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STAMP - The SWOE Thermal Analysis and Measurement Program: Summary of the 1990 Field Tests

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The Balanced Technology Initiative on Smart Weapons Operability (BTIO/SWOE) has a goal to develop a computer simulation capability of the radiant field from the natural environment. This simulation capability would then be used by designers and testers of smart weapons electro-optic sensor systems to study the performance of the systems under anticipated environmental conditions.

Vegetation offers a particular challenge to the BTI/SWOE modeling community due to the wide variety in types, shapes , sizes, and distributions of vegetation. To aid in the development of energy budget models of surfaces containing vegetation, a measurement program was designed and conducted near Howland, Maine. The SWOE Thermal Analysis and Measurement Program (STAMP) was designed with the goal of providing data tosupport models for a 3-D thermal model of an individual trees and an interim model of the thermal response at a forest edge.

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STAMP - The SWOE Thermal Analysis and Measurement Program: Summary of the 1990 Field Tests

1 INTRODUCTION

The Balanced Technology Initiative on Smart Weapons Operability Enhancement (BTI/SWOE) has as a goal to develop a computer simulation capability of the radiant field from the natural environment. This simulation capability would then be used by designers and testers of smart weapons electro-optical sensor systems to study the performance of the systems under anticipated environmental conditions.

Vegetation offers a particular challenge to the BTI/SWOE modeling community due to the wide variety in types, shapes, sizes, and distributions of vegetation. To aid in the development of energy budget models of surfaces containing vegetation, a measurement program was designed and conducted near Howland, Maine. The SWOE Thermal Analysis and Measurement Program (STAMP) was designed with the goal of providing data to support model development efforts for a 3-D thermal model of an individual tree[1] and an interim model of the thermal response at a forest edge.

[1] Hummel, J.R., Jones, J.R., Longtin, D.R., and Paul, N.L. (1991) "Development of a 3-D Tree Thermal Response Model for Energy Budget and Scene Simulation Studies," Phillips Laboratory, Hanscom AFB, Massachusetts, PL-TR-91-2108, ADA 240693.

1.1 Overview of STAMP

STAMP was conducted near Howland, Maine on land owned by the International Paper Company. The measurement program was held 6-24 September 1990 in conjunction with a NASA program on Forest Ecosystem Dynamics (FED).

STAMP was designed and organized by SPARTA, Inc. with logistical support generously provided by personnel from the University of Maine. Personnel from SPARTA, Inc. and the Keweenaw Research Center (KRC) of the Michigan Technical University participated in the field test efforts.

1.2 Organization of Report

The purpose of this report is to describe the specific goals of STAMP, outline the measurement procedures used, summarize the data obtained and their significance, and provide recommendations for further measurement efforts. Chapter 2 details the specific goals of STAMP and the measurements designed to achieve the goals. Chapters 3 and 4 summarize and discuss the data that were obtained at the two primary test sites. Finally, Chapter 5 provides a summary and recommendations on additional measurements that will complement the STAMP database and SWOE modeling efforts. Two appendices are also provided containing the meteorological data and the complete set of tree thermal data.

2 GOALS OF STAMP

2.1 Overview

There were two specific goals of STAMP. The first was to obtain temperature measurements of the internal temperature distribution of a single tree to support the development of a 3-D energy budget model for an individual tree. The second goal was to provide data of the surface and soil temperature distribution at a forest edge. These data would be used to aid in the development of an interim, 1-D model of the thermal response at a forest edge.

2.2 The STAMP Field Sites

Two field sites were selected for study. Both sites were located near a seed orchard maintained by International Paper. The two sites are shown in Figure 1. The first site contained the individual tree that was selected for study. This site, referred to as the Joyce site (after the nickname "Joyce Kilmer" given to the tree) was located at the southeast corner of the seed orchard and adjacent to an instrument building operated by the University of Maine. Located on the roof of this building was a sui e of meteorological instruments. SPARTA personnel operated from this site with logistical support from the University of Maine and supporting infrared imagery from KRC.

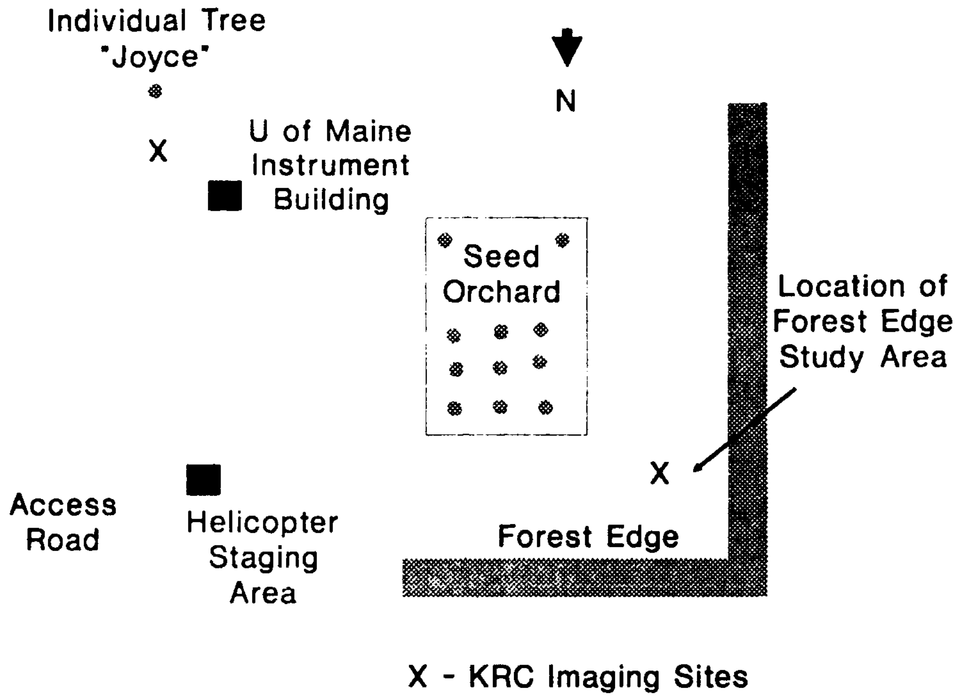


Figure 1. Schematic Representation of the STAMP Field Sites at the University of Maine Howland Field Site

The second site, referred to as the edge site, was located at the opposite corner of the seed orchard. This site was used to obtain data for use in understanding the phenomenology at forest edges. KRC operated from this site, obtaining meteorological, surface and soil temperatures, and infrared imagery data based on a test plan prepared by SPARTA.

2.3 Overview of Measurements

A variety of measurements were taken to support the SWOE modeling efforts. Table 1 summarizes the data taken, who obtained the data, and the time periods covered. Appendix A contains a copy of the field test log.

Table 1. Summary of Data Taken at the STAMP Field Tests

DATA TAKEN	SOURCE OF DATA	TIME PERIOD COVERED
Meteorological Data at Joyce Site	University of Maine	6 - 24 Sept 1990
Tree Thermal Data	SPARTA, Inc.	6 - 24 Sept 1990
Tree Infrared Imagery	KRC	9 - 11 Sept 1990
Meteorological Data at Edge Site	KRC	9 - 11 Sept 1990
Forest Edge Infrared Imagery	KRC	9 - 11 Sept 1990
Soil Temperatures at Forest Edge	KRC	9 - 11 Sept 1990
Leaf and Bark Reflectivity	Spectral Sciences, Inc.	

2.4 Supporting Meteorological Measurements

The primary meteorological measurements were taken and averaged every fifteen minutes by the University of Maine. Data were taken from an instrument suite located on the roof of the building adjacent to the Joyce site. The measurements obtained included air temperature, relative humidity, wind speed and direction, barometric pressure, and total downwelling solar radiation. These data were provided for the period 7 - 23 September 1990. Table 2 provides an overview of the meteorological conditions during the test period.

In addition to these data, KRC obtained meteorological data from the edge site with a portable weather station for the period 9 - 12 September 1990. Their data set included those provided by the University of Maine and additional measurements of the downwelling diffuse solar and downwelling infrared radiation.

Table 2. Summary of Weather Conditions During the 1990 STAMP Field Program. Maximum and Minimum Temperatures are Based on Surface Weather Observations From the Bangor International Airport, About 30 Miles to the South of the Test Site

DATE	WEATHER SUMMARY	T_{max} (C)	T_{min} (C)
6 September 1990	Partly Cloudy	22.8	11.1
7 September 1990	Overcast With Light Rain, Clearing After Sunset	21.1	9.4
8 September 1990	Clear, Bright Sunny Day	17.8	6.1
9 September 1990	Clear and Bright in Morning. A Warm Front Passed Through in the Afternoon, Light Rain Began in the Evening	18.3	6.1*
10 September 1990	Overcast With Rain	18.3	13.3
11 September 1990	Early Morning Shower. Partly Cloudy Rest of the Day	21.7	14.4
12 September 1990	Overcast to Partly Cloudy	17.8	14.4
13 September 1990	Overcast to Partly Cloudy	22.8	16.1
14 September 1990	Overcast to Partly Cloudy	18.3	14.4
15 September 1990	Overcast With Clearing Late in the Day	20.6	10.6
16 September 1990	Partly Cloudy	17.2	8.3
17 September 1990	Partly Cloudy to Overcast	13.3	5.6
18 September 1990	Partly Cloudy Early, Overcast With Light Rain Late in the Day	11.7	3.9
19 September 1990	Partly Sunny in the Morning, Overcast Late in the Day	17.2	3.3
20 September 1990	Overcast With Rain, Clearing in Late Evening	13.9	7.2
21 September 1990	Clear in the Morning, Cloudy Late in the Day	17.8	5.6
22 September 1990	Overcast With Rain	15.6	10.0
23 September 1990	Overcast With Rain Until Morning. Clearing Rest of Day	21.1	8.9
24 September 1990	Partly Sunny and Dry	16.1	5.0

* Freezing Conditions Measured at "Joyce Site"

3 SUMMARY OF MEASUREMENTS FROM THE JOYCE SITE

Four sets of measurements were obtained at the Joyce site. First, a geometric description of the subject tree, "Joyce Kilmer", was obtained. Second, internal temperatures of "Joyce Kilmer" were taken using a combination of thermistors and thermocouples. Third, a full set of supporting meteorological data were taken by the University of Maine instrument suite. These data were supplemented with data taken by KRC at the edge site. Fourth, infrared (8-12μm) imagery were taken by KRC.

3.1 Tree Physical Measurements

The tree selected for study was a bigtooth aspen, *Populus grandidentata*, approximately 7.6 meters high. The tree was located in a small stand of trees approximately 15 meters from the University of Maine instrument building. Trees and brush surrounding the selected tree were cleared away in order to isolate the tree. At the completion of the tests, the tree was cut down and a detailed analysis of the internal structure performed. The tree was estimated as about twelve years old, based on an analysis of tree rings. Figure 2 displays a photograph of the selected tree.

3.1.1 Trunk and Branch Structure

The subject tree consisted of a single trunk with twenty nine major branches extending from the trunk. The diameter of the trunk was about 11 cm at the ground. The first branch was found at about 78 cm above the surface, where the trunk diameter was about 11 cm. Table 3 lists the height above ground of the twenty nine branches, the diameter of the trunk at the nodal location, and the orientation of the branches relative to the trunk.

3.1.2 Leaf Structure

Leaves on "Joyce" are broadly ovate with a short-point tip and rounded at the base. The leaves were generally about 6 - 10 cm long and 5 to 9 cm wide. The leaves are serrated with coarse, curved teeth. They are a dull green on the upper surface and a paler green on the underside. The leaves were attached to the branches with a stem that was between 4 to 5 cm long.

Leaves were grouped in clusters of about 6 leaves. The leaves were arrayed in somewhat spherical nature with a cluster diameter of from 25 to 30 cm. Leaf clusters were distributed on the branches in a generally uniform spacing with a leaf distribution of about 100 leaves per meter of branch.

The leafy crown of "Joyce" was well ventilated and the leaves were strongly affected by the wind. Under calm conditions the leaves were generally oriented horizontally but the leaves fluttered even in light winds. This observation suggests

Figure 2. Photograph of the Tree "Joyce Kilmer" That was Selected for Study. The vegetation around and behind the tree were removed to provide a clear view of the tree by the infrared imaging system

that in developing a model for the leaf energy budget, the leaves can be assumed to have a random orientation in the presence of wind.

3.2 Tree Thermal Measurements

Measurements of the temperature distribution within the tree were primarily focused on the tree trunk. Measurements were also taken of temperatures from one living and one dead branch. The tree trunk measurements were made at three locations on the trunk at about 1, 5, and 8 feet above the ground. Appendix B contains plots of all of the tree temperature data.

At the one and five foot level, measurements were taken of the center and temperatures at different depths within the trunk. The in-depth temperatures were taken along lines corresponding to the compass directions. Four temperatures were taken at about one inch 1/4 inch from the bark outer surface. The latter depth was

Table 3. Height of Branches Above Ground, Diameter of the Trunk at the Branch Location, and Orientation of the Branch, Relative to Magnetic North, for the Subject Tree

BRANCH #	HEIGHT (m)	TRUNK DIAMETER (cm)	BRANCH ORIENTATION (deg)
1	0.8	11.4	296
2	1.3	11.4	310
3	1.3	11.4	207
4	1.3	11.4	0
5	1.6	11.4	284
6	1.6	11.4	160
7	1.7	11.4	318
8	1.9	11.4	198
9	2.0	11.4	258
10	2.2	7.6	162
11	2.4	7.6	358
12	2.7	7.6	283
13	3.0	7.6	170
14	3.7	7.0	280
15	3.8	7.0	110
16	4.0	7.0	205
17	5.1	7.0	284
18	5.2	7.0	80
19	5.5	6.4	110
20	5.9	6.4	28
21	6.3	6.4	60
22	6.5	6.4	344
23	6.7	6.4	275
24	7.1	5.1	178
25	7.1	5.1	124
26	7.3	5.1	12
27	7.3	5.1	157
28	7.8	2.5	260
29	7.8	2.5	64

chosen to correspond to the approximate location of the inner surface of the bark. At the eight foot level, a probe was placed to measure the trunk center temperature.

The living branch was instrumented with four temperature probes. Two measured the branch center temperatures and two were placed under the bark at a depth of about 1/8 inch from the surface.

The dead branch was instrumented with two probes. One was placed to measure the branch center temperature and the second about 1/8 inch from the surface.

A series of probes were also placed to measure surface and soil temperatures around the tree. One was placed by the tree trunk and about three inches below the surface. Another probe was placed just below the surface in a clump of vegetation about six feet north of the tree. On 12 September 1990, the probes measuring the east and west trunk temperatures at the one inch in-depth locations were removed from the tree and relocated to measure the surface temperatures outside and inside the shadow zone of the tree.

Model 101 thermistors were used with two Campbell Scientific CR-21 data loggers to measure the trunk center and 1" depth temperatures. Type K chromel-alumel thermocouples were used with a Campbell Scientific CR-21X data logger to measure the under bark temperatures on the bark and the branch temperatures.

Between 7 - 12 September 1990, the tree temperature measurements were sampled every minute with fifteen minute averages, maximum, and minimum values collected and recorded. After 12 September 1990, only fifteen minute averages were collected. Also, the thermocouple measurements of the branch and under-the-bark trunk temperatures were discontinued because that equipment had to be returned to the lender.

Figure 3 displays a set of temperature data from "Joyce" from 8 September 1990. The data were measured from the thermocouples at the one foot level, approximately $\frac{1}{4}$ inches from the bark and from the center. Figure 3 (a.) displays the temperatures as a function of time of day from the probes on the north and south sides of the tree and (b.) displays the temperatures along a north-south gradient along a plane at the one foot level. The day in question was one with clear skies throughout the day and low relative humidities.

The size of the observed temperature difference between the north and south faces, as large as 12° C, was a surprise, especially considering the small size of the tree trunk at that point, about 11 cm. Although radiometric temperatures of the north and south faces were not made on this day, radiometric temperatures made with an Everest IRT Model 110C infrared thermometer on subsequent days were consistent with the thermocouple temperatures.

Another unexpected result was that shortly after sunset, the north side of the trunk registered temperatures slightly larger than those from the south side. This reversal occurred around 1800 LST and persisted for about an hour. During this time, the south face is cooling off at a faster rate than the north face. It is believed that this is due to the effects of thermal interia from the interior portions of the trunk near the north face. This observation of a temperature crossover was also made by Derby and Gates[2] in similar study involving tree trunks.

3.2.1 Impact of Changing Environmental Conditions

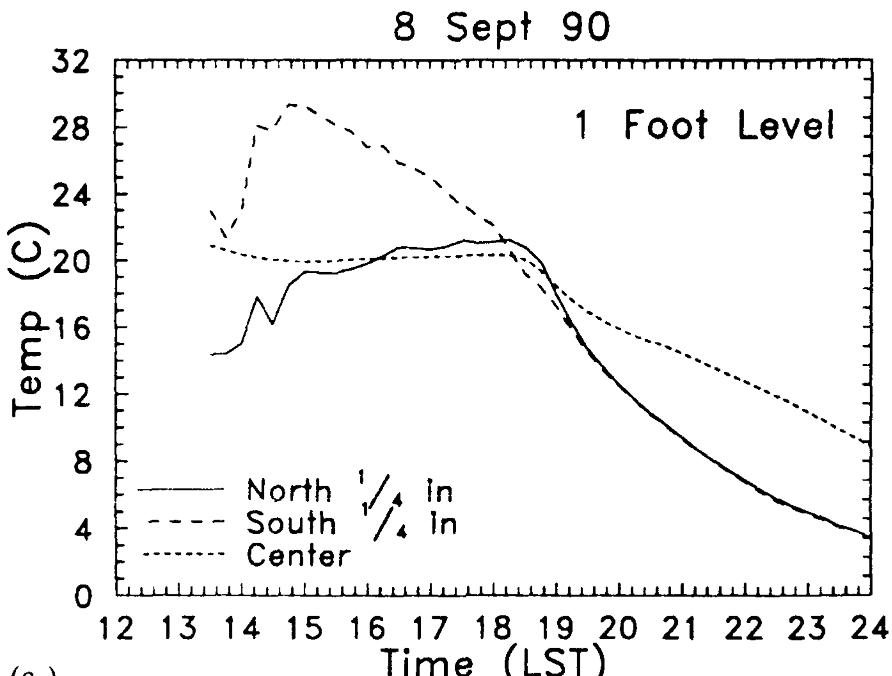
As expected, the temperature structure of the tree responded to changes in the environmental conditions. This is demonstrated in Figure 4 which displays the temperatures as a function of time for (a.) 8 September 1990 and (b.) 22 September 1990. The temperatures were measured at the one foot level by the north and south thermistors approximately one inch in from the bark and from the center. The weather on 8 September was clear and sunny while on 22 September, the weather was overcast with rain. The tree temperatures for 8 September show the effects of the changing solar loading conditions during the course of the day while the temperatures for 22 September show essentially no difference from one side to another.

3.2.2 Temperature Variations With Tree Position

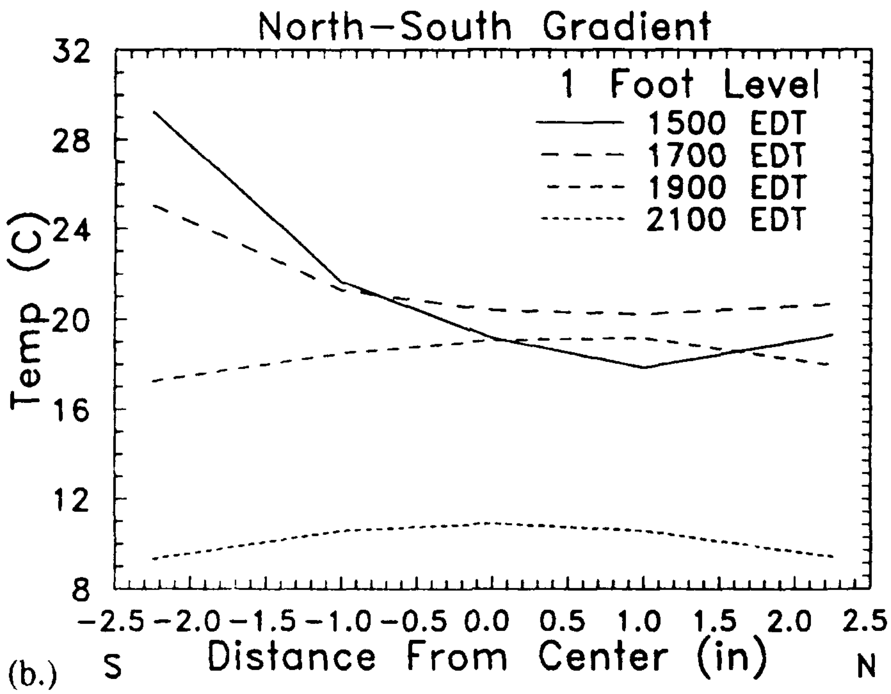
The temperature probes measuring the temperature of the center of the tree were placed at different locations along the tree trunk. Figure 5 displays the measured temperatures as a function of time for probes located 1, 5, and 8 feet above the surface. The day in question was one with partly sunny conditions. The trunk diameters at the various locations were approximately 11.5, 8.9, and 7.6 cm, respectively.

As shown in the Figure, the temperatures at the center are a function of the diameter of the trunk. This is as one would expect. The temperature at the center should be a function of the amount of material between the center and the outside world where the driving energy sources are found. The Figure also shows the impact of self shading from the leafy crown of the tree. The temperatures at the 8 foot level show a decrease around 1300 LST. Visual observations revealed that the shadow from the crown of the tree shaded the trunk at the 8 foot level at about that time. The other probes were not shaded by "Joyce's" crown. The self shading is also shown to have a rapid temporal response in the tree temperatures. The temperatures were sampled every minute and averaged over a fifteen minute period. By reviewing the individual temperatures sampled every minute, it was observed that the self shading from the crown evidenced itself as a change in the

[2] Derby, R.W., and Gates, D.M. (1966) The Temperature of Tree Trunks - Calculated and Observed, *Amer. J. Bot.*, **53**:580-587



(a.)



(b.)

Figure 3. Tree Temperatures for 8 September 1990 (a.) as a Function of Time of Day and (b.) Along a North-South Gradient in the Trunk for Different Times From Measurements Made at the One Foot Level

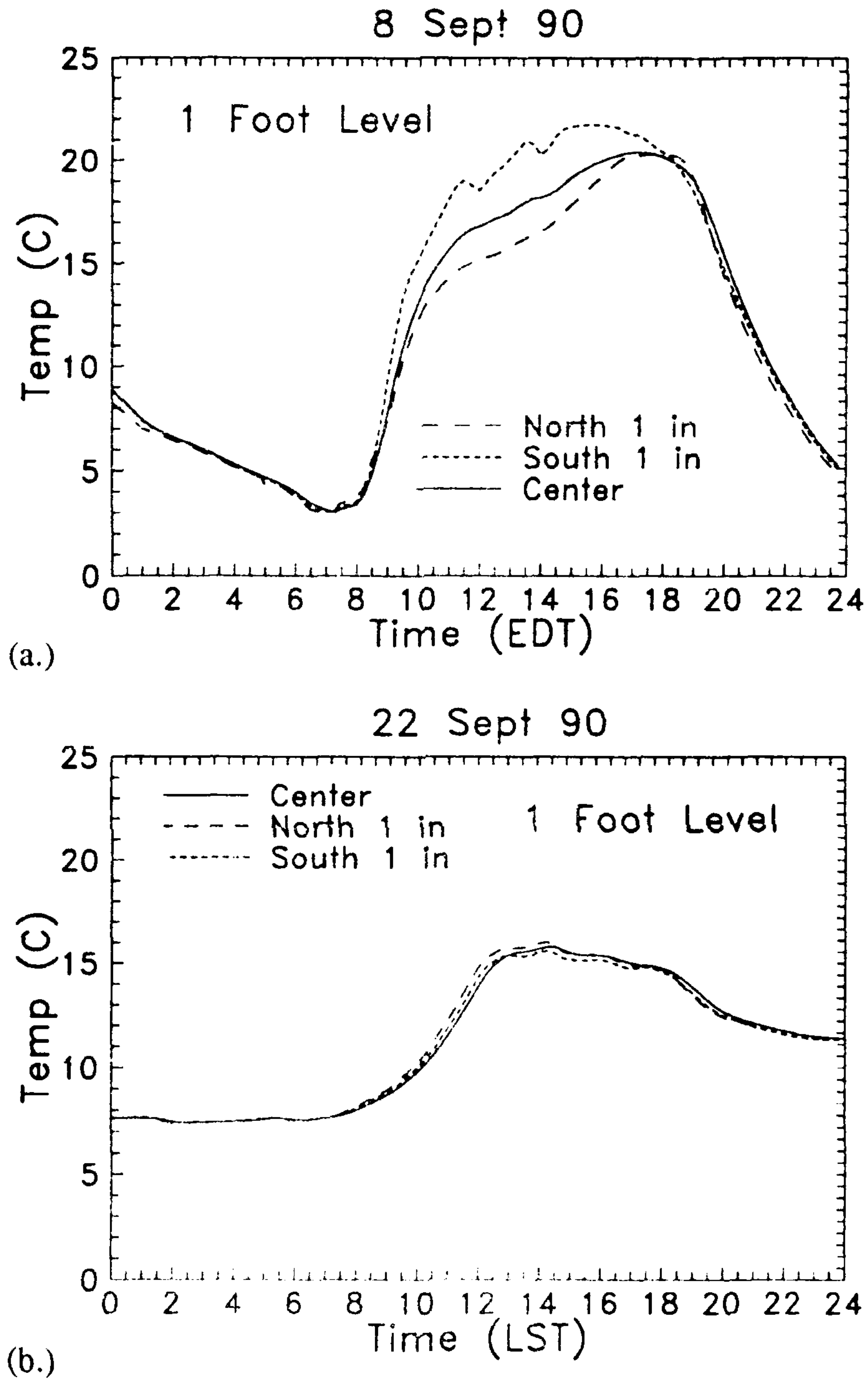


Figure 4. Tree Temperatures From the One Foot Level as a Function of Time of Day for (a.) 8 September 1990, a Clear Day, and (b.) 22 September 1990, an Overcast Day With Rain

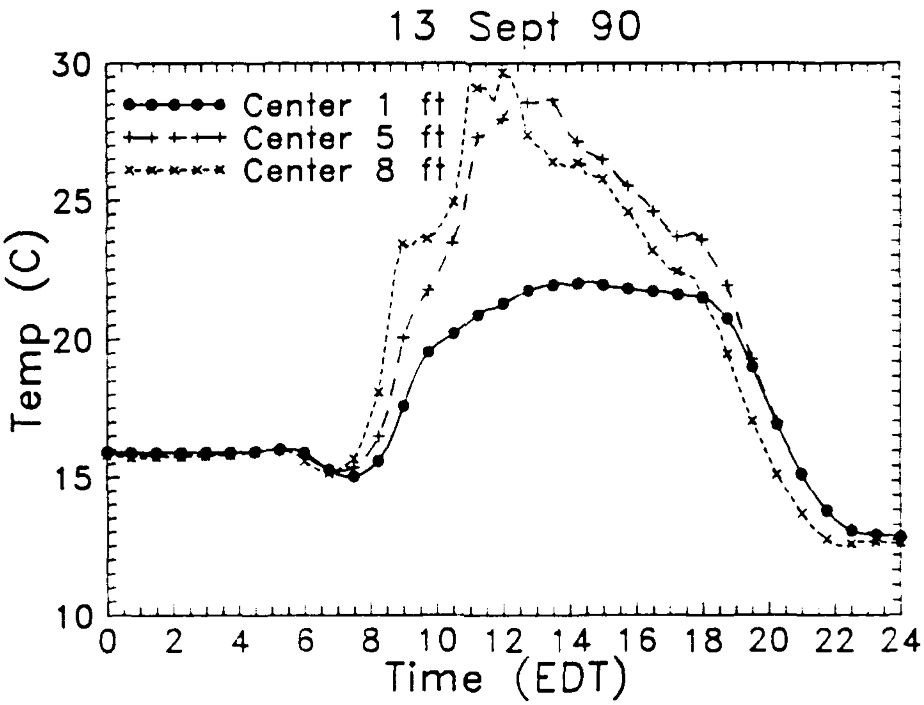


Figure 5. Tree Temperatures as a Function of Time of Day for Probes Located 1, 5, and 8 feet Above the Surface as Measured on 13 September 1990

temperature of the center on the order of a minute or two. This rapid response was also observed in the temperatures at other locations on the tree as clouds obscured the sun.

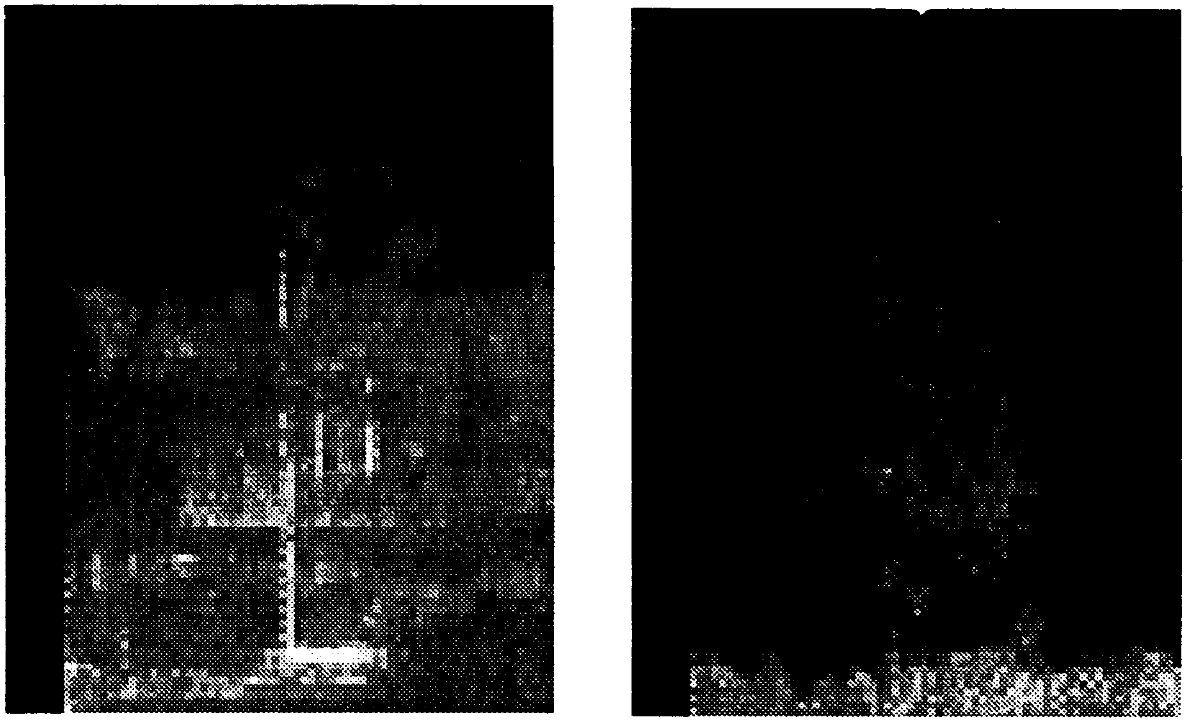
3.3 Tree Infrared Imagery

KRC obtained 8 - 12μm infrared imagery of the single tree at approximately hourly intervals between 9 - 11 September 1990.[3] The images were obtained from an AGEMA Thermovision 880 imager.

The tree was originally imaged against with a backdrop of a stand of young deciduous trees some 30 - 50 feet behind the tree. The trees in the stand in the field of view were removed on 10 September 1990 due to the difficulty of differentiating "Joyce" from the background stand of trees. After that, the tree was imaged against a mature stand of trees located at least one hundred meters behind "Joyce".

Images were obtained from about 1130 Local Standard Time (LST) on 9 September 1990 to 1500 LST on 11 September 1990. Over 40 images were obtained along with images of the calibrated blackbody. Due to field of view considerations, the complete tree could not be imaged at one time. Images were,

[3] LaHaie, A.M.L. (1991) "Single Tree Thermal Imagery and Measurements SWOE/FED MAC Field Test, Howland, Maine," Keweenaw Research Center, Michigan Technological University, Houghton, Michigan.



(a.) Lower Portion, 10 Sept 1990, 1744 LST (b.) Crown Portion, 11 Sept 1990, 1213 LST

Figure 6. Infrared Images of the (a.) Lower and (b.) Upper Portions of "Joyce Kilmer". Note that in (a.) a portion of the image includes vegetation from two lines of trees behind "Joyce"

therefore, taken of the lower two thirds of the tree, emphasizing the trunk and lower branches, and the crown portion of the tree. Figure 6 displays a set of representative images of "Joyce."

After the tests, the images collected by KRC were reviewed by SPARTA and twelve images identified for further analysis. KRC digitized the requested images and provided SPARTA with ASCII data files of the images. In addition, KRC performed a preliminary statistical analysis on various portions of the images, including portions of the trunk, surrounding ground, leaves from the crown of "Joyce, and the surrounding vegetation. Due to the pixel size in the images, a direct comparison of the apparent temperatures from the images to the measured values is difficult, but a relative comparison is possible. This comparison indicates a reasonable agreement between the measured data and apparent temperatures in terms of both values and tendencies.

3.4 Reflectivity Measurements of Tree Materials

Directional and bidirectional reflectivity measurements of leaf and bark samples were obtained from Joyce.[4] A number of leaf samples were taken and analyzed. In addition, bark samples obtained from two locations on the trunk. In total, 24 samples were studied. Care was taken to try and preserve the samples during shipment from the field location to the laboratory but it is recognized that the reflectivity measurements are most likely not totally representative of the reflectivity of the living materials.

Total hemispheric reflectance was measured over the 0.3 - 25.0 μm region and the bidirectional reflectance measured at three infrared wavelengths, 1.4, 4.6, and 10 μm. The leaves were studied on both the top and bottom sides and the reflectance spectra for the top and bottom halves were observed to be noticeably different. The leaves were also observed to be translucent, so transmittance measurements were also taken over the 0.3 to 26.0 μm region.

Figure 7 displays an example of directional reflectivities from one of the leaf and bark samples. Figure 7 (a.) displays the reflectivity of the underside of the leaf for two viewing directions. Figure 7 (b.) displays the reflectivity of a bark sample for the same two view angles. Attempts were made to keep the samples as fresh as possible, but deterioration of samples did occur. Reflectivity measurements were then made at different stages to study the impact of the leaves drying out. Comparisons were made of the measurements for "fresh" and dry leaves and it was observed that the greatest changes was in the reflectivity in the top surface. When the leaf was fresh, the reflectance for the top side in the0.5 - 2.0 μm region was 8 - 12 % units less than that for a dry leaf. In the 3.5 - 6.0 μm region, a dry leaf exhibited a small peaking in the reflectivity from the top face relative to that seen in the fresh leaf. The bottom surface exhibited little change between the fresh and dry states. This is consistent with leaf physiology in that the top surface of a leaf has a higher density of cells than the lower face and would be more susceptible to moisture loss.[5]

These results of changes in reflectivity due to drying out are interesting because they provide a hint of the changes in leaf reflectivity that would occur as a result of changes in the physiological state of the leaf. While these results are not fully indicative of what happens on leaves attached to trees, they are still of interest and point to one area where continued research is necessary.

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[4] Neu, J.T., Dummer, R.S., Beecroft, M., McKenna, P., and Robertson, D.C. (1990) "Surface Optical Property Measurements on Bark and Leaf Samples," Phillips Laboratory, Hanscom AFB, Massachusetts, PL-TR-91-2009, ADA 240714.

[5] Kimmins, J.P., (1987) Forest Ecology, Mac Millan Publishing Company, New York, pp 161-162.

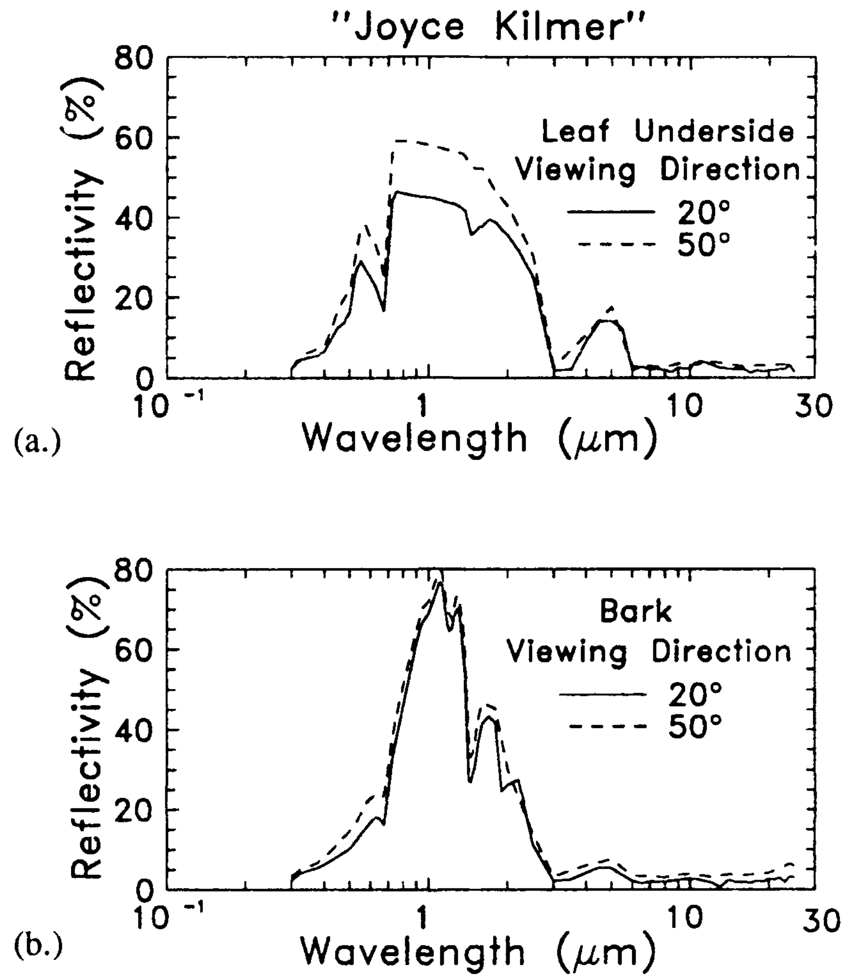

Figure 7. Examples of Directional Reflectivity Measurements Obtained From (a.) Leaf and (b.) Bark Samples From "Joyce Kilmer"

4 MEASUREMENTS AT FOREST EDGE SITE

The KRC team set up at the forest edge site and obtained supporting meteorological data, soil temperatures, infrared imagery, and measurements of leaf area index.[6] Data were obtained over the period 0800 LST on 9 September 1990 to 1530 LST, 11 September 1990.

4.1 Supporting Meteorological Measurements

Meteorological measurements were obtained from a variety of sensors. Table 4 summarizes the meteorological data that were taken at the edge site. The data were primarily taken from the open field at a location about 200 feet from the forest edge. Air temperatures at the 1 m Above Ground Level (AGL) were also measured at the edge of the forest site.

Table 4. Summary of Meteorological Data Taken by KRC at the Forest Edge Site

PARAMETER MEASURED	UNITS	SAMPLING RATE
Global Solar Irradiance (0.285 - 2.8 μm)	W m^{-2}	Once per minute
Downwelling Longwave Radiation (0.3 - 50 μm)	W m^{-2}	Once every 5 minutes
Air Temperature (0, 1, 2, 3, & 5 m AGL)	C	Once every 5 minutes
Wind Speed (0, 2, & 8 m AGL)	m s^{-1}	Once every 5 minutes
Wind Direction (8 m AGL)	deg	Once every 5 minutes
Dew Point Temperature	C	Once every 5 minutes
Barometric Pressure	mb	Once every 5 minutes

The KRC supporting meteorological data were assembled into a data set and made available to SPARTA for analysis. In general, the KRC meteorological data agreed well with the data taken by the University of Maine at the Joyce site. An exception, however, was with the KRC solar irradiance data. The data did not agree

[6] LaHaie, A.M.L. (1990) "Preliminary Report on Maine Field Test: Thermal Imagery and Supporting Measurements," Keweenaw Research Center, Michigan Technological University, Houghton, Michigan, October 1990.

well with the University of Maine data. An analysis of the KRC data indicated the possibility that the solar radiation sensor was not completely level and may have been measuring additional solar radiation reflected from the forest edges.

4.2 Soil Temperatures

The KRC team obtained measurements of soil temperatures along a transect that extended from a gap at the forest edge and extended approximately 70 feet into the forest. The temperatures were obtained using thermocouples embedded into wooden stakes. The stakes were inserted into the ground at the desired locations. Data were sampled from the thermocouples every five minutes with no averaging of the data. In addition, a second probe measuring soil temperatures was placed out in the open field. This probe measured a soil temperature profile at 0, 0.01, 0.05, 0.1, 0.2, and 0.5 meters below the surface.

Figure 8 displays a comparison of the soil temperatures over the test period from the edge location and 69 feet from the edge. Figure 8 (a.) compares the temperatures at the surface and 5 cm below the surface and (b.) compares the temperatures at the surface and 15 cm below the surface. Appendix B contains plots of all of the soil temperature data.

The KRC soil temperature data are not considered completely reliable and are only being used to identify relative variations. The procedure of embedding the thermocouples into the wooden stakes is not considered a proper method of obtaining soil temperatures. First, the thermocouples, as mounted, are probably measuring the thermal response of the wooden stake rather than that of the surrounding soil. Second, the procedure of pounding the stakes into the soil tends to compact and disturb the soil. This means that the soil being measured is not representative of soil desired to be studied.

4.3 Forest Edge Infrared Imagery

The KRC team obtained infrared imagery in the 8 - 12 μm range using an Inframetrics 610 imager. Images were obtained on an hourly basis of the two edges with extensive foliage, the forest edge with the gap, and the calibrated blackbody sources. Figure 9 shows an example of an image taken of the forest edge with the gap.

The infrared imagery were taken for more than two diurnal periods during a wide range of weather conditions ranging from clear skies to rain and fog. Two fields-of-view were also employed. These data are being analyzed separately by KRC and a report detailing their results will be issued by them.

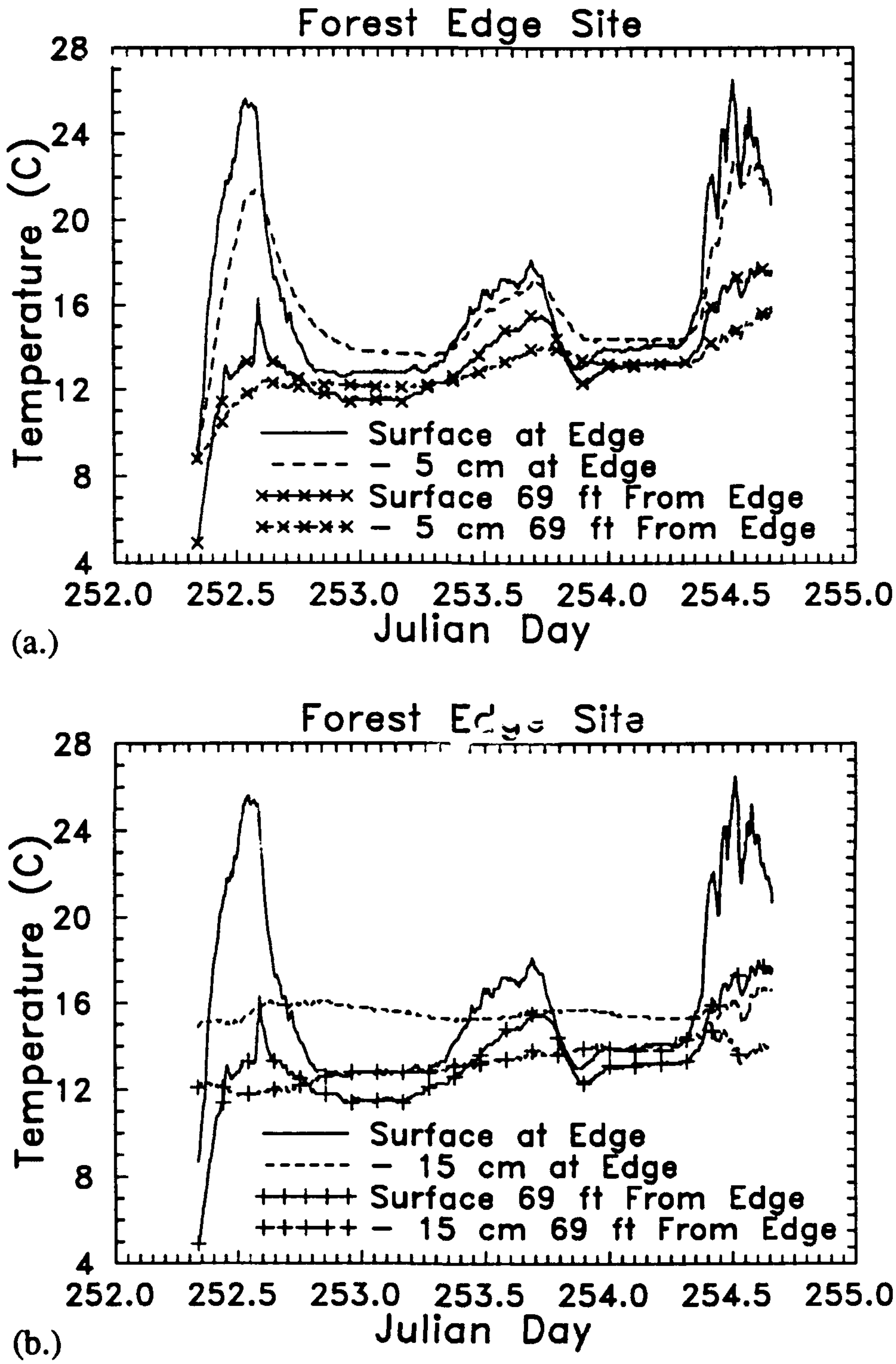

Figure 8. Comparison of the Soil Temperatures Measured by KRC at the Forest Edge and 69 feet Inside the Forest. (a.) Compares the temperatures at the surface and 5 cm below the surface and (b.) compares the temperatures at the surface and 15 cm below the surface

Figure 9. An Example of the Infrared Imagery Obtained by KRC From the Forest Edge Site. This example was obtained on 11 September 1990 at about 1100 local time

5 SUMMARY AND RECOMMENDATIONS FOR FUTURE STUDIES

5.1 Summary

A field test prog.am designed to provide data to support the development of a 3-D thermal model of an individual tree and an interim model of the thermal response at forest edges was conducted near Howland, Maine during September 1990. Data were collected at two locations, one devoted to a single tree and one at a forest edge.

SPARTA, Inc. designed the field test program with logistical support being provided by the University of Maine. The University of Maine also provided supporting meteorological data. Personnel from the Keweenaw Research Center collected data and infrared imagery at the forest edge site and infrared imagery at the site studying the individual tree. A limited set of directional and bidirectional reflectivity data were also collected of leaf and bark samples under a program managed by Spectral Sciences, Inc.

5.1.1 Summary of Tree Measurements

The data collected from the individual tree have been used to support the development of a 3-D thermal model of individual trees. The tree that was studied was a bigtooth aspen approximately 7.8 m in height. Temperatures at various depths from the trunk and at different heights above the ground were collected over the 6 - 24 September 1990 and during a variety of environmental conditions.

The tree temperatures demonstrated considerable variations in response to changing environmental conditions. During clear sky periods, a significant temperature difference between the sunlit and shaded sides was measured. This temperature difference exceeded 10 ° C during one period of totally clear skies. During overcast conditions, essentially no difference in temperature was observed from one side of the tree to another.

Tree temperatures were observed to respond rapidly in response to changes in solar loading either due to changes in cloud conditions or self shading from the tree's leafy crown. These changes were observed to occur on the order of the sampling time of the temperature measurements, one minute.

5.1.2 Summary of Forest Edge Measurements

The data collected at the forest edge site consisted of supporting meteorological data, soil temperatures at a number of locations, and infrared imagery. The meteorological data were generally consistent with those taken by the University of Maine near the individual tree site but some inconsistencies in the solar data were observed. It is postulated that the solar sensor employed by the KRC team was not completely level.

Soil temperature data were obtained at three depths along a line extending into the forest edge. The data are not considered reliable from an absolute standpoint due to the procedures used to deploy them. The thermocouples were embedded in wooden stakes at preset depths and the stakes were then pounded into the ground. This procedure does not give a correct measure of the thermal response of the surrounding soil.

The infrared imagery obtained at the forest edge site were collected over a wide range of environmental conditions. These data are being analyzed separately by KRC and a report will be issued by them.

5.2 Recommendations For Future Studies

The data collected from the individual tree provided valuable insight into the phenomenology of the thermal response of individual trees. These data have been extensively used to support the development of a 3-D thermal model of individual trees that has subsequently been completed and delivered to the SWOE program.[1]

Additional measurements of the optical properties of the leaf and bark samples should be made, preferably with a system that can be used in the field and on living samples. These measurements should also be made at different times of the year in order to study the changes that occur in response to changes in tree physiology.

The data from the forest edge offered a limited glimpse of the thermal response. A more extensive program is required to offer more insight into the phenomenology required to model the thermal response of forest edges. Therefore, the primary recommendation from the 1990 STAMP effort is that a more extensive effort to study the thermal response at forest edges be performed.

It is recommended that this more extensive program include a series of soil temperature measurements extending over different seasonal periods as well as various radiometric measurements. Calibrated infrared imagery should also be obtained during periods when leaves are present as well as when leaves are gone. Supporting meteorological data should also be obtained throughout the test period. Finally, data on the soil hydrology should also be obtained.

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Appendix A
Field Test Log

A-1. September 6, 1990

Thursday, 6 September 1990, was spent obtaining the first set of physical measurements of Joyce. The measurements taken related to the geometry of the tree. In particular, the height of the tree, location of the branch connections on the trunk, angle of the branches relative to the trunk, and trunk diameter were measured. A series of photographs were also taken for photo registration purposes. The weather on this day was mild and sunny.

A-2. September 7, 1990

Friday, 7 September 1990 was an overcast day. Later in the day, a light rain began. After sunset, the weather cleared.

Two tasks were attended to. First, the thermistors used to obtain the center and in-depth temperatures were installed. Two CR-21 data loggers and #101 thermistors, supplied by the US Army Waterways Experiment Station, were used.

The second task involved the examination of the leaves on the big tooth aspen. The size, shape, and distributions of leaves were studied on aspens similar to the one selected for study.

Each data logger obtained data from seven thermistors. Data logger #1, connected to the five thermistors measuring data at the one foot level. The remaining two thermistors collected data from three inches below the surface at the base of the tree and from inside the weather proof case housing the unit. The second data logger was connected to a cassette tape recorder for data storage. Five thermistors collected data from the five foot level. A sixth measured the trunk center temperature at the 8 $\frac{1}{2}$ foot level. The remaining probe was placed just below the sparse vegetation at a location north of the tree.

The primary goal of the study was to obtain data on the thermal structure of trees for use in validating a 3-D thermal response model of trees that SPARTA is developing. To obtain these data, the tree was instrumented with temperature probes. The probes were installed at various locations on the trunk and at different depths within the trunk. At two trunk locations, temperature probes were installed at the center and along the four compass directions. The latter probes were installed at about 1" and $\frac{1}{4}$ " from the bark outer surfaces. The $\frac{1}{4}$" depth was chosen to be near the interface between the bark and woody material.

A-3. September 8, 1990

Saturday, 8 September 1990 was a clear, bright sunny day. Weathe· conditions were ideal for all of the NASA tests and the day was dubbed the "golden day".

Efforts on this day focused on completing the instrumentation on Joyce. Sixteen type "K" thermocouples were installed and tied to a CR-21X data logger loaned by the Army Cold Regions Research and Engineering Laboratory.

Eight of the thermocouples were installed at the $\frac{1}{4}$" depths at the 1' and 5' levels. Four were installed on a living branch, two on a dead branch, and two left free.

On the living branch, two thermocouples were inserted into the branch center. The remaining two were inserted under the bark level. On the dead branch the thermocouples were installed in the center.

A-4. September 9, 1990

Sunday, September 9 began as a carbon copy of the previous day, clear and sunny. Morning temperatures approached zero as a result of intense radiational cooling. A cirrus shield associated with the approach of a warm front began to have an impact on solar loading in the late morning. Winds were brisker, averaging 55 m/s during the daylight hours.

This days activities were focused on a final check out of the equipment and an examination of the thermal response phenomenology within the tree. For an hour centered around the approximate solar noon (1230), spot measurements of the temperatures from the thermistors at the one fool level in the trunk were made. The purpose of these spot measurements, made at five minute intervals, was to study the temperature gradients along the E-W and N-S lines. The observations yielded the (expected) result that the sunny side was warmer than the shaded side and that the shift in temperatures from the E and W sides followed the solar cycle. That is, the peak in the E side (am sunny side) temperatures occurred slightly after local noon.

A second series of spot measurements was conducted from 1500-1600 hours involving all of the temperature probes at the one foot level. In addition, measurements of the trunk skin temperature were also made using a borrowed Everest hand held infrared thermometer, model 110C. These measurements were also taken at five minute intervals.

Of particular interest was the impact of the cirrus clouds on the tree temperatures. Individual wisps of cirrus were observed to obscure the sun with immediate, relative to our spot sampling rate, impact on tree temperatures. As would be expected, the response was greatest for the thermocouples nearest the surface. The response was also seen in the fifteen minute average temperatures.

A-5. September 10, 1990

Monday, 10 September 1990 was affectionately dubbed the "drowned rats" day. The weather was overcast with rain. The forecast called for afternoon clearing, which never materialized. The air temperature at the site reached a low of just under 12°C. Winds were generally light, 1-2 m/s, and coming from the south.

Spot measurements were conducted of the trunk center temperatures at the one, five, and eight foot levels. These measurements were made at fifteen minute intervals from 0900-1300 hours. Measurements of the ground temperatures in the root area and a spot distance from the tree were also made.

The trunk center temperatures were nearly uniform at each time interval with the values from the one foot level being generally slightly higher. However, due to the slight increase in these values (< 0.5C) it is not clear if any physical significance should be assigned to this difference.

A problem was discovered with the cassette recorder being used to store the data from the second CR-21 data logger. The recorder was found to not having recorded any of the data collected since the beginning of the tests with the exception of the spot data recorded by hand. New batteries were put into the recorder as a first attempt to correct the problem.

A-6. September 11, 1990

Tuesday, 11 September 1990 began with a morning shower that ended shortly after reaching the field. Weather conditions were generally partly cloudy during the day. Temperatures ranged from 13°C to 22°C with generally light winds out of the north to northeast.

The problem with the cassette tape recorder with the shocked CR-21 data logger was traced to a bad connector cable between the data logger and the tape recorder. A replacement cable was installed and the data began to flow onto the tape.

Spot measurements of all of the thermistor data were taken from 0930-1530 hours at fifteen minute intervals. (The data from the CR-21X were being manually downloaded as a precaution so were not included in this series of spot measurements.) Channel 5 of the first CR-21 data logger was acting "funny" during part of the tests giving rapidly fluctuating values over large and unrealistic ranges.

A-7. September 12, 1990

Wednesday, 12 September 1990, was intended as the day to perform a shadowing experiment in which a series of photocells would be placed in and around the tree to get a relative measure of the variation of sunlight due to cloud and self-shadowing. It was also planned that the faster responding thermocouples would be removed from the tree and relocated to spots adjacent to the photocells.

Unfortunately, that was not to be. Weather conditions were unfavorable with conditions ranging from partly cloudy to overcast. Late in the morning, the decision was made to cancel the shadowing experiment and to begin the breaking down of the equipment. The CR-21X probes were removed at 1030.

The decision was made to keep the two CR-21 data loggers in place and to relocate the thermistors from the east and west locations from the one and five foot heights. One probe from the first CR-21 was moved to a location about eight feet due south of the tree. This location was chosen because it would not be in the shadow zone of the tree. The second CR-21 probe was relocated almost due east from the tree at a distance of about ten feet. This spot was in a slight depression and also not in the shadow zone. Soil types were similar. The first probe was at a location with light grass while the second spot was bare.

The two probes from the second CR-21 that were moved were both placed in the shadow zone of the tree. The first probe was placed about four feet from the tree at a location shadowed in the afternoon. The second probe was placed in the morning shadow area about five and a half feet from the tree. The first afternoon shadow spot had light grassy vegetation while the second, morning shadow spot was bare soil.

With all of the relocated probes, care was taken to disturb the soil as little as possible. The surface was scratched with a small rake, the probes placed in the depressions, and then covered up with the soil.

Leaf and bark samples were also taken for shipment to Surface Optics in San Diego for analysis. Two bark samples were from the trunk along with a number of leaf samples.

The bark samples were approximately one inch wide and two inches in length. They were cut from the tree in such a way so as to minimize damage to the bark. The samples were wrapped in moist tissues and sealed in plastic bags immediately after removal. The samples were taken from areas with differing textures and visual appearances.

The leaf samples were taken by immersing the leaf clusters in a bath of water and cutting them from the branch while under water. The clusters were then inserted into stoppered vials containing water and placed and sealed in plastic bags. The final package was then express shipped to San Diego, California.

A-8. September 13, 1990

Thursday, 13 September 1990, was departure day. A final visit to the site was made to check on the data loggers prior to going home.

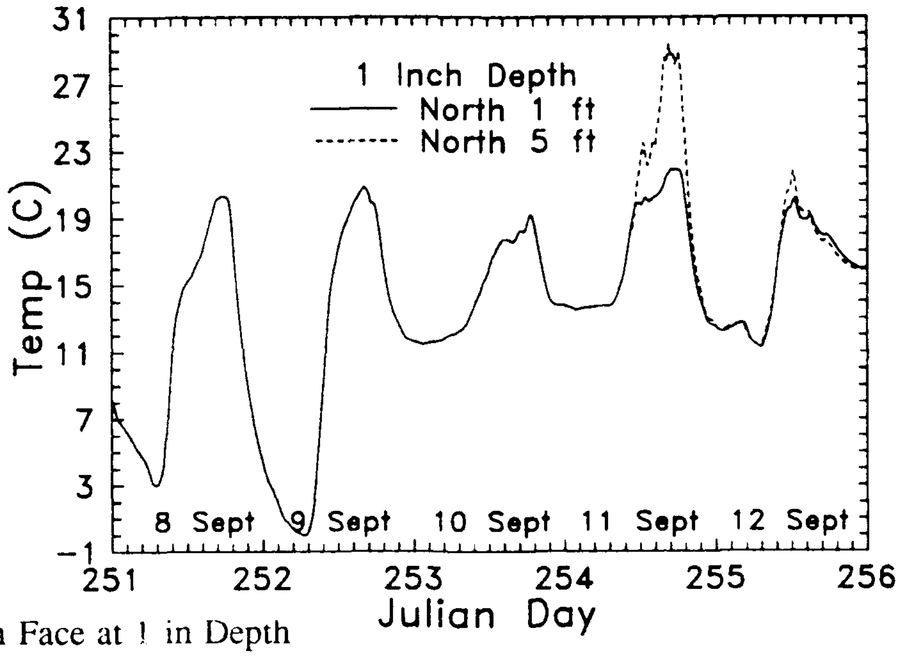
A-9. September 24, 1990

Monday, 24 September 1990, a final visit was made to the site to pack up the two CR-21 data loggers and to take down Joyce for the final set of measurements. Those measurements consisted of leaf and branch distributions, internal distributions of woody material, and the exact location of the temperature probes.

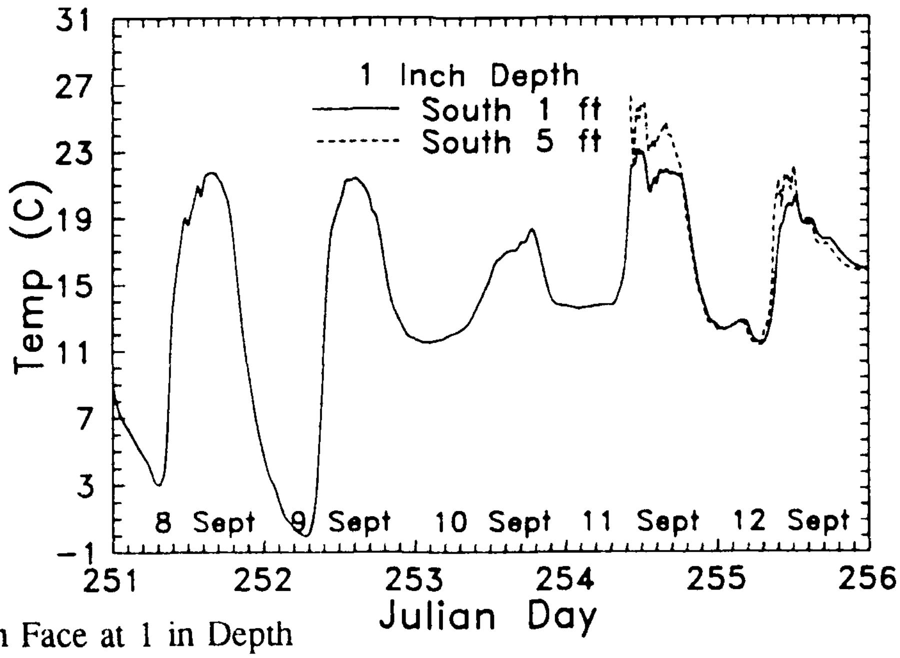
Appendix B

Tree and Soil Temperature Data From STAMP

This appendix displays the complete set of temperature data from STAMP from "Joyce" and the forest edge site. Figure B-1 displays the temperatures from "Joyce" for 8 - 12 September 1990, B-2 for 13 - 17 September 1990, and B-3 for 18 - 22 September. Figure B-4 – B-6 displays the soil temperature data taken by KRC along the transect extending into the forest edge. Figure B-4 is for 9 September 1990, B-5 for 10 September 1990, and B-6 for 11 September 1990.

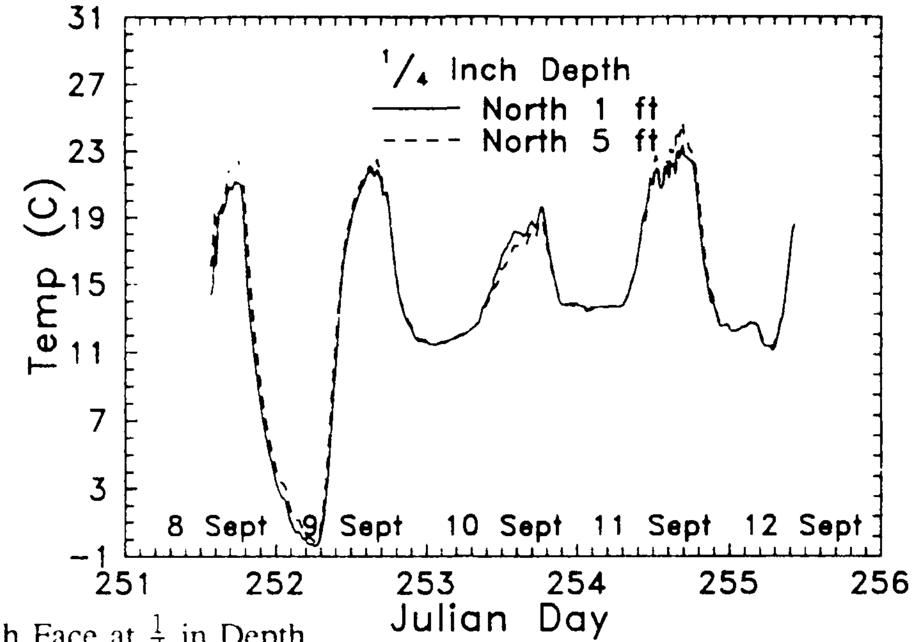


(a.) North Face at 1 in Depth

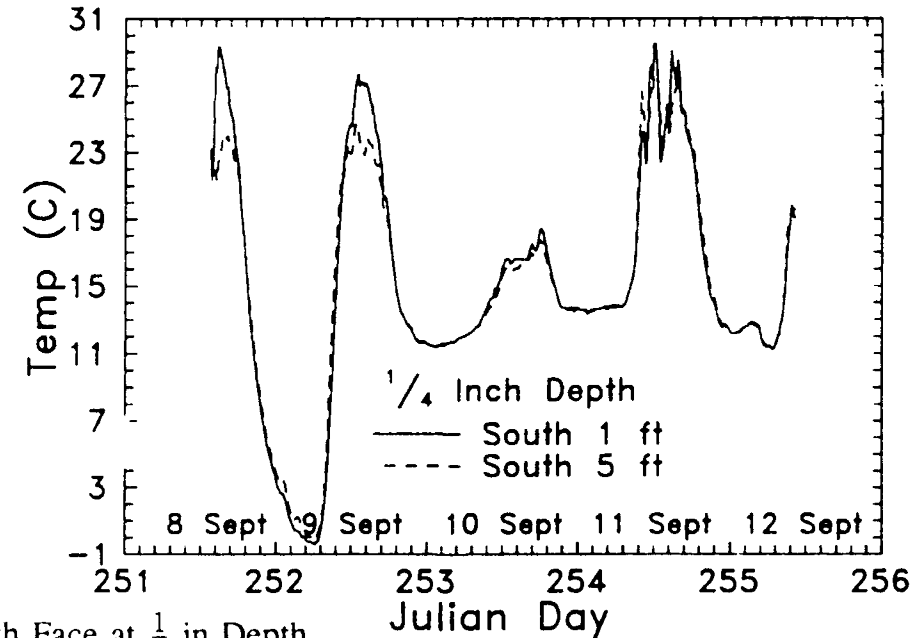


(b.) South Face at 1 in Depth

Figure B-1. Temperatures From "Joyce Kilmer" for 8 - 12 Sept From the (a.) North and (b.) South Face Probes at the 1 in Depth

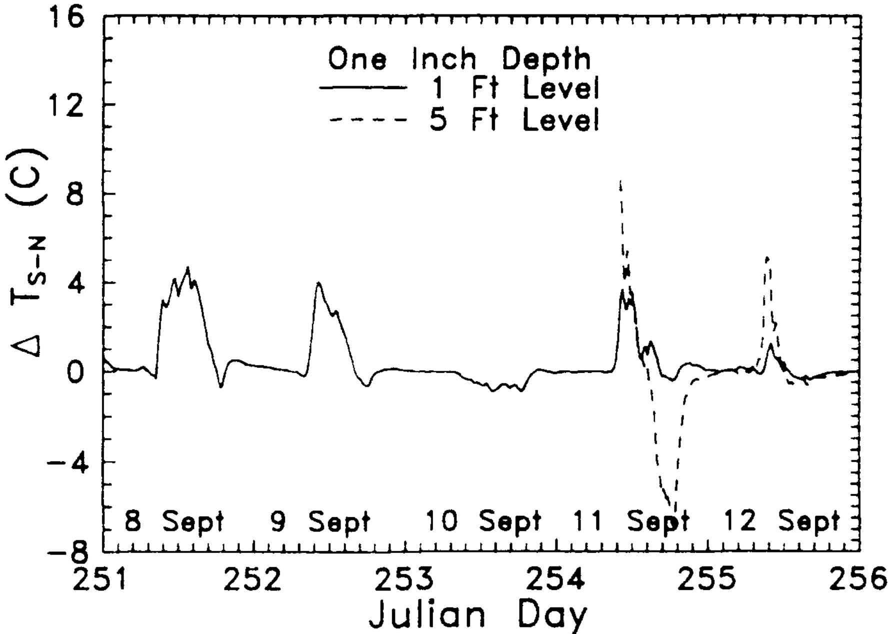


(c.) North Face at $\frac{1}{4}$ in Depth

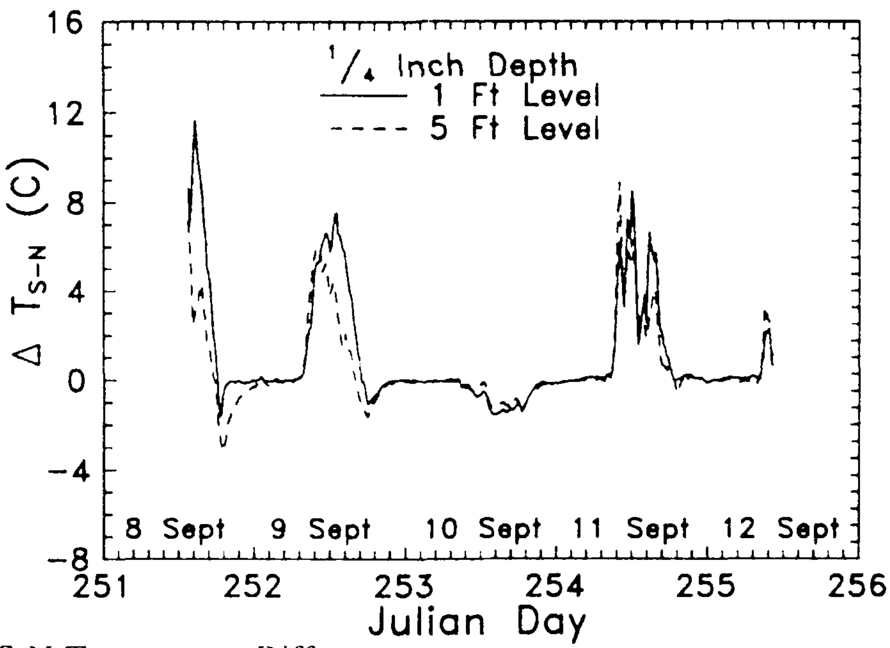


(d.) South Face at $\frac{1}{4}$ in Depth

Figure B-1. (Cont.) (c.) North and (d.) South Face Probes at the $\frac{1}{4}$ in Depth



(e.) 1 in. S-N Temperature Differences



(f.) $\frac{1}{4}$ in. S-N Temperature Differences

Figure B-1. (Cont.) S-N Temperature Differences at (e.) 1 in and (f.) $\frac{1}{4}$ in Depths

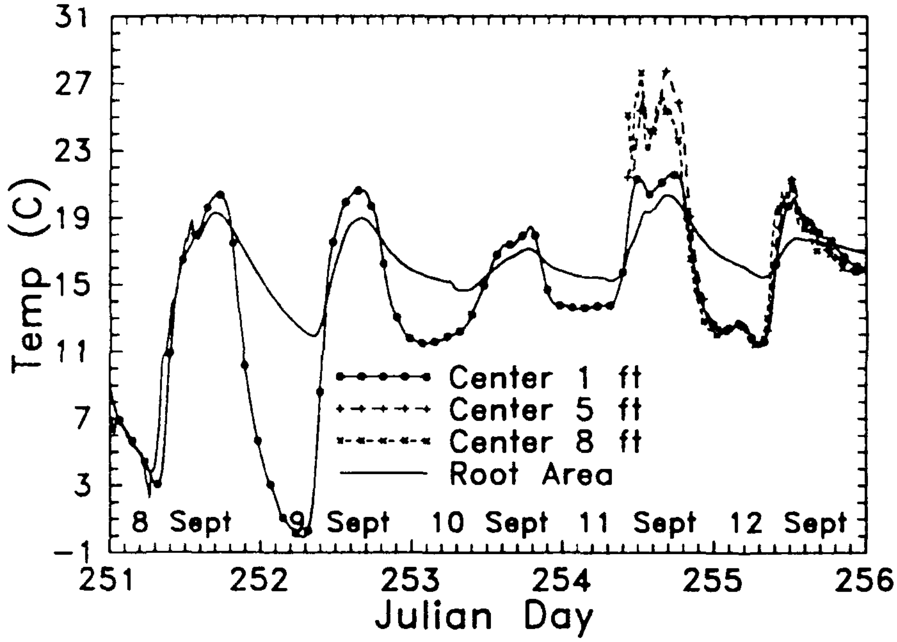
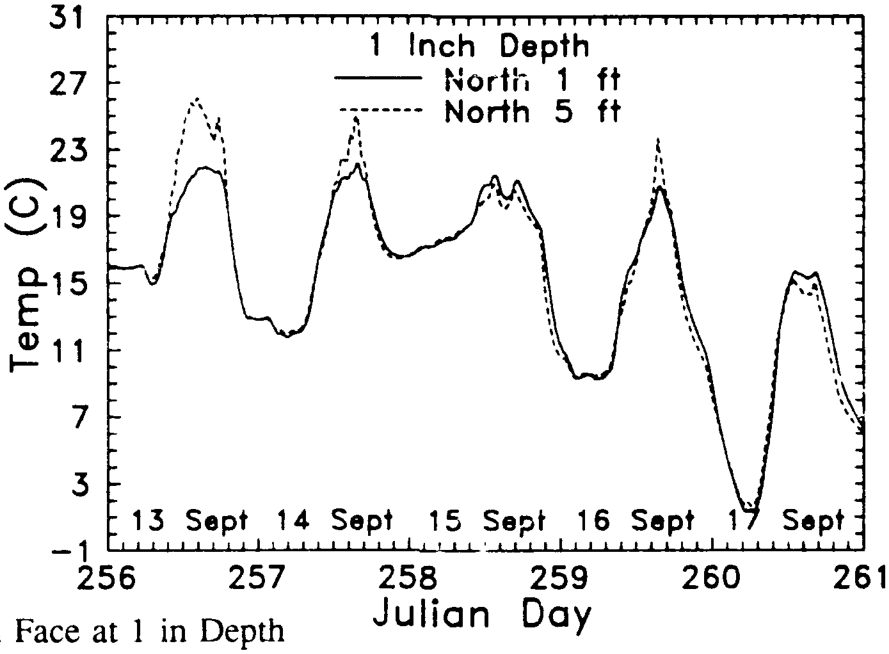
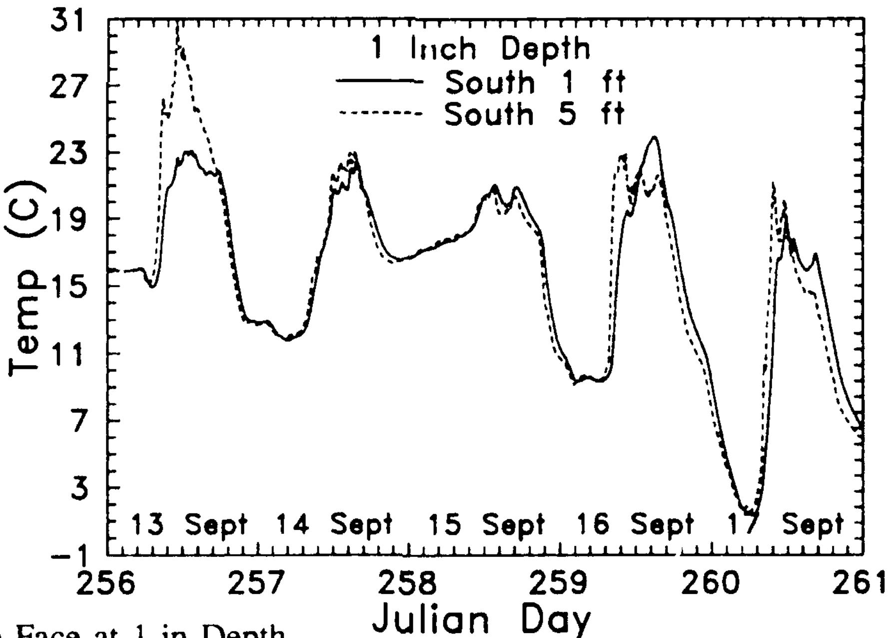


Figure B-1. (Cont.) (g.) Center Temperatures

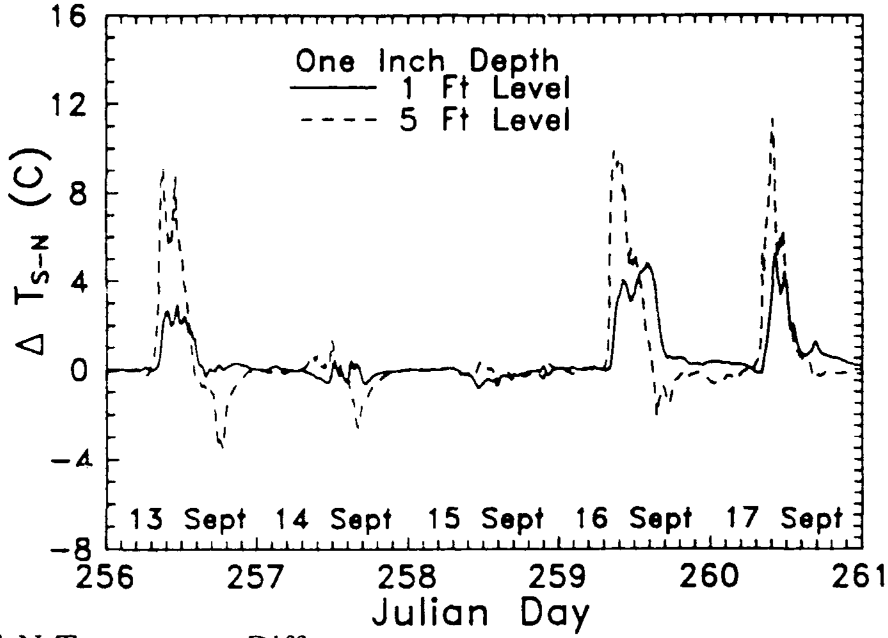


(a.) North Face at 1 in Depth

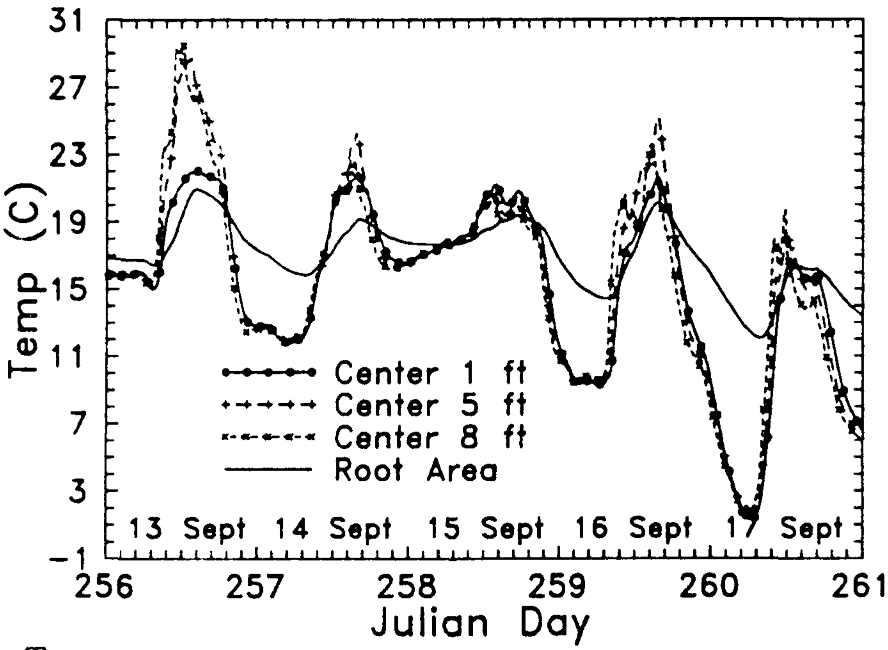


(b.) South Face at 1 in Depth

Figure B-2. Temperatures From "Joyce Kilmer" for 13 - 17 Sept From the (a.) North and (b.) South Face Probes at the 1 in Depth

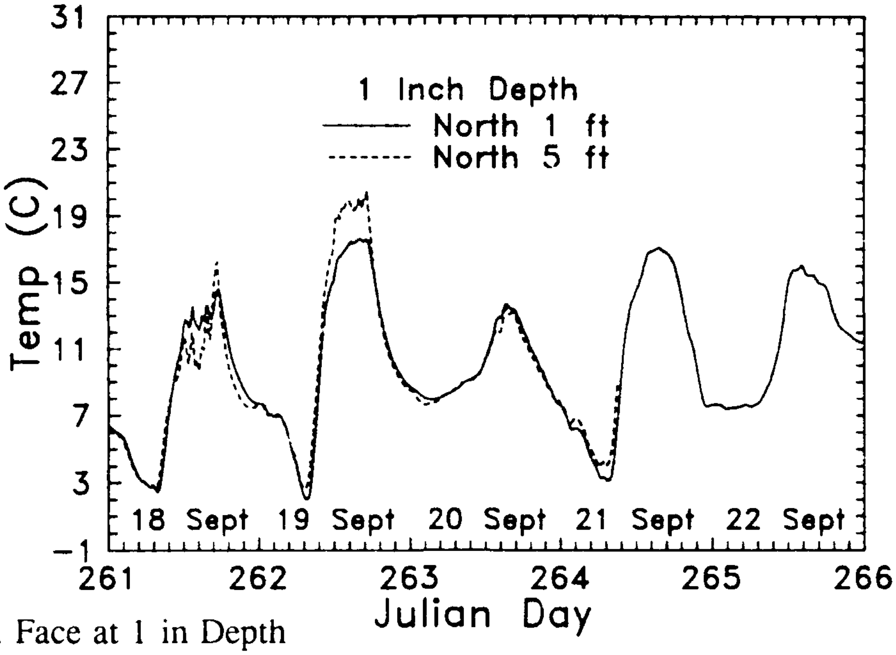


(c.) 1 in S-N Temperature Differences

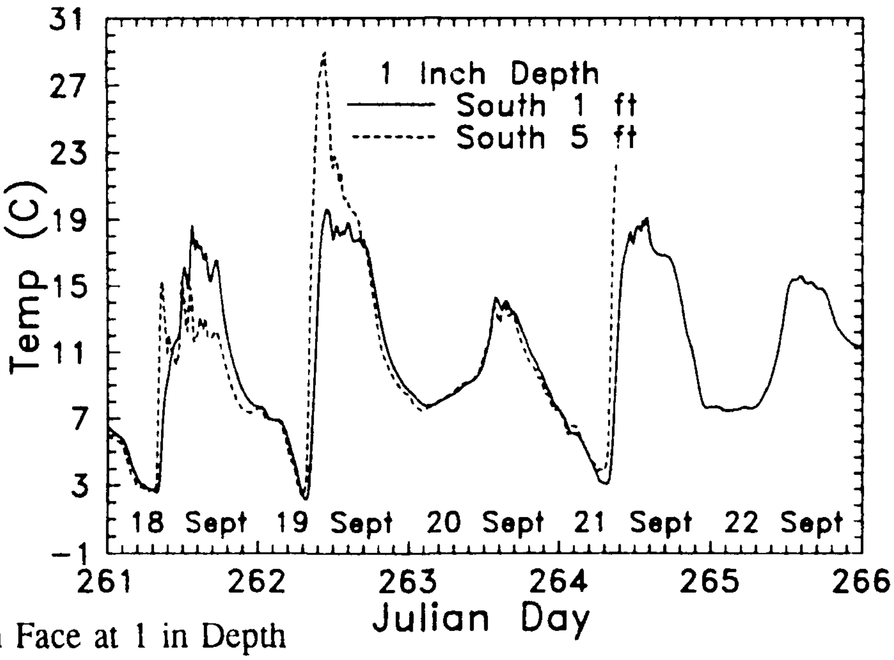


(d.) Center Temperatures

Figure B-2. (Cont.) (c.) S-N Temperature Differences at 1 in and (d.) Center Temperatures

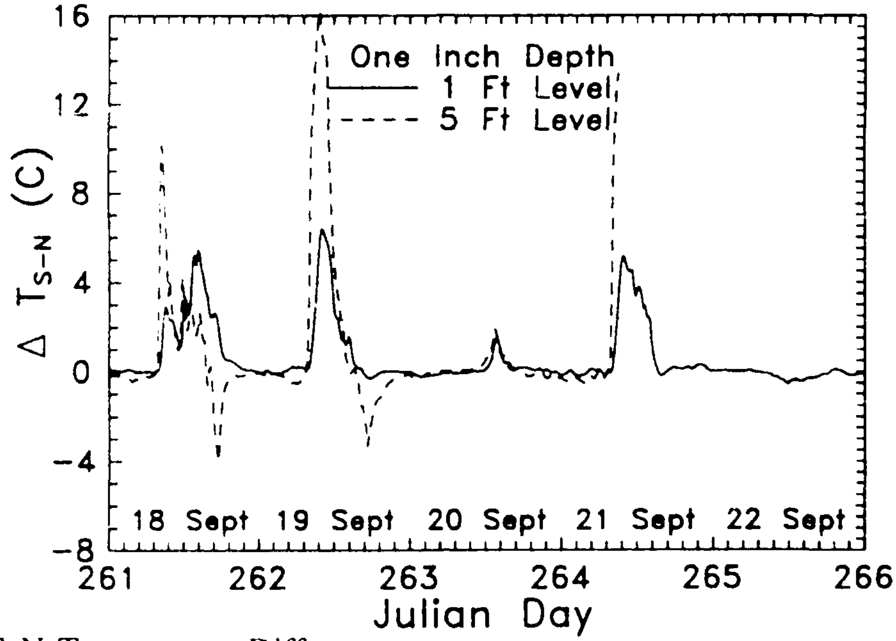


(a.) North Face at 1 in Depth

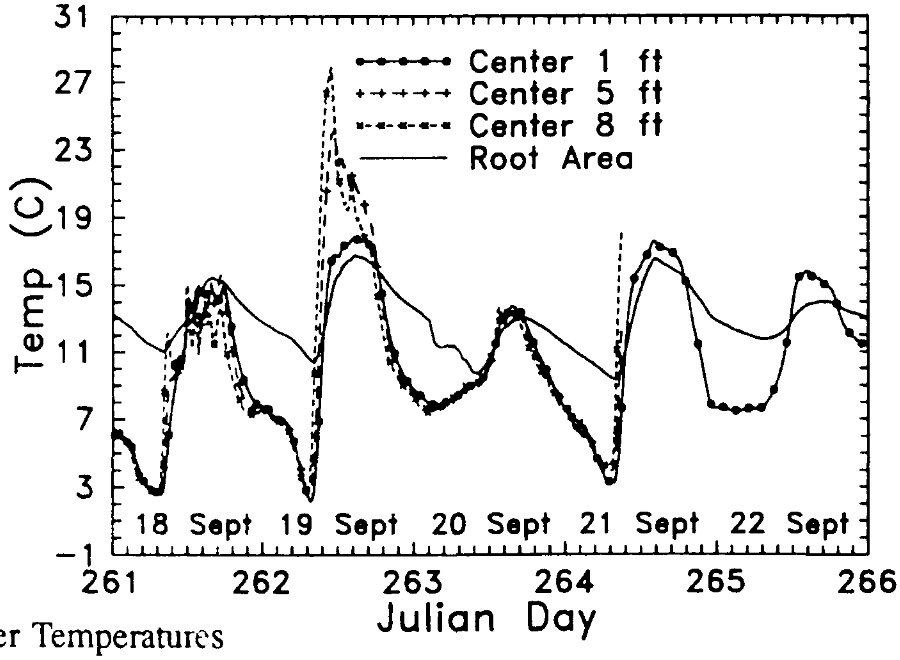


(b.) South Face at 1 in Depth

Figure B-3. Temperatures From "Joyce Kilmer" for 18 - 22 Sept From the (a.) North and (b.) South Face Probes at the 1 in Depth

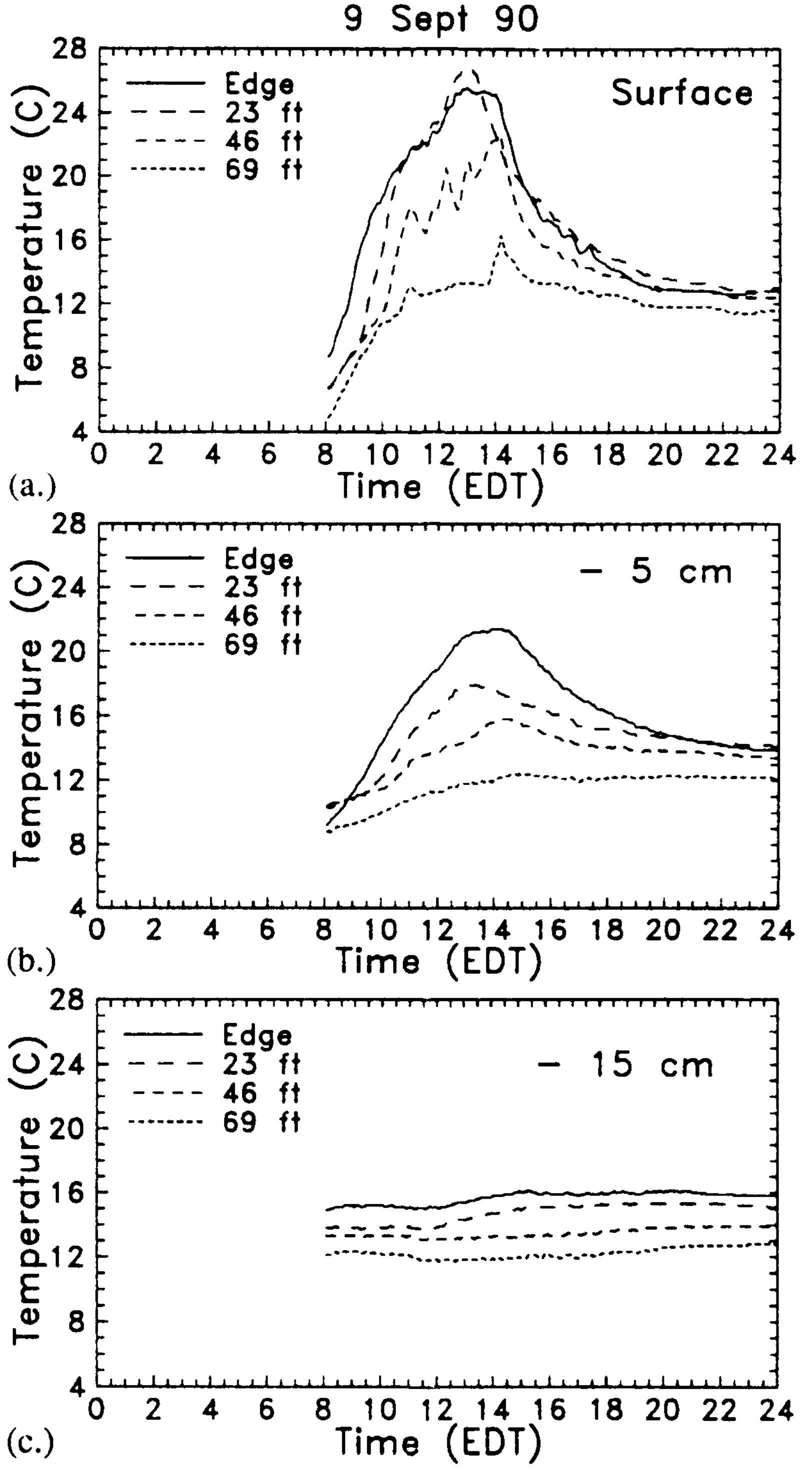


(c.) 1 in S-N Temperature Differences

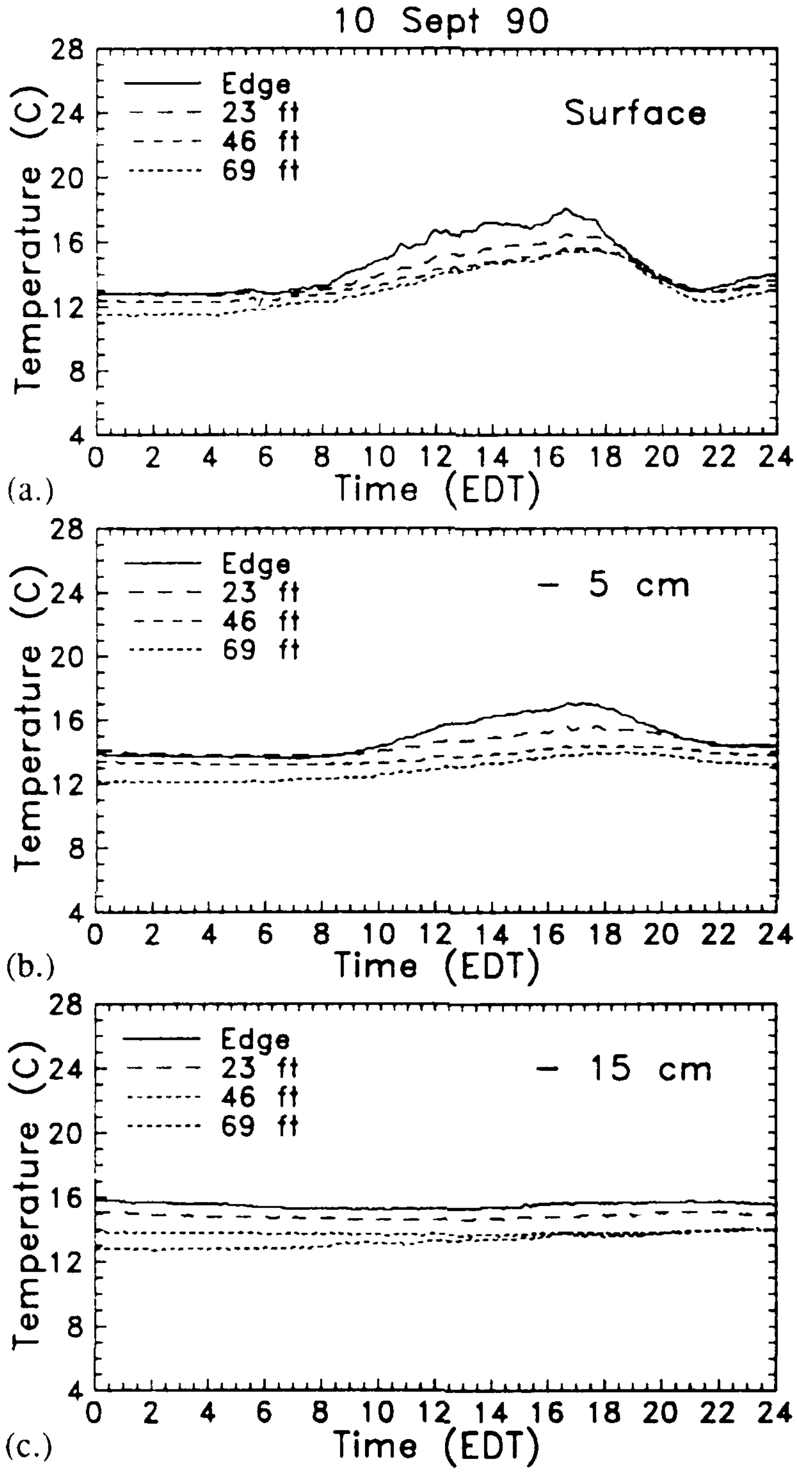


(d.) Center Temperatures

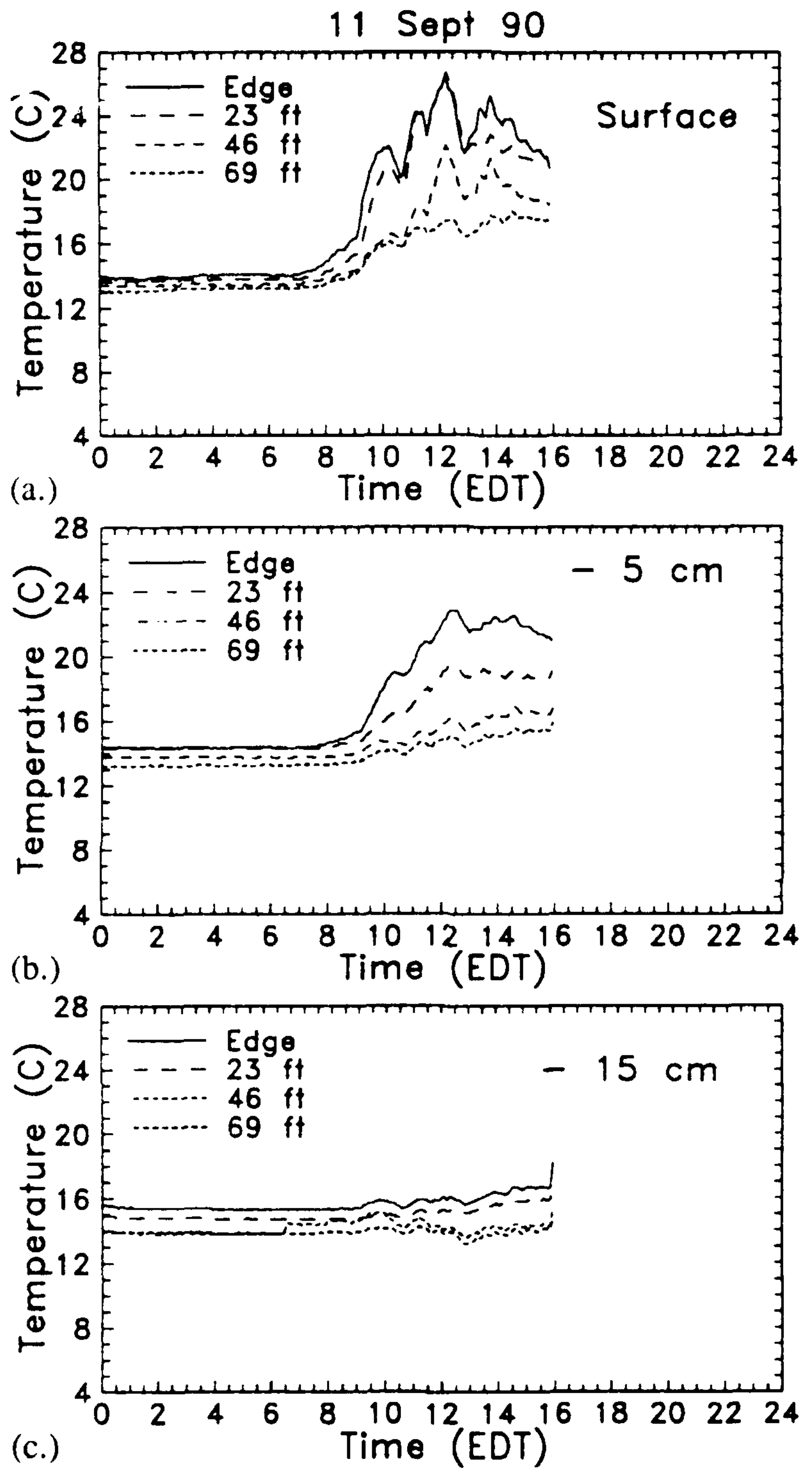
Figure B-3. (Cont.) (c.) S-N Temperature Differences at 1 in and (d.) Center Temperatures



B-4. Soil Temperatures on 9 September 1990 at (a.) the Surface, (b.) 5 cm Below the Surface, and 15 cm Below the Surface Measured by KRC at Four Locations Along a Line Extending Into the Forest Edge



B-5. Soil Temperatures on 10 September 1990 at (a.) the Surface, (b.) 5 cm Below the Surface, and 15 cm Below the Surface Measured by KRC at Four Locations Along a Line Extending Into the Forest Edge



B-6. Soil Temperatures on 10 September 1990 at (a.) the Surface, (b.) 5 cm Below the Surface, and 15 cm Below the Surface Measured by KRC at Four Locations Along a Line Extending Into the Forest Edge