some extent by downscaling model results, either through dynamical or statistical downscaling. Through dynamical downscaling with RCMs, grid resolutions of 25 km or less are now possible. RCMs can be run with boundary conditions determined from a range of GCMs to create ensembles at regional scales, but an issue with this could be that the process representation of the RCM does not match with that or the GCM providing boundary conditions, leading possibly to distortions and discontinuities. The UK Met Office Hadley Centre have overcome this issue by generation ensembles from a matched GCM and RCM, with model parameters adjusted between ensemble members within probably limits to represent modelling uncertainty. This method is incorporated in UKCIP09.

Figure 11 Forecast Caspian Sea levels using the results of a range of GCMs and a range of emissions scenarios



2.2 The UK Climate Impacts Programme (UKCIP09)

In UKCIP09 the UK Met Office Hadley Centre explored the uncertainty associated with their climate model by varying certain model parameters within what were considered to be feasible ranges. In total 31 model parameters were varied, and about 300 model versions created. They were thus able to create a large ensemble from which to sample variability. Ensembles were created for three emissions scenarios, but no probabilities were attached to the emissions scenarios as they are considered to be determined by human choice. Probabilistic results were produced for each emissions scenario.

Probabilistic forecasts were produced for temperature and for precipitation on a 25 km grid for the whole of the UK. A "Weather Generator" was also developed that can be used to investigate extremes on a 5 km grid. The probabilistic forecasts are available for seven overlapping thirty year periods, stepped in ten year blocks. It is pointed out in UKCP09 that there are some common deficiencies in all models, and the probabilistic approach does not make up for these deficiencies. The UK Met Office does not recommend use of their probabilistic approach outside of the 10% - 90% range.

The weather generator produces time series of daily data on temperature (mean, maximum and minimum), precipitation, relative humidity, vapour pressure, solar radiation and potential evapotranspiration (no wind are produced). This is done for each 30 year period, and for each emissions scenario. The weather generator needs to be run about 100 times for any particular time slice. It can also be used to construct hourly data by disaggregation, but no new information is added when doing this. Data from the weather generator are not spatially consistent, and data from a series neighbouring of grids could not be used to prepare a time series of catchment rainfall for example.

2.3 Climate change and engineering design

In relation to water resources, climate change will impact on a number of key systems for which engineering design is required:

- Urban drainage
- Fluvial flood mitigation works
- Transportation cross drainage routes
- Agricultural field drainage rates
- Water resources reliability (surface and groundwater)
- Saline intrusion in coastal aquifers and estuaries
- Drainage in coastal areas with tidal outfalls
- Coastal flood defence

It is useful to consider how the UKCP09 approach could permit some of the above issues to be addressed.

Urban drainage

Urban drainage design is based on knowledge of the frequency of short duration high intensity rainfall events at any particular location. The Weather Generator that accompanies UKCP09 could be used to determine annual maximum one day rainfall at a particular location at different future planning horizons, for each of three available emissions scenarios, and any desired non-exceedance probability. This would then be distributed into hourly or subhourly data using a standard rainfall profile. Urban drainage is typically designed for relatively short return period events, that would typically have a non-exceedance probability of less than 0.9, and for which the Met Office consider their Weather Generator to be satisfactory.

Fluvial flood mitigation works & transportation cross drainage routes

Design flood estimates are often made using a single event rainfall-runoff model, driven primarily by estimates of precipitation at a defined critical duration and non-exceedance probability for the catchment area draining to the point at which the flood estimate is required. The Weather Generator could be used to generate point rainfall values at different representative locations in the catchment, at appropriate non-exceedance probabilities. From these, arealy reduced design catchment rainfall estimates would be produced for input to the rainfall-runoff model. Flood mitigation works are, however, generally designed for long return period events that typically would have a non-exceedance probability of 0.99 or greater. This is outside the Met Office recommended range and clearly a cautionary approach is required.

Agricultural field drainage

The approach would basically be as outlined above. Often longer duration precipitation events would be used, depending upon the type of crops being grown, and relatively short return periods. A typical non-exceedance probability would be 0.80.

Water resource reliability

An assessment of water resources reliability generally requires analysis of a long time series of hydrological data. For surface water resource assessment it would be streamflow data that are analysed, and for groundwater it would be data on all contributions to groundwater recharge. The UKCP09 probabilistic data does not provide any direct means of assessing water resources reliability. Included with supporting data from UKCP09, however, are eleven variants of 150 year regional climate model integrations (1950-2099). These data are available on a 25 km grid, and could be used to provide inputs to eleven hydrological modelling scenarios. The results of the scenarios could each be analysed for resource assessment purposes, and while a full probabilistic assessment could not be made, the range within which the resource assessment lay at any particular level of reliability could be assessed.

It should be noted that the approach outlined above permits quantification of water resource availability, but account must also be taken of the changes in water demand. Changes in potable and industrial demand result from socio-economic development and demographic shifts, and are not affected to a great extent by climate change. Changes in water demand for irrigated agriculture, may, however be much more significant.

Saline intrusion and coastal flood defence

In UKCP09, probabilistic estimates are given of relative sea level rise around the UK coastline. These data can be used directly in assessments of saline intrusion, coastal flood risk and impeded drainage from coastal towns and cities. The data could be used to adjust storm surge estimates, although a pragmatic approach to this is required. Urban drainage in coastal towns and cities will be affected by higher rainfall intensities and higher tailwater levels in levels, with increased risk of coincidence of storm surge with peak drainage rates.

Pragmatism in design

As UKCP09 has only been released, it has yet to find its way into design practice. In the immediate future, reliance will be placed on the previous pragmatic adjustments made to design parameters in the UK. Table 2 provides the present design guidance in the UK to take account of climate change risk.

Sea level rise estimates were better defined regionally following UKCIP02, and the regional net sea level rise allowances are as shown in Table 3.

In engineering design for flood mitigation or water supply, the approach is generally to design to a specified risk of failure, or for a specified level or reliability. When climate was assumed to be stationary, this involved a relatively straight forward approach to analysis. However, with a non-stationary climate, there has to be a managed approach of progressive intervention to maintain reliability (e.g. defence raising at regular intervals), or the application of a precautionary approach with less frequent intervention required, and initial over-design. Figure 12 demonstrates the concepts.

In many countries provisions are not made for climate change impacts in design, in part because of the level of uncertainty that exists in climate projections, and in part because well defined methodologies for incorporating climate change impacts do not exist. However, a "do nothing" approach will lead to higher failure risks, and to higher long term costs when maintenance and upgrading are considered.

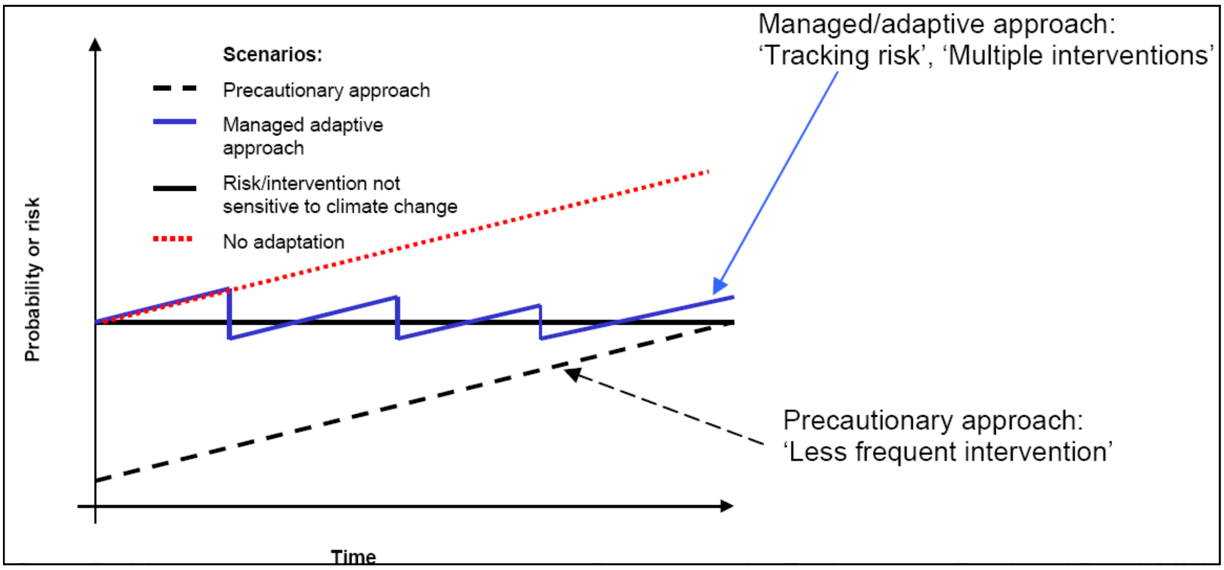
Table 2 Pragmatic adjustments to design parameters currently used in the UK

Parameter	***1990-2025***	***2025-2055***	***2055-2085***	***2085-2115***
Peak rainfall intensity (preferably for small catchments)	+5%	**+10%**	+20%	+30%
Peak river flow volume (preferably for larger catchments)	+10%	**+20%**		
Offshore wind speed	+5%		**+10%**	+10%
Extreme wave height	+5%		**+10%**	+10%

Table 3 Regional net sea level rise allowance for design in the UK

Administrative or Devolved Region	***Assumed Vertical Land Movement (mm/yr)***	***Net Sea-Level Rise (mm/yr)***				***Previous allowances***
		1990-2025	***2025-2055***	***2055-2085***	***2085-2115***	
East of England, East Midlands, London, SE England (south of Flamborough Head)	-0.8	4.0	8.5	12.0	15.0	6mm/yr* constant
South West and Wales	-0.5	3.5	8.0	11.5	14.5	5 mm/yr* constant
NW England, NE England, Scotland (north of Flamborough Head)	+0.8	2.5	7.0	10.0	13.0	4 mm/yr* constant

Figure 12 Comparison of approaches to managing climate change impacts



Source: Defra, 2006

3 Assessing Climate Change Impacts on Agriculture

3.1 Introduction

Globally, consumptive water use in irrigated agriculture far exceeds that in any other sector. Changes in crop water demands as a result of climate change could have a significant impact on water resources in many parts of China. Climate change may influence agriculture and crop production in a number of ways:

- elevated temperatures permit earlier planting dates;
- elevated temperatures may shorten crop growing period;
- with earlier planting and shorter growing periods, double cropping may become possible in areas where only single cropping was possible in the past;
- changes will occur in crop suitability;
- elevated CO_2 concentrations can result in higher crop yields;
- elevated CO_2 can result in lower crop evapotranspiration;
- potential evapotranspiration is likely to increase;
- changes in precipitation patterns may affect suitability of rain-fed agriculture and the requirement for supplemental irrigation.

There are clearly many interacting factors related to plant physiology and climate to consider, and added to these are the demographic and socio-economic factors that influence crop production methods and crop demand. The cultivated area in China has been decreasing, but the planted area has been increasing with more double cropping being introduced. About 20% of the cultivated area is now double cropped, and this trend is expected to continue. Climate change will make double cropping possible in more northerly areas, and there is evidence that double cropping does make for more efficient water use as water loss per crop from residual soil moisture during fallow periods is reduced. Also, as the rural population decreases, there will have to be consolidation of land holdings in larger farming units. In these larger units there may be other efficiency gains in terms of irrigation infrastructure for example that would encourage double cropping. The trend of declining cultivated area, particularly in water stressed areas is therefore likely to continue. If there is to be more double cropping then this must be accompanied by reductions in cultivated area, as otherwise water stress would again be exacerbated.

There have been significant changes in the composition of cropped area in China over the last 30 years. The area of the staple grain crops of wheat and rice has been in decline, while the area of maize, oil seeds, and vegetables has increased significantly. Figure 13 presents the observed national trends. Despite the reduction in the areas of rice and wheat, national production of these crops has continued to increase through continued yield improvements. Figure 14 shows how yields have improved for rice, wheat and maize over the past 25 years. Yields for rice do seem to be stabilising, and the indication is that maize yields are also stabilising. The trend in wheat yields does not appear to be slowing at present, however. However, these observations do not presuppose that future genetic or agronomic developments will not provide further improvements. They may well do.

Coupled with the changes in cropping have been changes in diet, with significant changes in meat, milk and egg consumption. The increased demand for meat and dairy products requires increased livestock numbers and increased production of forage crops for livestock. Maize is the main forage crop. Trends in per capita consumption of meat, milk and eggs are shown in Figure 15. The trends show no indication of levelling off, and the expectation is that they will continue in line with national economic growth as China's consumption approaches that of more developed countries.

Figure 13 Trends in planted areas of main crops in China

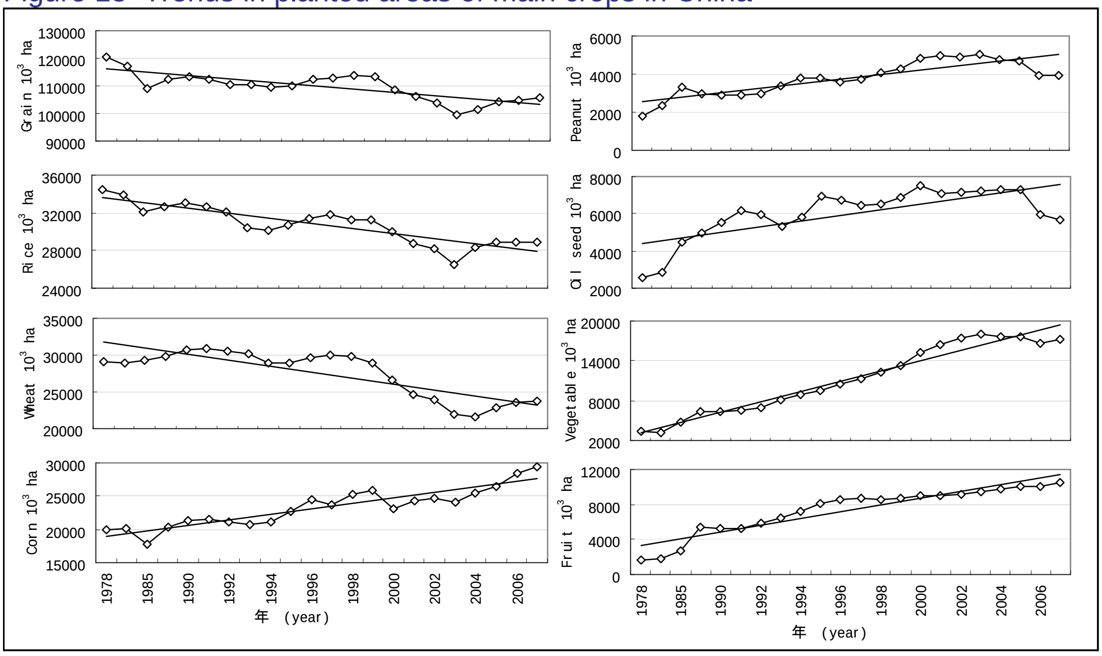


Figure 14 Trends in major crop yields in China

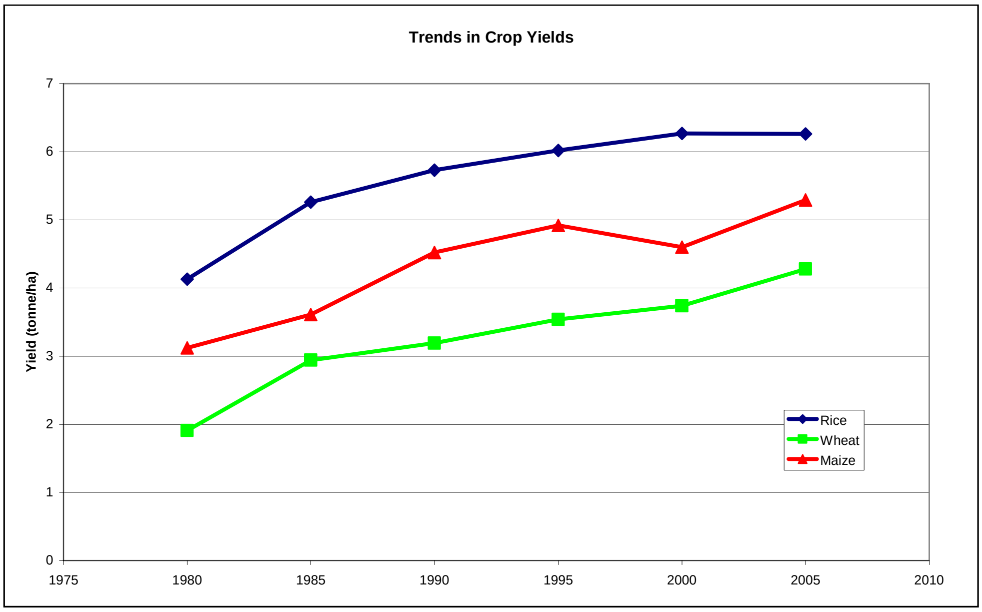
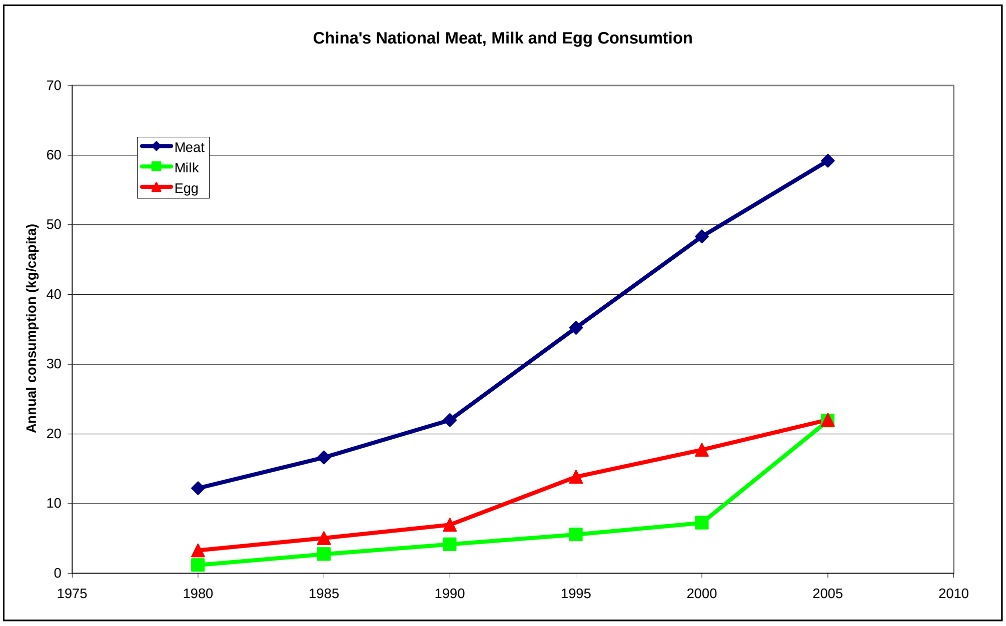


Figure 15 Trends in China's meat, milk and egg consumption



3.2 Modelling crop yield response to climate change

The effects of climate change on the yield of a number of crops can be modelled. FAO has recently released the AquaCrop model (http://www.fao.org/nr/water/aquacrop.html) which is capable of simulating yield response to elevated CO_2, and to changes in the length of the growing season for several herbaceous crops.

At present the most widely applied crop modelling software is the DSSAT (Decision Support System for Agrotechnology Transfer http://www.icasa.net/dssat). The DSSAT package incorporates models for some 27 different crop types, and has been in use for over 15 years by researchers in more than 100 countries. These models take account of a wide range of factors, including changes in planting dates, growing season lengths etc., and can crop water demands as we a crop yields.

In China the CERES-Wheat and CERES-Rice and CERES-Maize models (CERES – Crop Environment Resource Synthesis), which are modules of DSSAT, have been used by the Institute for Environment and Sustainable Development in Agriculture (IEDA) in a study entitled "Investigating the Impacts of Climate Change on Chinese Agriculture" (ICCCA). A focus of the study was on determining the potential impacts of climate changes on the yields of rice, maize and wheat. Two climate change emissions scenarios were considered: the SRES A2 and B2 scenarios. The UK Hadley Centre's PRECIS model was set up for China under the project, and run for the baseline climate (1960-90) and with the two emissions scenarios for the period 2071-2100. Boundary conditions were taken from HadCM3, the Hadley Centre's Global Climate Model. The PRECIS model operates on a 50 km grid and permits much more detailed resolution of local climate features than is possible with a GCM.

Crop modelling was carried out using the CERES (Crop Environment Resource Synthesis) and COPRAS (Cotton Production Regional Assessment System) models. The effects of temperature and CO_2 changes on crop yield were considered, but not the effects of pests and diseases, water availability, nutrients, socio-economics, or improved crop varieties. The results indicated that in north China yields of maize were likely to decrease, while yields of wheat were likely to increase. Cotton yields in north China were likely to increase.

The minimum data required for a crop yield model are summarised on DSSAT's website and include site weather data for the duration of the growing season, site soils data, and crop management and yield data on which to validate the model. The minimum weather data required include the latitude and longitude of the weather station used, daily incoming solar radiation, daily maximum and minimum temperatures, and daily rainfall. The soils data required includes the soil classification, slope, soil colour, permeability, drainage class, and a variety of soil profile data. Crop management data includes information on planting dates, planting density, row spacing, planting depth, crop variety, irrigation, and fertilizer practices. Data are also required on crop growth, yield, fertility and soil water, with which to validate the model. Applying a crop model is not a trivial task.

Recent studies by Xiong et al. (2009) have indicated that while in many parts of China the total water resource available is likely to increase with climate change, changes in rainfall intensity in many areas result in less effective precipitation for crop production and increased irrigation demand.

4 Assessing Climate Change Impacts on Non-irrigation Water Demands

4.1 Demand forecasting

Non-irrigation water demands include potable water demands, industrial water demands, and livestock water demands. The starting point for all demand forecasts is knowledge of the existing water supply situation, and of population distribution. Urban and rural potable water demand forecasts are based on forecasts of population growth and demographic shifts between rural and urban areas and changes in water use characteristics based on increasing standards of living, but allowing for improvements in water supply efficiency. Industrial water demand forecasts are based on assumed rates of industrial growth and of water use characteristics with consideration of water re-use practices. Growth in livestock demand is based on simple annual growth rates that are linked to population growth and livestock development policies – allowing for continued changes in diet that result in larger livestock numbers. Ideally the demand forecasts should be linked to the emissions scenarios used in the climate change modelling and due consideration given to changes in water use practices as a consequence of climatic changes. Consideration also has to be given to changes in water use as a result of water pricing and the government policy of achieving a water saving society acknowledging that current levels of water use are unsustainable, particularly in agriculture and industries. (Note: Nationwide, the cost of residential water use rose by 42 percent from 2000 to 2005, according to a survey of 36 cities by the National Bureau of Statistics. The average household water expenditure in 2004 still only accounted for 1.8 percent of the household income in Beijing. The upper limit of this ratio set by the World Bank for the developing countries is 5 percent. Changes in this area are expected but it is unclear as to the price elasticity that will apply in different areas.)

In demand forecasting, there is generally a short term forecasting approach that relies heavily on data and statistical analysis of water use trends. Longer term forecasting, which is required for the climate change studies, requires a more conceptual approach to the forecasting.

4.2 Population growth forecasts

Provincial level population growth forecasts for China, including demographic shifts from rural to urban areas, are available through the MWR, and some of these data are available at municipality level. General practice is to adopt high, medium and low forecasts, and to test the sensitivity of development proposals to changes in the resulting demand forecasts.

4.3 Changes in per-capita water demands

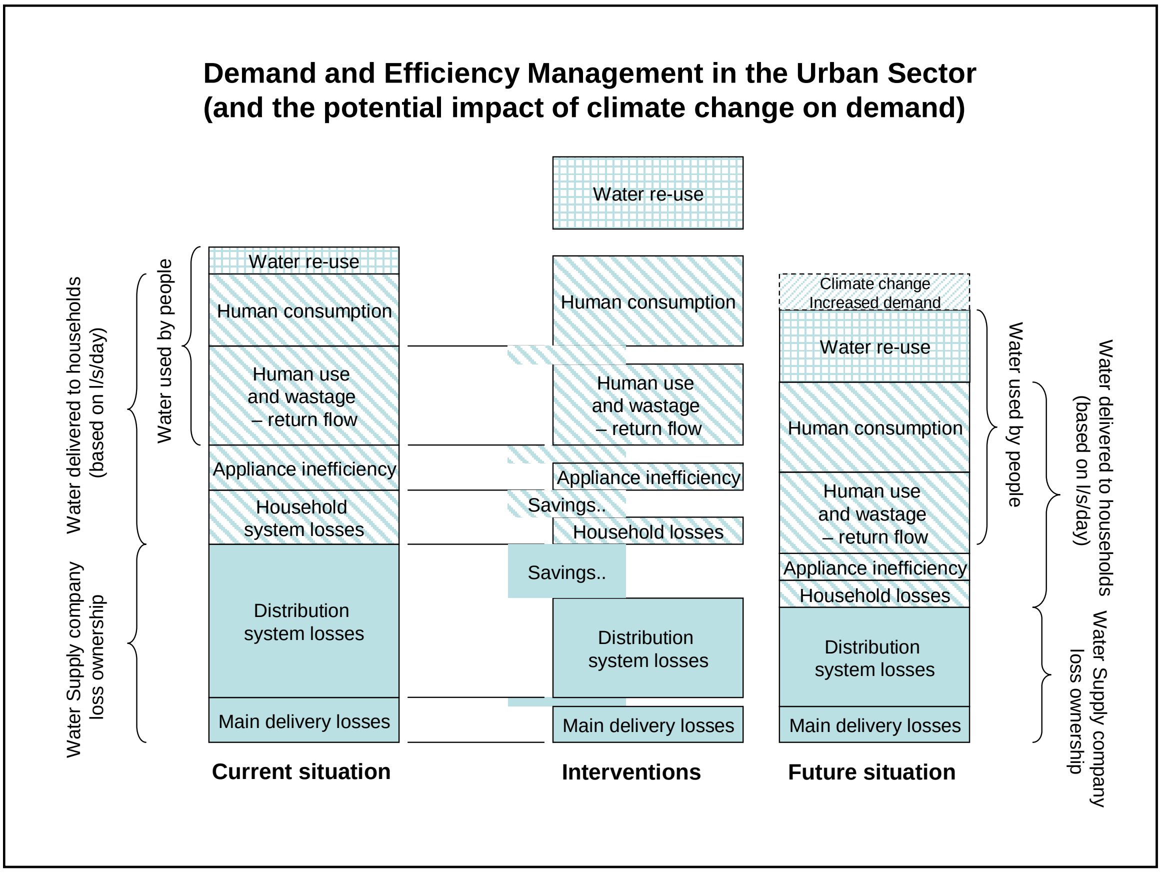
Existing per-capita water demand (or supply) estimates are generally available through municipal water affairs bureaus. In urban areas it may be expected that per-capita demands will converge in future. With economic growth there will be an increase in the use of household appliances such as dishwashers and washing machines, but it is also expected that there will be improvements in the water use efficiency of these devices, and leakage management within urban areas. In the UK, per-capita potable water demand in urban areas is typically in the range of

140 – 150 L/c/d, with negligible future growth expected. It is considered reasonable to expect that per-capita potable water demands in China will stabilize by 2020 at a more uniform figure.

A comprehensive study on the possible effects of climate change on water demands in the UK was published by Downing et al in 2003. Their study indicated that there could be modest increases in domestic demand in the UK in the range of 1.0%-1.8% by the 2020s, and in the range of 2.7%-3.7% by the 2050s, under a medium high global temperature increase. Given the pressures that exist on water resources in northern China, and the steps being taken towards demand management, it is reasonable to expect that any climatically induced changes in water demand will be very low. Figure 16 demonstrates how efficiency savings can accommodate demand growth.

Rural per-capita demands are likely to increase more significantly in future. These demands are likely to increase at a higher rate than urban water demands, in part because they are beginning from a lower base, and the gap between rural and urban living standards must be expected to decrease.

Figure 16 Potential of demand and efficiency management



4.4 Changes in livestock water demands

Livestock water demands are likely to increase as a result of increasing livestock numbers in the short term (local policies), but thereafter might be expected to stabilise and follow more closely with human population growth. There has been increasing demand for meat in China with changing dietary habits and this is having an impact on agricultural practices as the demand for fodder crop increases.

4.5 Changes in industrial water demands

The studies by Downing et al (2003) indicated that in the UK, climate change could increase industrial / commercial demands by 1.7 – 3.1% by the 2020s, and by 3.6 – 6.1% by the 2050s. They indicated that sectors such as soft drinks, brewing and leisure would have the largest increases, and that there were regional differences influenced by the mix of industrial sectors present. They found that changes in industrial demands were not particularly sensitive to the climate scenario assumed.

In China, future industrial demand for water will be driven mostly by economic growth in the coming years, and by shifting demographic patterns. Few industrial water uses are significantly consumptive (excepting some food processing industries) although often water is returned to river courses in a polluted state that reduces potential for its further utilization elsewhere in a basin. Increased recycling of water is to be expected in industrial processing in the future, thereby improving receiving water quality and reducing overall demand for certain processing uses. In northern China, the stress on water resources is such that means of constraining industrial water demands will be essential although it is appreciated that local economic drivers are likely to remain strong. Data on water use in various industrial sectors has been extracted from the Statistics Canada web site (www.statcan.gc.ca) and is presented in Table 4 in terms of the percentage of withdrawals actually consumed. On average consumption accounts for only 13.5% of industrial withdrawals.

Table 4 Industrial water consumption as a percentage of withdrawals in Canada

Industrial sector	% consumption
Food	20
Beverage and tobacco	50
Textile mills	16.3
Wood processing	25.3
Paper	5.2
Petroleum and coal	11.6
Chemicals	28.1
Primary metals	14.8
Transportation equipment	3.8
Miscellaneous	12.5
Total weighted average	**13.5**
Thermal-electric power	2.8

5 Assessing Climate Change Impacts on Water Resources

5.1 General

Climate change is expected to modify water resources in a number of ways. In global terms, the quantity of available water resources is expected to increase, but there will be shifts in the spatial availability and variability of resources. Some areas will become drier with increased drought frequency and severity, while other areas will become wetter with increased annual runoff. The seasonal distribution of runoff may change in many areas, and particularly in areas that are currently supplied by glacial melt water. In the near and middle term, rates of glacial melt are expected to increase, but in the longer term, as glacial storage is decreased, water supply from such sources will rapidly decrease and could disappear completely. In China the impacts of climate change on water resources will vary significantly regionally.

Assessing the impacts of climate change on water resources at regional, basin, and sub-basin scales is generally based on a series of modelling approaches. GCM results are downscaled either dynamically using a RCM, or statistically, and these downscaled results are in turn used to drive a rainfall-runoff model that might subsequently be used with a water resources systems simulation model. Various approaches exist, but in view of the changes in precipitation variability and intensity that are expected, deterministic approaches that attempt to model the physical processes of runoff and groundwater recharge generation are preferred.

A fundamental difficulty at present in assessing the impacts of climate change on water resources is that precipitation is one of the least well represented parameters in both GCMs and in RCMs. The difficulties arise in part as a result of scaling associated with grid averaged values, and through uncertainty in modelling the processes associated with precipitation formation. The scale issues are being overcome through the use of RCMs, and the science associated with representing precipitation generation processes is improving all the time. The confidence with which changes in precipitation can be forecast will continue to improve.

5.2 Practical downscaling

When results of a GCM are downscaled for hydrological modelling, data sets are prepared for the baseline climate that is generally still taken to be the 1961-1990 period, and for future climate scenarios at different planning horizons. Often 30 year blocks of simulated data are used. The 2040s for example would be represented by a time series of simulated data running from 2031 to 2060, and the 2080s by a period of data running from 2071 to 2100.

The output data required from a climate model for subsequent hydrological modelling are precipitation, and sufficient data from which to calculate potential evapotranspiration: maximum and minimum daily temperature, maximum and minimum daily relative humidity, daily incoming solar radiation, and wind speed. There are two approaches by which the downscaled simulated climate data can be used in hydrological modelling:

1. Changes in the monthly means of the climatic parameters are determined from the simulated climatic data between the

baseline and different planning horizons; these changes are subsequently applied to the observed historic climatic data to produce scenarios of future climate;

2. The monthly means in the simulated climatic data for the baseline period are compared with historic observations for the same period, and correction factors determined for the simulated data (these will vary throughout the model domain); the simulated base period data is adjusted and variances compared with observed variances; the derived corrections for the base period climate simulations is then applied to the simulated data at the different future planning horizons to create bias adjusted data sets.

The first of the above approaches was often used prior to RCMs becoming available. The main criticism of the approach from a hydrological point of view is that it is only the magnitude of the observed climatic data that is adjusted, and that the data used in scenarios contains exactly the same sequences of wet and dry periods as was observed in the historic series. The frequency of wet and dry periods does not change.

The second approach is generally now considered to be more appropriate. Two different approaches for transferring the climate change signal from a RCM to hydrological models have been addressed in recent literature (Lenderink et. Al., 2007; Graham et. Al., 2007a, Graham et. Al., 2007b). The scaling approach corrects future climate based on biases between present-day simulated climate and the observed climate. The delta approach adds the change between future and present day simulations to the observed climate. These studies discuss the pros and cons of both approaches. However, the best approach is likely to be model and basin dependent, therefore a test is necessary to determine the most appropriate approach.

Care is required in bias correction. Bias corrections are determined at discrete points in the model domain. These corrections must then be interpolated to each grid square in the model domain using surface fitting techniques. Surface fitting can lead to unusual results at domain boundaries, particularly when there is a lack of observed data close to the boundaries and if there are significant gradients in model biases. Topographic features may influence model biases, and it may not always be possible to objectively account for these. It is very important that adjustment fields are carefully reviewed before they are applied, and where large bias adjustments are made, the implications for extremes must be carefully considered.

The main advantage in using bias corrected RCM results directly is that the simulated data should properly represent expected changes in weather patterns and related sequences of wet and dry periods. Changes in the variance of RCM simulated data will be preserved.

5.3 Simulating climate change impacts on the hydrological cycle

A deterministic rainfall-runoff model is generally used to assess the impacts of climate change on river flows, and in some cases on groundwater recharge also. Groundwater recharge estimates are sometimes made from soil moisture accounting models that are often modules in deterministic rainfall-runoff models.

The approach may be summarised as follows:

- the rainfall-runoff model is calibrated on the basis of available historical hydro-meteorological data, and the statistical characteristics of the simulated flow series or groundwater recharge series established (this can be done for any process represented in the model);
- the model is then run with input baseline hydro-meteorological data that has been downscaled and bias corrected either by a RCM or through statistical techniques from GCM model results, and that is representative of the period of observed historical data; the statistical characteristics of the simulated flow series or groundwater recharge are compared with those derived from the simulations based on the observed historical hydro-meteorological data;
- if the statistical characteristics of the simulated flow (or recharge) series derived from climate model inputs are sufficiently close to those of the simulated flow (or recharge) series derived from the observed historic hydro-meteorological data, then the models can be used directly as forecasts or scenarios of future hydrological response;
- if the statistical characteristics of the simulated flow (or recharge) series derived from climate model inputs are not sufficiently close to those of the simulated flow (or recharge) series derived from the observed historic hydro-meteorological data, then changes in simulated flow characteristics for different future climates may be derived, but results should be compared with those developed from a delta-shift approach to hydro-meteorological data.

The approach is presented graphically in Figure 17. Calibration of the SWAT model on part of the Shiyang River Basin is shown in Figure 18.

Figure 17 Hydrological modelling for climate change

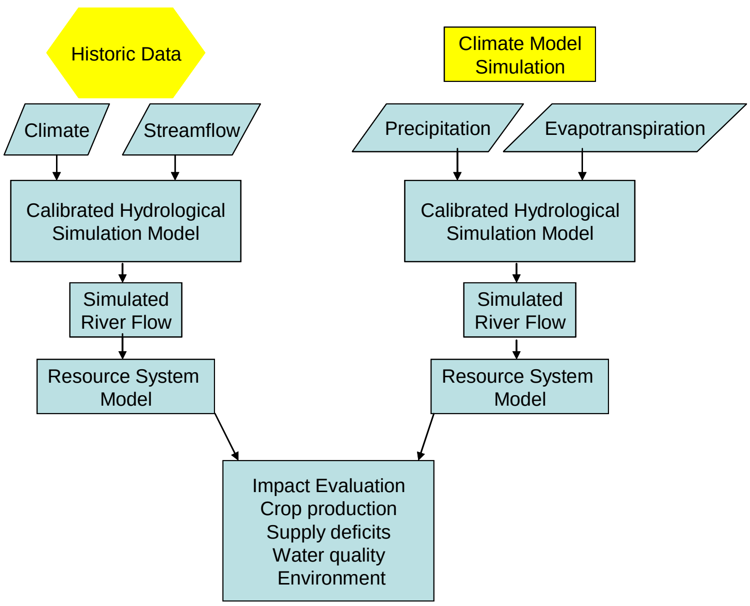
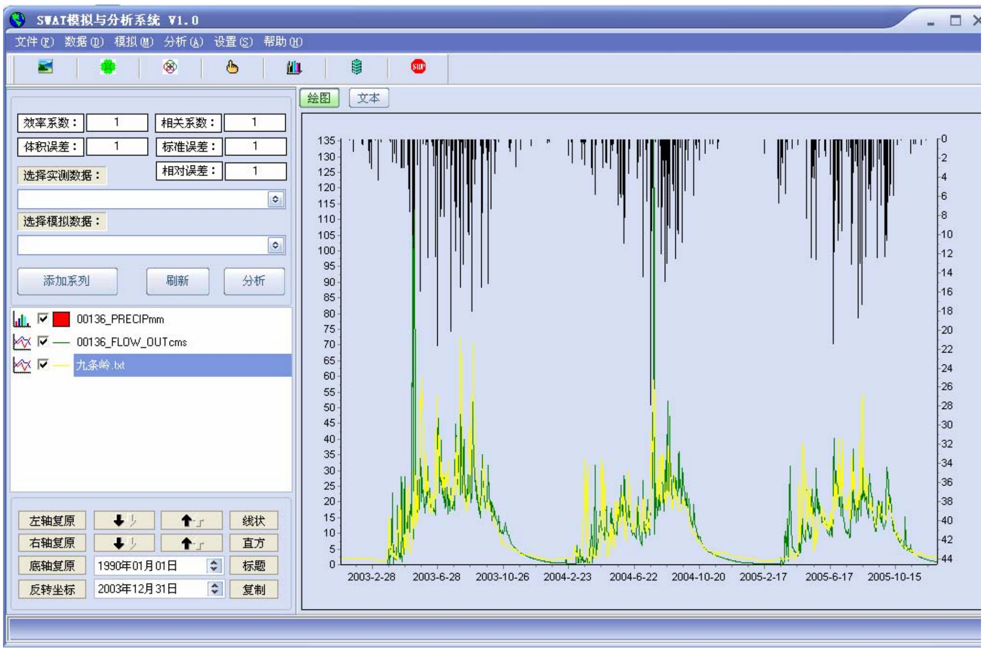


Figure 18 SWAT model calibration on the Zamu River in the Shiyang River Basin

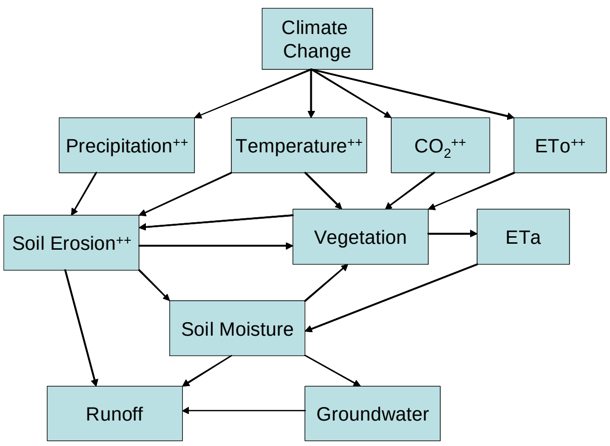


The basis of the modelling approach outlined above is that the hydrological conditions in a catchment do not change significantly as a result of climate change. However, this may not in fact be the case, and a hydrological model calibrated under present climatic conditions may not be representative of future climate conditions. As noted above, climate change will result in changes in precipitation and potential evapotranspiration, and simulating the impacts of these changes on runoff and groundwater recharge can be done satisfactorily if there are no changes in land cover and soil characteristics. Natural land cover and land use is, however, very likely to change with climate. Factors to consider include:

- CO_2 fertilization that may reduce transpiration;
- plant species may adapt, resulting in changes in interception storage, evapotranspiration and soil moisture balances;
- more intense rainfall may result in increased soil erosion, further impacts on vegetation cover and soil water balances, with corresponding changes in infiltration and runoff;
- the complex set of interacting vegetation and land surface processes are not yet represented in hydrological rainfall-runoff models.

The feedbacks and interactions involved at the land surface are indicated in Figure 19 below.

Figure 19 Links between land surface processes



6 Adapting to Climate Change

6.1 Adaptation defined

Numerous international organisations are addressing the issue of climate change and associated adaptation strategies and these organisations provide sources of useful definitions and outline information. The first box below provides a basic definition of '**adaptation**'.

> **Understanding Adaptation**
>
> From Department for Environment, Food and Rural Affairs (Defra) UK:
>
> *"Changing our behaviour to respond to the impacts of climate change is known as 'adaptation'. Adaptation to climate change involves making decisions that are sustainable, made at the right time, maximising the benefits and minimising the costs. Adaptation needs to be built into planning and risk management now to ensure the continued and improved success of businesses, Government policies and social operations."*

The second box provides a summary of considerations for adaptation strategy, derived from an international synthesis of adaptation responses.

6.2 Approaches to adaptation

There are two main types of adaptation: 'autonomous' and 'planned' adaptation.

- Autonomous adaptation is the reaction of, for example, a farmer to changing precipitation patterns, in that s/he changes crops or uses different harvest and planting/sowing dates.
- Planned adaptation measures are conscious policy options or response strategies, often multi-sectoral in nature, aimed at altering the adaptive capacity of the agricultural system or facilitating specific adaptations.

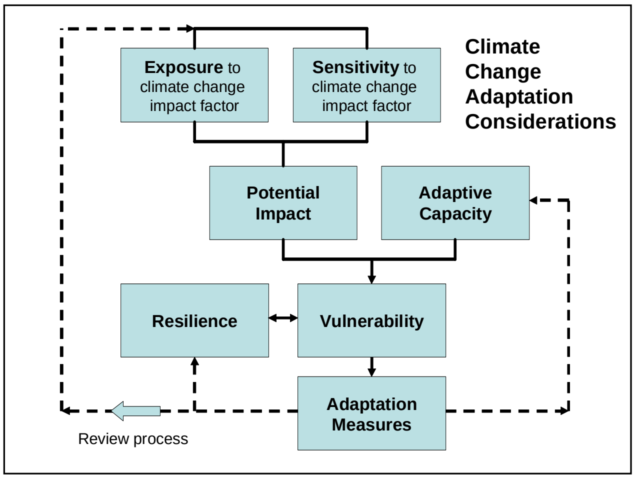
Autonomous adaptation is undoubtedly taking place, but it is unlikely to be sufficient. The concern is to ensure that there is adequate planned adaptation.

UKCIP (http://www.ukcip.org.uk) categorise adaptation "as measures and strategies that contribute either to:

- Building adaptive capacity – creating the information (research, data collecting and monitoring, awareness raising), supportive social structures (organisational development, working in partnership, institutions), and supportive governance (regulations, legislations, and guidance) that are needed as a foundation for delivering adaptation actions; or
- Delivering adaptation actions – actions that help to reduce vulnerability to climate risks, or to exploit opportunities."

Adaptation in water resources thus needs to be considered as a process.

Figure 20 Process for developing adaptation measures



Vulnerability and Adaptation …to the impacts of climate change

From the World Resources Institute:

"*The impacts of climate change are already upon us, and are likely to grow more serious even under the most optimistic mitigation scenarios. Given the high **vulnerability** of poor communities to the impacts of climate change, and the threats posed by global warming to the provision by ecosystems of critical services, efforts to adapt to the changing climate are intricately tied up in the broader challenges of development and ecosystem management.*

*The response to climate change will overlap heavily with traditional development concerns. A significant increase in the resources dedicated to sustainable development will be needed, since climate impacts are raising the costs of economic development and environmental protection efforts that are already under-resourced. Moreover, **effective adaptation** calls for the "mainstreaming" of climate responses into a wide range of planning and management processes. This means finding new ways to transcend institutional boundaries, bring together diverse stakeholders, and to incorporate complex information into decision-making.*

Strategy:

*National (or regional) development policies that take the changing climate into account will provide an essential foundation for enabling effective action on adaptation. WRI's **Vulnerability and Adaptation** project tackles questions of how policy design can respond to the range of challenges raised by climate vulnerability.*

Some of these questions include:

- *Are all adaptation activities a subset of sustainable development, or are there actions that are specifically needed to reduce vulnerability to climate change?*
- *What processes are needed to integrate adaptation to climate change into national (and/or regional) development plans?*
- *What information and institutions are required to promote adaptation activities?*
- *Once adaptation activities are implemented, how can progress be monitored?*
- *How can synergies between adaptation and mitigation be captured in national (and/or regional) plans?"*

http://www.wri.org/project/vulnerability-and-adaptation

Information sources on adaptation
http://www.climate-adaptation.info/
http://www.ccchina.gov.cn/cn/index.asp
http://www.sccip.org.uk/default.aspx?pid=1
http://www.ukcip.org.uk/
http://unfccc.int/2860.php
http://www.eldis.org/go/topics/dossiers/climate-change-adaptation
http://www.waterandclimate.org/
http://www.newater.info/index.php?pid=1000
http://www.weadapt.org/
http://www.aiaccproject.org/

It is important to use consistent terminology for this process:

- Exposure – to climate change of the system at risk, which may be defined in terms of geographical extent, location and distribution of the population or system at risk.
- Sensitivity – to climate variability.
- Adaptive capacity – of a system or population to adjust to climate change, to moderate potential damage, and to cope with the consequences of change; this will depend on institutional capacity to respond to change.
- Vulnerability – of systems to adverse impacts; this is a function of exposure to climate risk, sensitivity to climatic variability, and inherent capacity to adapt.
- Resilience – of a social or natural system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity of self-organisation and the capacity to adapt to stress and change.
- Flexibility; an effective approach to adaptation should consist of enhancing the flexibility or resilience of hard-to-reverse investments, particularly those expecting a long design life.
- Adaptation measures – actions to enhance resilience or reduce vulnerability to changes in climate.
- Adaptation pathways – for introducing adaptation measures (covering awareness, organisations, decision-making processes and leadership, skills, operational practices, etc).

As indicated in the figure above, the process should be iterative, to improve resilience and reduce vulnerability. This is achieved through active monitoring and feedback to achieve adaptive management. This iterative process was fundamental to the DFID-funded project, 'Impacts of Climate Change on Chinese Agriculture'. This included design of an adaptive framework, on the basis of studies in Ningxia.

Application of the framework in Ningxia highlighted important lessons and insights for wider adaptation measures in China:

- Adaptation must be seen as an ongoing process
- There is a need for awareness raising, flexible treatment of the framework and co-ordinated management across sectors
- Climate risks and adaptation priorities vary across the region and sectors
- Opportunities for adaptation lie in reducing vulnerability to existing climate hazards
- Consultation with stakeholders at all stages of the framework is crucial for identifying appropriate adaptation measures
- There are no blueprints for moving adaptation into the mainstream of policy. Local context is critical.

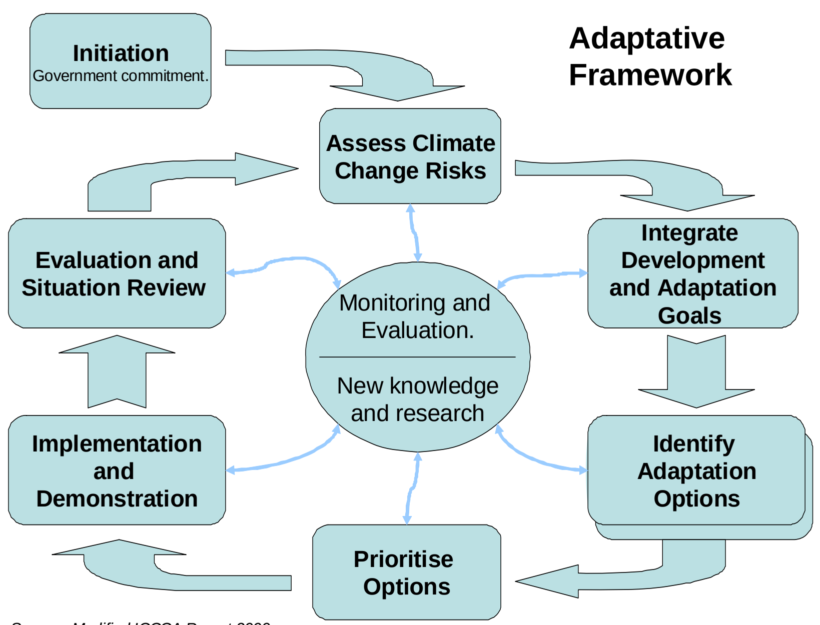
In addition, adaptation planning will be more effective if it is systematic and strategic: it is unlikely to succeed if done in isolation from other activities. A strategic planning approach will:

- engage stakeholders
- identify and set priorities for action
- assign responsibility for action and monitor implementation
- keep adaptation strategies under regular review.

The Adaptation Framework – Ningxia

The framework for **Ningxia** was developed with considerable input from stakeholder organisations in the region and in cooperation with the UK Climate Impacts Programme. Following the framework will not lead directly to the creation of an adaptation strategy or the implementation of adaptation actions. However, the process identifies a number of necessary and important stages (and the required resources) in developing an adaptation strategy. The framework should be viewed by individuals and organisations as an ongoing process of engagement with changing climate risks. It consists of six main stages and has a number of key elements:

- An iterative process is required so that any strategy is constantly updated based on appropriate planning cycles
- A continuous system of review and feedback encourages the engagement of local stakeholders to help identify and monitor relevant activities
- Following the framework and engaging with local stakeholders and institutions will help build capacity to achieve greater understanding and implement adaptation measures
- A certain amount of information (e.g. regional climate projections and an understanding of local vulnerabilities to weather events) is required
- Following this process should enable those involved in promoting adaptation to gather the key pieces of information necessary to develop an adaptation strategy and then refine it through implementation.



Source : Modified ICCCA Report 2009

6.3 Common features in adaptation strategies

This section outlines some general generic factors which should be considered in designing adaptation measures.

Adaptation strategies and IWRM. The handling of the development of adaptation strategies, researching climate change factors more deeply, the development of adaptation planning and subsequent implementation process could easily be incorporated within IWRM. All the requirements associated with establishing responses to climate change impacts are covered by the IWRM process especially the need for stakeholder consultation and participation. Many of the adaptation requirements will be dominated by improved water resources management, demand management and changed agricultural practices (both rain-fed and irrigated).

There are many uncertainties about the timing, direction, and extent of potential climatic change, as well as about its implications for society. However, the most important effect of climate change on water systems will be to increase greatly the overall uncertainty that water manager's have to deal with. Coping with such uncertainty is a key feature of IWRM, and incorporating the requirements to cope with climate change can be incorporated in IWRM planning and implementation

Consultation and engagement with vulnerable groups. Key agencies for disseminating information to vulnerable groups in the Chinese context include the Neighbourhood Residents Committee or the Village Committee. Working with relevant local NGOs, they could improve substantially the process of dissemination. As is well known, there has been a proliferation of environmental NGOs in China in the last decade, and most recently this has extended into the water resources sector (A good recent example of this is the participation of the Green Earth Volunteers and other NGOs in the water resources development planning for the Nujiang River, in Yunnan and Tibet).

Current vulnerability. Before adaptation strategies can be considered, current vulnerabilities need to be assessed in relation to different parts of the river basin, to different socio-economic activities and to the environmental situation. Livelihoods can often be strengthened to improve the ability to cope with current vulnerabilities, and these can form the basis for or provide guidance for developing strategies for adaptation to climate change.

Both natural and human systems are vulnerable to changes in water resources availability. However, this vulnerability is a continuation of vulnerability to the already high level of water stress for which coping strategies are being developed. Human vulnerability is likely to lead to significant changes in agricultural practices and production, and hence to rural livelihoods. Old and infirm people and poor people more generally will be most vulnerable to these changes. Natural ecosystems are also vulnerable, which is likely to result in increases in desertification, or deterioration in other systems (such as mountain environments).

Learning from other areas. An important aspect will be in knowing other regions that have had or have similar climatic and physical conditions to that which the region may be moving towards. Gaining knowledge of livelihoods and agricultural practices for example in such areas can greatly assist in understanding adaptation measures and potential future lifestyles that will be required in the region. Climate change will in many situations result in zonal shifts that can be monitored although extremes might be a new characteristic. Consequently, stakeholder and intra/inter institutional dialogue and knowledge sharing will become important.

Review of and monitoring climate change and adaptation responses. An important task at the provincial and river basin level is to keep a commitment to researching both climate change and topics related to adaptation measures at a local level. There is a danger that the issues will either not be considered worthy of attention until the issue is adversely affecting communities, or that communities and the agricultural sector will just 'sort it out themselves IF it happens'. This attitude must be avoided. Autonomous adaptation will occur, but it may not be sufficient and they may not have the resources or capabilities to adapt in the way that they need.

Potential adaptation measures should be based on sound research and it is important to establish a network of research organisations and dissemination programmes to support this process. Knowledge management will be a vital element in supporting the climate change adaptation process.

Direct impact of warmer conditions. It is clear that people will have to live under increasingly warmer conditions in future, and much has been written about the possible impacts of very high temperatures, particularly with regard to health. An increase in the frequency or severity of heat waves would cause an increase in mortality and illness (predominantly from cardio-respiratory factors). Studies of urban populations in temperate Asia have indicate that the number of heat-related deaths would increase several-fold in response to modelled climate change scenarios for 2050 (see, for example, the Intergovernmental Panel on Climate Change: Special Report On the Regional Impacts of Climate Change: An Assessment). Increases in non-vector-borne infectious diseases-such as salmonellosis, and other food- and water-related infections-could also occur as a result of climatic impacts on water distribution, temperature, and micro-organism proliferation.

6.4 Financial and economic aspects of climate change

The Stern Review on the Economics of Climate Change, a report written for the British Government, demonstrated that adaptation to climate change is economically justifiable, though it recommends caution in this area and stated that the model used for economic analysis (PAGE2002) *"must rely on sparse or non-existent data and understanding at high temperatures and in developing regions, and it faces difficulties in valuing direct impacts on health and the environment. Moreover … the PAGE2002 model does not fully cover the 'socially contingent' impacts. As a result, the estimates of catastrophic impacts may be conservative, given the damage likely at temperatures as high as 6 – 8 C above pre-industrial levels."*

PAGE2002 indicates that, *"in industrialised parts of the world, adaptation will reduce the impacts of climate change on market sectors of the economy such as agriculture by 90%, at all levels of warming. In lower-income regions—Africa, India and Southeast Asia, and Latin America—adaptation reduces market impacts by 50%,* *irrespective of warming. Worldwide, non-market impacts, primarily on human health and ecosystems, are reduced by 25% in value terms through adaptation, again at all levels of warming. This lower non-market adaptive capacity partly reflects the insuperable challenges facing natural systems in adapting to rapid shifts in habitat conditions. Adaptation is highly cost-effective in PAGE2002, coming at a fraction of the cost of avoided impacts as global mean temperatures rise to higher levels".* (Simon Dietz, Chris Hope, Nicholas Stern & Dimitri Zenghelis, World Economics Vol. 8 No. 1 Jan-Mar 2007).

A simple analysis of the economic productivity of water has recently been undertaken in the Shiyang River Basin (SRB) under various climate conditions, taking account of on-going IWRM / water demand management (water saving society) measures. Under the conditions prevalent in the SRB, it is not considered appropriate yet to distinguish between measures needed to cope with the existing unsustainable situation and with future climate change adaptation requirements. The economic analyses thus leave the question of what the additional cost of adaptation beyond that of 'normal' water management will be and who should bear it. These calculations do, however, confirm the economic justification for adaptation measures.

Document Reference Sheet

Glossary:

IPCC	**Intergovernmental Panel on Climate Change**
AR4	Assessment Report 4 of the IPCC
Anthropogenic	A result of human activity; human influence
GCM	Global Circulation Model
AOGCMs	Atmosphere Ocean Global Circulation Models
MMD	Multi-model Data Set
Adaptation	The process of changing our behaviour to respond to the impacts of climate change

Bibliography:

SL documents 183-2005

IPCC, Working Group 1

IPCC, Working Group 2

IPCC, Assessment Report 4

IPCC Assessment Report 3

UK Climate Impacts Programme 2009

Related materials from the MWR IWRM Document Series:

Thematic Paper 1.8	Water Demand Forecasting
Advisory Note 1.8/1	Water Demand Forecasting
Advisory Note 1.8/2	Agricultural Water Use Norms

Where to find more information on IWRM – recommended websites:

Ministry of Water Resources: www.mwr.gov.cn

Global Water Partnership: www.gwpforum.org

WRDMAP Project Website: www.wrdmap.com

China – UK, WRDMAP

1. WRA

Integrated Water Resource Management Documents
Produced under the Central Case Study Documentation Programme of the GoC, DFID funded, Water Resources Demand Management Assistance Project, 2005-2010.

Documents will comprise of:

Thematic Papers

Advisory Notes

Manuals

Examples

Training Materials

IWRM Document Series materials, English and Chinese versions, are available on the following project website

WRDMAP Project Website: www.wrdmap.com

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