VULNERABILITY AND ADAPTATION ASSESSMENT

Regional Climate Change Scenarios

FINAL REPORT

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1. Introduction

The development of regional climate change scenarios was undertaken at the University of Cape Town (UCT), with collaboration from University of Witwatersrand[1]. The primary objective was to utilize available Global Climate Model (GCM) simulations as a basis for the development of regional climate change scenarios. This work is founded on methodologies developed through research funded by the Water Research Commission (WRC), full details of which may be obtained in the WRC report "Deriving Regional Precipitation Scenarios from General Circulation Models". Sections from the WRC report and other journal papers form the basis of the methodological sections of this document.

This report summarizes the broad scenarios developed, while full graphics and data are made available on the Internet[2], and will, depending on funding, be updated in future work as further GCM results become available. The material that follows covers four fundamental aspects of the of the regional scenarios:

- Characteristics of the General Circulation Models (GCMs)
- Downscaling methodology
- Coarse resolution results
- Downscaled precipitation results

It should be noted that the nature of this area of research is one of intense activity in the global community, with the consequence that the foundational data from the GCMs are constantly improving in quality and spatial resolution. As a result the data used in this project are not the very latest GCMs from 1999, currently used in drafting the third assessment report for the Intergovernmental Panel on Climate Change (IPCC)) and are too recent for inclusion here. However, preliminary evaluation of the latest data that has been accessible suggests that the results presented here are in line with the more recent simulations, and that the newer simulations show qualitatively similar climate change.

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[1] The collaboration with the University of the Witwatersrand (Wits) unfortunately could not continue beyond the early phases of the project due to the departure of personnel from Wits.

[2] http://www.egs.uct.ac.za/fccc

2. Characteristics of the General Circulation Models

Three GCMs are used in this study, being those that were readily accessible within the tight time frame of this project. These GCMs represent a range of complexity that encompass an older model with simplified oceans (Genesis), an earlier coupled ocean-atmosphere model (HadCM2, a leading GCM in the last IPCC assessment), and a recent current-generation fully coupled ocean-atmosphere model (CSM).

GCMs simulate the global system with a finite spatial resolution, typically of the order of 3° latitude by 3° longitude. The models represent the larger scale dynamics directly, while parameterizing sub-grid-scale resolution features. The atmospheric component is generally far better developed and validated than the oceanic component, while the land surface processes are even further simplified. Nonetheless the GCMs are capable of simulating the synoptic scale dynamics well, and have been shown to have significant ability in reconstructing the temperature changes of the last century (see Figure 1). For details on GCMs, particularly when applied in the climate change context, see the IPCC second assessment report.

The Genesis model[3], while included in this study, is an older generation model and uses a mixed layer ocean whereby the ocean is represented by a 50m deep slab of water with prescribed horizontal transport. Furthermore, the climate change simulations are conducted with a step change in atmospheric CO_2. Therefore, while the patterns of change from this model are informative, the magnitude of change is likely to be less accurate, particularly for derived parameters such as precipitation. Consequently, less attention is paid to this model in the report. The CSM[4] and the HadCM2[5] models both incorporate a fully dynamical ocean model. The HadCM2 ocean model includes flux correction parameters to ensure correct exchange between ocean and atmosphere. The simulations used from the CSM and HadCM2 are transient simulations, whereby the models are run to quasi-equilibrium with present-day atmospheric conditions, and then increasing atmospheric CO_2 by 1% per annum. An additional run is supplied from the HadCM2 where the effects of atmospheric sulphate aerosols are incorporated through an approximation by adjustments to the surface albedo. While in principle the sulphate run

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[3] http://www.essc.psu.edu/genesis

[4] http://www.cgd.ucar.edu/csm/index.html

[5] http://www.meto.gov.uk/sec5/NWP/NWP_sys.html

is more accurate, there are increased uncertainties induced by the simple manner in which the sulphate effects are incorporated. Additionally, the variability of future sulphate emissions induces further uncertainties.

Within the context of the above, two fundamental issues need to be raised about the application of GCM data for regional impacts studies:

- forecasts versus projections versus scenarios
- scale dependencies of impact variables

In addition, given that the regional climate responses are dominantly a response to the GCM circulation changes, the GCM circulation must be validated, and the circulation change investigated. The first two points are discussed below, and the circulation evaluation developed in section 3.

2.1: Forecasts versus projections versus scenarios

An important consideration when using GCMs in climate change mode is that such simulations do not represent a *forecast*, which implies a prediction of specific atmospheric states, but are rather a projection of future climate. As such, these represent a *possible* evolution of the global climate system. There is mixed usage of the terms projection and scenarios, and it is best to consider the climate change results as a *climate response* to a given emissions *scenario*.

It is well recognized that not all the complexity of the system is understood, and in particular that there may be surprises in terms of thresholds and possible rapid non-linear climate response to anthropogenic forcing. Nonetheless, the simulations are a "best-guess" understanding of future climate, and the GCMs have been shown to be skillful in simulating the climate of this century, as well as paleoclimates. Such performance thus supports the view that the models are capturing the primary dynamical response to the increased radiative forcing from changing concentrations of atmospheric greenhouse gasses.

2.2: Circulation dependencies and spatial resolution

A second point to be made is that the GCMs are most skillful in capturing the fundamental dynamics of the atmosphere represented by the synoptic, or large-scale, circulation. The variables of direct concern for regional impact assessment, most commonly precipitation and surface air temperature, are themselves derived variables, and are increasingly erroneous as spatial resolution increases, and thus individual grid cell data need to be interpreted with caution.

Precipitation is a particularly problematic variable when used at the individual grid cell scale. The precipitation in GCMs is a simplified parameterization of the real-world complexity, and hence usually contains significant errors when used at any scale finer then the broad spatial patterns of monthly means. A particular pitfall is the common approach of using simple spatial interpolation from the grid cell data to a higher resolution. As noted above, the precipitation data of individual grid cells are problematic, and moreover, the grid cells represent area averages, and thus have reduced amplitude and increased rain-day frequency than what is found with station observation data. Thus, impacts derived directly from individual grid-cell precipitation may lead to highly erroneous interpretations.

Temperature at the grid cell scale is, however, significantly more reliable since temperature is a spatially continuous variable (unlike precipitation), and in particular, the surface air temperature is a simple derivative of the intrinsic dynamics of the GCMs. Thus, with due cognizance that the grid cells are area averages and not points, and that there is thus a reduced amplitude and variance, the grid-cell temperature data is substantially more robust in comparison to precipitation.

3. Circulation in the General Circulation Models

The Genesis model circulation has been extensively validated and the changes investigated by Hudson and Hewitson[6]. In general it was shown that the model captures the synoptic circulation of southern Africa moderately well. This section examines the

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[6] Hudson, D.A., and Hewitson, B.C., 1997: Mid-latitude cyclones south of South Africa in the Genesis GCM: *Int. J. of Climatology*, 17(5), 459-473.

more sophisticated CSM and HadCM2 simulations. A fundamental difficulty in validating a GCM is that of how to compare a set of daily fields with observational data, as one does not have a specific day in the observational record with which to compare a given day from the GCM simulation. A coarse comparison may be undertaken with mean fields, as shown in figure 2. However, on this basis it is not possible to state conclusively the degree of error or accuracy displayed by a model other than in terms of mean bias. Thus more detailed evaluation is required at the daily time frame.

Given that a particular time observation in the GCM or observational data represents a sample along a continuum of events, the ideal would be to compare the continuum of circulation states between the GCM and the observational data. Until recently, the best approximation to this ideal was to use cluster analysis. However, cluster analysis is, in some respects, problematic; the relationship between clusters is not readily apparent, and the procedures are biased to generating a few large clusters for regions of the data space encompassing the bulk of the observations. A more recent methodological alternative is that of Self Organizing Maps (SOMs). The SOM seeks to identify archetype states within the continuum of the (multidimensional) data. While effective clustering may be accomplished with SOMs, the underlying principles are essentially different to that of cluster analysis.

Figure 3 shows in concept how a SOM may be applied. Given a time series of multi-dimensional data (for example gridded sea level pressure data), the SOM performs a projection of the multi-dimensional data onto a 2-dimensional array of nodes. An analogy of this could be an optical camera, where 3-dimensional images are projected onto a 2-dimensional photographic surface. Each node has associated with it a vector with the same number of elements as a data observation. Initially a training phase applies all data in an iterative manner, where for each observation the SOM nodes "compete" to be the closest match. The "winner" is then updated in such a way that the node vector converges with the input vector, and the node neighbours are similarly updated but to a lesser degree. In this manner, at the end of the training, relatively similar input vectors would map (project) to nearby SOM nodes, and the distribution of node vectors represents archetype states within the continuum represented by the input data.

Figure 4 shows an example using simple two-dimensional data, artificially constructed to include attributes of both non-linearity and a step function. What is of note are the SOM characteristics that:

a) represent densely populated regions of the 2-dimensional space with more nodes, thus achieving greater representation of the details,
b) demonstrate the ability to capture the non-linearity,
c) show interpolation across data space where data observations are missing or non-existent.

3.1: Sea level pressure validation

The SOM thus represents an effective method for evaluating the circulation of the GCMs against that of observational reanalysis data. For validation the SOM is initially trained on a combined set of GCM (simulation of present day) and observational data, standardized to remove systematic bias between the data sets. The individual data sets are then mapped to SOM nodes, and the mapping of the observational and GCM data compared by looking at the frequency with which days are mapped to particular nodes. Figures 5 and 6 show the archetype circulation patterns for summer and winter respectively on a 5 by 7 SOM node surface. As can be seen the continuum of states are captured, and, as is characteristic of SOMs, the neighboring nodes are closely related. Having trained the winter and summer SOMs, the individual data sets are mapped to the SOMs, and the frequency of days on each node calculated. The frequencies may then be contoured on the grid of nodes, as shown in figures 7 and 8 (analogous to a 2-dimensional histogram). These show the frequency distributions of the NCEP reanalysis data, and the CSM and HadCM2 control simulation periods.

The frequency maps highlight two primary aspects of the GCM. Firstly, the CSM model well represents the observed with the limitation that the variability is far more constrained with a more focused occurrence of events on a limited range of circulation modes. Secondly, the HadCM2 model shows a marked deviation. On the basis of these results it would seem that the CSM model is suitable for climate change studies, while the HadCM2 is not.

3.2: Climate change impacts on circulation

While the control period shows differences between HadCM2 and the CSM, when considering the GCM simulated changes in circulation the HadCM2 results are in accordance with the CSM. This is valuable as it indicates that while the models have difficulties in some respects, they both concur on the dynamical response to the anthropogenic forcing. While not providing proof that the models are correct, this does support the validity of the changes in regional climate simulated by the models.

Figure 9 shows the frequency anomalies indicated by the two GCMs for summer and winter as a consequence of increasing atmospheric CO_2. Both models are in nominal agreement on the pattern of circulation change, especially for summer. In general, the indications are as follows.

For summer, an increased frequency of days with:

- a strong trough in the easterly wave over the center of the country,
- a more southerly and stronger South Atlantic high pressure system,
- an increase in high-pressure ridging.

These changes, coupled with an expected increase in atmospheric moisture, allow the following broad inferences:

- increased intensity of precipitation events in the north-eastern quadrant of the country,
- increased orographic rainfall on the southern coastline,
- drying in the southwestern Cape, and a potential increase in pollution with an increase in subsidence inversions.

For winter,

- an increased frequency of mid-latitude cyclones / frontal systems to the southwest of the continent (CSM only) with matching decrease on cyclones to the southeast,
- an increased frequency of ridging highs accompanied by a thermal trough over the center of the country.

The inferred implications of these are possible:

- increase in occasional winter convective activity in the north-eastern regions
- increased frontal passage in the western cape, with a decrease along the east coast

The changes above are fully in accordance with expected changes in the hemispheric dynamics, primarily due to an intensification of the Hadley cell, and southward shift of the mid-latitude westerly belt.

4. General Circulation Models coarse resolution grid cell results.

The coarse resolution scenarios are constructed directly from GCM output, and are monthly and seasonal aggregates of the daily grid-cell temperature and precipitation data. In evaluating these results it is important to keep in mind the caveats discussed earlier, in particular the poor reliability of precipitation at grid cell scales, and that the grid cells are area averages. For both the HadCM2 and the CSM model the grid cells are ~3.3° longitude by ~2.8° latitude. Consequently GCM grid cell data do <u>not</u> reflect the climate value for a point, and should not be used to infer pointwise climate response. The GCM grid cell data should rather be used as a basis for evaluating the larger regional pattern response of the climate system to anthropogenic forcing.

A further issue must be noted with regard to high-resolution interpolations of the GCM grid cell data provided by the CCWR. These data sets appear as high spatial resolution through an interpolation process. However, interpolation does <u>*not*</u> add information to a data set. Thus the data created through interpolation does not contain any more information in the regional scenarios than does the original GCM grid cell data, but does include all the *error* in the GCM data! To some degree, one may use such data at the point scale if the source GCM variable is spatially continuous, as is seen with temperature. In contrast, no such assumption should be made with regard to precipitation.

As there are a broad range of graphics that may be generated from this data, only the seasonal mean anomalies are presented, and further graphics and the source data are made available on the web site[7] noted earlier. Figures 10-17 show the climate change precipitation and temperature anomalies in the form of seasonal means for simulations from the CSM, the HadCM2 without sulphates, and the HadCM2 with sulphates. The Genesis model is not shown as it is less accurate, lower resolution, and an older

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[7] http://www.egs.uct.ac.za/fccc

generation model. The general climate change indicated by the CSM and HadCM2 GCMs are summarized below.

4.1: Temperature

The CSM simulation (figure 10) only has daily mean temperature available, while the HadCM2 simulations (figures 12,13,15,16) have daily maximum and minimum temperatures. In general, the CSM shows larger changes than both the non-sulphate and the sulphate runs from the HadCM2. In both cases the continent shows the most significant warming, with the warming greatest in the northern regions of the sub-continent. For the South Africa domain only, the HadCM2 minimum temperatures and the CSM daily means both show the minimum warming in summer and an expansion of the summer into the shoulder seasons. The HadCM2 maximum temperatures differ to some degree, showing a warming of the daily maximum in summer and autumn. These results are in agreement with the inferred response one would expect from increased radiative forcing from greenhouse gasses, and increased summer solar radiation resulting from enhanced subsidence and reduced cloud cover in summer.

The warming is biased to the western half of the continent, and shows a greater warming for daily maximum than minimum temperatures (HadCM2 only), and a resultant increase in the diurnal range. The inclusion of sulphates in the one HadCM2 simulation has the expected effect of reducing the overall warming.

Seasonally, the CSM and HadCM2 (with sulphates) have the maximum warming *over South Africa*, outside of summer. In contrast the HadCM2 without sulphate warming shows summer warming more than winter, but the shoulder seasons warming more than either winter or summer. In all cases the GCMs indicate an extension of the summer season characteristics.

In general, the climate projections indicate a continental warming of between 1°C and 3°C, with the maximum focused on regions of aridity, and the minimum along the coastal regions.

4.2: Precipitation

The two GCMs (figures 11, 14, 17) show less agreement with regard to precipitation, and considering the caveats when interpreting GCM grid cell precipitation, this is perhaps not too surprising. Again, the HadCM2 model shows smaller changes than the CSM, with the net significant impact being a broad reduction in summer rainfall, and less significant positive and negative changes in the other seasons. The sulphate simulation shows stronger changes, and in both cases the features have a general north-west/south-east alignment. Overall, the HadCM2 indicates broad reductions on the scale of 5-10% of current rainfall.

The CSM model shows changes in the 5-10% range, but with greater regional structure. For summer there are indicated increases in the northeast and the southwest, with an axis of precipitation reduction from the northwest to the southeast across the center of the country. Both shoulder seasons indicate a reduction in the northeast, suggesting a reduction of the duration of summer rains in this area. The winter season has nominal increases in the northeast.

In general, the CSM pattern of change would seem to be a better reflection than HadCM2 in light of the circulation changes suggested by both models, as discussed earlier.

5. High resolution scenarios

As noted in the section 2, interpolation does not add information over that found in the original source data. The high-resolution scenarios discussed here, however, are created through the process of downscaling, which derives local climate response to the larger scale atmospheric dynamics. The high-resolution precipitation scenarios were completed through the downscaling procedure initially developed in earlier work for the Water Research Commission, for full details see the report noted earlier. In this application, the downscaling was performed for precipitation to a spatial resolution of 0.5° degrees latitude and longitude.

5.1: Downscaling principles

Downscaling, whereby one uses the larger scale circulation dynamics to infer local climate, is one widely recognized methodological approach for dealing with GCM inadequacies in developing regional scale climate change scenarios. Multiple approaches to downscaling are available, although some have significant infrastructural constraints or problematic assumptions that underlie their procedures.

Of all empirical downscaling techniques, the direct transfer function approach is arguably the method with the least problematic assumptions, and provides a tractable procedure for developing regional scenarios from long term GCM simulations, as well as for use with multiple GCM data sets. In this approach transfer functions are derived using observed atmospheric and local climate data. After validation, the functions are applied to atmospheric data from GCM simulations of future climates, and used to derive the local climate response, and hence climate change scenarios.

The methodology uses regional and large-scale atmospheric dynamics (the strength of GCMs), with scale transfer functions derived from observational data, to generate local scale climate data that is directly in relation to the large scale atmospheric forcing. The means adopted for deriving the functions are that of Artificial Neural Nets (ANNs), a non-linear procedure analogous to multiple regression.

In determining the local climate response three primary sources of forcing need to be accounted for:

a) Atmospheric circulation dynamics. This determines the transport characteristics of the air mass, and the dynamics determining vertical motion, and hence condensation, cloud formation, and the precipitation process.

b) Atmospheric water vapour content. This attribute, neglected by many other studies, is of critical importance in the context of global warming. The water vapour content determines the precipitable water from the atmosphere, and under global warming it is probable that atmospheric water vapour will increase due to increase evapo-transpiration from land and ocean surfaces.

c) Local sources. These refer to variance from features such as the particular trajectory taken by a precipitating convective cell. This source of variance is important if analysis of future climates is to be done with daily resolution data from the GCM, as opposed to seasonal means. As this source of variance is relatively insensitive to the climate change signal, it can be treated mathematically as a stochastic process.

The three sources of forcing on the local climate are incorporated into a downscaling methodology based on ANN empirical transfer functions using observational data. Validation of the ANN techniques has shown the procedure to be viable and effective in capturing the primary forcing over a wide range of climate regimes and seasonal variation. Using geopotential height fields representing circulation dynamics, and atmospheric humidity as an indicator of precipitable water, the ANN procedure is able to effectively capture the spatial and seasonal attributes of precipitation over South Africa.

In the context of a GCM's skill in simulating the larger scale atmospheric dynamics, and given the limitations of alternative regional scenario schemes, the downscaled procedure represents a viable, justifiable, and pragmatic solution for meeting the immediate and near future climate change impact research needs. A flow chart of the procedure is shown in Figure 18. Step one creates an index of circulation mode, which is combined in step 2 with the atmospheric and related surface climate to derive a quantitative relationship. In step 3 the relationship is validated using independent observational data for which the local climate response is known, and in step 4 the relationships are applied to GCM atmospheric data. Based on this procedure downscaled precipitation was generated from the Genesis and CSM models. The HadCM2 model could not be downscaled, as the required atmospheric variables were not available from the simulations. Nonetheless, based on the circulation response identified in the SOM analysis earlier, a similar precipitation response may be expected.

5.2: Downscaling results

Figure 19 shows the regional precipitation response as monthly means. While there is significant regional detail in the results, some general points may be made. Overall the results can be viewed as changes in the southwest, the northeast coastal regions, and in the interior.

For the southwestern cape, the most significant changes are for an early winter increase of the order of 10%, followed by a marginally drier remainder of the winter. The increases are a maximum in the coastal mountains, most likely due to increased orographic rain from the increased atmospheric moisture. Under climate change precipitable water is likely to increase on the order of 4mm per 2ºC warming (Peter Whetton, CSIRO Australia, *pers comm*). In the interior, the most significant results are the drier conditions evident in late summer, and are in agreement with the GCM grid cell results. The remainder of the year has marginal changes that are likely to be non-significant. The northeast region displays some of the most marked changes, most significantly an extended early summer rainfall with increases up to 20%. The late summer shows a complementary short extension into March.

6: Conclusions

Collectively the results concur with the expected changes in the atmospheric dynamics. Notably, the atmospheric changes are evidenced by increased Hadley circulation, increased moisture, and an increase of winter fronts in the southwest (see SOM analysis). These changes, in conjunction with the changes in temperature and precipitation may be used to infer a number of possible consequences.

1) For the critical summer season the circulation infers greater subsidence over the continent. This is evidenced in part by the increased temperatures. However, increased subsidence also leads to enhanced inversions and greater pollution potential. More critical is the consequent suppression of convective precipitation. This is noted in the precipitation changes in the interior, but also is likely to indicate greater dry-spell duration followed by more intense convective events when they do occur, with the possibility of inducing more frequent flood events. The net effect is likely to be greater evapotranspiration and increased stress on arid and marginal zones. These conclusions are backed by other downscaling work in the WRC project noted earlier.

2: The broad precipitation increases in early summer for the northeastern regions are likely a reflection of the increased atmospheric moisture content. Complementing this are the regional characteristics of greater atmospheric instability due to the proximity of warm sea surface temperatures and the orographic forcing. Nonetheless, the possibility of greater dry-spell lengths and intensified convective rainfall with a greater frequency of flood events, as inferred for the interior, are likely to apply in this region as well.

3: For the southwestern region the implications are increased early winter frontal and orographic rainfall, likely due to the increased moisture with warmer sea surface temperatures and an indicated increase in frontal activity. The later winter decrease is nominal.

In conclusion, it is critical to emphasize that these results are projections of possible climate evolution based on a given CO_2 and sulphate emissions scenario, and use GCMs that are only now coming of age. Consequently the error bars, or levels of confidence are possibly large. The latest series of simulation data for the IPCC third assessment report, only now coming online, represent significant improvements, and in particular, make available ensemble simulations to assist in reducing levels of uncertainty. In addition, the new simulations incorporate substantial improvements in greenhouse forcing scenarios and sulphate emission scenarios. Analysis of these data sets would greatly strengthen the results, and provide enhanced understanding of the potential regional and temporal changes.

Thus, in conclusion, the results presented here represent an indication of the magnitude and possible spatial distribution of climate change that may impact South Africa. It is noted that these changes are likely to have major consequences for society, and thus further investigation, with greater refinement in spatial and temporal resolution across multiple GCMs would be strongly advised prior to the development of further adaptation policies and strategies.