BUTTERWORTH HEINEMANN

Global Environmental Change, Vol. 5, No. 3, pp. 221 234, 1995
Elsevier Science Ltd
Printed in Great Britain
0959-3780/95 $10.00 + 0.00

0959-3780(95) 00045-3

Future climate at Yucca Mountain, Nevada proposed high-level radioactive waste repository

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Physical and social science techniques were combined to quantitatively predict distance future climate using formal expert elicitation. Natural and human induced environmental changes for the next 10 000 years at the site of the proposed high-level radioactive waste repository at Yucca Mountain, Nevada were analyzed.[1] Experienced climatologists were formally elicited to detail anticipated changes in controls and consequent climate at Yucca Mountain. Future climate at Yucca Mountain was described as very stable, due to the dominant control of the rainshadow effect of the Sierra Nevada Mountains. Anthropogenically caused warming (less than +3000 years) and astronomically induced cooling (more than +5000 years) will significantly influence the future climate.

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Overview and background

The great prophecy of the future is uncertainty.[2] There can be few more salient demonstrations of the importance of this truism than forecasting the combined effects of natural *and* human induced environmental changes at a single terrestrial locality over the next ten millennia. Given the dynamic and synergistic nature of the climate human system, and the relative newness (and unfamiliarity) of significant global scale anthropogenic alterations, what is the best available method of anticipating distant future climates? Are such 'forecasts' likely to be broadly reliable? Even so, can they be sufficiently quantitative and specific to be useful for policy planning purposes?

In order to even begin to address such demanding questions, an innovative approach is required which includes appropriate techniques of natural science (eg climate modeling) and social science (such as expert judgment elicitation and assessment). Such multidiscipline studies, while still uncommon, seem destined to become a more widely used means of developing distant future predictions based on current and anticipated changes of the human environment system.

This paper reports the results of a study which aimed at the prediction and assessment of 10 000 years of future climate change at Yucca Mountain, Nevada (Figure 1). The study was conducted as part of an ongoing assessment of the efficacy, stability, and safety of the proposed Yucca Mountain site as a high-level nuclear waste repository. The current environmental regulation[3] requires a geologic repository to isolate wastes from the public for 10 000 years. Thus, in the near and distant future, any increase in percolation of water through the proposed repository (which will be located in the unsaturated zone

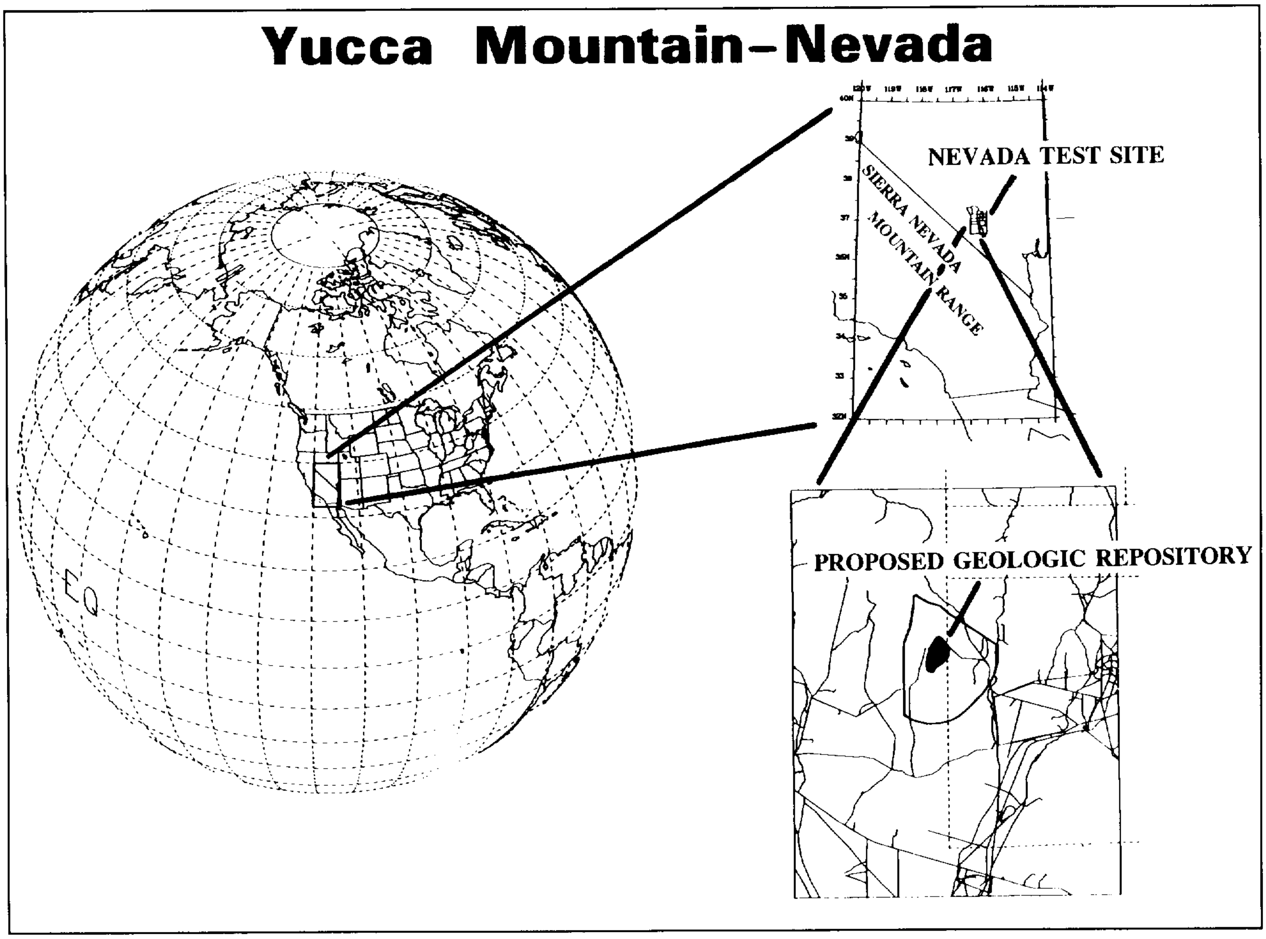

Figure 1 Yucca Mountain Area

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This paper was prepared to document work performed by staff at the Center for Nuclear Waste Regulatory Analyses (CNWRA) for Nuclear Regulatory Commission of the United States of America (NRC) under Contract Number NRC-02-93-005. The activities reported here were performed on behalf of NRC Office of Nuclear Material Safety and Safeguards, Division of Waste Management. This paper is an independent product of CNWRA snd consultants and does not necessarily reflect the views or regulatory position of the NRC

[1]A DeWispelare, L T Herren, M Miklas and R Clemen, 'Expert Elicitation of Future Climate in the Yucca Mountain Vicinity-Iterative Performance Assessment Phase 2.5', CNWRA 93-016, San Antonio, TX, Center for Nuclear Waste Regulatory analyses, 1993
[2]K E Boulding, 'Science: our common heritage', *Science*, Vol 207 (4433), 1980, pp 831–836
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above the current water table) might enhance the transport of released radionuclides to areas of public access. The primary source of percolated water is infiltration resulting from surface precipitation. Because current global climatic models cannot evaluate the entire 10 000 year period and are not sufficiently precise to allow an evaluation of a region as small as the study area surrounding Yucca Mountain, Nevada, it was decided to conduct a focused expert elicitation of the future climate.

Because of the limitations of current atmospheric science (eg the validation of models of long-term climate projections), this study employed a strategy for quantifying prediction uncertainties which relies on judgments of multiple experts.[4] A panel of five expert climatologists was selected and assembled to develop future climate scenarios and their controls. The experts were individually asked to identify and explain each of the *current* (1993) climatic controls and to detail the *anticipated* changes in such controls which would produce climate change at the Yucca Mountain site. The experts were encouraged to use conceptual, computational, empirical, and judgmental knowledge to evaluate and report on the range of probable future climate at the site. Time slice vignettes at 100, 300, 1000, 3000, 5000 7500 and 10 000 year increments were requested. The climate scientists were asked to predict precipitation, temperature, cloud cover, and the maximum 10 day (short term) precipitation expected during the period. Additionally, they were to quantify the uncertainties in the form of probability distributions associated with the climatic parameters such as temperature and precipitation which would serve as input to performance assessment models.

Expert elicitation

The expert elicitation procedure that was refined and used in this study consists of 11 steps: (i) determine the objectives and goals of the study; (ii) identify and recruit the experts (specialists, generalists, normative experts); (iii) identify the issues and information needs; (iv) provide initial data to the specialists; (v) conduct the elicitation training session; (vi) discuss and refine the issues; (vii) provide a multi-week study period; (viii) conduct the elicitations; (ix) provide post-elicitation feedback to the specialists; (x) aggregate the experts' judgments (optional); and (xi) document the process.

Nuclear Regulatory Commission (NRC) personnel in conjunction with staff at the Center for Nuclear Waste Regulatory Analyses (CNWRA) defined the goals and objectives of the effort. These objectives ensured that both the process and the content of the expert elicitation were examined in the study.

An elicitation team was assembled from the CNWRA and South-West Research Institute (SWRI) personnel and from outside consultants. The elicitation team consisted of normative experts with backgrounds in decision theory, probability theory and assessment, and psychology, and generalists with backgrounds in climatology and an overall understanding of the technical issues presented by the high level waste repository.

The elicitation team accomplished the recruiting of specialists. The generalists identified relevant professional societies and organizations as potential sources for the nominations for the experts. Nominees were formally requested by letter from climatology/geography associated societies and organizations. In addition to lists of nominees, these requests occasionally resulted in 'leads' to individual members of these societies and organizations who supplied additional nominations. Finally, some of the nominees who declined suggested possible alternatives. A list of 42 potential panelists resulted from the nominations.

The list was reduced to 21 candidates by screening based on conflict-of-interest (for example, previous work for the Department of energy on the Yucca Mountain Project caused rejection of the individual), general interest in participating, and availability. Then, the elicitation team, NRC personnel, and the nominees themselves were asked for a confidential ranking of the filtered list of nominees based on the problem at hand. Statistical correlation of these rankings led the assessment team to select five experts.

The issue statement was developed concurrently with the panel selection. The issue statement charged the specialists with predicting the future climate conditions in the Yucca Mountain Nevada vicinity (YMNV). Because groundwater infiltration is a matter of concern at a HLW geologic repository, the primary variables at issue were changes in annual precipitation and temperature as well as changes in the

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[3]40 CFR 191 (Code of Federal Regulations). 1989. Title 40, Protection of Environment, Part 191, *Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes*. US Environmental Protection Agency. US Government Printing Office: 7–16 (currently remanded)

[4]DeWispelare, *op cit*, Ref 1

seasonal variability of precipitation at the site over the course of 10 000 years. The statement also indicated the intent to evaluate these changes at a series of future time slices: 100, 1000, 3000, 5000, 7500 and 10 000 years after the present (AP) (300 years AP was added later). At each of these time slices, the specialists were charged with discussing the climatic controls that were postulated to cause any expected changes and providing and quantifying estimates of uncertainty in the form of probability distributions for the main variables.

The contents of the elicitation team provided data package covered the major approaches to investigating climate in the Great Basin Region of the Western United States (the geographic province containing Yucca Mountain) such as paleoclimate data and general circulation model (GCM) results. The experts had several weeks to review a data package and any other information prior to the initial group meeting.

The group was given extensive training in probability elicitation and debiasing including an overview of subjective judgments of uncertainty. Through practice, the experts were taught to recognize biases that can affect judgments, including motivational (self-interests such as economic) and cognitive biases.[5] Examples of overconfidence, anchoring, availability, non-regressive predictions, and the confirmatory bias helped the specialists learn firsthand about possible cognitive biases. Probability assessment was practiced using graphical techniques for display and consistency feedback. Each meeting and all elicitations were documented on videotape and with collations of extensive notes taken by the elicitation team.

The experts were given time to develop their analysis and then were elicited. At the elicitation, the experts were each asked to identify controls which would influence the climate at each time. The controls and effects were to be described in position papers and subsequent presentations to the group. The following sections summarize the information presented in the experts' position papers and initial presentations. The entire text and references used by each team member is contained *in toto* in 'Expert Elicitation of Future Climate in the Yucca Mountain Vicinity – Iterative Performance Assessment Phase 2.5'.[6]

Yucca Mountain vicinity climate controls

Present climate

Each expert identified the topographic/physical location of the YMNV in the 'rain shadow' or leeward site of the Sierra Nevada Range as the single most dominant climatic control for the present. The dry conditions at the site are caused primarily by the blocking effect of the Sierra Nevada Range on the movement of ocean derived moist air into the region. Each expert noted that the infrequent excursions of moist oceanic air into the region from around the south end of the Sierra Nevada Range or from North Pacific wet air masses traversing from north to south resulted in precipitation at the site, particularly in the winter portion of the year. The remaining controls identified by the experts were a more diverse set, including westerly wind direction, anthropogenic effects, and various climate excursions including El Niño/Southern Oscillation (ENSO), volcanic activity, storm tracks, and current mean values, of temperature and precipitation. Only one of the

[5] Kahneman, D P Slovic and A Tversky, *Judgement Under Uncertainty: Heuristics and Biases*, Cambridge University Press, Cambridge, MA, 1982

[6] DeWispelare, *op cit*, Ref 1

experts alluded to Milankovitch astronomical forcing as one of the current controls. Because the Sierra Nevada Range is a relatively stable part of the regional environment, the experts believe that a change of more than 50% increase in precipitation at the YMNV would be extremely difficult to justify on the basis of climate/atmospheric mechanics.

One authority described the Greenland Above (GA) circulation pattern as a key to the present and future YMNV climate. (Greenland Above pattern is defined by above normal temperatures in Jakobshawn, Greenland coincident with an amplification of the normal temperatures at Oslo, Norway). 'The GA pattern is ... significantly linked to warmer winter temperatures in the YMNV region ... Consequently, warmer global temperatures should produce greater occurrences of the GA pattern (perhaps 25–30% of all values instead of the current 19%) and warm temperatures in Nevada. In general, this matches GCM simulations'.[7] It should be noted, however, that another of the five scientists stated that 'the Pacific-North American circulation pattern is of more consequence to the regional YMNV climate than the Greenland Above circulation pattern'.[8]

Future climate

For the expected climatic controls at +100 years from 1993 (approximately 2100 AD), the rain shadow effect was the dominant control, and each of the five experts identified anthropogenic forcing, which warms the atmosphere, as their second most important control. The experts believed that the so-called 'greenhouse effect' will be a major factor in causing warming of the atmosphere globally and regionally in the YMNV. Each expert identified the effect of anthropogenic warming on the movement of the atmosphere across the site as their third most important control, although each expressed the control in slightly different terms including: (i) storm tracks moving north, (ii) more tropical air incursion on the YMNV, (iii) the westerlies move south in winter, (iv) more moisture in the west to east moving air, and (v) Greenland Above circulation causing a change in precipitation at the site. One expert saw an enhancement of the ENSO resulting in increased precipitation at the site. The experts saw little additional change at the 300 year time slice.

At +1000 years from 1993 (c 3000 AD) in the YMNV, each expert again identified the rain shadow effect as the most dominant control with anthropogenic forcing resulting in a warming of the atmosphere as the second most dominant control. However, each expert now identified an offsetting cooling of the atmosphere resulting from the effects of Milankovich orbital variations on the climate. The third most often identified controls remained those dealing with atmospheric movement as at +1000 years. These controls persisted through the 3000 year time slice.

For the +5000 year time slice (7000 AD), the panel again listed rain shadow as the dominant control. However, two of the five experts favored astronomical forcing as the second most important control while three of the experts continued to list greenhouse warming due to anthropogenic forcing second. The three experts who placed anthropogenic factors second included Milankovich forcing as their third most important control, while the two experts who rated Milankovich second had increased westerly wind flow as their third

[7] *Ibid*
[8] *Ibid*

control. The remaining controls included shifting of mid-latitude storm (cyclonic) belts, increased availability of moisture, and meridional flow. These trends continued through +7500 years AP.

At the +10 000 year time slice (12 000 AD), two of the experts contended that anthropogenic warming would still be experienced in the YMNV, although in a waning mode. Three of the experts believed that the Milankovitch orbital forcing will have brought colder temperatures to the YMNV as the second most dominant control after the rain shadow effect. Again, the two individuals believed that greenhouse warming will still be perceptible at YMNV. Ice sheets, westerly wind belt migration, and increased moisture availability comprised the balance of the third through fifth climatic controls.

Two experts expressed differing perspectives regarding the future importance of human effects in the Yucca Mountain region. One argued that 'human induced atmospheric and surface changes (eg greenhouse gas changes, land surface alterations included increased agriculture, and absolute human population growth) will lead to such dramatic climate changes that the paleoclimatic record will *not* be the key to the future climate',[9] Another, however, stated the following: 'In the YMNV, human effects are not regionally great. Land use cannot change that much unless the YMNV is irrigated. It is difficult to imagine this because water will be a very expensive resource. Thus, extreme human-action scenarios and their attendant effects do not apply as directly to this region as might be the case elsewhere'.[10] In general, three of the climatologists leaned to positions emphasizing atmospheric 'robustness' or stability (the past is the key to the future) while the other two tended to emphasize human effects as the key to forecasting and understanding distant future climate states. Figure 2 shows the composite temperature, precipitation, and insolation (cloud cover surrogate) curves for the 10 000 year future at the YMNV as forecast by each of the five experts.

Likely future temperature in the YMNV

Distributions associated with the temperature estimates for each expert are shown in Figures 3 and 4. Generally, all the experts agreed that the next 100 years will be getting warmer by as much as 3 °C, on average, due to the greenhouse warming associated with anthropogenic activities. Following 100 years AP, the temperature trends across the 10 000 year period represented two distinct approaches *vis-à-vis* the relative impact of the forcing factors on the YMNV climate. Two of the panelists believed that anthropogenic warming would have a more durable impact than Milankovitch forcing across the 10 000 year period. These two panelists predicted that temperatures would rise to a maximum of a 3.5 °C increase between 300 and 1000 years AP and then would decrease somewhat across the remainder of the period. However, at no point did their temperatures decrease below current levels.

The other three panelists viewed anthropogenic warming differently. These three experts agreed that temperatures will drop beginning 300 years AP and will continue dropping through the remainder of the 10 000 year time frame of interest. All five of the experts agreed that anthropogenic warming would have an effect out to between 1000 and 3000 years AP. However, three panelists forecast some cooling relative to current, after 1000 to 3000 years AP, due to a decreased impact of

[9] *Ibid*
[10] *Ibid*

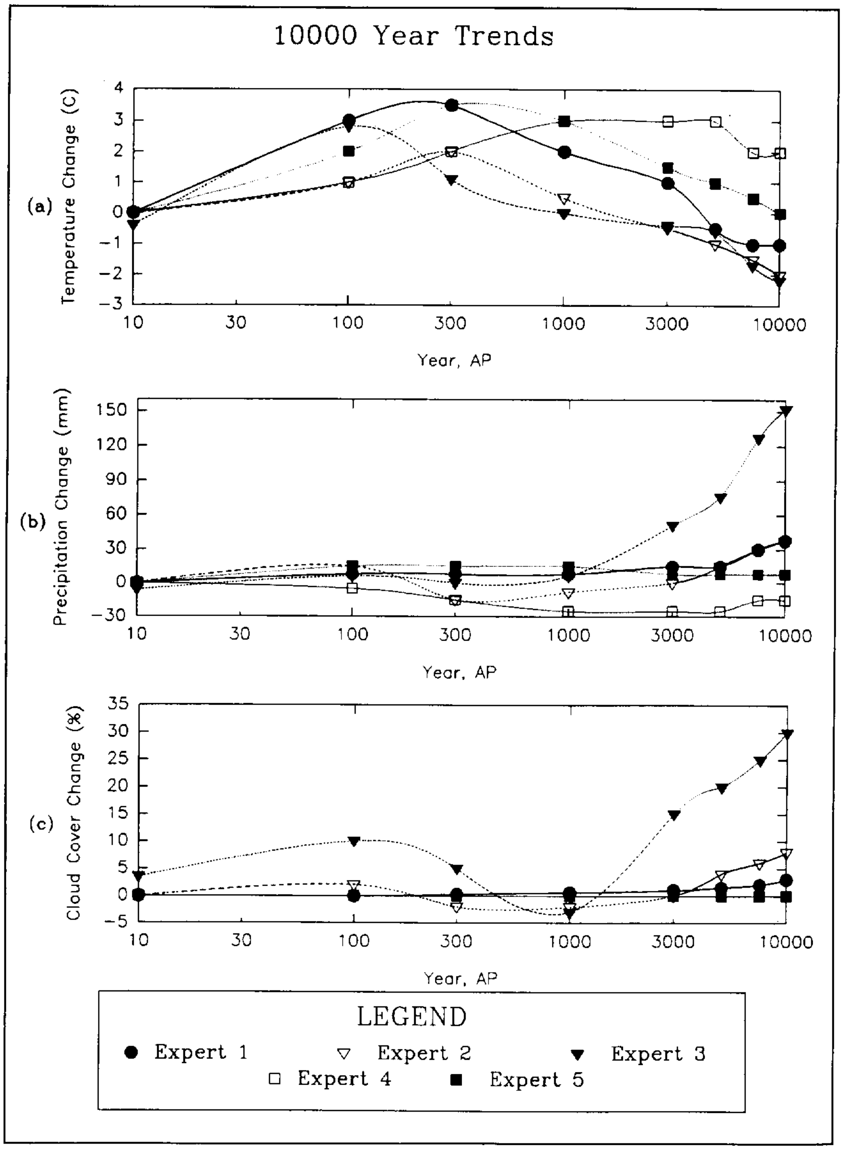

Figure 2 10 000 year trends – median values of the elicited probability distributions

anthropogenic forcing and increased influence of Milankovitch forcing. One expert predicted maximum warming effects will continue through the 10 000 years but superimposed on the warming will be cooling associated with Milankovitch forcing with a slight cooling overall in the last 5000 years. Final temperatures at 10 000 years AP ranged from −2°C to +2°C with one expert saying that temperatures in the YMNV 10 000 years from now will be about the same as present temperatures. All experts agreed that the overall effect from 3000 years AP to 10 000 years AP will be a net cooling of the +3000 years AP atmospheric temperatures.

Likely future precipitation in the YMNV

The experts' distributions associated with the precipitation estimates are shown in Figures 5 and 6. Each climatologist expressed the opinion that temperature and precipitation were not consistently conditionally related in the YMNV (ie temperatures could rise with increasing

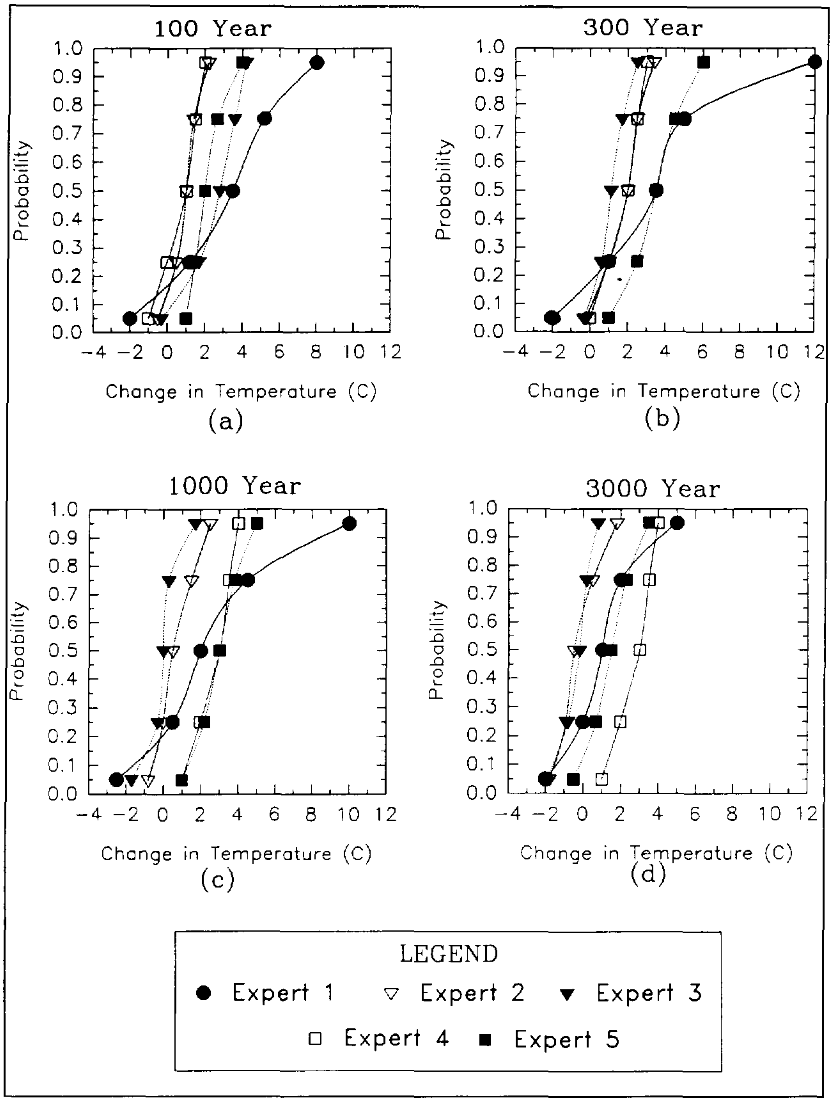

Figure 3 Cumulative probability distributions for temperature at 100 to 3000 years AP

precipitation or temperatures could decrease with increasing precipitation and *vice versa*). Precipitation in 1993 was assumed to be 150 mm annually.[11] For the first 100 years, four of the five agreed that precipitation in the YMNV might increase by as much as 10% on an annualized basis while one researcher suggested that precipitation might decrease by a comparable quantity. One expert predicted a significant lessening of precipitation from 100 to 300 years AP while four predicted similar precipitation quantities with relatively no change between 100 and 300 years AP. Between 300 and 1000 years AP four scientists predicted relatively little change while the fifth had precipitation declining to 25 mm less than present level where it remains for 4000 years before increasing the last 5000 years but still to a −15 mm per year in the year 12 000 (10 000 years in the future). One of the four remaining experts forecast precipitation remaining very similar to 1993 precipitation for the last 7000 years of the 10 000 year time frame while two researchers showed increases by as much as 40 mm (27%) above present values. The final individual showed a substantial increase in precipitation from 3000 years AP to a high 10 000 years AP. His final

[11] *Site Characterization Plan, Yucca Mountain Site, Nevada Research and Development Area, Nevada*, US Department of Energy, Vol I, Part A, Chapter 5, 1988, pp 5–1 to 5–106

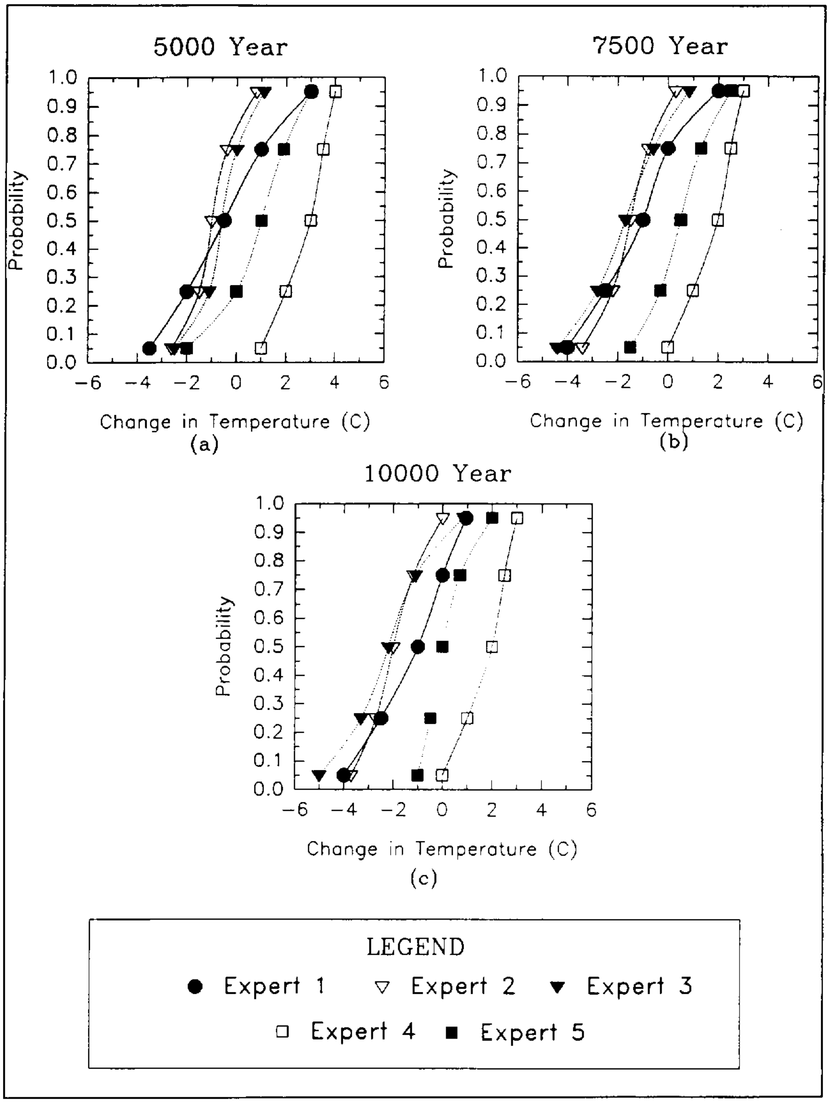

Figure 4 Cumulative probability distributions for temperature at 5000 to 10 000 years AP

values in 12 000 are 150 mm more annually than during 1993 which represents a doubling of the 1993 precipitation. 'A full-blown pluvial period is in place at the YMNV ... Circulation of the atmosphere will be similar to 10 000 years before present where the westerlies are consistently found to the south of the YMNV'.[12]

Other individuals suggested precipitation maximums were no more than about 30% wetter than 1993. In summary, four of the panelists predicted increased precipitation during the 10 000 year time period. The average precipitation amounts at 10 000 years AP ranged from a 15 mm decrease (−12%) to a 150 mm increase (+100%) over current values.

Seasonal variability of precipitation

Probability distributions were not assessed for seasonal variability, instead, proportions of annual precipitation were allocated to winter and summer seasons. For the purposes of this study, the winter season was defined as October through March, and the summer season included the months of April through September. The distribution of

[12]Dewispelare, *op cit*, Ref 1

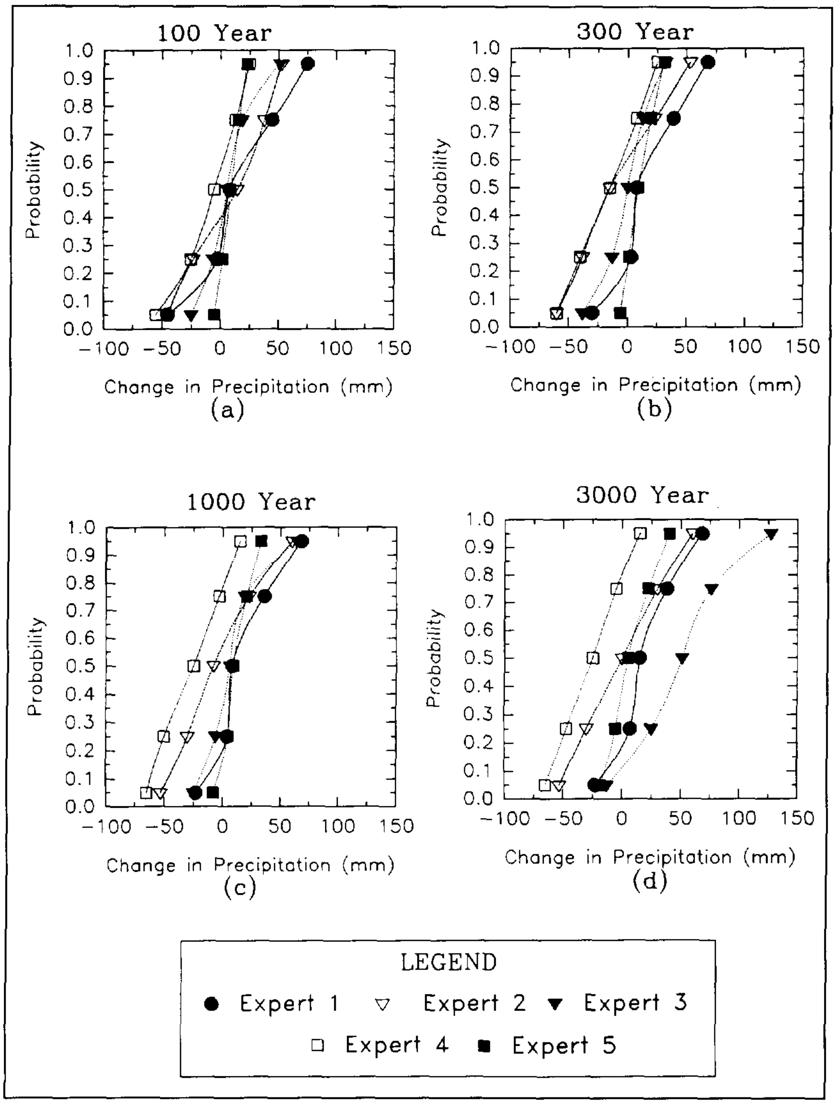

Figure 5 Cumulative probability distributions for changes in precipitation at 100 to 3000 years AP

precipitation in the current climate in the YMNV is 60% in the winter and 40% in the summer. This discussion refers only to the changes in distribution of precipitation not to the actual amounts.

For the +100 year time slice, two experts predicted an increase in the winter precipitation associated with greenhouse induced warming, two predict no change from current, and one expert suggested that winter precipitation will decrease relative to summer due to a northward shift of the cyclone belt resulting from increased global temperature. At the +300 year time slice, two experts predicted a decrease in winter percentage of precipitation, two predicted no change from current, and one predicted an increase in winter's share of the precipitation. Any increases in summer percentage were explained by the ability of warmer air to hold extra moisture, while winter decreases were tied to a northward shift of the cyclone belt. At the +100 year time slice, the experts were again divided with two favoring more precipitation in winter and two favoring more precipitation distributed to summer while one saw the distribution as relatively unchanged. Again, decreases in winter were attributed to cyclones moving to the north. Interestingly,

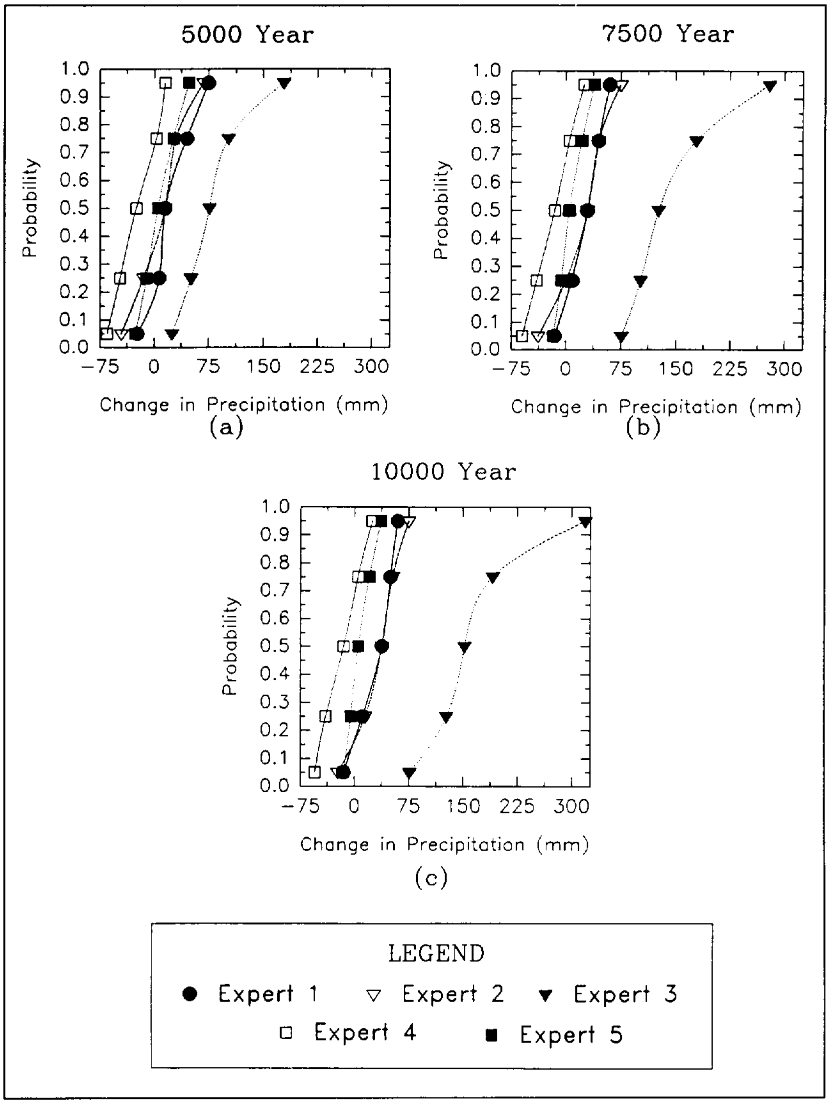

Figure 6 Cumulative probability distributions for changes in precipitation at 5000 to 10 000 years AP

one expert saw tropical storms bringing more summer precipitation: anthropogenic global warming was seen as the driving force. At +300 year time slice, three experts saw a proportionately wetter winter due to an atmospheric cooling trend inspired by Milankovitch forcing, while two experts predicted a drier winter and a wetter summer due to increased summer convection (overall precipitation has decreased in one expert's scenario due to global warming). At +5000 years AP, three predicted wetter winters and drier summers, one predicted the same as the previous time slice (70% winter/30% summer), and one predicted drier winters (30% winter/70% summer). The differences result from the contention by the wetter winter proponents that Milankovitch forcing is cooling the atmosphere significantly, resulting in more winter storms, while the drier winters were said to result from the atmosphere being affected by global warming associated with human effects resulting in increased summer convective rainfall. A similar pattern to that at +5000 years persisted in the +7500 year time slice, although one expert acknowledged that human effects are waning and the previous dry winter pattern is beginning to be reduced. At the +10 000 years time slice, three experts saw no change from the +7500 year distribution while two experts saw wetter winters and drier summers resulting from the atmospheric cooling due to Milankovitch forcing (now recognized by all).

In summary, the seasonal variability was projected to rely either on Milankovitch cooling dominance (increased winter precipitation) or atmospheric warming due to human effects (either summer increases in precipitation proportion due to increased convection or decrease in winter proportion due to changing winter cyclone storm tracks). The experts were unified on the aspect that the proportions were of relatively small absolute amounts of precipitation. However, because winter precipitation is more effective for recharge, even a modest change in winter precipitation may have a significant effect on infiltration and repository performance.

Short term intensity of precipitation – surrogate for storm intensity

Figures 7 and 8 summarize the cumulative probability distributions of the experts for short term intensity. The short term intensity of precipitation was defined as the maximum 10 day total of precipitation

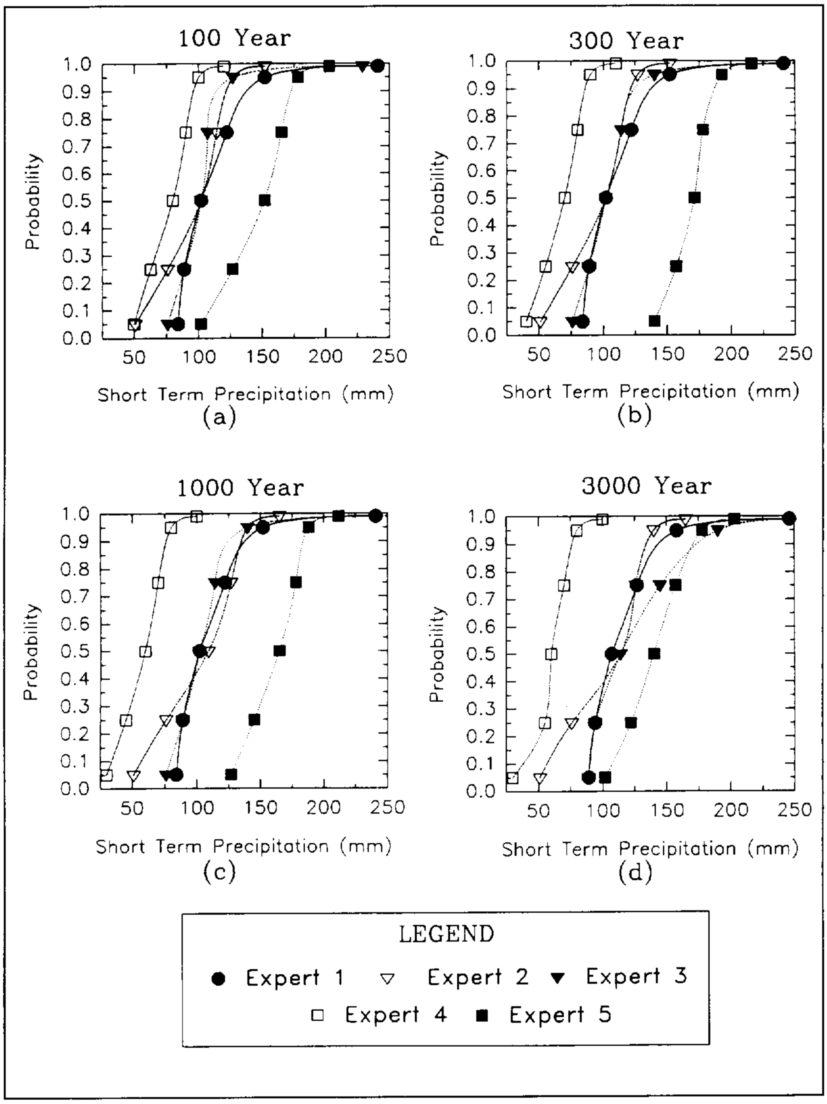

Figure 7 Cumulative probability distributions for short term precipitation intensity at 100 to 3000 years AP

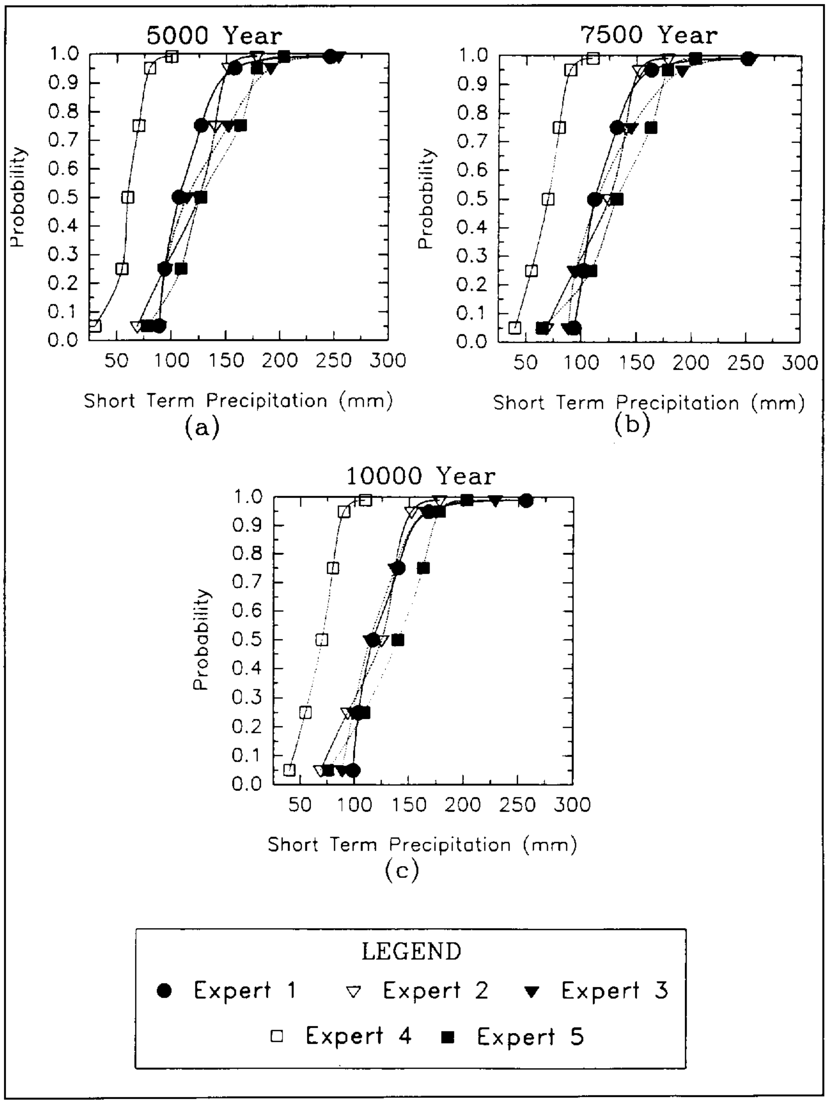

Figure 8 Cumulative probability distributions for short term precipitation intensity at 5000 to 10 000 years AP

expected to be received within a 100 year period encompassing each of the time slices. Of the five experts, three predicted 102 mm in 10 days as the median in the +100 year time slice. At +300, +100, +3000, and +5000 years the experts expected little change from the +100 year levels. According to one expert the atmosphere is at its peak moisture holding capacity at this time slice and will not be holding more moisture in the future as the atmosphere continues cooling due to the Milankovitch effect. At the +7500 year time slice, the opinion of all five experts was that there will be a very slight increase in 10 day maximum precipitation due to the many cyclonic storms which will migrate through the area in response to cooler atmospheric temperatures forced by Milankovitch orbital variations. At the +10 000 year time slice there was again a slight increase in the median probability 10 day maximum but a slight decrease in the 0.99 probability precipitation. This was attributed to temperatures that have continued cooling and less moisture availability in the cooler atmosphere.

Overall, as temperatures begin cooling in response to Milankovitch forcing at about +3000 years, more precipitation will result at the site.

However, as cooling continues, the declining ability of the air to hold moisture will cause the precipitation increase to cease and a slight regression in peak intensity from previous time slices would be evident at the 10 000 year time slice. Of the experts, four predicted that the 10 day maximum in +10 000 year will be greater that the 10 day maximum is currently.

Summary and conclusions

Future climates

The experts were consistent in their estimation of a relatively small median temperature change of no more than plus or minus 2 °C for the 10 000 year future period of interest. Precipitation predictions were more varied with one estimate predicting a doubling of precipitation, with the opposite extreme estimate foreseeing 15% less precipitation in 10 000 years AP. Even the doubling of precipitation increases the absolute quantity from 150 mm (6 inches) to only 300 mm (12 inches). Coupled with the relative lack of predicted temperature change, the area would remain a desert (or at least semi-arid) even with the doubled precipitation. The wettest decade predictions were also relatively consistent in their prediction of modest amounts of precipitation even during the wettest expected conditions. Overall, the results of this elicitation indicate the climate at YMNV is expected to be very stable, undoubtedly due to the great control on regional precipitation which is exerted by the rain shadow effect of the Sierra Nevada Range.

Concluding remarks

'Weather forecasters... are among the few groups whose (expert) judgments have been found to be well calibrated'.[13] The training, background, and forecasting experience of atmospheric scientists was one key factor in the outcome of this research project. A second key was the fact that the long-term climate of the Yucca Mountain site – semi-arid to arid for many thousands of years – is, has been, and will almost certainly remain unusually stable because of the dominance of the Sierra Nevada rain shadow. Thirdly, the experts anticipated, in general, only two other primary present and future climate controls/effects at Yucca Mountain over the next 10 millennia: i) anthropogenic ('greenhouse') warming, and ii) astronomical ('Milankovitch') cooling. Finally, the formal expert opinion elicitation was carefully structured and effected.

Cohen recently pointed out that '... it will be necessary to have better climate models, more environmental and socioeconomic data, and better assessments of the impacts of projected changes in climate'.[14] The 'syncretic' nature of this project suggests that formal expert elicitation has the potential to be increasingly useful in future studies of complex – especially distant future – environmental systems in which both natural and anthropogenic change must be forecast for planning and policy purposes.

[13] John D Stearman, 'Overconfident Opinions?', *American Scientist*, Vol 82(3), May–June 1994, p 204
[14] Stewart J Cohen, 'Climate Change and Climate Impacts', *Global Environmental Change*, Vol 3, No 1, March, 1993, pp 2–6