6/13/95

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Yucca Mountain Site Characterization Project

Preliminary Evaluation of Techniques for Transforming Regional Climate Model Output to the Potential Repository Site in Support of Yucca Mountain Future Climate Synthesis

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Prepared by
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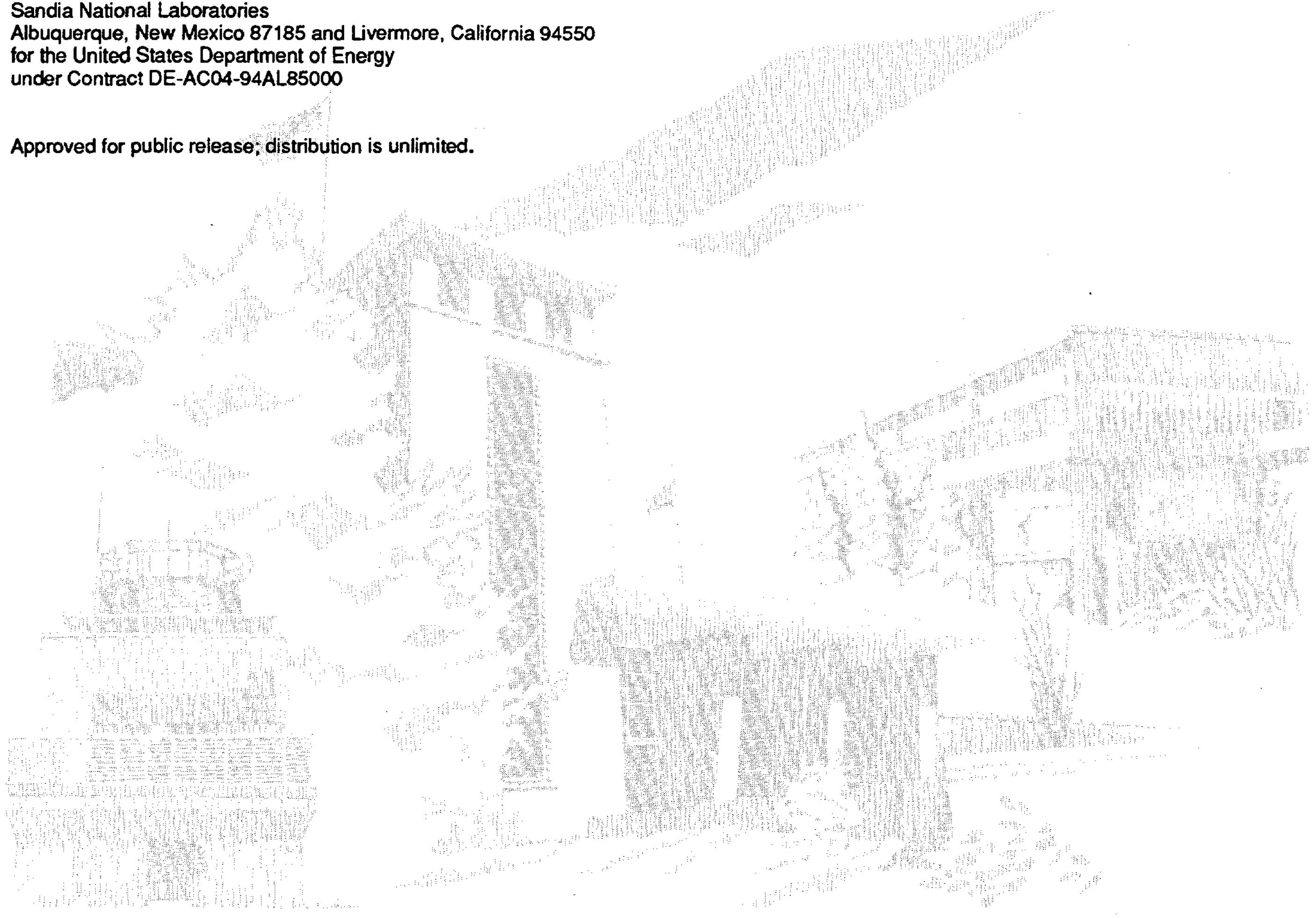
for the United States Department of Energy
under Contract DE-AC04-94AL85000



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PRELIMINARY EVALUATION OF TECHNIQUES FOR TRANSFORMING REGIONAL CLIMATE MODEL OUTPUT TO THE POTENTIAL REPOSITORY SITE IN SUPPORT OF YUCCA MOUNTAIN FUTURE CLIMATE SYNTHESIS

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Abstract

The report describes a preliminary evaluation of models for transforming regional climate model output from a regional to a local scale for the Yucca Mountain area. Evaluation and analysis of both empirical and numerical modeling are discussed which is aimed at providing site-specific, climate-based information for use by interfacing activities. Two semiempirical approaches are recommended for further analysis.

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Future Climate at Yucca Mountain

Purpose of Report

This report describes a preliminary evaluation of models for transforming regional climate model output to more localized spatial scales. This work was undertaken as part of a numerical climate modeling study being performed for the Yucca Mountain Site Characterization Project (DOE, 1988) to determine the effects of future regional climate change on the long-term waste isolation performance of a potential high-level nuclear waste repository located at Yucca Mountain, Nevada. Because the relatively coarse resolution of regional climate models (of order 50 km x 50 km) may not provide adequate detail to assess local climatic effects on hydrologic processes, and hence, on repository performance, it may be necessary to establish methods for obtaining more localized results. It should be noted, however, that because of the large uncertainties in future climate and in the coupling to hydrologic processes, as well as the extremely long time periods considered (10,000 - 100,000 years), it is not clear that such transformations will be significant for meeting the objectives of the overall study.

History and Background

Under the Nuclear Waste Policy Act, as amended, DOE is characterizing a site at Yucca Mountain, Nevada for a potential repository for the disposal of high-level spent nuclear reactor fuel and other high-level radioactive wastes.

One of the elements of the ongoing program to characterize the Yucca Mountain site is a study of the future regional climate, the results of which will support assessment of the repository total system performance with respect to long-term isolation of the highly radioactive waste from the accessible environment. Climatic processes are important to the waste isolation performance. If water enters the subsurface system, is transported through the system, and contacts the waste containers, various hydrologic processes are anticipated to provide the greatest threat to mobilization and release of radionuclides from the system. For example, the waste containers, emplaced in the unsaturated zone and located several hundred meters below the ground surface and a similar distance above the ground water in the saturated zone (water table), could be broached by corrosion processes in the presence of percolating water, which could subsequently dissolve and transport the waste to the accessible environment. Under certain geologic conditions, water could also have the potential for creating preferential pathways for the movement of materials to the accessible environment. Under known climatic conditions, only a small fraction of the precipitation that falls on the surface of Yucca Mountain is believed to enter the unsaturated zone and eventually move downward to the water table (Flint, 1989; Norris, 1989), discharging in the

Amargosa Desert to the south of the site (Czarnecki and Waddell, 1989).

The current climate in the Yucca Mountain area is semi-arid, receiving an annual average precipitation of approximately 150 to 200 mm (Flint et al., 1993; Dept. of Comm., 1968), primarily as snowfall, but augmented by summer thunderstorms. The region is characterized by linearly, north-south-trending mountain ranges and valleys, ranging in elevation from roughly 350 to 1600 m above sea level. Evidence exists that climate in the Yucca Mountain region has undergone substantial change in the past, and has at times been much cooler and wetter. Hence, it would be highly questionable to assume that the current climate will persist over the period of concern for the potential repository. The indirect nature of the relationship between hydrologic processes, such as infiltration and percolation, and climatic processes, pose a major challenge to those responsible for hydrology modeling and system performance assessment.

The planned approach to the future regional climate study, described in the Study Plan, involves the synthesis of possible future climate and relies largely on interpretation of the results of numerical simulations of different selected climate conditions, which are generated by a global climate model. Global climate models are generally based on general circulation models, or GCMs.

Climate Modeling

Available GCMs, however, have grossly insufficient resolution (typically of order 400 x 400 km, and at best 100 x 100 km) to be of much value in making local, or even regional scale interpretations specifically for the Yucca Mountain area. The definition of "regional" is not universally accepted, but for present purposes, implies a scale between several hundred km down to perhaps several km in extent.

The need for higher resolution (subregional) model output definition is driven by several factors: comparison of model results with climatic data or with higher resolution complex terrain flow or hydrology models, or because of possible impact of local terrain features on precipitation details and local and long term subsurface hydrology.

The computational cost of running a model increases roughly with the inverse cube of the grid size, and can become prohibitive. In addition, it is not altogether clear that such fine detail would lead to commensurate increased knowledge of practical use to the hydrologists and performance assessors.

Over the last several years, progress has been made in overcoming the resolution limitations of GCMs by "nesting" a Regional Climate Model (RegCM) within a GCM, which produces boundary conditions for the RegCM (Giorgi et al., 1993). Given current computational costs, this consideration presently sets the affordable resolution for multi-year nested GCM-RegCM production runs to around 50 x 50 km. Cost is not the only limitation. Numerical stability and fundamental applicability of the algorithms used set limits on RegCM resolution in the vicinity of 10 x 10 km (depending on the specific RegCM). This may still be inadequate to simulate the relevant climate conditions over the area of interest.

Fortunately, the rapid development of global climate models has been paralleled by similarly rapid development of numerical weather prediction models. Actually, 30 years ago, GCMs, the most sophisticated class of climate models, grew out of the early numerical weather prediction models.

In applying the results of global and regional climate models to specific locations, climate modelers face difficulties also faced by numerical weather modelers. The numerical weather prediction modelers, together with the users of their products, have developed a tool-kit of techniques for overcoming these difficulties. A selected set of these techniques is considered in this report. However, to reiterate, the purpose of the report is to examine the techniques for interpreting regional results on a local scale, should it become necessary in synthesizing future climate effects for hydrologic modeling.

For purposes of the YMP future regional climate study, regional scale numerical model output is produced by the NCAR GENESIS global climate model (Thompson and Pollard, 1994) nested with the RegCM2 regional model (Giorgi et al., 1993).

Technique Evaluation to Transform Regional Scale Output to Local Scale

The various approaches for transforming regional scale model output to local scales for use in total system performance model calculations can be divided into two broad categories: semiempirical and physical model-based.

Semiempirical Approaches

Over the years, numerous semiempirical approaches have been attempted to scale down the climate model's output to local scales with varying degrees of success. A succinct review of most of these techniques has been provided by Giorgi and Mearns (1991). An independent evaluation of these techniques and other techniques that have since been developed was performed here, keeping in mind their specific application to the Yucca Mountain Site Characterization Project. The results of this evaluation are briefly described below.

All semiempirical approaches involve developing empirical mathematical models or relationships to describe the spatial distribution of observed data over the region of interest. The model output available at some large, regional scale is then interpolated using these relationships to redistribute the output to smaller scales inherent in the observational data. The differences in various approaches result from the methodology, assumptions, and variables used in developing these relationships. It should be mentioned at the outset that most of these approaches have been developed to relate GCM information to regional scales. However, it is anticipated that these approaches can be applied to relate RegCM output to local scales with little or no modification. Furthermore, application to RegCM output involves less of an extrapolation than application of the same techniques to GCM output.

The semiempirical approaches can be grouped into two categories: one involving surface variables only and the other involving surface and free-atmosphere variables. In one of the simplest approaches, observational data are adjusted by the difference between the model predictions and the control model output; the control model output is obtained by calibrating the model's adjustable parameters for the best fit to the observational data (e.g., Smith and Tirpak, 1989; Cohen, 1990). Thus, if the model predictions for a given region show a 0.5°C positive bias over the control model temperature, then the model output temperatures for each station over the region will be uniformly increased by 0.5°C. The assumption implicit in this approach is that any phenomenon or event affecting the regional climate will do so uniformly. However, this assumption is valid for only those phenomena that have characteristic scales much larger than the local scales of interest and which interact linearly with local scale phenomena and orographic features. Because this assumption has limited validity, so has this approach.

In another approach involving only surface variables, Kim et al. (1984) developed regression relations using empirical orthogonal functions between the surface variables obtained from data stations in a given region and their average over a 30 year data set. These relationships were then applied to the output of the GCM grid(s) matched to the specified region to predict the surface variables at the station locations within the region. The model prediction relative errors for temperature and precipitation departures were within about 30% of the observational data from 49 stations within the approximate 500 x 500 km area. The same basic methodology has been used by Wilks (1989) with mixed results. This performance disparity could be caused by the fact that Kim et al. used monthly averages and Wilks used daily averages. This suggests that these relationships are sensitive to the time scales of physical processes and that the phenomena occurring at short time scales render these spatial relationships less effective at larger scales.

Recently, Hevesi et al. (1994) applied geostatistical techniques to determine the spatial variability of measured precipitations around the Yucca Mountain area. They focussed on winter- and summer-type storms and found that although both types can be represented by an exponential variogram, the spatial variability of the two types of storms was significantly different as reflected in significantly different variogram parameters for them. It should be noted that these empirical models are based on limited data and the quality of the performance of these empirical models is not well understood. However, this technique has some advantage over other techniques in that this is the only one that has employed actual data from a region surrounding Yucca Mountain.

There are two techniques that fall under the other semiempirical category of developing relationship(s) between surface variables and free-atmosphere variables, namely the perfect prog (PP) technique and the model output statistics (MOS) technique (see Karl et al., 1990 and references cited therein for more details on these specific techniques). The PP technique uses suitable observed free-atmosphere variables and the MOS technique uses model-generated free-atmosphere variables. These techniques have been developed based on the fact that current atmospheric models perform much better in simulating free-atmosphere variables than surface variables (Giorgi and Mearns, 1991). Moreover, free-atmosphere variables are much more nearly constant over regional scales relevant to regional climate models than are surface variables.

Wigley et al. (1990) have applied the PP approach to develop relationships between monthly means of local surface temperature and precipitation and large-scale variables such as area averages of air temperature and surface precipitation, grid point values of mean sea-level pressure, and 700 mb height. They found that it was possible to obtain useful local information from examination through empirical relationships of the large-scale variability despite difficulties of comparing near-surface mean values, i.e., there are wide spatial variations in the extent that local climate can be determined by the large-scale climate.

Karl et al. (1990) attempted to correlate the statistics of surface variables and free-atmosphere variables using standard statistical techniques such as principal component analysis, canonical correlation, and inflated regression analysis. These techniques minimize the number of predictors used, relate multiple predictand variables to multiple predictors, and tend to minimize differences between statistical distributions of predictand variables. This approach is referred to as Climatological Projection by Model Statistics (CPMS) and can be viewed as a generalization of PP and MOS approach used in numerical weather prediction models. Karl et al. applied the CPMS approach to predict daily minimum and maximum temperatures, precipitation, and cloud ceiling at five different locations throughout the USA. There were 22 predictor variables used in this exercise including daily sea level pressure, and temperature, relative humidity, wind components, and geopotential height at several pressure levels (Karl et al., 1990, Table 1). With some exceptions, the CPMS approach provided very good predictions at local scales at all locations investigated by Karl et al. (1990).

In addition to specific shortcomings of each semiempirical approach, the main problem with all semiempirical approaches is that empirical relationships developed by these techniques are not based on mechanistic models. Therefore, there is no guarantee that these relationships based on present climate data and tested under present conditions will be valid under different physical conditions prevalent at a different time in the past or future. In addition, empirical relationships developed for one location may not apply to another location.

Because most of the semiempirical techniques described above were developed to transform GCM outputs to regional scales, regional-scale predictions are fundamentally constrained by the reliability and accuracy of the grid point GCM output, and the predictive capabilities of individual GCM grid points are quite limited (Wigley et al., 1990). For the Yucca Mountain site suitability studies, the RegCM2 output is to be scaled down to local scales, and the predictive capabilities of individual RegCM2 grid points are also limited. However, over a single grid point of a GCM, there would be 25 to 100 RegCM2 grid points, and averages over 25 or more grid points of a regional climate model have in general very good predictive capabilities.

Although these semiempirical techniques have not been extensively used and tested to clearly define their level of skill, it is expected that there are enough data available to obtain statistically meaningful daily or monthly averages of surface parameters of interest. The local scales to which the large-scale data can be translated will of course depend on the density and distribution of weather stations in the region of interest.

Numerical Modeling Approaches

Since the empirical relationships developed with semiempirical techniques are not based on mechanistic models, they may not be valid under the wide range of conditions needed to be explored for the Yucca Mountain site suitability study. To address this limitation, several numerical modeling approaches, which have been under development to translate model data available at larger scales to smaller scales, were evaluated.

One modeling approach under investigation involves multiple nesting. In multiple nesting, a regional model such as RegCM2 provides boundary conditions to drive a high-resolution model in the same way as RegCM2 is driven by boundary conditions provided by a GCM. The MM5 model under development at NCAR allows for multiple nesting. No results are yet available from this model to determine the model performance. Another possibility is to use other mesoscale complex terrain, or high-resolution models such as the RAMS (Pielke et al., 1987), or HOTMAC (Yamada et al., 1992) model, which have the capability to run at higher resolution of, say, 1 to 5 km. Both possibilities have the same drawbacks: the time and effort required to bring these codes on-line may be prohibitive and so may be the cost of running these models for simulation periods of several years for numerous scenarios as required for the future climate and environment study.

Another modeling approach being developed applies specifically to the study of orographic effects on spatial variations of precipitation field. This approach has recently been reviewed by Barros and Lettenmaier (1994). In this approach, the spatial distribution of precipitation in mountainous areas is determined by numerically solving various equations representing physical processes known to control the precipitation field. The existing models have spatial resolution greater than or equal to 5 km and are driven by boundary conditions derived from observational data or a regional model such as RegCM2.

The performance of these models has been evaluated and results are promising, but these performance evaluations are based on only limited amounts of data because existing weather monitoring networks do not extensively cover mountainous areas. Moreover, the data quality in terms of spatial and temporal resolution was not adequate for rigorous verifications of models. The limitations of model validation and verification are more fully discussed in Barros and Lettenmaier (1994).

Another problem with these models is that they are site-specific. Because these models use parameterization schemes for some of the physical processes, they have to be calibrated using available data. It has been observed that these model calibrations are generally site-specific. This is borne out by the fact that a model calibrated for one location quite often does not perform very well at another location (see Elliott, 1977, for an example). Moreover, model calibrations based on present data may not be valid for past and future scenario runs envisioned for the Yucca Mountain area. These limitations diminish the advantages of a physically based approach over semiempirical approaches.

There are other problems as well. For example, though the 5-km resolution of these models is better than the 50-km resolution of RegCM2, this still may not resolve the Yucca Mountain site adequately. Moreover, even at this resolution, the models may not adequately address some of the processes occurring at smaller scales (such as local drainage basins) that could introduce large uncertainties in model predictions. And further increasing resolution will increase the computational cost of running these models for the specific Yucca Mountain applications.

Because of various problems associated with mechanistic approaches, as discussed above, the high resolution model approaches are not included in the short list of models for further consideration at this time.

Conclusions and Recommendations

Based on the performance of each technique and the defensibility of underlying assumptions employed in each technique, the CPMS approach appears to be the most promising semiempirical approach for transforming regional scale output to local scales of the Yucca Mountain. Another technique that appears promising is the geostatistical approach. It should be mentioned here that the performance of most of the techniques has been evaluated based on the specific application(s) for which they were used. The application of these techniques appears to improve the climate predictions on local scales in most instances. However, the relative performance of all techniques based on a carefully designed test problem has not been determined. Therefore, the superiority of a specific semiempirical and model-based approach over others is not well established. Thus, the selection of preferred techniques for further consideration is based on a technical judgment and should be considered preliminary, pending further work.

For application to the Yucca Mountain site, new empirical relationships in the CPMS approach will have to be developed using RegCM2 and the data available from stations located on and near the Yucca Mountain area. The demonstration of the CPMS approach by Karl et al. (1990) was based on a 10-year data set for five weather station sites. However, because of missing data, only about 70% to 90% of the seasonal daily observations were available. This suggests that recently acquired data sets near the Yucca Mountain site (Hevesi et al., 1994) might be adequate for developing reliable empirical relationships, provided they do not have extensive data gaps. Based on performance assessment requirements, the predictands set must include at the minimum daily temperature, precipitation, relative humidity, and wind speed. This set of predictands is different from the one used by Karl et al. (1990). This may mean that a new predictors set analysis also would be needed. This problem requires further investigation.

To test and develop the CPMS approach for the Yucca Mountain area, the RegCM2 model output are needed for the period covering the above-mentioned data set at a time resolution of 6 hours. Additional requirements for this RegCM2 run are being developed. It appears that this approach would be more questionable for paleoclimate scenarios because of the lack of adequate paleo data. However, under the circumstances, it is planned that empirical relationships developed using present climate data will be applied to model paleoclimate data to obtain high resolution paleoclimate simulations.

The geostatistical technique is very attractive because of its simplicity. It would be considerably easier to implement and test than the CPMS approach. Even though its performance has not been tested for climate applications, this technique is widely used for geological applications; this is the basis for its name.

To decide between the CPMS and the geostatistical approaches, it is proposed that the possibility of testing the geostatistical approach using the same data as used by Karl et al. (1990) should be explored. The relative performance of the two techniques using the same data could be used in making the final selection.

Given the current trend toward improved computational capabilities at lower cost, the most straight-forward solution to the scaling problem under consideration is to increase the resolution of both GENESIS and RegCM2 to that required and eliminate the need for any further processing of the RegCM2 model output. This approach may be out of reach today, but it might be feasible in a few years. At the very least, as resolution improves, the size of the adjustments will shrink, and thus presumably improve overall accuracy. However, there may be a practical limit to the high resolution sought through these techniques. This is because the benefits gained may become insignificant in comparison with the uncertainties in connection with the long time scales of interest to repository performance assessment, and the uncertainties involved in both the hydrologic coupling and the evolution of future climate change.

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