Tutorial on Projected Climate Change and Impacts

1.0 Background

State-of-the-art climate, or "earth system", models rely on our best available understanding of the science governing atmospheric, land and oceanic processes. The models utilize sophisticated mathematical approaches and are implemented on some of the world's fastest supercomputers. Precise simulations are generated in space and time for the entire globe at daily, yearly decadal and century scales. Thus, the Community Climate System Model, version 3 (CCSM3), which includes atmospheric and land components, currently generates outputs for variables like temperature, precipitation and stream flow at 75 km spatial resolutions for every six hours from 1870 till 2100. However, the generation of projections at decadal to century scales in the future requires an assessment of demographic, economic and technological changes. The Intergovernmental Panel on Climate Change (IPCC) handles these uncertainties through what are called the Special Report on Emissions Scenarios ("SRES scenarios"). The projections reported here are based on what is known as the "A1FI" scenario. The A1 storyline "describes a future world of very rapid economic growth, global population peaks in mid-century and declines thereafter, and the rapid introduction of new and efficient technologies" (IPCC Special Report on Emissions Scenarios: Summary for Policymakers), while the specific A1FI scenario describes a fossil-fuel intensive development of energy technology. The fact that observations in recent years appear to align themselves with projections from fossil-intensive scenarios have sparked significant interest in A1FI projections. The CCSM3 model is co-developed by the Oak Ridge National Laboratory (ORNL) and the National Center for Atmospheric Research (NCAR), while the model outputs (hindcasts and projections) are archived on ORNL's computers. Analysis of the model outputs may range from simple operations like averaging to sophisticated approaches for extreme values and nonlinear correlations, which in turn may require complex mathematical methods and fast supercomputers. The results presented here[*] are exemplary rather than definitive, but nonetheless provide insights into a plausible climate change scenario and potential impacts.

2.0 Analysis Setup

The results on the website, as of Tuesday, July 15, 2008, reflect the following:

1. A1FI projections from CCSM3
2. Decadal Change
    a. Average of 2050 (2045-2055) minus average of 2000 (2000-2009)
    b. Average of 2100 (2090-2100) minus average of 2000 (2000-2099)
3. Regional Change: China, European Union, India, US
4. Variables
    a. Temperature (difference in monthly averages) in degree Celsius
    b. Precipitation (difference in monthly averages) in cm (rainfall only)
    c. Stream flow (difference in annual averages) in m^3/s
5. CCSM3 outputs aggregated in time and interpolated in space

[*] Website: http://www.ornl.gov/knowledgediscovery/WarGaming

3.0 Regional Changes in Mean Climate and Hydrology

3.1 Caveats

While insights about changes in mean climate and hydrology can be directly inferred from the maps, any insights about extremes must be interpreted with caution at this time. However, preliminary insights about extremes may be suggested on occasion, which need to be verified by additional analyses of the underlying data. As of now, the analyses in this section focus primarily on insights about decadal changes in regional mean values, unless otherwise stated. The assertions about extremes are conjectural. It should be noted that these results are from a single model run according to the A1FI scenario. It is common for up to multiple model runs to be completed and this allows a better characterization of the variability and uncertainties inherent to the modeling system.

3.2 China

<u>Mean Summer Temperature:</u> The average summer (July) temperature in the entire country show a relatively minor increase of 1°C–2°C in 2050 compared to current temperatures. However, a large area, surrounding Beijing and along the China-Mongolia border shows almost no perceptible temperature increase. This area coincides roughly with the Gobi desert. The largest projected temperature change in 2050, about 2°C–3°C, occurs in the West (North, North-Central and South), which include some uninhabited lands (deserts, water bodies, mountain ranges and plateaus) but also the politically active regions of Tibet (including Lhasa) and the Xinjiang Uygur autonomous region. When compared with the current (2000) summer temperatures, the average temperatures in parts of Tibetan plateau which were below freezing appear to cross the threshold to above freezing. This may have an impact on the areas which are currently permanent glaciated. This may be very important in the timing and magnitude of the hydrologic cycle.

<u>Mean Summer Precipitation:</u> July precipitation decreases along almost the entire Eastern coast (including cities like Shanghai and Wuhan) and Hong Kong roughly by about a fifth to a quarter, and even about a third in some places. In the already arid regions of the sensitive West and North-West regions, there is further decrease in summer rainfall.

<u>Annual Stream flow:</u> Almost all the major rivers, including the Huang He and Yangtze which flow into the populated eastern seaboard, as well as the Brahmaputra (or, the Tsangpo) and Mekong which flow into India and Burma, show a significant decrease in the average annual flows.

<u>Mean Summer Wetness:</u> Precipitation less evapotranspiration ("P–E") over land provides an indication of the "wetness", in terms of the overall water content in the soil (including surface and sub surface water) and vegetation. The average summer, or July, (P–E) in Central China increases by up to 7 cm, while the most populated and cultivated areas in the east shows a decrease of 4 cm.

<u>Temperature Extremes:</u> The possibility of an increase in heat waves or cold spells appears relatively low especially since most of the relatively larger temperature increase

in the summer is confined to regions which are relatively cooler on the average. However, the south eastern coastal areas, which are already warm and heavily populated, do grow warmer by about a degree to a couple of degrees. However, rigorous insights on temperature extremes cannot be developed with an analysis geared towards extremes.

Hydrological Extremes: No direct insights can be drawn about extreme storms or possible increase in flood hazards from the maps, especially because floods may often occur due to extreme storms rather than average change in rainfall. However, the reduced annual stream flows, especially in densely populated regions, suggest the possibility of droughts more than floods.

3.3 European Union

Mean Seasonal Temperatures: The summer (July) temperatures in the European Union appear to increase uniformly in 2050 by about one to two degrees Celsius in the entire European Union, except on the West (all the way from Sweden and Finland to Poland, Austria and the Italian Alps) where the temperature increase is about 2°C–3°C. The additional temperature increase happens on the border with Russia and the republics of the former Soviet Union. The shape of the additional warming does not correspond to the current (2000) summer (July) temperature patterns, but somewhat to the current lows in the winter (January) temperature patterns. This is somewhat intriguing and may indicate an artifact. However, the summer temperature increases significantly in 2100 and the patterns of increase appear different compared to the 2050 patterns. The countries in the Balkan regions, Austria, and parts of the Italian Alps have projected average monthly temperature changes of 8°C–9°C. This implies a sub-tropical to tropical climate for most parts of Southern Europe. The increases in temperature in Spain, as well as most of France and Germany, range from 6°C–7°C, which implies that even northern France and Germany begins to resemble current South Italy and may lend credence to the so called "Africanization of Spain" theory. The winter (January) temperatures increase by about one or two degrees Celsius in most of the western parts of Europe, but by one or two additional degrees in the North and Eastern part of the European Union, which are much cooler (with below freezing average monthly temperatures) to start with. Thus, these latter regions may get a bit of respite from the harsh winters. This trend for winter temperatures appears to continue into 2100, with areas experiencing very cold winters in the north and eastern parts of the European Union getting milder.

Mean Summer Precipitation: Trends in July precipitation for 2050 shows nearly the entire European Union getting relatively drier, with a few areas, which usually get relatively more rainfall in July (e.g., parts of Southern France, South Germany, Switzerland and northern Italy, as well as the Scandinavian countries), drying by as much as a fifth to a quarter. The major exception appears to be the area near Greece, Bulgaria, Serbia and Bosnia, which shows a substantial increase in rainfall compared to current conditions in July. Europe has significant spatial variability in the seasonality of rainfall patterns, thus considering rainfall in the month of July alone (or even just summer rainfall alone) may not provide a complete picture of the precipitation patterns.

Annual Stream flow: The entire European Union, except the Scandinavian countries and parts of northern Germany, Belgium, Scotland and northern Poland, show a significant decrease in annual average stream flow by 2050. The most pronounced effects appear to be in the Danube, which flows right through Serbia and Bulgaria, as well as the Seine in France and a few rivers in the Iberian peninsular region.

Mean Summer Wetness: Switzerland and the Scandinavian countries exhibit the largest decreases in (P–E) on the average in the summer (July), with decreases of up to 3 cm expected in northern Norway and Sweden and central Finland. Land areas adjacent to the North Sea will see slight increases in (P–E), up to 1 cm, as will many of the former Eastern Bloc countries.

Temperature Extremes: No insights about temperature extremes can be drawn from the maps, although the very high temperature difference in 2100 does appear to corroborate previous studies which suggested the possibility of more intense, more frequent and longer duration heat waves in parts of Europe in the 21st century.

Hydrological Extremes: Just as in China, no direct insights can be drawn about extreme storms or possible increase in flood hazards from the maps, especially because floods may often occur due to extreme storms rather than average change in rainfall. However, the reduced annual stream flows, especially in densely populated and relatively poorer Southern regions, suggest the possibility of droughts and water scarcity more than floods by 2050. The fact that southern Europe is getting both significantly warmer and dryer may have additional consequences.

3.4 India

Mean Seasonal Temperatures: Summer (July) temperatures appear to increase uniformly in the Indian sub-continent by less than a degree Celsius in 2050 and about one to two degrees in 2100. However, the Kashmir region along the Himalayas where the borders of India, Pakistan and China merge appear to show enough warming by 2050 to nearly get above freezing and by 2100 the region gets significantly above freezing, with possible implications for snow melt of the major glaciers. Winter (January) temperatures increase by a couple of degrees in the entire sub-continent rather uniformly. There is an interesting warming pattern (about 2°C–3°C) in 2050 right on the source of four major rivers, specifically, Brahmaputra, Sutlej, Indus and Karnali, in and around the Lake Manasarower (Mapum Yumco) in Tibet. The warming pattern encompasses Mount Kailash, the legendary abode of Lord Shiva. The warming pattern intensifies in 2100 when a similar smaller pattern develops near the source of the Ganges. These circular patterns of warming may be an artifact caused by the presence of the lake and the inability of climate models to resolve the area adjoining a lake perfectly. The Tibetan plateau and almost the entire Indian sub-continent grow significantly warmer by 2100, with implications for snowmelt in the Himalayas, among other impacts.

Monsoon Precipitation: The monsoon (July) rainfall shows interesting patterns by 2050. The monsoon in Arabian Sea appears to lose about a quarter of the total intensity in the northern part of the Western Ghats mountain range near Bombay, while the Eastern and

Southern parts of South India get more rain. The Bay of Bengal monsoon appears to intensify and both the east-central part of India and Northwest India / Pakistan get more rainfall. There is almost no change elsewhere, especially in the Gangetic plain. A small area near Chherrapunji, which gets the highest rainfall in the world, appears to grow a bit wetter in July. However, this is small and may be an artifact.

Annual Stream flow: India is the only region of the four regions considered here which show an overall increase in the annual average stream flow. India is also the only region (out of the four analyzed here) which lies completely in the tropics / sub-tropics. While it is likely that stream flow increases in the low latitudes and decreases in the higher latitudes, this remains to be proven based on additional regional analysis. In any case, the average stream flow increases for nearly all Indian rivers in 2050 and the increasing trends continue in 2100. The Ganges and the Indus, which flow from India to Bangladesh and Pakistan respectively, show significant increase in average annual runoff. Most South Indian rivers, namely Mahanadi, Narmada, Godavari and Krishna, show an increase as well. The Brahmaputra is the only river which shows a decrease in the Tibetan plateau and shows no increase near the mouth in Bangladesh.

Mean Summer Wetness: While northeastern India may see increased "wetness" (P–E) of up to 7 cm during July, a small area to the south of Bombay will simultaneously experience increased "dryness" (reduced P–E) of as much as 14 cm. On the whole, while a large proportion of the Indian sub-continent will experience increased wetness, a swath around the western city of Bombay and some northern lands bordering Nepal and Bangladesh being the exception.

Temperature Extremes: Just as for the other regions, rigorous insights on temperature extremes cannot be developed without detailed extremes analysis. However, the fact that summer temperatures do not rise significantly in the Indian plains but winter temperatures do in most of the north and central India, suggest that winters may become milder and summers will remain the same. Temperature related extreme events may be more likely to occur from snowmelt in the glaciers of the Himalayas, where significant warming appears to occur.

Hydrological Extremes: Just as for the other regions, no direct insights can be drawn about extreme storms or possible increase in flood hazards from the maps, especially because floods may often occur due to extreme storms rather than average change in rainfall. A recent published article showed from observations that while monsoon rainfall on the whole may exhibit a slightly decaying trend, localized extreme rainfall events may have actually increased. In addition, increased annual stream flows, especially in densely populated regions, suggest the possibility of floods more than droughts. This is the only one (of all four) regions where water (stream flow) appears to be growing more abundant and the region is getting wetter rather than dryer on the average.

3.5 United States

Mean Summer Temperature: The increase in average summer (July) temperatures in 2050 and 2100 show a pronounced east-west (longitudinal) structure almost for the entire country. In 2050, the eastern seaboard, all the way from the heavily populated east coast (except Florida, which shows a degree of additional warming) to the longitudinal extent marked by east Tennessee and Indiana show an average monthly increase of 1°C–2°C, while most of Florida and the central US (from Illinois and Alabama in the east to the eastern parts of New Mexico and Montana in the west) show an increase of 2°C–3°C. The region around Nebraska shows slightly lesser increase compared to the surrounding region, with projected increase (in/near Nebraska) of 1°C–2°C. However, the rest (western part) of the country gets significant warmer, with temperature increases of 4°C–5°C. Even the west coast appears to suffer an increase of 3°C–4°C in mean monthly July temperatures by 2050. These increases would make the summers of Washington and northern Oregon as intense as current summers in northern California, while summers in the US part of California as well as Nevada and Arizona would begin to resemble summer conditions currently prevalent in Mexico. The warming trend continues into 2100, with almost identical longitudinal structures, but with couple of degrees (Celsius) of additional warming. Thus, by 2100 the eastern part of the country is projected to warm by about 3°C–6°C on the average and the western part by about 6°C–8°C. The increased summer temperatures, especially in the west, appear to be significant enough to alter comfort levels of current populations and perhaps alter some patterns of travel, vacation and retirement planning.

Mean Summer Precipitation: The average summer (July) rainfall appears higher in most of the Eastern US (other than Florida and southern Georgia) as well as in the Midwest, parts of central US and parts of New Mexico and Texas. In the Western US, there is significant reduction in summer rainfall. Roughly speaking, the rainfall shows an increasing trend for July in areas which get more rainfall compared to other parts of the US, and a decreasing trend in areas which get less rainfall in July. This may exacerbate existing problems related to both floods and droughts (or water scarcity), although more detailed study on extremes must be performed before any conclusive assessments.

Annual Stream flow: Significant reduction in annual average stream flows is projected for all rivers by 2100. The most notable are the major rivers, namely, Columbia, Colorado, St. Louis and Mississippi. This suggests a major stress on the water resources.

Mean Summer Wetness: The eastern USA will experience more significant changes in summertime (P–E) than the western USA. The tip of the Florida peninsula exhibits the greatest likelihood of drying (up to 7 cm reduction in July P–E), which will likely increase the strain on already overdrawn fresh groundwater supplies. West of the Rocky Mountains, minimal decreases in P–E of about 1 cm will occur. There will be some slight increases in wetness of about 1 cm along the eastern portion of the Rockies extending down into central Texas. A roughly triangular area of increased wetness of up to 2 cm can be seen stretching from Tulsa, OK in the west to Sault Saint Marie, MI in the north to Virginia Beach, VA in the east. Within this moisture triangle, particular wetness increases of 2-3 cm in net P–E are projected over the Mississippi River area north of

Memphis, TN and over the center of North Carolina. The north-south trending portion of the wetness triangle appears to reflect the presence of the Appalachians. The east-west portion of the wetness triangle may result from frontal precipitation patterns in the region. The heavily populated northeast (New Jersey and portions of New York), will experience decreases in P–E of up to 2 cm/month.

Temperature Extremes: No detailed insights about temperature extremes can be drawn from the maps, although the very high temperature differences both in 2050 and (more intensely) in 2100 do appear to corroborate previous studies which suggested the possibility of more intense, more frequent and longer duration heat waves in parts of the US in the 21st century. A rigorous study on extremes appears urgently needed in the entire US, especially the Western regions.

Hydrological Extremes: No direct insights can be drawn about extreme storms or possible increase in flood hazards from the maps, especially because floods may often occur due to extreme storms rather than average change in rainfall. However, the reduced annual stream flows all over the US suggest the possibility of droughts more than floods. While the average July rainfall appears higher in most of the Eastern US (other than Florida and south Georgia) as well as in the Midwest, parts of central US and parts of New Mexico and Texas, even in these regions the average annual stream flow is lower suggesting reduced rainfall in other seasons. In the Western US, drying is consistent: in the summer month and in terms of average annual rainfall. This is combined with very high warming compared to the central and eastern US. Thus, significant dryer and hotter climatic conditions are expected in the entire Western US compared to current conditions, which may have significant impacts on hydrological cycle and possibly water-related extremes that may impact agriculture. A recent published article reported how climate change may drastically impact water resources management in the region (western US).

4.0 Plausible Relations to Regional Impacts Assessments

4.1 Population Projections

Population growth and distribution are critical factors in assessing regional impacts of climate change. Here we have developed maps for population counts based on the IPCC SRES A1FI scenario, which make assumptions about population projections at country levels from now till 2100. The IPCC scenarios, however, do not provide precise grid-based population projections. Here we have utilized the state-of-the-art 30 arc-second (about 1 km in the US) LandScan Global population model and database, developed at ORNL, to spatially disaggregate the population projections. LandScan data are generated for current population and not for projections. Thus, while our country-level estimates are based on projections, the spatial distribution is based on current population estimates.

4.2 Caveats

While we have investigated regional changes in climate means as well as explored population projections, impacts assessments and corresponding insights based on the results reported here must be interpreted with caution for the following reasons:

1. The analysis of regional mean change is incomplete. Given time and resources, we have only looked at a few variables. Thus, we have investigated monthly averages for one or two months for temperature and precipitation, and annual average stream flow.
2. We have not performed any rigorous analyses of extreme values. While the data and the methodologies for extremes analysis exist (in fact, some have been recently developed at ORNL and reported in the published literature), time and resources have not permitted a detailed analysis in the context of this study. Thus, insights about extremes are qualitative and conjectural.
3. Integrated assessments of climate change impacts need to consider not just the change in the mean or extreme values of climate variables, but also a variety of economic, technological, societal and human issues. Thus, changes in population and demographics, as well as a variety of "human factors", need to be considered in conjunction with projected climate change to determine the overall effects on water resources, agriculture, energy usage, disasters and humanitarian aid, as well as regional tensions and disputes. We have not even begun this analysis in this report.

The following is presented as suggestive of the type of analyses that can be done with the intersection of climate change and population data, and the following should be viewed in that light, as an approach, rather than as even a preliminary analyses.

4.3 Infrastructural / Sector-wise Impacts

Accepting the caveats in 4.2, we will attempt to generate plausible inferences about regional impacts by considering five human factors / infrastructural sectors (Table 1):

1. Water Resources Management
2. Agriculture and Food Production
3. Energy Consumption and Management
4. Natural Hazards and Humanitarian Aid
5. Regional Tensions and Disputes

Table 1: Regional Impacts Assessments*

Sector \ Region	China	European Union	India	United States
Population (2050)	Increase in the eastern region, especially large in the urban regions; No change elsewhere	Overall increase in Western Europe; No change in Scandinavia or in the east	Significant increase in the entire region, especially in the urban areas and the Ganges plain	Increase in the eastern half, especially urban areas, and isolated urban pockets in west coast
Population (2100)	Significant decrease in the eastern half; No other major change	Slight increase in Western Europe and decrease elsewhere	Significant decrease in the entire region, other than Nepal	Slight increase in the eastern half and a few other isolated urban areas
Water Resources	Significant water scarcity in 2050; Less population in 2100 helps	Water short-fall likely in 2050 and even beyond due to population	Increased supply and demand may compete till 2050	Less supply in the west and elsewhere but more demand in the east
Agriculture / Food	Dry conditions in the eastern cultivatable lands may cause food scarcity	Dryer south east and warmer south may impact agriculture	Winter crops may be impacted by increase in temperatures	Croplands in the west and Midwest may be affected by reduced water
Energy Usage	No warming related change as temperatures grow milder	Increase in AC usage, especially in the South	No change for 2050; Less winter heaters in 2100	Increase in AC usage in the West and other areas
Hazards and Human Aid	Drought appear more likely than floods; water and food scarcity may require prompt delivery chain	Droughts, dry conditions and heat waves may imply assistance for less developed EU nations	Increased chance of flood hazards may require enhanced humanitarian assistance	Droughts and water scarcity may mean that farmers will require federal subsidies and assistance
Regional Tensions	Reduced flow in the Brahmaputra may cause some water disputes with India	Possible water disputes in the tense Balkan regions and the south-east	More water may reduce water disputes with Pakistan or Bangladesh	Dryer condition may increase water disputes between states

* Notes: (1) The caveats described in Section 4.2 should be applied to the inferences in the last five rows of this table, particularly the last two (hazards and tensions). (2) Population projections at country levels are based on IPCC scenarios, but spatial distributions are based on current estimates (see Section 4.1).