Representation of Global Climate Change in Performance Assessment Models for Disposal of Radioactive Waste - 17183

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ABSTRACT

Evolving concepts of global climate change that include impacts of anthropogenic greenhouse gases require reassessment of conventional conservative approaches in performance assessment studies that assume cold and wet future glacial climates. Global paleoclimate data for the Quaternary (past 2 million years) show saw-tooth patterns (temperature/proxy temperature data versus time) of glacial and interglacial intervals accompanied by cyclical changes in the atmospheric content of CO_2 (low contents during glacial cycles and higher contents during interglacial cycles). These cycles are correlated with changes in the earth's orbital configurations (Milankovitch cycles) but require nonlinear linkages with additional climate-forcing components to reproduce past glacial and interglacial transitions. The earth is currently in an interglacial period and the timing of the inception of the next glacial period is critically important for forecasting future climate states. Climate modeling studies coupling Milankovitch cycles with variable atmospheric CO_2 content demonstrate conclusively that the earth is very unlikely to return to a glacial state when CO_2 concentrations remain above pre-industrial levels (~ 280 parts per million; current levels exceed 400 parts per million). A return to pre-industrial concentrations will likely require > 50,000 years and may require hundreds of thousands of years even if current emissions were to drop dramatically. The most likely scenario for the future global climate is persistence of the current interglacial period with variable but progressively increasing temperatures. Performance assessments need to revise site-specific evaluations of future climate assuming global warming within a prolonged interglacial period with increased probability of extreme weather events. Four radioactive waste disposal sites are illustrated that currently incorporate or will incorporate revised current climate concepts in modeling studies for performance assessments.

INTRODUCTION

The potential effects of global climate change on the performance of underground disposal sites for radioactive waste are typically assessed for waste inventories requiring long isolation periods (10,000 years or longer; for example, high-level waste and transuranic waste). Climate studies for radioactive waste requiring relatively short isolation periods (1,000 years or less; for example, low-level radioactive waste) generally assess local and regional climatic conditions using historic weather data/measurements and assume persistence of these conditions. When climate change is assessed, its effects are treated as disruptive events that could potentially change the background model representation of the ability of a disposal site to safely isolate waste from the environment (base-case conditions). These changes may affect regulatory compliance for waste-specific performance objectives, for prioritization of studies during active site maintenance and monitoring and the requirements for site closure.

The standard approach in past performance assessments is to assume bounding or worse-case effects of future climate changes through model evaluations of the wettest and coolest glacial climate in order to maximize future precipitation and infiltration. While potentially useful, these bounding/conservative approaches do not consider the range of possible site-specific effects from both long-term and abrupt anthropogenic driven climate change. Instead, climate scenarios used in performance assessments evaluate natural variations in past climate associated with glacial and interglacial conditions (defined below). Further, the timing of future climate change or climate-driven events are not assessed; transition to a glacial climate is *assumed* during the isolation or compliance period of disposed waste. The rationale for such conservative climate assumptions in performance assessments are:

1. Attempted avoidance of *underestimation* of the effects of future climate change.
2. Technical and regulatory concerns with the uncertainty of predicting future climate states because of significant natural variability in global climate over time.
3. Uncertainty in emissions of greenhouse gases (GHG) derived from scenarios based on future socio-economic conditions and assumptions.

The Intergovernmental Panel on Climate Change (IPCC) was established by the World Meteorological Organization and the United Nations Environmental Program in 1988 to assess . . . “scientific, technical socio-economic information produced worldwide relevant to the understanding of climate change” (https://www.ipcc.ch/organization/). They have produced five assessment reports with the sixth report scheduled for 2022. The second through the fifth assessment reports provide progressively stronger statements on the likelihood of anthropogenic effects on multi-decadal climate change and its role in global warming since the twentieth century [1]. The fifth assessment report concludes that a glacial inception (end of the current interglacial conditions) is not expected within the next 50 ka (kilo-annum is one thousand years) as long as atmospheric CO_2 concentrations exceed 300 parts per million (ppm) or cumulative carbon emissions exceed 1000 PgC (petagrams of carbon) [2]. Further, they conclude that atmospheric CO_2 concentrations under the lowest emission scenario will exceed 300 ppm through calendar year 3000 and it is *virtually certain* (> 99% probability) that there will not be a return to glacial conditions before the end of the next millennium.

Given the strength of the IPCC conclusions and the recognition by the majority of climate-change researchers that climate forcings from anthropogenic GHG will profoundly impact future global climate states, it is imperative that climate change studies for radioactive waste disposal be revised consistent with the evolving climate-change literature.

Definitions

The IPCC definition of *global climate change* is, “. . . a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer.” Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use" [2]. Anthropogenic changes must be included in *historic definitions of climate change* as the observed changes in the energy balance of the earth since the mid-twentieth century cannot be reproduced solely by internal climate variability (<5% probability) [3,4].

The phrase *global climate change* is used to identify changes that occur on a global scale versus regional or local changes. *Global warming* is a subset of multiple changes associated with *global climate change*. *Milankovitch cycles* include any of three cyclic variations in the orbit of the Earth around the Sun including the obliquity of its axis, the precession of the equinoxes, and the eccentricity of its orbit. *Glacial and interglacial cycles* refer to periods in Earth's history, particularly during the Pliocene and Quaternary, marked by large variations in the continental and sea ice volume and global sea level [2]. A *glacial period or ice age* refers to intervals characterized by long-term reduction in global temperature, reduction in atmospheric CO_2 and growth of ice sheets and glaciers resulting in falling sea levels. *Interglacial periods* are warmer periods between glacial cycles with sea levels close to current sea levels.

GLACIAL AND INTERGLACIAL CYCLES

Global paleoclimate data show that the Earth throughout geologic time has had two fundamental climate states: 1) a cool or "icehouse" state characterized by bipolar glaciation and waxing and waning of continental ice sheets in the high latitudes of the Northern Hemisphere and 2) a "greenhouse" state characterized by warm temperatures on a global scale with limited or no ice sheets [5]. Figure 1 shows reconstructed global surface temperatures for the Cenozoic Era (last 65 Ma; mega-annum is one million years). Notable features of Figure 1 include:

1. The Paleocene-Eocene Thermal Maximum, the last major greenhouse global climate state.
2. A gradual decline in global surface temperatures for the last 50 Ma that coincides with decreasing CO_2 content of the atmosphere.
3. Development and persistence of Antarctic ice sheets starting in the Late Eocene-Early Oligocene.
4. Development of Northern Hemisphere ice sheets in the Late Miocene-Pliocene.

The causes of the long-term Cenozoic cooling trend are multiple and are topics of continuing debate [6–8]. The Pliocene-Pleistocene climate record includes two additional patterns: the onset of cyclical glacial and interglacial intervals in the Northern Hemisphere at about 2.7 Ma (asymmetrical saw-tooth cycles) and a transition in the periodicity of glacial cycles from 41 ka to 100 ka in the Middle-Pleistocene [9; see Figure 2 this paper]. The latter change was also accompanied by increased severity and duration of cold glacial states and increased global ice volume [10].

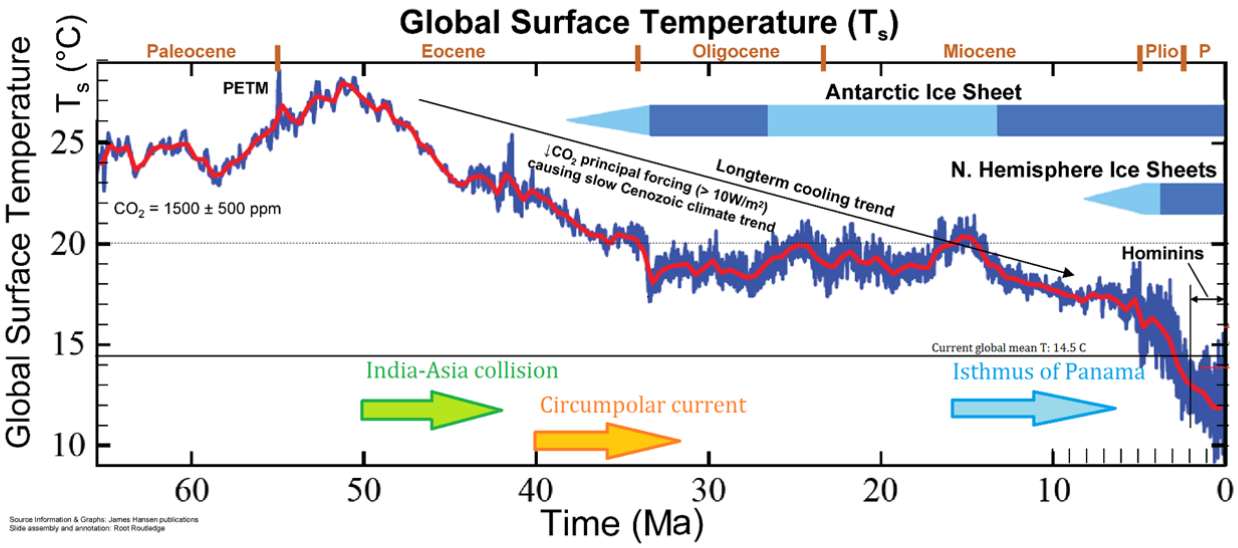


Fig. 1: Global surface temperature for the Cenozoic era showing the systematic decline in temperature from the Paleocene-Eocene Thermal Maximum (PETM) ~ 50 Ma until the cyclic glacial and interglacial intervals of the Quaternary (Pliocene and Pleistocene). Figure from Steven Earle (https://opentextbc.ca/geology/chapter/16-1-glacial-periods-in-earths-history/).

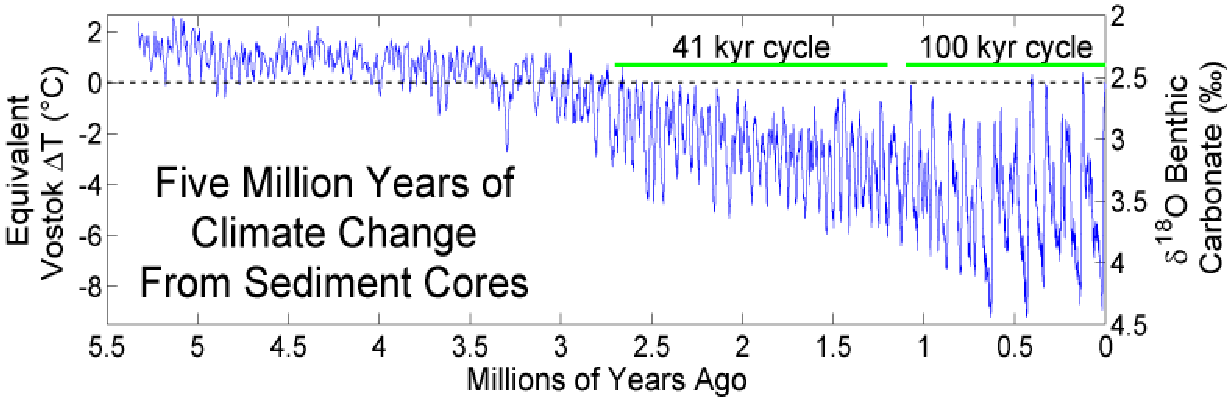


Fig. 2: Plot of ΔT and $\delta^{18}O$ for the last 5.3 million years (plot from the glacial cycle discussion of the Azimuth Project (http://www.azimuthproject.org/azimuth/show/Glacial+cycle) using the benthic $\delta^{18}O$ data from [9]). Note the progressive cooling trend, the increased amplitude of the cyclical patterns and the transition from the 41 ka to 100 ka glacial cycles since the onset of Northern Hemisphere glaciation at 2.7 Ma.

Interglacial Intervals

Interglacials are intervals of warmer global temperatures that generally last thousands to tens of thousands of years and are separated by longer duration glacial periods. On a large scale, the glacial and interglacial periods are best explained by the progression of Milankovitch orbital parameters and there is a consensus that the initiation of interglacial periods tends to be associated with maximum summer insolation (incoming solar radiation) in the higher latitudes of the Northern Hemisphere [11]. However, the global energy budget of orbital variations is insufficient to fully drive the documented large magnitude changes in glacial cycles or cause the observed rapid climate transitions [12].

Tzedakis et al. [13] recognize two patterns of interglacial durations—shorter (~ 13 ka) and longer (~28 ka). They suggest that the current interglacial should be categorized with the short-duration interglacials if the effects of GHG are ignored. Using this assumption, the current interglacial (~ 12 ka) should be near its end.

However, the timing and characteristics of interglacial cycles remain difficult to explain [14, 15]. This is attributed to three problems. First, the onset and termination of interglacial periods are difficult to define. Interglacials are typically identified by significant temporal changes in global temperature, sea level, atmospheric CO_2 and ice volume. These climate parameters show significant decadal, centennial and millennial variations that are difficult to resolve using paleoclimate data. Second, the timing of glacial events is progressively more difficult to refine with increasing age. Govin et al. [16] evaluate the limitations in chronology data used for paleoclimate studies for the last interglacial (MIS 5e; glacial intervals are labeled by marine isotope stages; MIS). They note that limitations in correlating regional versus global paleoclimate records complicates interpretations of climate data and applications in climate model simulations. Third, recent data reveal the complexity of global climate patterns during glacial-interglacial transitions [17]. Paleoclimate proxy data must be integrated for both the Northern and Southern Hemispheres. For example, temperature and CO_2 variations in both hemispheres are strongly affected by the strength of the Atlantic meridional overturning circulation (AMOC; [17]). Ganopolski and Roche [18] argue that temporal analysis of leads and lags in climate parameters cannot be used to infer causative relationships in climate without a global scale understanding of climate processes. They note that local ice core data can contradict global CO_2 and temperature variations.

Atmospheric CO_2 Variations with Glacial Cycles

Ice core studies show cyclic variations in atmospheric CO_2 during glacial and interglacial periods [12]. Atmospheric composition of CO_2 is typically near 280 ppm during interglacial periods and about 180 to 200 ppm during glacial periods. A consensus has not been achieved on the mechanisms controlling the cyclic variations in atmospheric CO_2. Sigman and Boyle [12] summarize explanations for the CO_2 variability based on sequestration of carbon in the ocean by the sinking of organic carbon at the surface of the ocean and burial in marine sediments (biological pump). They describe two mechanisms to explain the variations in atmospheric CO_2 with glacial cycles: 1) larger reservoirs of algal nutrients during glacial times increasing the biological pump at low latitudes, and 2) increased utilization of algal nutrients at high latitudes during glacial times.

Complexity of Glacial Cycles

There are multiple issues with attempts to match paleoclimate data and model simulations to the detailed climate variations observed in glacial cycles. Some of the major issues include:

1. The glacial and interglacial climate data follow asymmetric saw-tooth patterns with longer glaciations and shorter interglacials. These patterns are not easily reproduced in modeling studies without adding additional internal climate forcing components [19, 12]. Crucifix [14] argues that many of the problems explaining the stability patterns of glacial-interglacial periods arise from attempts to apply statistical inferences to dynamical climate systems that are hampered by sparse data sets with large interpretative and chronological uncertainties.
2. Lisiecki [20] uses statistical analyses (cross-wavelet analysis) of insolation and climate over the last 5 Ma to evaluate the linkage between orbital eccentricity and the 100 ka glacial cycles. She argues that eccentricity is unlikely to force 100 ka glacial cycles directly and instead cyclic patterns probably result from internal feedbacks of the climate system that are phase locked to eccentricity.
3. Modeling studies of glacial inceptions [21] show that the models must integrate all major components of a climate system as well as nonlinear feedbacks between components. Climate models require amplifying feedbacks in combination with insolation forcing to trigger glacial-interglacial transitions [22].
4. Paleoclimate data show that global changes during the last glacial transition are complex and involve dynamic and nonlinear processes operating across both hemispheres [17]. Orbital changes must be coupled to other dynamic processes particularly snow-albedo feedbacks and atmospheric CO_2 contents as well as other processes including variations in the AMOC, vegetation changes with climate feedbacks, carbon variations in the ocean and atmosphere.

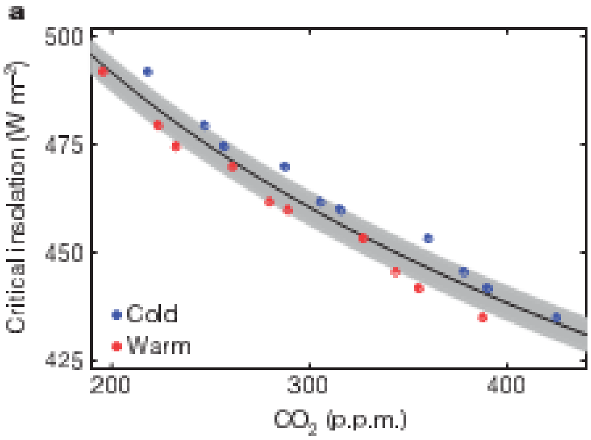
TIMING OF THE NEXT GLACIAL INCEPTION

Mysak [23] surveyed climate literature on the timing of the next glacial inception and concludes that the present interglacial could last longer than 100 ka if CO_2 concentrations remain above pre-industrial levels.

Archer and Ganopolski [22] use the CLIMBER-2 (an Earth System Model of Intermediate Complexity; EMIC) coupled with the SICOPOLIS ice sheet model to simulate the past five glacial cycles. They evaluate the stability of the climate-cryospace system under orbital and CO_2 atmosphere forcings and explore a threshold curve in the Northern Hemisphere insolation values as a function of CO_2. The rate of ice growth in the Northern Hemisphere in the CLIMBER-2 model depends on both the duration of an insolation minimum and how far the minimum falls below the threshold curve. When the baseline CO_2 is raised, a deeper minimum in summertime insolation is required to initiate ice growth. Archer and Ganopolski [22] note that the Earth's orbital configurations are entering a period of low eccentricity with low variability in the summer insolation. An assumed release of 1000 Gt (gigaton) of carbon (or GtC) during the 21st century would prevent a new cycle of glaciation until 130 ka from the present.

Ganopolski et al. [24] update the critical insolation-CO_2 relationships for assessing future glacial inceptions. They compare earth orbital configurations for the present interglacial (MIS 1) with other interglacial intervals that transitioned to glacial intervals (MIS 11 and MIS 19). The CO_2 concentrations for MIS 11 and MIS 1 are about the same as the ~ 280 ppm pre-industrial era for MIS 1 but are lower for MIS 19 (~ 250 ppm). The CLIMBER-2 EMIC model with the SICOPOLIS ice sheet model was again used to run multiple model simulations exploring orbital configurations and CO_2 concentrations for the three interglacial intervals. Simulations were screened consistent with the observation that MIS 11 and MIS 9 transitioned to a glacial interval (simulations with at least an ice-buildup equivalent to a 5 m decrease in sea level were included) and MIS 1 has not transitioned (simulations with more than a 1 m equivalent of ice-volume change were not included); four realizations passed their screening constraints. At 280 ppm of CO_2 none of the screened model versions simulate significant ice sheet growth. At 240 ppm of CO_2, all 4 model realizations simulate rapid ice growth within several thousand years. Ganopolski et al [24] speculate that the earth may have escaped a Holocene glacial inception with only a 40 ppm difference in initial CO_2 contents.

Ganopolski et al. [24] explore the threshold values of CO_2 levels versus the maximum summer insolation at 65 degrees North (Fig. 3a) expanding the initial work by Archer and Ganopolski [22]. Points in insolation-CO_2 space cluster along a logarithmic curve consistent with radiative forcing of CO_2 being proportional to the logarithm of CO_2 concentration and a linear temperature response within the range of the modeled CO_2 concentrations. Past glacial inceptions all plot below the critical insolation-CO_2 line (Figure 3b). The Holocene interglacial (MIS 1) plots above the threshold value using the pre-industrial CO_2 content of 280 ppm. Ganopolski et al. [24] conclude that the current Holocene interglacial has no analogue within past interglacials for the last 1 Ma. They simulate the onset of a new glaciation by running the four screened model realizations for 100 ka (after present) using different carbon emission scenarios. For a 1,000 Gt carbon scenario projected in 2100, the model simulations show that a glacial inception is impossible over a period comparable to the duration of previous glacial cycles, approximately 100 ka [24].



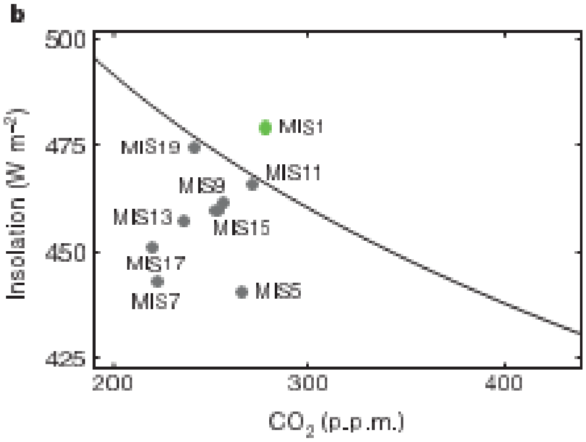


Fig. 3a: Best-fit logarithmic relation between maximum summer insolation at 65 degrees N and the CO_2 threshold for glacial inception (from [24]; their Figure 3). Blue and red dots are the coldest and warmest model version in the CLIMBER-2 simulation runs used to explore the threshold relationship. The shaded area is one standard deviation of the threshold curve.

Fig. 3b. Plots of the location of the Quaternary glacial inceptions (MIS numbers) for the best-fit curve from Figure 3a (from [24]; their Figure 3). Glacial inception in the model simulations is only possible below the insolation-CO_2 curve. The current interglacial (MIS 1) plots above the insolation curve assuming a pre-industrial CO_2 value of 280 ppm.

DISCUSSION AND CONCLUSIONS

Milankovitch cycles must be combined with the climate effects of anthropogenic GHG to forecast future climate states. These studies can be compared with past patterns of glacial and interglacial cycles to provide a conceptual framework for forecasting future climate in performance assessments. We have a much improved understanding of the longevity of CO_2 in the atmosphere [25, 26]. Twenty to fifty percent of the anthropogenic CO_2 released within the next 100 years will remain in the atmosphere after 1,000 years, and a return to pre-industrial CO_2 concentrations may require hundreds of thousands of years [26]. Recent data for the monthly mean atmospheric CO_2 content at the Mauna Loa Observatory in Hawaii are greater than 400 ppm (http://www.esrl.noaa.gov/gmd/ccgg/trends/, accessed January 2017) and equal or exceed maximum atmospheric concentrations measured in ice cores for the last 800 ka [2]. Estimated CO_2 concentrations within the next century will exceed the highest estimated CO_2 concentrations in the last 30 Ma of the Earth's history [5]. Modeling studies show that the impact of high atmospheric CO_2 is profound when dynamically linked to other climate components and will suppress transition to a future glacial climate. The most likely scenario for the future global climate is continuation of the current interglacial climate under conditions of variable but progressive global warming. Previously used assumptions in performance assessments of bounding glacial climates (coldest/wettest conditions) are no longer applicable and under some conditions may require design of overly protective and costly closure covers to reduce infiltration.

Performance assessments need to reassess conceptual model assumptions for potential impacts of future climate states. Ongoing global climate studies clearly demonstrate a high probability of persistence of the current warm interglacial climate with progressively higher mean temperatures, increased aridity in the southwestern US and increased frequency of extreme weather events. Current and future performance assessments should evaluate on a site-specific basis:

1. Impacts of higher mean temperatures and changes in regional climate patterns on site vegetation and operational and closure design features of disposal facilities.
2. Changing recurrence rates of extreme weather events. Higher temperatures will result in increased atmospheric moisture (humidity) and increased thermal energy affecting the magnitude of storm events.
3. Increased aridity in the southwest US will affect infiltration, ground water and may impact local water usage/demand. Future policy decisions on climate change by state and local government institutions can impact water supplies at disposal sites.
4. Uncertainty in future climate data at regional versus global scales. Coupling between global and regional climate modeling studies will be a topic of increased focus in future climate studies [5].

Ongoing performance assessments by Neptune and Company at multiple radioactive disposal sites incorporate or will incorporate the revised climate change impacts described in this paper. Historical weather and climate data (current conditions) may no longer be applicable to future forecasts. The following are preliminary assessments of future climate change impacts for performance assessments at four disposal sites:

1. **Material Disposal Area G Site, Los Alamos, New Mexico:** Increased aridity associated with expanded drought conditions in the southwestern United States; decreased vegetation growth and density of cover; increased impacts of forest fires; increased magnitude and possible frequency of maximum monsoonal weather events that may increase local erosion (closure covers, mesa surfaces and cliff faces).
2. **Clive Low-Level Radioactive Waste Disposal Facility, Clive, Utah:** Decreased likelihood of future rise of the Great Salt Lake (lake rise to the Clive elevation almost certainly requires a future glacial climate); modified climate affecting aridity and vegetation patterns; increased duration of aeolian deposition with future deeper burial of the disposal site.
3. **Waste Control Specialists Disposal Site, Andrews County, Texas:** Probable increased aridity and drought with resulting changes in vegetation; increased intensity of monsoonal precipitation patterns; increased aeolian deposition but general stability of the landscape (the geology of the Waste Control Specialists site demonstrates landscape stability during past Quaternary glacial and interglacial cycles).
4. **Western New York Nuclear Service Center, West Valley New York:** Continuation of observed multi-decadal warming; poleward shifting of storm

tracks, jet streams and contraction of the northern polar vortex; possible climate impacts from abrupt climate change associated with weakening of the AMOC; increased probable maximum precipitation events with decreased frequency of forecast storm events (for example, more frequent 100-year storms); reassessment of erosion rates and potential changes in watershed base level from increased precipitation and increased magnitude of maximum precipitation events.

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