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Spatial Variability of Waste Temperatures in MSW Landfills

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ABSTRACT: Spatial variability of waste temperatures in MSW landfills was determined over different physical and temporal scales. Data have been obtained at four landfills located in different climatic regions in North America: Alaska, British Columbia, Michigan, and New Mexico. Temperatures were measured using 100 to over 250 sensors at each site. Data were obtained for 5 to 10 year periods at the sites. Temperatures were measured in wastes with a broad range of ages: newly-placed and old (up to 40-year old). The characteristic shape of waste temperature vs. depth relationships consists of a convex temperature profile with maximum temperatures observed at central locations within the middle third fraction of the depth of the waste mass. Lower temperatures with trends similar to air temperatures were observed above this central zone. Temperatures near the base of the landfills and in the liner systems were relatively steady and elevated above mean annual earth temperature, yet were below the maximum values in the central zones. The location of the maximum temperatures/heat gain is affected in the short term by waste placement temperature and in the long term by heat generation and dissipation. Sustained concave temperature profiles were observed for waste placement in cold temperatures. In British Columbia with high heat generation, temperature increases occurred for multiple years and then dissipated for tens of years. Longer periods of temperature increase were observed at the other sites with relatively lower heat generation rates. Temperatures continue to increase at these sites after approximately a decade since waste placement. The highest temperatures were observed in Michigan followed by British Columbia, New Mexico, and Alaska. The time-averaged waste temperature ranges were 0.9 to 33.0°C, 14.4 to 49.2°C, 14.8 to 55.6°C, and 20.5 to 33.6°C in Alaska, British Columbia, Michigan, and New Mexico, respectively.

INTRODUCTION

Elevated temperatures occur in MSW landfills due to decomposition of organic wastes. Significant amounts of heat are generated in landfills resulting in long-term elevated waste temperatures (Yesiller et al. 2005). Temperature increases and heat gain occur during both aerobic and anaerobic decomposition stages. In most cases, heat gain over long-term (anaerobic) conditions exceeds the short-term heat gain associated with aerobic conditions. Most of the temperature data provided in the literature to date have been either direct reports of temperature vs. time trends at individual landfills with limited number of measurement locations (Lefebvre et al. 2000, Yoshida and Rowe 2003, Rowe 2005) or modeling of heat transfer in landfills with no actual field temperature

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measurements (El Fadel et al. 1996, Doll 1997). Detailed investigations of temperature distributions in a single landfill, comparisons of temperatures in multiple landfills, and identification of underlying fundamental trends in temperature distributions in landfills are limited (Yesiller et al. 2005).

The study described herein was conducted to investigate spatial variability of temperatures in landfills. Data from four instrumented landfills located in different climatic regions were used in the investigation. Common underlying trends in waste temperature variability were established. Effects of climatic and operational conditions on waste temperature distributions were determined.

FIELD TEST PROGRAM

Field Test Sites and Instrumentation

Temperature data have been obtained at 4 MSW landfills located in different climatic regions in North America: Alaska, British Columbia, Michigan, and New Mexico (Table 1). The facilities located in Alaska, Michigan, and New Mexico are Subtitle D landfills, whereas the landfill in British Columbia contains a base support/liner system and a gravity-flow leachate collection system (Table 1).

Table 1. Climate Statistics at the Sites (adapted from Yesiller et al. 2005)

Parameter	**Alaska**[b]	**British Columbia**[c]	**Michigan**[b]	**New Mexico**[b]
Climate description[a]	Oceanic boreal	Woodland oceanic	Humid continental temperate	Semi-desert
Average Air T_{high} (°C)	6.2	13.5	14.7	25.1
Average Air T_{low} (°C)	-1.5	6.1	5	11.2
Average Air T (°C)	2.3	9.9	9.8	18.2
Annual normal precipitation (mm)	408	1167	835	240
Annual normal snowfall (mm)	1793	549	1046	135
Mean annual earth temperature (°C)	6.0	11.5	11.7	20.0
Design waste placement area (ha)	67	225	65	79
Average waste intake (t/year)	317,000	390,000	965,000	114,000
Average waste column height (m)	28.7	11.3	25.2	13.2

[a]based on Landsberg et al. (1966), [b]from NCDC (2006), [c]from MSC (2007)

Temperatures were measured throughout the landfill facilities including bottom liner, waste mass, cover, and perimeter control locations (in native subgrade soils away from the zone of influence of the waste mass). Temperatures were measured using Type K thermocouples that were deployed in custom-fabricated arrays. The arrays ranged in length between 1 and 60 m for vertical installations (through covers and wastes, and at control locations) and between 150 and 200 m for horizontal installations (within liners, covers, and wastes). Over 700 sensors were installed at the combined sites. Measurements were taken on a weekly basis at each site. The total monitoring periods have ranged from 5 to 10 years.

Analyses

The data from the test sites were used to investigate the characteristic shapes of temperature profiles with depth using a variety of parameters. Effects of climatic and operational conditions on waste temperature distributions were determined. In particular, the influences of placement temperature and age on the resulting waste temperature profiles were determined. Year-to-year comparisons were made for temperature vs. depth data at the test sites.

Additional analyses were conducted to determine the heat gain in the wastes. The average temperature differential of the wastes (as compared to unheated conditions) was calculated. The average temperature differential at a given depth was calculated as the time-averaged difference between the waste temperature vs. time curve and the equivalent unheated waste temperature vs. time curve (Yesiller et al. 2005). The unheated conditions were estimated using conventional earth temperature theory (Carslaw and Jaeger 1959) with representative thermal properties for wastes. The average temperature differential represents heat gain of the waste due solely to biological decomposition. This analysis effectively filters out both seasonal temperature variations and differences in ambient average ground temperatures between the sites. The relative position of maximum temperature differential was determined using normalized depth for the landfill profiles (zero corresponding to surface and 1.0 corresponding to bottom liner location) to compare the general patterns for temperature profiles, independent of the actual depth of the waste mass.

Contour maps of temperature were developed for Michigan and New Mexico, sites for which high spatial resolution in data was present. Maps are presented for multiple years of data to demonstrate variations in temperatures with time.

RESULTS AND DISCUSSION

Characteristic Shapes of Waste Temperature Profiles

The characteristic shape of waste temperature vs. depth relationships consists of a convex temperature profile with maximum temperatures near mid-depths of the landfill and lower temperatures both above and below this central zone. The locus of maximum temperature is modified with time as heat is generated, redistributed, and dissipated throughout the landfill system. Temperature profiles are presented in Fig. 1 for a cell in Michigan that was filled with wastes between 1999 and 2001. On all temperature-depth plots, horizontal dashed lines indicate the elevation of the liner system. Data provided in the figure represent average temperatures for a year at each depth. Waste temperatures generally increased with time at all depths. The profiles were convex at depth, whereas they were concave at shallow depths shortly after waste placement. The wastes at depth were placed during warm seasons while the shallower wastes were placed in cold seasons. The depth of the maximum temperature occurrence remained relatively constant with time.

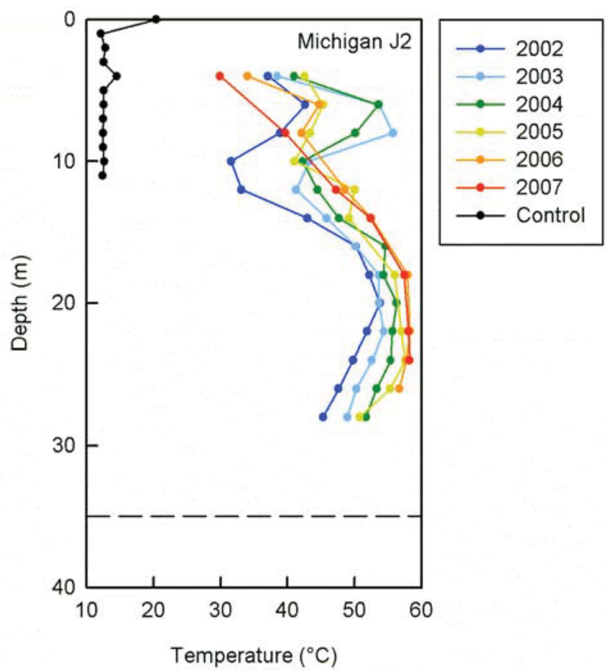

Fig. 1. Example of Temperature Profiles at Michigan over Time

Examples of temperature profiles are presented in Figs. 2 and 3 for British Columbia. Tautochrones are presented in these figures for February survey dates. The redistribution of heat is presented in Fig. 2 for Cell D (approximately 9 to 12 year waste age) and Cell E (approximately 7 to 10 years waste age). In both cells, waste temperatures decreased with time. At Cell E, a significant localization of elevated temperature zone was observed over the 3-year period presented in Fig. 2, whereas at Cell D, a global decrease in temperature was observed with a less pronounced localization. In both cases, the peak temperature occurred at deeper locations with time. Instantaneous temperature profiles on a specific date for vertical arrays were compared for six different cells at the British Columbia site over a broad range of waste age. The change in temperature profiles for all of the cells is presented in Fig. 3 where the maximum waste age was 38 years (Cell A) and the minimum waste age was 1 year (Cell F). The temperature profiles monotonically shifted to lower temperatures with age. Residual heat gain remains at depth for all cells. Temperatures near the surface are similar to unheated control ground temperatures. Heat generation occurs rapidly in British Columbia due to high precipitation (Yesiller et al. 2005, Hanson et al. 2008) and dissipates over a period of decades.

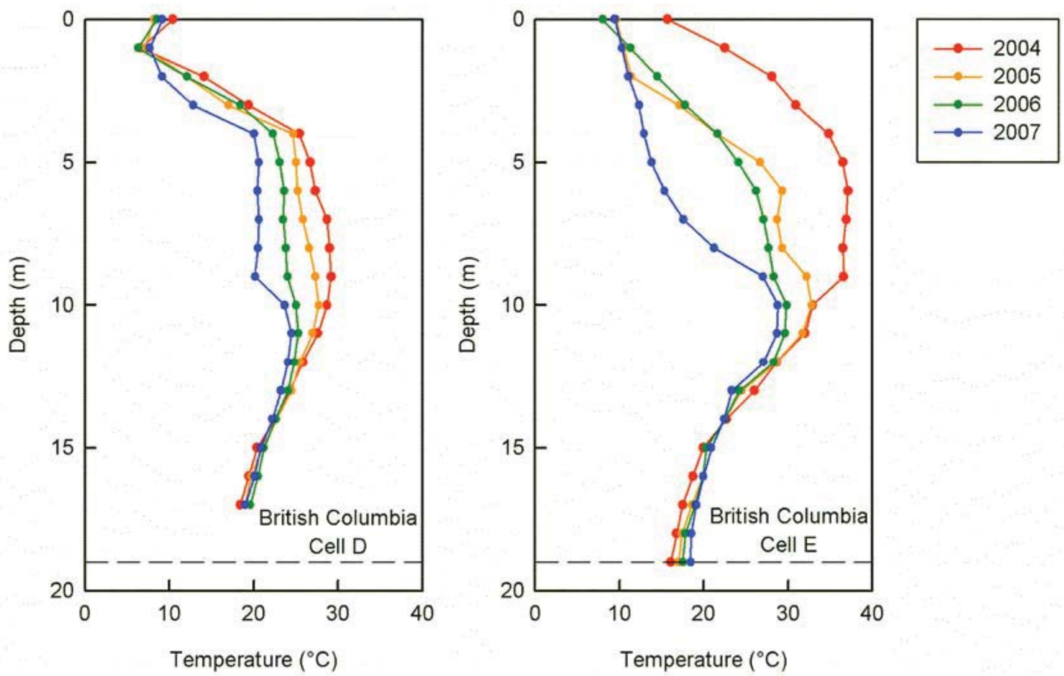

Fig. 2. Temperature Profiles at British Columbia with Time

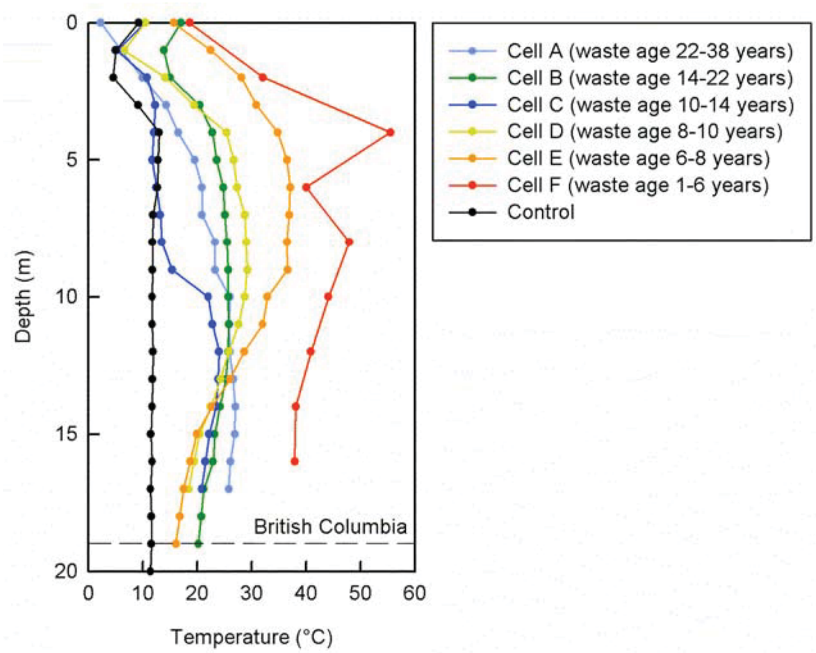

Fig. 3. Temperature Profiles for Variable Waste Age

Examples of temperature profiles in Alaska are presented in Fig. 4. Tautochrones are presented in this figure for May survey dates. In Cell 1A, the temperature profile exhibited a convex shape. Waste at Cell 1A ranged from 1 to 5 years old in 2004. Heat was both generated and redistributed over the 3-year period presented. Temperatures decreased at shallow depths and increased at greater depths. In Cell 6B, a concave temperature profile was observed that resulted from placement of a 7 m thick layer of frozen waste in winter. The waste ranged from zero to 2 years old in 2004. The frozen waste caused longstanding low temperatures that prevented heat generation and were not overcome by surrounding heat generation. Frozen conditions remained for 2 years at depth and even after 3 years, the temperature profile remained concave with minimum temperatures occurring at mid-depth (Fig. 4).

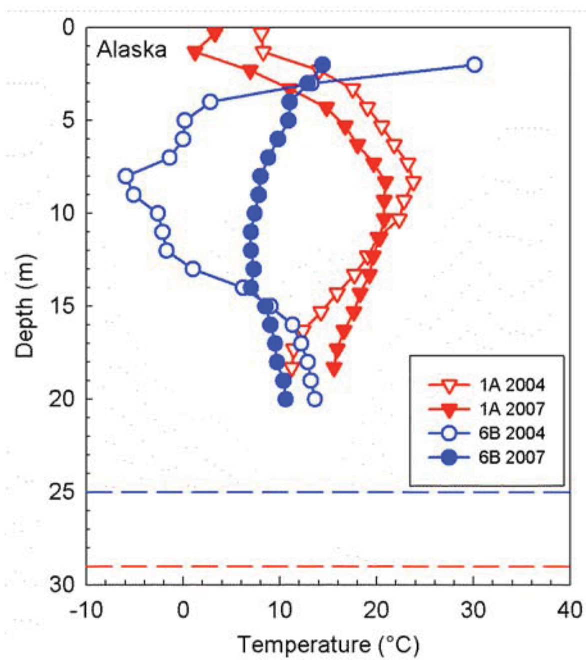

Fig. 4. Comparison of Temperature Profiles for Frozen and Unfrozen Waste Placement Conditions in Alaska

Heat Gain in Wastes

Variations of average temperature differential for each of the 4 sites are presented in Fig. 5. The arrays selected for this analysis extended through the greatest fraction of depth of wastes and had comparable waste ages (approximately 7 years). The highest average temperature differential was observed in Michigan due to the favorable precipitation/moisture conditions, whereas the lowest differential was observed in New Mexico due to the dry climate and waste conditions. The maximum temperature for Alaska and British Columbia were similar for 7-year old waste. For the waste age indicated on the plot, the temperatures in Alaska are increasing from previously cooler temperatures whereas the temperatures in British Columbia are decreasing from previously higher temperatures. The delay in heat gain in Alaska is attributed to dry conditions and cool ambient temperatures. The rapid heat gain in British Columbia is attributed to high precipitation. Further description of mechanisms of heat gain in wastes is provided in Yesiller et al. (2005) and Hanson et al. (2008). Limiting (maximum and minimum) temperatures are presented for wastes and liners at all the sites in Table 2. The data represent time-averaged values over the entire study period. The maximum temperatures were generally observed at central locations within the middle third fraction of the depth of the waste mass. The maximum liner temperatures occurred near the midpoint length of the cell floors. The minimum waste and liner temperatures occurred near the top surface and perimeter edge of the cells, respectively.

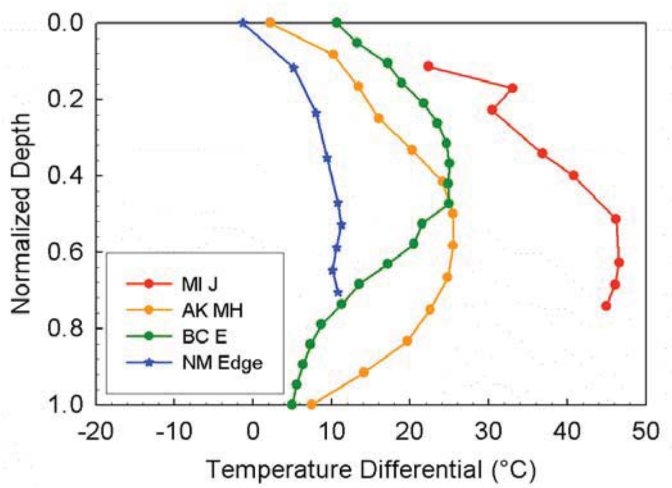

Fig. 5. Variation of Average Temperature Variation at All Sites

Table 2. Limiting Temperatures Observed in Landfills

Parameter	Alaska	British Columbia	Michigan	New Mexico
$T_{min\text{-}waste}$ (°C)	0.9	13.1	14.8	20.5
$T_{max\text{-}waste}$ (°C)	33.0	49.2	55.6	33.6
$T_{min\text{-}liner}$ (°C)	NA	17.5	12.6	19.0
$T_{max\text{-}liner}$ (°C)	NA	37.2	26.2	29.0

NA = not available

2-Dimensional Distributions of Temperatures

Results of year-to-year comparisons are presented as temperature contour maps in Figs. 6 and 7. For New Mexico (Fig. 6), maps were constructed using superimposed data from 2 adjacent cells (Cells 1 and 2). The temperatures increased slightly and stabilized with time. Data from a single cell (Cell D) is provided in Fig. 7 for Michigan. A general increase in temperature and expansion of elevated temperature zone at the central

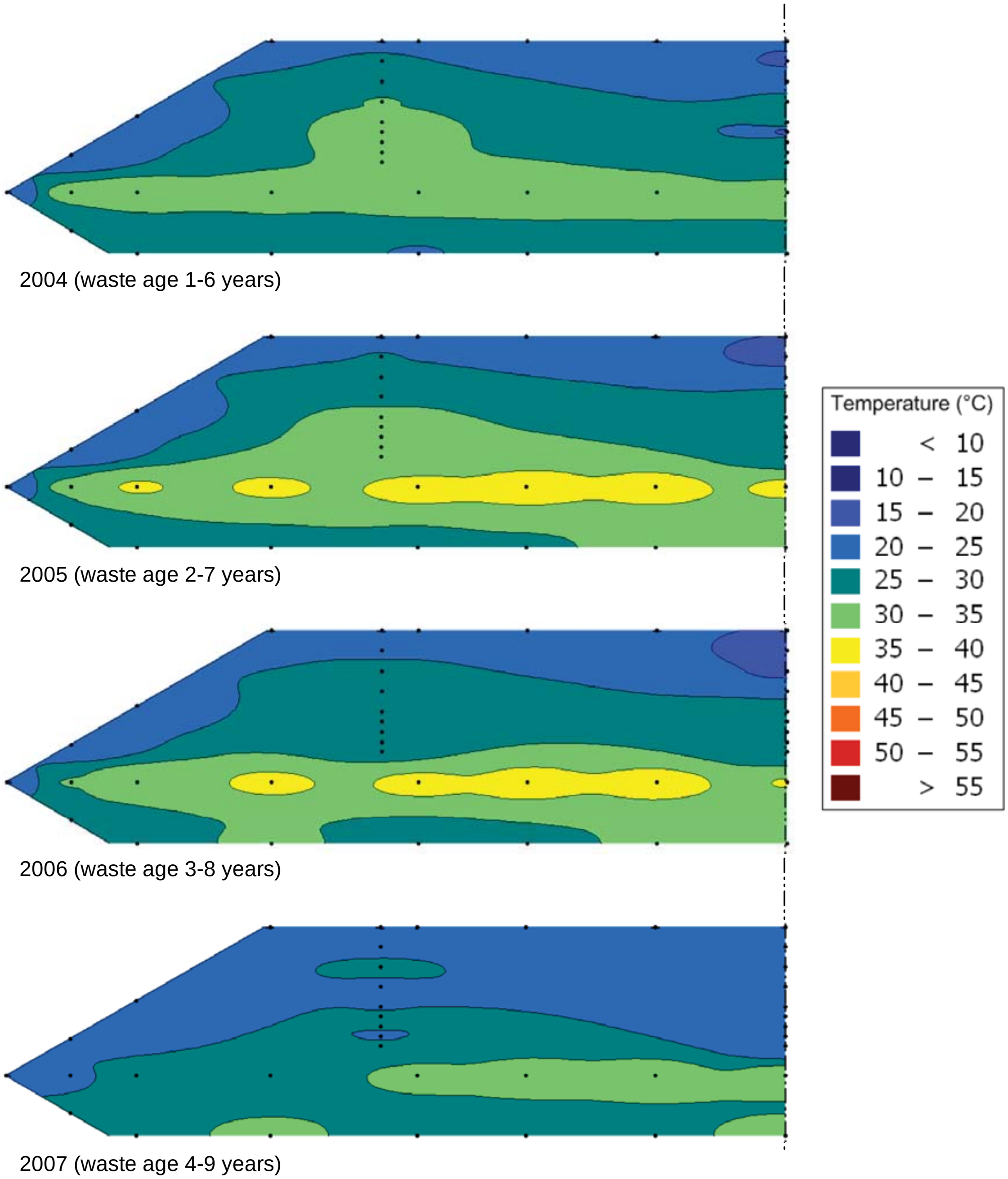

Fig. 6. Temperature Contour Maps for New Mexico

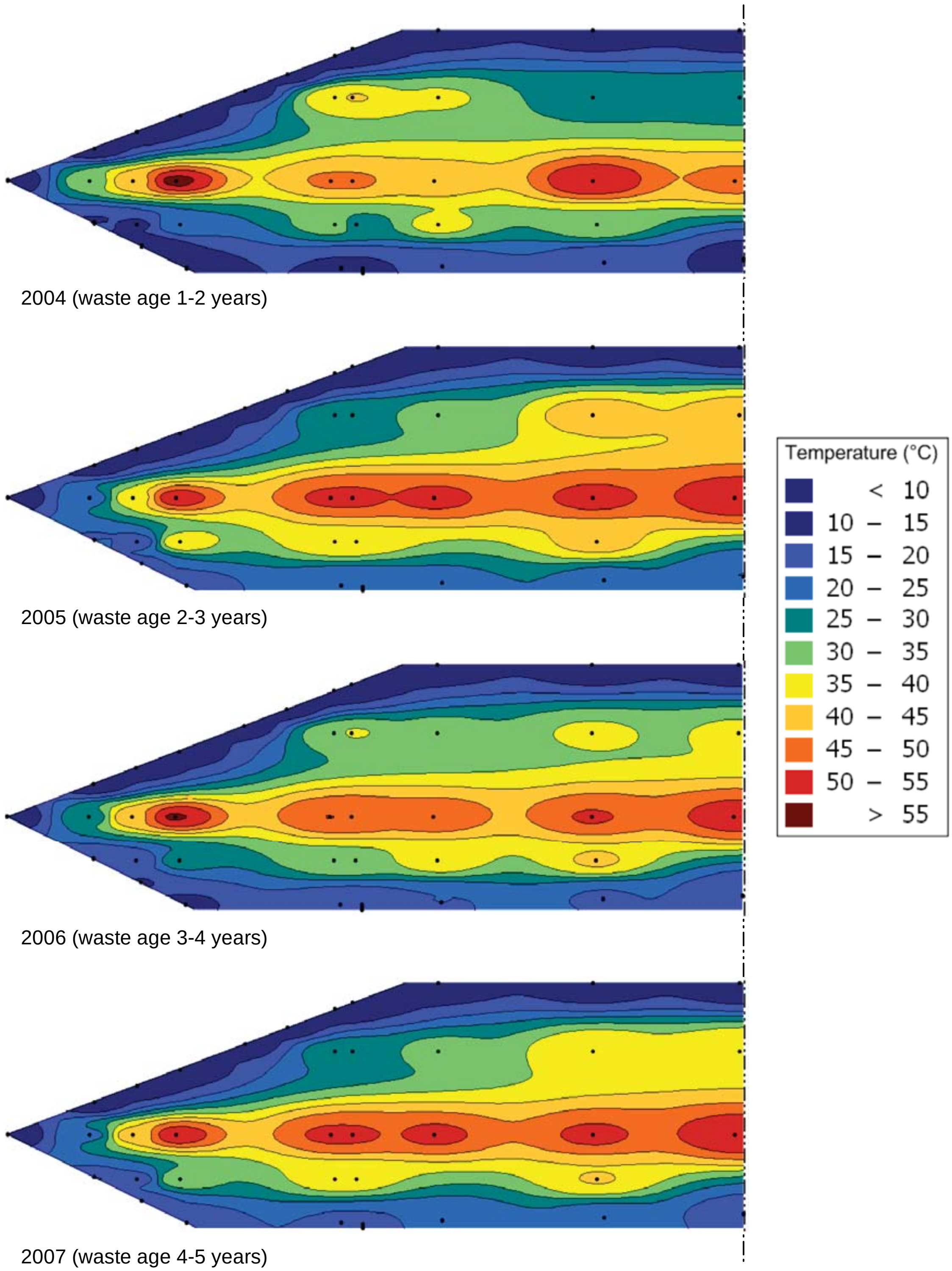

Fig. 7. Temperature Contour Maps for Michigan

elevations of the cell were observed. Overall, the temperatures throughout the entire cross section were significantly greater than in New Mexico. The spatial distributions of the waste temperatures were affected by climatic region and subgrade conditions. In particular, the difference between observed trends at New Mexico and Michigan were attributed to differential between peak waste temperatures and ambient mean annual earth temperatures at depth as well as thermal properties of the wastes and subgrade soils. As an example, in New Mexico the peak waste temperatures were approximately 35°C and the mean annual earth temperature was approximately 21°C, whereas in Michigan the peak waste temperatures were approximately 60°C and the mean annual earth temperature was approximately 12°C.

CONCLUSIONS

The conclusions provided below are based on long-term monitoring of temperatures at four MSW landfills in different climatic regions.

- The characteristic shape of waste temperature vs. depth relationships consists of a convex temperature profile with maximum temperatures observed at central locations within the middle third fraction of the depth of the waste mass.
- Lower temperatures with trends similar to air temperatures were observed above the central zone. Temperatures near the base of the cells and in the liner systems were relatively steady and elevated above mean annual earth temperature, yet were below the maximum values in the central zones.
- The location of the maximum temperatures/heat gain is affected in the short term by waste placement temperature and in the long term by heat generation and dissipation. Sustained concave temperature profiles were observed for waste placement in cold temperatures.
- In British Columbia with high heat generation, temperature increases occurred for multiple years and then dissipated for tens of years. Longer periods of temperature increase were observed at the other sites with relatively lower heat generation rates. Temperatures continue to increase at these sites after approximately a decade since waste placement.
- The time-averaged waste temperature ranges were 0.9 to 33.0°C, 13.1 to 49.2°C, 14.8 to 55.6°C, and 20.5 to 33.6°C in Alaska, British Columbia, Michigan, and New Mexico, respectively.

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