Frost Heave and Thaw Settlement in Tundra Environments:
Applications of Differential Global Positioning System Technology

by

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APPLICATIONS OF DIFFERENTIAL GLOBAL POSITIONING SYSTEM TECHNOLOGY

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ABSTRACT

Technological advances in Differential Global Positioning Systems (DGPS), used in conjunction with specially designed survey targets, provide a means for accurately detecting frost heave and thaw settlement in cold environments, and for relating positions precisely in worldwide geodetic reference systems. Evidence acquired at West Dock and Flux Plot 3 in the Kuparuk River basin, North Slope of Alaska, confirm that DGPS is able to measure heave and thaw effectively and accurately at the centimeter-scale in tundra environments. Preliminary results indicate that heave and settlement show patterns of similar spatial variation to those of active-layer thickness (ALT), and weak to moderate correlations between ALT and heave/thaw. Preliminary DGPS results from Barrow, and a comparison with the records from the 1960s indicate that ground subsidence since the 1960s may have occurred. Results suggest that DGPS constitutes the current recommended approach for monitoring cryogenic phenomena and promises to be utilized for many years.
Chapter 1
INTRODUCTION

1.1 Purpose

Vertical and lateral movements of the ground surface resulting from freezing and thawing processes in cold, nonglacial (periglacial) environments have been monitored with various devices by soil scientists (e.g., Everett, 1963), geomorphologists (e.g., James, 1971; Matsuoka, 1994), and engineers (e.g., Linell and Kaplar, 1959; Croney and Jacobs, 1967). Many periglacial regions are underlain by perennally frozen ground (permafrost). Permafrost (Figure 1.1) is defined as any part of the Earth’s crust with a temperature at or below 0°C for two or more years (Muller, 1947). Intense alternating and repeating freezing and thawing of moisture in soil and rocks (frost action) directly affect the periglacial landscape. Frost action forms numerous distinctive geomorphic features (French, 1996; Washburn, 1980; Péwé, 1969, 1983). Two frost-action processes, frost heave and thaw settlement, form frost boils, frost mounds, and patterned ground (Clark, 1988) and are responsible for the churning and interfingering of soil layers known as cryoturbation.

Heave and settlement are not uniform over geographic space. Differential heave contributes to engineering difficulties by creating stresses that can lead to structural damage or failure to infrastructure. The magnitude of annual heave can range from a few centimeters of upward movement to well over ten or more cm, and can vary substantially over only a few meters of lateral distance.
Heaving and subsidence of the surface are of considerable significance to engineers, inhabitants in cold regions, and climate change research (Williams and Smith, 1989). Frost heave and thaw settlement have the potential to damage roads and structures (Williams and Smith, 1989). Such geotechnical hazards are common in much of North America, Europe, and Asia (Ferrians et al., 1969). O’Neill and Miller (1985) estimated that $1 billion worth of property is damaged or destroyed every year from the consequences of frost heave. The International Union of Geological Sciences has recognized the importance of frost heave and thaw settlement as indicators of short-term climate change by including them in a list of “geoindicators” (Berger and Iams, 1996).

Figure 1.1  Permafrost distribution in the Northern Hemisphere based on Brown et al. (1997; 1998).
Frost heave measurements began in the 1920s with studies by St. Bac (Fahey, 1971). Subsequent studies of heave and subsidence have utilized a wide variety of mechanical tools and sampling designs (Haywood, 1961; Fahey, 1971; James, 1971; Lewellen, 1972; Mackay, 1977a; Smith 1987a,b; Hinkel, 1992; Matsuoka et al., 1988; Mazhitova et al., 2004; Walker et al., 2004). A problem common to the techniques described in these sources is their inability to tie into a worldwide geodetic reference system. Moreover, a standardized heave and settlement instrument has not been established. At the Sixth International Permafrost Conference in Beijing in 1993, the International Permafrost Association (IPA) Working Group (WG) on Periglacial Processes and Environments declared the need to establish standardized monitoring (Humlum and Matsuoka, 2003). Measurement of frost heave and thaw settlement is an integral part of the Circumpolar Active Layer Monitoring (CALM) program’s second phase (Nelson et al., 2004).

Recent development of high-precision Differential Global Positioning System (DGPS) technology provides the potential to measure vertical movements accurately in a worldwide geodetic coordinate system, allowing for comparison of results from ground-based surveys with those from remote sensing platforms.

DGPS appears to be a promising tool to measure ground movements, and has been successfully applied in many environments (Sheperd et al., 1998; Sneed et al., 2001; Malet et al. 2002). Recently, Berthling et al. (2000) used DGPS successfully to measure three-dimensional slope movement in an alpine environment. Although Mazhitova et al. (2004) and others (see James, 1971) have measured heave and thaw with optical surveying instruments, DGPS provides several advantages over traditional surveying, among them excellent planimetric accuracy. Under favorable
circumstances, one can recover position even after a long period of time, or when the target has disappeared. In addition, the accuracy of DGPS does not diminish with distance from benchmarks (i.e., between horizontal and vertical control benchmarks and points of interest). Under ideal conditions, DGPS has the potential to measure frost heave and thaw settlement of 1 cm or less. As technology improves further, DGPS measurements will become easier and faster. One of the primary goals of this thesis is to assess the effectiveness of DGPS as a tool to measure the vertical component of frost heave and thaw settlement, at resolution of one centimeter or less, in several diverse tundra environments of northern Alaska.

1.1.1 The Active-Layer/Transient layer/Permafrost system and Heave/Thaw

Frost heave and thaw settlement result from subsurface processes in the soil of ice-rich permafrost environments, specifically the active layer, transient layer, and permafrost (Figure 1.2). The active layer is the “top layer of ground characterized by annual freezing and thawing in areas underlain by permafrost “ (Permafrost Subcommittee, 1988, 13). The transient layer (upper permafrost) is ice-rich, and freezes and thaws over multi-decadal periods and is located between seasonally frozen ground and permafrost (Shur, 1988a,b; Shur et al., 2005). These three layers, referred to as the Active-Layer/Transient layer/Permafrost system in this thesis, act in concert with frost heave and thaw settlement. In ice-rich terrain, downward displacement of the surface may accompany long-term temperature warming. Spatial patterns of frost heave, thaw settlement, and active-layer thickness may be similar, because they are manifestations of an interrelated suite of geomorphic processes operating in cold regions.
Figure 1.2  Seasonal changes in the active layer/transient layer/permafrost system from (a) late summer, (b) fall and winter (freezing), (c) late winter, (d) spring and summer (thawing). Not to scale. Modified from Clark (1988).
1.1.2 Detecting Subsidence of the Ground

Thaw of ice-rich permafrost has the potential to damage human infrastructure (Nelson et al., 2002; Khrustalev, 2003). Volume loss accompanying phase change, in combination with drainage of the generated meltwater, can induce settlement of several meters if the initial surface is underlain by massive ice (Figures 1.3 and 1.4; McCarthy et al., 2001; Nelson et al., 2001). Recent concerns about degradation of permafrost have been reported in popular media (Linden, 2000; Egan, 2002; Goldman, 2002).

![Figure 1.3](image)

Figure 1.3  a) Thermokarst terrain, caused by thaw settlement, Mongolia. Photo courtesy of N. Shiklamonov.  b) Recent thermokarst development along the Dalton Highway, a few kilometers south of Deadhorse, Alaska. Photo taken by J. Little June 2003.

Concerns about thaw settlement extend into the realm of global change science. Diverse types of data sets collected in recent years indicate that climate warming is underway in the Arctic (Serreze, 2000; Hinzman et al., 2005). Warming may modify the earth’s energy balance at the surface, increase heat flux to the subsurface and ultimately lead to thaw of ice-rich sediments, ground subsidence, and development of thermokarst terrain, with potential for damage to engineered structures (Figure 1.4; Nelson et al., 2002). In Russia, permafrost engineering hazards have
been examined extensively (e.g., Khrustalev, 2003). In 1966 in Noril’sk, Russia, for example, a building collapsed due to differential thaw, killing 20 people. In 1998, Yakutsk, Russia, was declared a disaster area as a result of thaw settlement (Nelson et al., 2002). In Yakutsk and Noril’sk, thawing permafrost has damaged approximately 300 apartment buildings (Goldman, 2002). Nelson et al. (2002) created hazard zonation maps of areas in the Northern Hemisphere at risk for thaw-induced subsidence. Population centers in northern Alaska (Nome and Barrow), northwestern Canada (Inuvik), and in the Sakha Republic in Siberia (Yakutsk) have been identified as locations at risk for ground subsidence-induced disruptions (Nelson et al., 2002).

![Image](image.jpg)

**Figure 1.4** The effects of thawing of ice-rich permafrost can lead to severe damage of structures. Building in Faro, Yukon Territory, Canada subsiding differentially due to thaw of ice-rich permafrost (Nelson et al. 2002). Photograph courtesy of F. Nelson.

Because thawing of permafrost may evolve gradually (Riseborough, 1990), an extensive program of heave and settlement monitoring may help to avoid damage and save resources. The IPA Working Group on Periglacial Processes and Environments at the Sixth International Permafrost Conference in 1993 in Beijing...
supported establishment of a long-term international monitoring network. This idea gained additional support at the 1995 Berlin meeting of the IPA Council. A resolution stated:

> Considering the importance of documenting and understanding long-term change in permafrost terrain the IPA recommends: 1) the establishment of an international network for long-term monitoring of the thermal state of the permafrost and active layer in both hemispheres; and 2) the standardization of methods for measurement and site selection... (Humlum and Matsuoka, 2003).

Because thaw settlement is a consequence of changes in the thermal regime of the active layer and permafrost, establishing a standardized method of measuring thaw settlement is within the context of IPA’s resolution.

1.1.3 Sampling for a Frost Heave/Thaw Settlement Monitoring Network

The benefits to humans from DGPS measurement of frost heave and thaw lie in its potential to accurately and rapidly warn of areas at risk for thaw subsidence. Before this possibility is realized, however, information regarding the spatial variability of heave and thaw must be explored via sampling techniques. An appropriate sampling scheme for heave and thaw measurement is required before a circumpolar heave and settlement network can become a reality. Although the physical basis of frost heave and thaw settlement is well understood, little is known about their spatial variability, except across areas 10 m² or smaller. Frost heave and thaw settlement develop within the three-tier active-layer/permafrost system. As a result, vertical changes of the surface are dependent on this system. It might first appear that remote sensing, with its ability to cover large geographic regions, could be applied to assess the variability of heave and settlement. However, remote sensing has
yet to be proven effective for measuring heave and subsidence (Hall, personal communication, 2002; Hall, 2002; Lovick, personal communication, 2002; and Lu et al., 2003).

Nelson et al. (1999) and Gomersall and Hinkel (2001) successfully applied variants of a sampling design (Webster and Oliver, 1990) that promoted further understanding of the variability of active-layer thickness at multiple scales. DGPS, used in conjunction with similar sampling strategies, may provide the ability to address spatial problems involving frost heave and thaw settlement.

1.2 General Research Objectives

Despite difficulties inherent in establishing an instrumented network, recent scientific and geodetic advances have the potential to measure vertical movements accurately and rapidly, to survey large, remote regions over extended periods, and to compute survey results in precise, worldwide referenced coordinate systems. Differential Global Positioning Systems (DGPS) are among the most promising of these technological developments. Unlike traditional surveying methods, DGPS accuracy does not diminish with distance from benchmarks. DGPS also provides extremely good planimetric accuracy, and position can be recovered even after a long period of time or when a platform target has disappeared. Technological advances in DGPS provide the potential to measure heave and subsidence at sub-centimeter resolution in tundra environments. As technology improves further, measurements will become easier and faster. The ability to make comparative studies with remote sensing makes DGPS a cutting edge tool for geomorphic studies.
This thesis investigates the ability of DGPS to measure frost heave and thaw settlement at three locations on Alaska’s North Slope. It documents a preliminary exploration of three closely related topics: (1) the feasibility of DGPS to measure frost heave and thaw settlement at several locations representative of tundra environments in northern Alaska; and (2) the spatial variability of heave and settlement in tundra environments and correlation between active-layer thickness and frost heave/thaw settlement; and (3) long-term thaw settlement in an area where data were collected forty years previously by precise optical measurement. The study is a contribution to active-layer research under the Circumpolar Active Layer Monitoring (CALM) program, and offers a potential solution for monitoring subsidence, one of CALM II’s core activities (Nelson et al., 2004).
Chapter 2

BACKGROUND: FROST HEAVE AND THAW SETTLEMENT

The occurrence and magnitude of frost heave depend on a complex interplay between the moisture and thermal regimes of soils. Frost heave is dependent on the process of ice segregation (Figure 2.1), which can be conceptualized as having three sequential steps: (1) unfrozen water migrates from areas of warm (unfrozen) to cold (frozen) soils; (2) formation of segregated ice; resulting in (3) upward heaving of the ground surface. Williams and Smith (1989) and Davis (2001) provided good summaries of the frost-heave process.

Prior to the formation of ice lenses (ice segregation), two factors (adsorption pressure and capillarity) significantly influence the freezing point of unfrozen water in soils. Adsorption pressure, the interaction between soil solids (particles) and water in the soil, binds water molecules with soil particles. In turn, ice crystallization develops only after the temperature drops below 0°C. Capillarity, the relative attraction between a particle and a liquid due to surface tension (Davis, 2001), can increase or decrease the freezing point. Figure 2.2 illustrates the effects of pore size on ice segregation. Although salinity and pressure can depress the freezing point, their effect under most natural conditions is minor (Davis, 2001).

In medium-textured soils, water migrates from warm (unfrozen) to cold (frozen) soils as a result of molecular forcing (i.e., a temperature gradient exists, creating a pressure difference and subsequent water migration (Harlan, 1973; and Miller, 1978, 1980)). Near the surface, water migrates from the unfrozen central
portion of the active layer upward to the freezing front (Figure 2.3). Under conditions of two-sided freezing, water also migrates from the central portion of the active layer downward toward the permafrost table (Figure 2.3).

Figure 2.1  Picture of horizontal ice lenses. This ice is a result of water drawn upward to the freezing zone, causing expansion known as frost heave, referred to as the ice segregation process. Photo courtesy of Dr. W. Eisner.
Figure 2.2  The diagram above illustrates the ice segregation and ice pore process. Pore ice is not segregated ice, rather it is ice occurring in the inter-grain pores of soil and rock (van Everdingen, 2002). The view is a cross section of soil near the freezing level. The symbol $\sigma$ represents the tension between liquid water and the radius, $r$, of the ice-water interface. Diagram (a) shows two mineral soils in general conditions before the formation of segregated ice and pore ice. If the ground freezes, the freezing plane can remain stationary above the soil, or ice tongues may descend, forming pore ice (b). If the freezing plane continues to remain above the soil, water will migrate upward toward the freezing plane. (c) Depending on moisture availability, ice crystals may materialize, forming an ice lens, depending on moisture availability. The growth of ice lenses promotes upward heave of the overlying soil. Modified from French (1996, 34).
Figure 2.3  Diagram depicting two-sided freezing within the active layer/transient layer/permafrost system. The relative positions of the frozen fringe, freezing front, and cryofront are shown in a fine-grained, frost susceptible soil as freezing is occurring. The freezing front, and the boundary between cryotic (frozen) and noncryotic ground (the 0°C isotherm), referred to as the cryofront (van Evergingen, 2002) are shown. Ice lens formation is black. Arrows depict movement of moisture to the developing segregated ice layer. Two-sided freezing refers to the development of ice lenses near the surface and at the bottom of the active layer. Ice lens formation tends to thicken as depth increases as a result of slower progression of the freezing front with increasing depth. The most substantial ice lens growth occurs at the base of the active layer, which often contains excess ice. The upper permafrost layer (or transitional layer) is located below the base of the active layer and above the long-term (centuries to millennial) permafrost.
The process and rate of ice lens formation (ice segregation) at the bottom of the active layer and near the surface differ, significantly affecting the size of ice lenses and the vertical distribution of ice (Mackay, 1984). Ice lens growth in the upper portion of the active layer is much smaller than at the base of the active layer for several reasons. Gravity (or load) works against upward water migration, reducing water supply near the surface. At the base of the active layer, gravity works with water migration, increasing water supply. Near the surface, the freezing front remains at one location for a very short time period as compared to the base, decreasing the time of ice lens growth at the surface. High freezing rates for a short time period result in decreased ice lens formation near the surface (Kaplar, 1968; Davis, 2001), whereas at the base of the active layer, the freezing rate is low but is sustained over long periods of time, promoting development of larger ice lenses (Kaplar, 1968; Mackay, 1984) and, in some cases, massive ice.

During the formation of ice lenses, upward pressure overcomes the surface load, resulting in upward movement of the ground surface, or frost heave (Sutherland and Gaskin, 1973; Penner, 1970). The amount of segregated ice formed directly affects the degree to which the ground heaves.

2.1 Brief History of Frost Heave and Thaw Settlement Research

2.1.1 Ice Segregation

Study of the physical processes involved in frost heave began in 1765 with Runeberg (Fahey, 1971), who thought that upward movement of the ground surface resulted from the expansion of water in the frozen phase. Years of research
and many investigations (e.g., Taber, 1918; Taber, 1930; Beskow, 1935; Troll, 1944; Carlson, 1952; Everett, 1961; and Miller, 1978) have shown that simple expansion of porewater is not the prime mechanism responsible for frost heave.

The classic work of Taber (1918, 1930) showed that a significant amount of ice can accumulate in soil during freezing, forming horizontal ice layers surrounded by relatively dry, ice-free material. Taber (1930) concluded that: (1) horizontal ice layers (ice lenses) increase in soils with fine-grained material (e.g., size composition of 0.01 mm in diameter or less), and (2) ice crystal growth occurs within material towards the point where heat is being most rapidly conducted away. Taber’s work discredited the assumption that heave is attributable only to the expansion of water in the solid phase (Beskow, 1935).

The most significant work in the 1930s was that of Beskow (1935), who studied mechanisms responsible for the formation of ice lenses. Beskow (1935) determined that moisture is needed for ice segregation to occur. He found that molecular forcings between water and ice (capillary or cryosuction) and between soil solids and water (adsorption) are responsible for creating pressure differences, resulting in migration of water to the freezing area. As water moves toward the freezing fringe, ice lenses form, a process that became known as ice segregation (Figure 2.1, 2.2, and 2.3). Beskow developed the first conceptual model of ice segregation, the capillary model. The principles formulated by Taber (1930) and Beskow (1935) provide the foundation on which all subsequent physical studies of frost heave are based.

During the 1950s, work focused on the relation between edaphic (soil/vegetation) and climatic factors (e.g., Cook, 1955; Jackson and Chalmers, 1958;
Penner, 1959), with special focus on such applied topics as road construction and maintenance (Beskow, 1935). In the 1960s, frost heave research became focused on laboratory investigations. This work was aimed primarily at improving Beskow’s capillary model (e.g., Dirksen, 1964; Hoekstra, 1966; and Penner, 1967).

The 1970s was a period of intensified research on frost heave, a result of the planned construction of the Trans-Alaska Pipeline System, which began functioning in 1977. Work in the 1970s made significant strides in the improved understanding of ground thermal and moisture regimes and their influence on ice segregation. Research involved: (1) the relationship between heave magnitude and moisture supply (McGaw, 1972); (2) rapid release of latent heat and subsequent rapid freezing (Penner, 1972) and decreasing heave rates (Kaplar, 1968); (3) the effects of soil properties on the rate and magnitude of heave (e.g., Penner, 1970; Sutherland and Gaskin, 1973); and (4) development of mathematical and numerical models of ice segregation to describe the movement of water in response to thermal gradients (e.g., the hydrodynamic model (Harlan, 1973) and the rigid ice model (Miller (1978, 1980)).

The main aim of research in the 1980s was to predict frost heave (Konrad and Morgenstern, 1980), primarily through refined numerical modeling exercises (e.g., Gilpin 1980; Perfect et al., 1991). Field investigations addressed closely related issues, such as secondary heaving (e.g., Mackay, 1984). During the 1990s, refinements to the capillary, hydrodynamic and rigid-ice models were developed (e.g., Dash et al., 1995; Wettlaufer et al., 1996; Wettlaufer, 1999; Worster and Wettlaufer, 1999), taking into consideration the stable layer of water located between ice and soil surfaces that allow for very high heaving pressures to develop (Davis, 2001).
The physical basis (Henry, 2000) of frost heave is currently well enough understood that models have been produced to solve practical engineering problems (Guymon et al., 1993). Research continues on the physical processes governing frost heave (Vilches, 2002).

2.1.2 Two-sided Freezing

Lab work by Miller (1972) and field-work by Mackay (1984) led to advanced understanding of two-sided freezing in permafrost environments (Figure 2.3). Miller (1972) developed a conceptual model, while Mackay (1984) performed detailed field experiments demonstrating that the active layer in periglacial environments freezes both from the surface downward and from the bottom of the active layer upwards. This process, referred to as “two-sided freezing,” is responsible for thick layers of segregation ice at the base of the active layer (Brown and Sellmann, 1973; Williams and Smith, 1989; Shur et al., 1995). The substantial heave that results is referred to as ‘secondary heave,’ distinguished from ‘primary heave,’ which arises from freezing near the surface (Miller, 1972). Whereas primary heave occurs in both temperate and permafrost regions, secondary heave occurs exclusively in permafrost regions. Two-sided freezing in the active layer/transitional layer/permafrost system is shown in Figure 2.3.

2.1.3 History of Research on Thaw Consolidation and Thaw Settlement

Two-sided freezing contributes to a distinctive vertical distribution of ice in permafrost regions, and is the reason for significant ice volumes at the base of the active layer (Brown, 1967; Pollard and French, 1984). Temperature increases at or near the ground surface make frozen soil vulnerable to thaw. Thawing of massive ice
formed at the interface of the active layer and permafrost can result in differential
thaw settlement at the surface (Figure 1.3). Degradation of massive ice can lead to the
formation of thermokarst terrain, extensive areas with high local relief resulting from
differential subsidence.

Numerous studies have addressed the manner in which frozen ground
thaws with depth (Neumann, c. 1860; Stephan, 1890; Berggren, 1943; Beskow, 1947,
Murray and Landis, 1959), providing the principles of thaw settlement (Terzaghi,
1952; Shelley, 1954; Morgenstern and Nixon, 1971; Andersland and Anderson, 1978;

Terzaghi (1952) developed the theory of consolidation. The term thaw
consolidation refers to compression of the soil as a result of thawing of frozen ground
and drainage of the excess water, resulting in thaw settlement (Andersland and
Anderson, 1978; Johnston, 1981; van Evergingen, 2002). Previous research (e.g.,
Terzaghi, 1952; Shelley, 1954; Morgenstern and Nixon, 1971) indicates that thaw
consolidation is caused by: (1) a reduction in the volume of any contained ice as it
liquefies; (2) a reduction in pore size as grains or soil move closer together during the
thaw process; and (3) drainage or escape of pore and excess water (Davis, 2001). The
thaw consolidation ratio describes the relationship between thaw and consolidation in
a thawing soil, and provides a measure of the generation and expulsion rates of excess
water during thaw (Morgenstern and Nixon, 1971; van Evergingen, 2002). The thaw
consolidation ratio $R$ (depth of thaw in m) is given (Washburn, 1980) as:

$$R = \frac{\alpha}{2 (c_v)^{1/2}}$$  \hspace{1cm} (2-1)
where $\alpha = d/(t)^{1/2}$ and $d$ is the depth of thaw (cm), $t$ is time (s), and $c_v$ is the coefficient of consolidation (cm$^2$ s$^{-1}$). End-of-season thaw depth can be estimated from any of a suite of solutions to the general Stefan problem (e.g., Harlan and Nixon, 1978). An elementary form of the Stefan solution is given by:

$$Z_t = \left[(2 \lambda S DDT)/(w \rho L)\right]^{1/2}$$

(2-2)

where $Z_t$ is the depth of thaw (m), $\lambda$ is thermal conductivity (W m$^{-1}$ °C$^{-1}$), $S$ is a scale factor (86,400 s d$^{-1}$), DDT is the total thawing degree days (°C days), $w$ is water content expressed on a percentage (dimensionless) basis, $\rho$ is the soil’s dry density (kg m$^{-3}$), and $L$ is the latent heat of fusion (J Kg$^{-1}$).

Cumulative subsidence ($S_{sub}$), or thaw settlement (cm), can be found by (Yershov, 1998):

$$S_{sub} = h_{fr}^i + h_{sw}^{th} - S_{sub}^i - S_{shr}^{th}$$

(2-3)

where $S_{sub}^i$ is subsidence of the ground due to thawing of the ice layers and pore spaces (cm), $h_{fr}^i$ is heave deformation due to water migration in the frozen part of the soil (cm), $h_{sw}^{th}$ is swelling deformation in the soil during the transition from frozen to thawed (cm), and $S_{shr}^{th}$ is subsidence in the thawed, dehydrated state (cm).

2.1.4 The Transient Layer and its Role in Climate Change Research

Cold environments are susceptible to climatic change, whether from anthropogenic sources or natural variation. Evidence from sea ice, temperature, snow
cover, precipitation, and permafrost (Lachenbrauch and Marshall, 1986; Romanovsky et al., 2002) indicates that change is underway in the polar regions (Serreze et al., 2000; Hinzman et al., 2004). Changes in frost heave and thaw settlement may also indicate climate change, but to what extent is unclear. Any changes in frost heave and thaw settlement are a result of developments in the ground, specifically the active layer and upper permafrost (Figure 1.2).

If ground cover and soil properties are held relatively constant, the thickness of the active layer decreases poleward in response to decreasing temperature. Much remains to be learned, however, about the behavior of the active layer under conditions of climatic warming. One of the original driving hypotheses behind the Circumpolar Active Layer Monitoring (CALM) program (Brown et al., 2000) was that active-layer thickness (ALT) will increase in conjunction with climate change (Brown, 1997; Brown et al. 2000). However, additional monitoring and analysis (Walker et al. 1998; Brown et al. 2000; Sturm et al. 2001) have confirmed that this hypothesis is in need of refinement (Hinkel and Nelson, 2003; Nelson et al., 2004). Penetration of thaw into the ice-rich layer of permafrost immediately below the active layer may, in some instances, result in subsidence at the surface without significant accompanying increase in the thickness of the active layer.

Nelson et al. (1998b) suggested that a system of self-regulating mechanisms in the upper permafrost minimizes significant ALT change except under extreme conditions involving accumulation or degradation of ice in the upper permafrost, and leading to abrupt and long-lasting (“Markovian”) changes in ALT that can persist for many years after the event.
Building on earlier Russian work (e.g., Yanovsky, 1933), Shur (1988a,b) reconceptualized the traditional two-tier model consisting of a seasonally frozen active layer and underlying permafrost. Shur directed attention to the existence of a third layer, the transitional or “transient” layer (upper permafrost), that alternates in status between seasonally frozen ground and permafrost over multi-decadal to millennial periods. Such a three-tier model is illustrated in Figure 2.3. Over a decadal time scale, incremental aggradation or melting of ice within the transient layer can result in substantial heave or thaw subsidence, respectively. Changes in the thickness of the transient layer in response to temperature change may be responsible for development of thermokarst terrain, which can have severe consequences for human infrastructure (Brown *et al.* 1969; Brown and Grave 1978; French, 1979; Nelson *et al.*, 2002; Khrustalev, 2003).

### 2.2 Temporal and Spatial Scales of Frost Heave and Thaw Settlement

#### 2.2.1 Temporal Scale

Ice segregation occurs at various temporal scales (e.g., diurnal, annual, decadal and millennial) in response to the general climatic and edaphic conditions at particular locations. Seasonal freezing and thawing may extend to depths of two or three meters, depending on the duration and severity of freezing. Segregated ice forms small ice lenses near the surface on a relatively short time scale in response to freezing (e.g., overnight temperature below the freezing point). Pipkrake or needle ice is a form of small (e.g., 2 cm) crystals that form overnight in locales that experience diurnal freezing events. Fahey (1973) studied the diurnal variations of heave in the Colorado Rockies. In high-latitude locations (e.g., arctic Alaska where mean annual
surface temperature is well below 0°C), massive ground ice can form through freezing at the base of the active layer over a decadal to millennial time scales, as shown in Figures 2.3 (William and Smith, 1989, 30-31). Figure 2.4 depicts a typical relationship in ice-rich terrain between ground ice volume and depth. On an annual basis, ice segregation can occur in permafrost environments near the surface of the active layer and at the base of the active layer (Figure 2.3), resulting in annual frost-heave events that are typically maximized by late winter on Alaska’s North Slope. Table 2.1 shows typical frost-heave magnitudes resulting from ice segregation in a variety of landforms.

Figure 2.4  A graph showing the typical relationship between ground ice volume and depth in ice-rich terrain. The peak near the surface corresponds to the long-term position of the active layer. Graph modified from Brown and Sellmann (1973).
Table 2.1 Typical frost heave magnitudes at various locations modified from French (1996, 132). Sources: (1) Chambers (1967); (2) Fahey (1974); (3) Everett (1966); (4) Mackay et al. (1979); (5) Burn (1989); (6) Matsuoka et al. (1988); (7) Smith (1987a); (8) Wang and French (1995). For comparison purposes, note University of Delaware Permafrost Group’s study locations on Alaska’s North Slope (Flux Plot 3\(^9\)) and West Dock\(^{10}\).

<table>
<thead>
<tr>
<th>Location</th>
<th>Climatic Type</th>
<th>Year of Record</th>
<th>Site Characteristics</th>
<th>Mean Heave, per yr (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signy Island, South Orkney Islands, (^1) 61°S</td>
<td>Low temperature range</td>
<td>1964</td>
<td>Sorted circle, highly frost-susceptible (a) Surface</td>
<td>4.0</td>
</tr>
<tr>
<td>Colorado Front Range, USA, (^2) 39°N</td>
<td>Alpine</td>
<td>1969-70</td>
<td>Frost boil; highly frost-susceptible. Surface</td>
<td>25.0-29.5</td>
</tr>
<tr>
<td>Cape Thompson, Alaska, (^3) 70°N</td>
<td>High Arctic</td>
<td></td>
<td>Frost boil; highly frost-susceptible</td>
<td>32.5</td>
</tr>
<tr>
<td>Inuvik, Mackenzie Delta, (^4) 69°N</td>
<td>High Arctic</td>
<td>1976-78</td>
<td>Mud hummocks (a) Undisturbed (b) Disturbed</td>
<td>10.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14.0</td>
</tr>
<tr>
<td>Mackenzie Delta (^5)</td>
<td>High Arctic</td>
<td>1987-88</td>
<td>Lake bottom sediments</td>
<td>9.4-20.5</td>
</tr>
<tr>
<td>Sor-Rondane Mountains, Antarctica, (^6) 72°S</td>
<td>High Arctic</td>
<td>1987</td>
<td>Ridge Site</td>
<td>Diurnal heave &gt; 0.2 mm &lt;1.8 mm occurred 12 times</td>
</tr>
<tr>
<td>Alberta Rockies, (^7) 50°N</td>
<td>Alpine</td>
<td>1980-82</td>
<td>Sloping terrain; non-sorted circle</td>
<td>2.0-4.5</td>
</tr>
<tr>
<td>Qinghai-Xizang (Tibet) Plateau (^8) N/A</td>
<td>N/A</td>
<td>1991-92</td>
<td>Sloping terrain (4 sites)</td>
<td>4.3-7.7</td>
</tr>
<tr>
<td>Flux Plot 3, Alaska, (^9) 69°N</td>
<td>High Arctic</td>
<td>2001-03</td>
<td>Foothills of Brooks Range; earth hummocks</td>
<td>1.9-5.4</td>
</tr>
<tr>
<td>West Dock, Alaska, (^10) 70°N</td>
<td>High Arctic</td>
<td>2001-03</td>
<td>Coastal Plain; drained thaw lake basin and polygonized “upland”</td>
<td>1.0-4.0</td>
</tr>
</tbody>
</table>
Thaw settlement occurs over an annual cycle (typically reaching maximum values in August or early September) on Alaska’s North Slope, after net solar radiation has peaked in Arctic Alaska’s short summer. Thaw settlement can occur as a result of thaw in the upper permafrost (transitional layer), seasonally at the base of the active layer, and at the surface (Clark, 1988, 158). Figure 1.2 illustrates the annual thaw that takes place in the active layer/transient/permafrost system.

Thaw settlement is a slow process (Riseborough, 1990). Davis (2001) suggests, however, that the current trend in warming conditions and thawing permafrost are creating topographic change at a rapid geologic time scale, although to the casual human observer these changes may not be obvious. Much of the permafrost that exists today has persisted for thousands of years, and many of its associated geomorphic features also developed thousands of years ago. Evidence today indicates that areas in the discontinuous permafrost zone are most at risk for widespread subsidence (Davis, 2001; Nelson et al., 2002).

2.2.2 Spatial Scales

At small geographical scales (i.e., over large areas), climate is the primary consideration in the frost heave process, while at large scales (small areas), edaphic (soil/vegetation) factors dominate. Air temperature generally decreases poleward in response to decreasing net solar radiation, subsequently increasing the size and thickness of segregated ice lenses. Air temperature is not, however, the only factor involved in energy exchange between the ground and the atmosphere; topography, soil, vegetation, and snow cover (i.e. microclimate) play very important roles and can increase or decrease ground temperatures several degrees (Williams and Smith, 1989).
Estimates of the volume and dominant type of ground ice vary widely. Ground ice distribution across the Northern Hemisphere is shown in Figure 2-5. Ice distribution in arctic Alaska is highly heterogeneous as a result of the complex interplay between edaphic and climatic factors. Brown and Sellman (1973) and Sellman et al. (1975) estimated ground ice volumes on Alaska’s North Slope, while Pollard and French (1980) made corresponding estimates in northwestern Canada. Results obtained through auguring and coring indicated that ice volume ranged from 50 to 75% in the upper 2 m in Barrow, Alaska (Brown and Sellman, 1973; Sellman et al. 1975). Pollard and French (1980) estimated the total ground ice volume within the upper 10 m in Richards Island (Mackenzie Delta area), an area with physiographic features similar to those of Alaska’s North Slope. Pollard and French (1980) found that over 80% of the total ice volume was a result of pore and segregated ice, and calculated that degradation of this ice in the upper 10 m of permafrost could lead to average subsidence of 1.4 m. These results indicate that differential thaw of ice-rich sediments could result in settlement-induced problems involving differential movements of a meter or more and many square kilometers.
Figure 2.5  Estimated ground ice distribution across the Northern Hemisphere (Nelson et al., 2002). Low equals 0-10%, medium 10-20%, and high is greater than 20% ground ice distribution. Adapted from Brown et al. (1997; 1998).

2.2.3 Annual Frost Heave/Thaw Settlement

The annual cycle of frost heave and thaw settlement depend on the ground thermal regime, which in turn is controlled by macro- and topoclimate and by vegetation, snow cover, moisture content, and soil properties. These factors affect the spatial variation of heave and settlement. Winter frost penetration may not be directly correlated with air temperature, as locations separated by only tens of meters or less can experience variations in the magnitude of frost penetration involving factors of
two or more (Williams and Smith, 1989). Wide variations in ground thermal conditions are known to occur within small areas (Brown, 1973; Brown, 1978) due to snow cover (Smith, 1975), soil type (e.g., non-conductive modes of heat transfer in organic material keep ground temperatures low in summer, from Nelson et al. (1985)), lithologic variations (e.g., bedrock results in deep penetration of summer warming, from Brown, 1973), thickness of the organic layer (Michaelson et al. 1996), soil changes from nonacidic to acidic tundra (Walker et al. 1998), shrub development (Sturm et al. 2001), and aspect (Price, 1971). Numerous investigations, summarized by Williams and Smith (1989, 60-79), have also demonstrated the importance of edaphic factors in frost heave processes.

Studies conducted by Nelson et al. (1999) and Gomersall and Hinkel (2001) addressed spatial variations in the thickness of the active layer. Within 1 km² areas on Alaska’s North Slope, maximum contrasts in ALT may occur over distances of as little as a meter or as much as 300 m, depending on vegetation, topography, soil material, and subsurface hydrology. Although variation in frost heave processes may have similar patterns of variability, this remains largely undetermined.
Chapter 3
HEAVE AND SETTLEMENT: MEASUREMENT TECHNIQUES

Several methods and a wide variety of instrumentation have been used to measure the vertical component of frost heave and thaw settlement. The measurement of frost heave began with the development of the motometer, introduced in the 1920s by the Polish geomorphologist, St. Bac (Fahey, 1971). James (1971) reviewed techniques employed to measure frost heave and thaw up to about 1970. Fahey (1971) contributed to the review of frost heave devices in his dissertation on frost heave in the Colorado Front Range. These sources are the only comprehensive reviews of the various frost heave techniques employed in the field, and obviously cannot convey developments beyond the 1970s. Although Matsuoka (1994) reviewed frost heave measurement techniques between 1970 and 1994, there has not been a comprehensive review of frost heave techniques since 1970. This chapter is intended to fill that void, as it provides a comprehensive review of frost heave techniques since the 1970s.

Engineers, geomorphologists, and soil scientists have used a wide variety of techniques and methods to measure frost heave in the field (James, 1971). Application of non-continuous heave devices include frame-and-rod instruments (e.g., Haywood, 1961), leveling of the ground surface (Beskow, 1935), leveling of frost-heave gauges (Penner, 1970), direct measurement of frost-heave gauges (Baracos and Marantz, 1953; Schmid, 1955; Washburn, 1969), steel tape and target surveys (Rapp, 1960), suspended thread (Pouquet, 1956; Benedict, 1970; Hinkel, 1992) and photogrammetric methods (Poulin, 1962). The focus of this review is on techniques
applied most often (e.g., frame-and-rod instruments) and those having the greatest effect on future tools. James (1971) organized the measurement devices into two categories, non-continuous and automatic.

3.1 Techniques Developed Prior to 1970

3.1.1 Non Continuous Recording: Frame-and-rod Instruments

Frame-and-rod devices create short linear transects (Smith, 1987a,b), and are often referred to as “bedsteads.” They are often smaller than 10 m². Frame-and-rod devices are comprised of vertical rods, supported by a metal frame stabilized by cementing the uprights into the bedrock or subsoil. The rods, in contact with the soil, move vertically as the ground heaves or subsides. Frame-and-rod instruments are used commonly, as they are inexpensive and easy to construct and maintain. Frame-and-rod instruments have measured heave successfully, especially where its magnitude is several centimeters (Peterson, 1963).

Holmes and Robertson (1960) developed a linear variant of the frame-and-rod device, which they called a “heavometer.” Fleischmann first designed a more elaborate frame-and-rod instrument, known as a “bedstead,” in 1935 (Fahey, 1971). In 1959, a student at McGill University’s research station near Schefferville, Labrador-Ungava, developed “Haywood’s bedstead,” which provided areal coverage of the ground surface (Haywood, 1961). A synopsis of Haywood’s research was provided by Andrews (1963). Czeppe (1961) used five simple rod and frame devices to measure movement in sorted circles in Spitsbergen.

Three significant advances in frame-and-rod instruments were made during the 1960s. The ability of the rods to move freely was limited by adfreeze
strength (the strength between frozen ground and steel or other materials) until Chambers (1967) added polyethylene to the rod exteriors. Caine (1962) and Matthews (1962) developed instruments to measure heave automatically. The principles behind these three improvements continue, with frame-and-rod instruments applied recently by Burn (1989), Matsuoka and Moriwaki (1992), Wang and French (1995), and Walker et al. (2004).

3.1.2 Non continuous Recording: Leveling of the Ground Surface

Many studies have employed traditional (“classical”) surveying techniques (Moffitt and Bossler, 1998), such as optical leveling, triangulation, or transits, to measure heave and thaw settlement. Swedish engineers were the first to use leveling to measure frost heave on sections of railways and roads (Beskow, 1935). The use of leveling continued with Brown and Johnson’s (1965) study of frost boils and linear transects of the ground surface near Barrow, Alaska. Washburn (1969) measured frost heave, settlement and lateral downslope movements with theodolite surveys of target cones in the Mesters Veg District of Greenland. Although leveling provides accuracy to the cm level, it requires a line of sight to the benchmark, preventing large areas from being studied. Recent studies continue to employ optical surveying equipment (Mazhitova et al. 2004).

3.1.3 Automatic Recording

James (1971) concluded that the most valuable contribution to frost heave measurement techniques was the development of automated instruments. Automatic devices became a reality with the invention of the clock-driven chart by Matthews (1962). In the same year, Caine (1962) incorporated a ratchet device to measure
maximum heave. Both advances improved upon the non-continuous frame-and-rod instruments. The ratchet device prevented return of the vertical rods when thaw began and the clock-driven chart provided a means to measure heave continuously. The clock-driven chart was commonly attached to bedsteads. In a particularly comprehensive study, Fahey (1971) measured continuous heave with a clock-driven chart at numerous 9 m² sites in the Colorado Front Range.

Everett (1963, 1966) improved the accuracy and resolution of automatic heave measurements with the development of relatively expensive linear motion transducers, also known as strain gauge transducers. In Everett’s design, aluminum rods with aluminum base plates were in contact with the soil and connected to a transducer shaft. Transducers measure the resistance of upward ground movements, which is proportional to the movement recorded by the transducer shaft. The transducers were first used to measure soil displacement and three-dimensional slope movement in Ohio and Cape Thompson, Alaska (Harris, 1981). Transducers are by far the most accurate tool to measure heave, as they can interpret vertical soil movements of as little as 0.1 mm. Although transducers may be difficult to employ at numerous sites, their success is exemplified by their continued use today (Matsuoka, 1994, 1996).

3.2 Developments Since 1970

Between 1970 and 1990 many minor improvements were made to heave measuring devices. The 1990s saw significant advances with new technology. Methods developed over the past thirty years have varied greatly in sophistication, some being capable of detecting vertical change of only 0.04 mm. Others were used to study larger increments of heave, but with less accuracy. The use of frame-and-rod
instruments has continued, although electrical sensors are being used for continuous measurement rather than clock-driven charts. Only in the past few years have field studies of heave and settlement taken advantage of the remarkable possibilities made available through satellite surveying technology (Wang and Li, 1999; Lovick et al. 2002; Lu et al., 2003).

### 3.2.1 Frame-and-rod Instruments (Bedsteads and Heavometers)

During the 1970s and 1980s the use of areal frame-and-rod instruments continued, although only minor improvements were made. Harris (1972), Fahey (1974, 1979), Smith (1987a,b), and Matsuoka and Moriwaki (1992) employed heavometers to detect heave in northern Norway, Colorado Front Range, southern Ontario, Canadian Rockies, and Antarctica, respectively. Although Smith’s (1987a,b) bedstead did not improve upon the areal coverage of previous devices, Fahey (1973, 1974) and Matsuoka and Moriwaki (1992) attached a fixed mechanical recorder or pen to the frame, improving the clock-driven chart method for continuous heave measurements. This technique measured heave continuously at high resolution (e.g., 0.1 mm), but often has mechanical troubles that prevent acquisition of data over the long term.

3.2.2 Frost/Thaw Tubes

Frost tubes have been employed in many areas to monitor the progression of freezing and thawing within the soil (Rickard and Brown, 1972). Mackay (1973) developed a frost tube to measure active-layer thickness, maximum heave, and ground surface subsidence. Thaw/frost tubes extend from the underlying permafrost through the active layer and above the ground surface (Mackay and Leslie, 1987). The design of frost tubes to measure water movement have varied widely, from neutron probes to detect vertical changes in water content (Cheng, 1982; Wright, 1983; Chen, 1984; Smith, 1985), to differential movement from telescoping tubes, markers and benchmarks in the frozen ground (Mackay et al., 1979; Mackay, 1981, 1983; Mackay and Lewis, 1981; Muir, 1983; Smith, 1985), water-filled holes adjacent to frozen ground to detect horizontal movement of water (Parmuzina, 1979), and magnet probes (Mackay and Leslie, 1987). Rickard and Brown (1972) installed frost tubes to measure changes in frost boils. The frost/thaw tube has been used widely in Canada, illustrated by Nixon (2000) and Tarnocai et al. (2004) studies in the Mackenzie Valley.

A typical frost tube is approximately 2.5 m in length and is installed vertically (Figure 3.1). A rigid outer tube with a diameter of approximately 3 cm serves as a vertically stable reference. A flexible inner tube contains water or sand containing a dye, such as methylene blue, that changes color upon freezing. Scribers outside the outer tube record thaw depth, surface level, and maximum heave or ground subsidence. The thaw tube is able to measure vertical displacements annually and, with modifications, can reach accuracy of 2 cm (Nixon, 2000).
Figure 3.1  Diagram of a frost/thaw tube, based on a design by Mackay (1973). Diagram courtesy of F. M. Nixon, Geological Survey of Canada (Tarnocai et al., 2004).

Thaw/frost tubes have three main advantages. They provide an inexpensive method to record maximum thaw depth and active-layer thickness. The greatest benefits of thaw tubes are in areas where thaw is too deep or the ground too rocky to measure with a simple mechanical probe. Because the outer tube acts as a stable reference, measurement of heave and thaw subsidence is possible. Berger and Iams (1996) designated the frost/thaw tube as an appropriate instrument for assessing the effects of environmental change on frost heave and thaw settlement.
3.2.3 Leveling

Kaufmann (1998) used reference points, permanently fixed in bedrock, to measure surface and vertical changes at about 70 points on a rock glacier in the Austrian Alps. Berthling et al. (2001) measured the movement of ploughing boulders in southern Norway with optical leveling equipment. Bolts were installed in the ground, acting as targets for leveling purposes. Repeated leveling with a Wild NAK 1 level from a fixed bedrock benchmark about 5 to 20 m from the targets, ensured precise readings to 1 mm. Mackay (1997) measured changes of the surface at an artificially drained lake along the western Arctic coast with a Wild NA 2 automatic engineer’s level between the period 1978-1995. Mazhitova et al. (2004) used a Russian 2H-10KL leveling instrument to measure subsidence in Russia as part of the CALM project.

Other traditional surveying techniques, used with survey targets, have been used to measure heave and settlement (Lewellen, 1972; Mackay 1977a). Examples of survey targets include magnetic probes (Mackay and Leslie, 1987), tin foil markers (French, 1974), painted stones (Price, 1973), wooden stakes (Wu, 1984), expanded-foot anchor pins (Nelson, 1986) chaining pins (Outcalt et al., 1986), bamboo skewers and nails (Wilkerson, 1994), and nylon lines (Ballantyne, 1996). Mackay et al. (1979), Mackay (1981; 1983), Muir (1983), and Smith (1985) used telescoping tubes, markers, and benchmarks to measure differential movement of the surface. Caternary devices (Hinkel, 1992) were employed for short transects across small bodies of water.

Berger and Iams (1996) suggested measuring heave associated with deeper freezing by repeated leveling. Although classical surveying methods allow for observation over large areas, they are limited because they require frost-defended
benchmarks within a reasonable distance of the survey area, an issue that is overcome with the use of DGPS.

3.2.4 Electrical Sensors

Over the past decade, electrical sensors, used in conjunction with data loggers, have been used to monitor frost heave continuously with high resolution and minimal (e.g., annual) maintenance, as compared to a reference frame (Giles, 1973; Lewkowicz, 1992; Matsuoka et al., 1997; Hallet, 1998). Williams (1957) first employed these devices, known as displacement or strain gauge transducers, to record solifluction movements. Lewkowicz (1992) designed the solifluction meter, a type of data-logging system to measure slope movement as a result of freezing and thawing near the ground surface. Displacement transducers are able to record displacement of up to 10 cm with a resolution of 0.04 mm (Matsuoka et al., 1997; Matsuoka et al., 2003). However, displacement transducers require use of a stable reference frame, which is often difficult as a result of the effects of heave and thaw consolidation on the frame. They are typically employed in small areas, as they are impractical for measurement over extended geographical areas.

3.2.5 Photogrammetry/Remote Sensing

Kaufmann (1998) and Hoelzle et al. (1998) employed photogrammetric methods to measure creep in the Austrian and Swiss Alps, respectively. Digital terrain models (DTMs) were referenced from aerophotogrammetric determination methods, and used to compare multitemporal DTMs to deduce terrain changes (Hoelzle et al. 1998). Accuracy was reported at 2–3 cm/yr (Hoelzle et al., 1998). Rubensdotter (2002) surveyed a small mountain watershed in Abisko, Sweden with aerial
photographs and ground-truthing. Kling (1996) measured patterned ground with aerial photos and a microscope.

Application of remote sensing techniques in cold regions has the potential to detect vertical changes of less than 1 cm (Smith, 2002), making it a potential tool for measuring frost heave. Processing two ERS (European Remote-Sensing Satellite) C-band images of the same location at different times (e.g., Interferometric Synthetic Aperture Radar or InSAR) has developed into a remote sensing tool capable of detecting small vertical changes in large, remote regions (Smith, 2002). Previous studies include attempts by Lovick et al. (2002) and Wang and Li (1999) to detect winter frost heave. Lu et al. (2003) found poor coherence between SAR images as a result of snow/ice melting and accumulating, as well as ground surface freezing and thawing in their study area, located in the Aleutian volcanoes. Moorman et al. (2003) found little coherence between RADARSAT images in their study, located in the Mackenzie River Delta, Canada. From correspondence with Lovick (personal communication, 2002) and a cryospheric remote sensing expert, it appears that fundamental problems exist with all current tundra-based synthetic aperture radar observations. Although, InSAR has proven especially useful in detecting subsidence in regions with arid conditions (Massonnet et al., 1993; Massonnet and Feigl, 1998; Amelung et al., 1999; Carnec and Fabriol, 1999; Galloway et al., 2000; and Hoffman et al., 2001), dynamic conditions (frozen ground, large topographic variations within small distances, variations in soil moisture, and severe weather) in tundra environments have the potential to degrade the coherence between SAR images, making detection of ground subsidence in tundra environments with InSAR very difficult at this stage of its development (Hall, personal communication, 2002; Hall,
Tait et al. (2005) have begun to incorporate satellite-based differential interferometric radar (DINSAR) to monitor subsidence as a result of natural gas extraction in the continuous permafrost area of the Mackenzie River Delta, however, they express similar concern as Hall (personal communication, 2002) and Lovick et al. (2002). However, the recent organization of the InSAR Working Group (JPL, 2006) suggests increased advances in radar remote sensing research.

3.2.6 Shortcomings of Existing Techniques

This literature review demonstrates that there have been numerous field studies using a wide variety of instruments to measure frost heave and thaw subsidence. It is evident that the frame-and-rod device has been used most often, despite significant drawbacks. The frame-and-rod device has difficulty in covering areas greater than 10 m². It is noteworthy that a problem common to classical surveying, frame-and-rod devices, and frost/thaw tubes is that the locations of geodetic reference markers (i.e., benchmarks) are not easily established precisely with respect to external (geodetic) coordinate systems. Without precise geodetic coordinates, the ability to georeference other periglacial variables in a Geographical Information System (GIS) is difficult. In addition, the amount and weight of the instruments themselves may prove difficult in initial insertion, especially in remote areas. Although remote sensing appears promising through its potential to provide large-region coverage with precise georeferencing, the attempt to detect heave and settlement with InSAR at C-band has thus far proven ineffective (Lovick et al., 2002; Wang and Li, 1999).
4.1 DGPS Field Applications

When this study began, geocryologists had rarely employed high-precision Differential Global Positioning System (DGPS) technology to monitor vertical changes induced by frost heave or thaw settlement. Applications in geocryology are developing rapidly, because DGPS technology has the capability to measure surface changes accurately in worldwide geodetic reference systems and to measure heave and settlement at centimeter or even sub-centimeter scales. DGPS technology has been used successfully in a wide range of scientific applications, including Joass’s (1993) measurement of quarry faces and Newmann et al.’s (1999) study of tectonic faults. Sneed et al. (2001) used DGPS to monitor subsidence associated with ground-water extraction in California. Malet et al. (2002) employed DGPS to continuously monitor a large landslide in southeastern France. Malet et al.’s (2002) one-hour monitoring sessions resulted in a 95% confidence interval of 14.5-19.5 mm of vertical accuracy. Theakstone et al. (1999) used kinematic GPS to produce maps and digital terrain models of a glacier in the Okstindan area of Norway, and reported vertical accuracy of 0.1 m. Sheperd et al. (1998) surveyed active volcanoes with rapid static DGPS, a technique used in the work described in this thesis. Sheperd et al. (1998) estimated vertical accuracy of 1.5 cm. Within the field of geocryology, Kaufmann (1998) used DGPS to evaluate the stability of reference
points in a study on a rock glacier in the Austrian Alps. Berthling et al. (2000) successfully measured three-dimensional displacement of the ground caused by solifluction with continuous DGPS in a mountainous region of southern Norway. Tait and Moorman (2003) concluded that the best method to monitor deformation of the surface in regions of continuous permafrost is with precise leveling and periodic DGPS surveys on established permafrost monuments. Sheng et al. (2004) assessed the feasibility of replacing precise leveling with DGPS in the Mackenzie River Delta of Canada, an area of continuous permafrost. Most recently, Tait et al. (2005) determined the most appropriate survey monument to monitor subsidence with DGPS in permafrost areas.

This thesis describes recent efforts by the University of Delaware Permafrost Group (UDPG) to employ DGPS to measure frost heave and thaw settlement in a permafrost environment. This study addresses applications of DGPS, specifically post-processed stop-and-go kinematic and rapid static carrier-phase DGPS, for measurement of frost heave and thaw settlement in various tundra environments.

4.2 Principles of the Global Positioning System

Global Positioning Systems (GPS) acquire coordinate positions through triangulation, by determining the distance between an antenna receiver and at least four satellites (UNAVCO, 2006). Normal code base GPS receivers are typically used for navigational purposes. To improve accuracy, differential GPS requires at least two antenna receivers: a base receiver with a known position tracking four or more satellites, and a rover receiver placed on a stable target device for a required length of time (Figure 4.1). DGPS improves accuracy by reducing systematic errors (e.g.,
atmospheric delays, precision of orbits) resulting from GPS signal propagation delays
or not knowing the precise location of a satellite’s orbit.

Expensive, carrier-phase GPS can improve accuracy to the centimeter level. "Code-Phase" and "Carrier-Phase" refer to signals used for timing measurements (Trimble, 2002). A GPS receiver calculates the signal travel time from a satellite by comparing the pseudo-random code (complicated binary patterns repeating every 1023 bits) with an identical signal from the satellite. After a period of time the continuous manipulation of the incoming signal code matches that of the receiver. The degree to which it should be modified is proportional to the signal’s travel time. However, the bits (or cycles) of the pseudo-random code are too wide, causing difficulty in matching up exactly. Receivers overcome this problem by using the pseudo-random code and measurements based on a particular code carrier frequency. The two carriers have short wavelengths (19 and 24 cm for L1 and L2, respectively). Because the carrier frequency is much higher than code base frequency, its pulses are closer together, resulting in improved accuracy. This method simply counts the number of carrier cycles between the satellite and the receiver. Although the carrier frequency is difficult to count because every cycle looks like another, the pseudo-random code is intentionally complex to make it easier to count the cycles (Trimble, 2002). For this study, use of carrier phase DGPS was essential, as it increases the accuracy potential to sub-centimeter scale.

Post-processed results are established with program software such as GPSurvey, version 2.35, or TGO software (UNAVCO, 2006). The greater part of this study employed a Trimble 4000 as base station receiver and a Trimble 4700 as rover receiver (Trimble, 2002). Detailed descriptions of post-processed rapid static and
stop-and-go kinematic DGPS methods can be found on-line via the University NAVSTAR Consortium (UNAVCO, 2006) under GPS Campaigns. In its later stages,
Figure 4.1  (a) Acrylite platforms installed at West Dock, Alaska. (b) DGPS rover antenna recording data atop a platform target. Photo by J. Little, summer 2002.
the study employed a Trimble 5700 rover receiver and a fixed Trimble 5700 base station.

4.3 DGPS Base Station

Permanent benchmarks were installed at locations without local obstructions that could block or impede satellite signals to the Trimble 4000 base station receiver antenna. The permanent benchmarks are composed of threaded ready rod, approximately 0.75 cm in diameter, and ad-frozen to permafrost. PVC pipe and a lubricated sleeve surround the ready rod, accommodating frost-heave-induced movement while maintaining a stable datum. The base station antenna is screwed onto a threaded benchmark (Figures 4.2 and 4.3). Detailed procedures on base station setup are provided in Appendix A.

Figure 4.2  West Dock, Alaska base station set up. The base antenna is located approximately 2 m to the right. The base station receiver is powered by batteries and the solar panels to the left. Photo taken by N. Shiklomanov, summer 2002.
4.4 Platform Targets

Survey targets must support a rover DGPS antenna, and should have the capacity to move freely atop the active layer with minimal environmental disturbance (Figure 4.1). The targets should not be affected adversely by flooding, cold weather, snow, or animal disturbance, and should be applicable to various locations and scales throughout the cold regions. The targets described here were designed specifically for this study by Heath Sandall, and were described in detail by Little et al. (2003a,b). Platform targets (Figures 4.1 and 4.4) are composed of Acrylite, a strong, durable, and lightweight plastic (Ridout Plastics, 2002) that is resistant to cracking in extremely...
cold conditions. The optical characteristics of this colorless material allow natural light to pass, minimizing changes in the microclimate and vegetation. Construction of over fifty targets requires a few hours’ use of machine-shop equipment (e.g., band saw or router).

The tube-shaped targets used by UDPG in Alaska are approximately twenty centimeters in height (Figure 4.4), but dimensions can be varied to accommodate particular circumstances and site characteristics. The targets are small (2.5-centimeter diameter), lessening the chance of animal disturbances, yet increasing the possibility of human foot damage and making surveying difficult, if not nearly impossible when snow-cover depth is equal to or greater than target height. Colored marker flags are labeled and inserted approximately ten centimeters from the target to avoid human trampling and to facilitate locating targets in subsequent surveys.

Proper insertion of the target is essential to minimize changes in the natural process and obtain accurate results. With proper insertion, the-prong-like design allows for liquid water to travel downslope, reducing pooling of water and allowing air movement, and decreasing possible disturbance to vegetation and microclimate modification. Targets should be installed after the frost table has retreated below the depth to which targets are inserted. The bottom prongs of the target should be sharpened prior to installation. Two notches are filed into the platform where it meets the ground, to permit reinsertion of the target at its proper height. Reinsertion may prove difficult early in the summer when the frost table is near the surface. Inability to reinsert the target perpendicular to the surface can result in elevation errors.
Air-ground interface

Ends of target are sharpened for ease in ground insertion.

Notches filed at air-ground interface with a file for reinsertion at proper location if ejected from ground.

Figure 4.4 Schematic diagram of UDPG tube shaped platform targets (Sandall, personal communication, 2002). The Acrylite (plastic) is approximately 0.2 cm thick. From Little et al. (2003).
Before placing the rover antenna onto the top portion of the target, a screw of appropriate size (approximately 6 cm in height) is manually threaded into the rover antenna. The rover antenna is placed atop the platform target, resting securely on the target as the screw fits firmly inside the upper portion of the tube-shaped target, with the use of duct tape, if necessary. Horizontal alignment of the rover antenna will reduce the potential for error. This is accomplished by manually adjusting the target with a small level. Rapid static or stop-and-go kinematic DGPS surveying is then possible if the base station receiver is recording data.

Both DGPS techniques require the ability of the rover antenna to track four or more satellites continuously. Any significant obstruction can cause a loss of count of wavelengths ("cycle slip"), necessitating reinitialization of the DGPS rover unit and loss of at least eight minutes. With the Trimble 4700 unit, stop-and-go kinematic DGPS requires 15-45 seconds to collect data, while rapid static DGPS requires approximately eight minutes or more.

When this study began, use of classical surveying was recommended for comparative purposes with DGPS methodology. The US Army Corps of Engineers (1996) did not recommend substituting GPS for differential leveling. Classical surveying (profile leveling) techniques (McCormac, 1999), requiring two people, were conducted with a Philadelphia rod, optical level, and tripod in this study. Most recently, the US Army Corps of Engineers (2003) recommend the use of differential leveling as a control check in combination with DGPS.

4.5 Rapid Static, Stop and Go Kinematic, and Real Time Kinematic DGPS

Methods for collecting high-precision DGPS data vary from continuous DGPS or static DGPS, and require occupation times ranging from hours to months or
more for sub-centimeter-scale resolution, to rapid static (“fast static”) and stop-and-go kinematic (“post-processed kinematic”) DGPS with occupation times of only seconds or minutes (e.g., 8-20) for accuracy of one to five centimeters (UNAVCO, 2006).

Real time kinematic (RTK) DGPS allows collection of data nearly instantaneously, with similar accuracy, although the US Army Corps of Engineers, 2003 recommends repeat DGPS surveying at each target. Vertical error $\xi_v$ (expressed in centimeters) for rapid static DGPS can be estimated with the following equation (UNAVCO, 2006; Trimble, 2005) using the Trimble 4700 as rover receiver and the Trimble 4000 as base station:

$$\xi_v = 1.5 \text{ cm} + 10^{-6} \text{ BL}, \quad (4-1)$$

where BL is baseline length, expressed in cm. $\xi_v$ can be estimated for stop-and-go kinematic DGPS using the Trimble 4700 and 4000 (Trimble, 2005) by:

$$\xi_v = 2 \text{ cm} + 10^{-6} \text{ BL}. \quad (4-2)$$

For RTK, $\xi_v$ varies dependent on mode (1 Hz or 5Hz) resulting in the following estimation for a Trimble 4000 and 4700 (Trimble, 2005):

$$\text{RTK estimated error (1Hz)} = 2 \text{ cm} + 10^{-6} \text{ BL}. \quad (4-3)$$
$$\text{RTK estimated error (5Hz)} = 2 \text{ cm} + 10^{-6} \text{ BL}. \quad (4-4)$$
Newer GPS equipment (e.g., Trimble 5700) has the potential to improve results. Vertical error for rapid static DGPS can be estimated with the following equation (UNAVCO, 2006) using the Trimble 5700 as rover receiver and the Trimble 5700 as base station:

$$\xi_v = 0.5 \text{ cm} + 10^{-6} \text{ BL}, \quad (4-5)$$

For RTK, $\xi_v$ can be estimated using Trimble 4700 and 4000 by (UNAVCO, 2006):

$$\text{RTK estimated error} = 1 \text{ cm} + 10^{-6} \text{ BL}. \quad (4-6)$$

Appendix B provides the salient aspects of the DGPS and surveying equipment.

At the time of the field investigations described in this thesis, rapid static DGPS occupations required a minimum of approximately eight minutes to resolve carrier phase integer ambiguity, using the Trimble 4700 as rover receiver and the Trimble 4000 as base station. Stop-and-go kinematic DGPS is able to resolve the carrier phase integer ambiguity by tracking a minimum of four satellites continuously. Combining base station setup time and rapid static DGPS and stop-and-go kinematic DGPS surveyed on targets, the minimum field time necessary for acceptable surveys of thirty points is approximately six or more hours, two and one-half hours or more, and fifty minutes respectively, depending on conditions. Shorter survey times are
possible with the Trimble 5700, which is used in the current extension of the study described here (Shiklomanov, personal communication, 2006).

A drawback to the DGPS/target methodology, besides limited spatial coverage and the time requirements associated with rapid static and stop-and-go kinematic, involves its physical demand. Any obstruction to the rover antenna (e.g., Trimble 4700) may necessitate re-initialization of the rover receiver, requiring a minimum of eight minutes. In practice, a surveyor must crawl and place a level rover antenna onto a target to avoid obstructing satellite signals. To overcome this difficulty, a 1.8 m or taller bipod could be used for rover antenna placement instead of the short target currently used.

4.6 Summary and Assessment

Post-processed rapid static (fast static), stop-and-go kinematic (post-processed kinematic), and real time kinematic (RTK) carrier-phase DGPS provide potential means for detecting frost heave and thaw settlement in tundra environments. Platform targets (Sandall, personal communication, 2002; and Little et al. 2003a,b) provide a cylindrical platform to support a rover DGPS antenna (Figure 4.4). The ability to progress from platform to platform facilitates data collection at time scales as short as 15 to 45 s for RTK and stop-and-go kinematic GPS. Rapid static DGPS necessitates an extended period of measurement (approximately ten minutes), but yields improved accuracy in discerning small elevation changes. DGPS/target methodology is capable of measuring vertical change resulting from frost heave and thaw settlement at the centimeter scale (Little et al., 2003b), assisting in monitoring thaw settlement. Potential disadvantages to the DGPS/target surveying technique include: (a) considerable time requirements; (b) target re-insertion difficulties as a
result of vandalism, animal disturbance or a shallow frost table; and (c) restrictions in spatial coverage imposed by practical constraints. Rapid improvements in DGPS technology have rendered some of the instrumentation used in this study obsolete although basic principles and applications remain unchanged. RTK, for example, was only employed in Barrow during the summer of 2003 because newer equipment has since been made available at this location.
Chapter 5

PROBLEM STATEMENT AND HYPOTHESIS

5.1 Statement of the Problem

There are many reasons to investigate the use of a new tool to measure frost heave and thaw settlement. Other methods may prove difficult to employ in remote regions or may lack technology capable of tying into the worldwide geodetic system. The literature review contained in Chapter 3 indicates that geocryologists have not employed DGPS technology widely to monitor frost heave and thaw settlement in tundra environments.

In principle, the potential of DGPS to measure frost heave and thaw settlement in tundra environments is promising. Technological advances in DGPS provide the opportunity to measure heave and subsidence at the centimeter scale in tundra environments. In addition, DGPS could be employed to measure many geomorphic phenomena and may prove beneficial in monitoring warming-induced thaw settlement. Given its excellent planimetric accuracy, DGPS provides advantages over traditional surveying. As technology improves further, DGPS measurements will become easier to implement and faster.

The magnitude of frost heave and thaw settlement vary across space, but little is known about their spatial variation. Because they are related to many of the same parameters governing thaw depth, variations in the magnitude of heave and settlement may show spatial patterns similar to those of active-layer thickness.
Quantitative determination of the geographic variability of heave and settlement requires use of a hierarchical sampling strategy, similar to those described by Webster and Oliver (1990), Nelson et al. (1999), and Gomersall and Hinkel (2001).

There is also some debate about whether active-layer thickness is a good indicator of climate change (Nixon and Taylor, 1998). Temperature increases resulting from regional warming will degrade permafrost, causing settlement of the ground. The CALM program uses graduated steel rods to measure the active layer depth at many sites, but this technique may not yield accurate assessment of long term changes if thaw settlement in the transient layer is occurring. Although simple thaw tubes anchored in permafrost provide a stable reference for thaw settlement measurement (Nixon, 2000), the device cannot be used to assess spatial variability. As a contribution to the CALM program, this study used DGPS to determine if thaw settlement or frost heave have occurred since the 1960s in Barrow, Alaska (Brown and Johnson, 1965), providing information on the transient layer’s role in climate change.

The goals of this study are threefold: (1) to determine the ability of DGPS technology to measure frost heave and thaw settlement in different tundra environments; (2) to ascertain the scale(s) of maximum variability of heave and settlement, and their covariation with active-layer thickness; and (3) to determine if thaw settlement has occurred over a period of several decades at a location initially surveyed in the early 1960s.

Goals (1) and (2) were addressed at two sites: West Dock and Sagwon, in the Arctic Coastal Plain and Arctic Foothills physiographic provinces of northern Alaska (Wahrhaftig, 1965), respectively. If DGPS can be shown to be an effective means for measuring heave and subsidence (Goal 1), a program of nested sampling
and analysis will provide information on the spatial variability of frost heave and thaw settlement (Goal 2), which is necessary for the potential design and installation of an extensive instrumental network across various scales and landcover types. Goal 3 involves comparing changes in surface elevation at points near Barrow, Alaska surveyed in the 1960s by Lewellen (1972).

5.2 Hypotheses

The core problem addressed in this thesis is to determine if differential GPS/target methodology is a viable strategy for detecting frost heave and thaw settlement, and to assess its relative effectiveness by comparing results with those from previously employed strategies. Related problems, highly dependent on the success with which DGPS measures heave and subsidence, are to ascertain the scale(s) of maximum variability within limited areas and to compare long-term data from a series of locations near Barrow. The set of interrelated hypotheses stated immediately below provide a means to implement a program of research addressing these problems.

**Hypothesis 1:** DGPS will be able to measure heave and thaw effectively and accurately at the centimeter-scale in tundra environments.

**Hypothesis 2:** Because they are determined by similar process suites, patterns of spatial variation in frost heave and thaw settlement are similar to those of active-layer thickness.

**Hypothesis 3:** By simultaneously measuring frost heave and thaw settlement with DGPS, and comparing results with existing data from the 1960s, DGPS will indicate if thaw settlement has occurred over a multi-decade period.
5.3 Implementation

**Goal 1:** The ability of DGPS to measure frost heave and thaw settlement will be tested in the Kuparuk River Basin of northern Alaska (Figure 5.1). Results from DGPS surveys of frost heave and thaw settlement will be assessed and compared with other methods through the use of data plots and descriptive statistics using data obtained in the Sagwon uplands of the Arctic Foothills, and at the West Dock CALM grid (Brown *et al.*, 2000).

**Goal 2:** Information about spatial variations of frost heave and thaw settlement will be obtained at the same locations using a nested sampling and analysis design (Webster and Oliver, 1990; Nelson *et al.*, 1999). These data will be compared with information about active-layer thickness obtained at the same locations using an identical sampling design.

**Goal 3:** Comparison of contemporary elevation data, obtained near Barrow, Alaska using DGPS technology, with data from the early 1960s (Lewellen, 1972) will allow assessment of long-term changes in various microtopographic settings and soil/vegetation units. Comparisons will be made using descriptive statistics and graphical procedures.
Figure 5.1  Map of the Kuparuk River Basin, Alaska. West Dock (WD), along the coastal Plain is located near the Arctic Ocean. Flux Plot 3 (F3) is located in the Arctic Foothills. Both sites are used by the University of Delaware Permafrost Group (UDPG). Map courtesy of N. Shiklomanov and A. Klene.
Chapter 6
STUDY AREAS

6.1 North Slope: General Description

Research was conducted on Alaska’s North Slope. This part of northern Alaska is bordered by the Brooks Range to the south and by the Chuckchi Sea and Beaufort Sea to the north. The North Slope falls gradually in elevation from the Brooks Range to the Arctic Ocean (Figure 5.1). Although the region is treeless and receives very little precipitation, it is covered by shallow thaw lakes, and several major north-flowing rivers (Sagavanirktok, Kuparuk, Colville) traverse it. Because ice-bonded permafrost underlies most terrestrial surfaces and low temperatures limit evaporation, an abundance of water occupies the land surface.

Following Wahrhaftig, the North Slope is composed of two physiographic regions, the Arctic Coastal Plain and the Arctic Foothills (Figure 5.1). The north-south extent of the Arctic Coastal Plain ranges from 20 km at 145°W to more than 150 km at 156.5°W. The Coastal Plain is composed of relatively flat terrain with numerous lakes; its elevation ranges from sea level in the north to approximately 200 meters near its border with the Foothills province. The Arctic Foothills province extends from the northern edge of the Arctic Coastal Plain south to the Brooks Range. It is made up of broad basins and river valleys, separated by north-south trending bedrock ridges.
Under Koeppen’s climate classification, the region is considered to have a Tundra (Et) climate, with dry, severe winters (September to May) and short springs (June) and autumns (August). Table 6.1 describes climatic parameters (temperature, precipitation, and snowfall) of the Arctic Coastal Plain and Arctic Foothills. Two factors dictate many of the North Slope’s climatic patterns and details: its northern latitude and distance from the Arctic Ocean. Along the coast (e.g., Barrow at 71.3° N, 156.5° W), the sun sets on 18 November and does not appear above the horizon again until 24 January (Hinkel et al., 2003). Similarly, the sun remains above the horizon from 10 May until 2 August (Hinkel et al., 2003). The mean annual temperature in both physiographic regions is -12° C (Stammes and Zhang, 2005). Between June and August, low, stable, stratus clouds become increasingly common (~74%) along the Arctic Coastal Plain (Weller, 1979). The stratus clouds cause a temperature gradient between coast and foothills (Weller, 1979). The temperature rarely exceeds 10° C at locations immediately adjacent to the Arctic Ocean (e.g., Prudhoe Bay and Barrow) with a mean monthly maximum of 4° C in July (Bowling, 1979). The climate becomes more continental inland. For example, July’s mean monthly temperature is approximately 4° C higher inland than near the coast, corresponding to a longer thaw season and promoting a deeper active layer (Zhang et al., 1997; Stammes and Zhang, 2005).

Precipitation averages less than 20 cm/yr (Bowling, 1979) in the region, with approximately half falling as snow (Benson and Rizzo, 1979). Even with this small amount of snowfall, the dry, wind-packed snow remains for three quarters of the year (Benson and Rizzo, 1979). The extended duration of snow cover (8-10 months) results in high reflectivity (albedo > 80%) and lower air temperature. Snow cover
becomes minimal to nonexistent in late May or early June, the same time at which incident radiation is increasing, sharply changing the amount of absorbed radiation, increasing air temperature (Benson and Rizzo, 1979), and signaling onset of the thaw season.

Table 6.1  Climatic parameters for two physiographic regions of the North Slope: Arctic Coastal Plain and Arctic Foothills. Note the temperature gradient between the coast and the foothills during thaw season. Sources: 1) Stammes and Zhang (2005); (2) Hinkel et al. (2003) as reported from Barrow, Alaska; (3) Rosentrater and Greenland (2005) as reported from Toolik Lake, Alaska; and (4) Bowling (1979).

<table>
<thead>
<tr>
<th>Region of North Slope</th>
<th>Annual mean temp (°C)¹</th>
<th>Min mean monthly temp (°C)</th>
<th>Max mean monthly temp (°C)¹</th>
<th>Mean annual precip. (cm)²</th>
<th>% as snow (cm)⁴</th>
<th>Mean snow cover duration (months)¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arctic Coastal Plain</td>
<td>-12.0°C</td>
<td>-26.6°C in February²</td>
<td>4°C in July</td>
<td>&lt; 20 cm/yr</td>
<td>~50%</td>
<td>8 to 10 months</td>
</tr>
<tr>
<td>Arctic Foothills</td>
<td>-12.0°C</td>
<td>-27.7°C in February³</td>
<td>8°C in July</td>
<td>&lt; 20 cm/yr</td>
<td>~50%</td>
<td>8 to 9 months</td>
</tr>
</tbody>
</table>

6.2 Magnitude and Variation: Kuparuk River Basin, Alaska

Two of the research sites, West Dock and Sagwon, lie within the Kuparuk River basin (Figure 5.1). These sites were selected as representative of the Arctic coastal plain and the Arctic foothills respectively, for their relative ease of accessibility, and to make use of the large amount of previous research on active-layer thickness conducted at these locations (Nelson et al. 1997; Nelson et al., 1998a; Nelson et al., 1999; Shiklomanov and Nelson, 1999; Hinkel et al., 2000; Gomersall and Hinkel, 2001; Shiklomanov and Nelson, 2002; Hinkel and Nelson, 2003).
Nelson et al. (1998a, 1999) conducted intensive investigations to determine the scales at which variations in active-layer thickness are maximized, and to develop appropriate sampling designs for the sites. Active-layer thickness (ALT) in the Kuparuk river basin has been modeled using a variety of analytic strategies, including empirical modeling (Nelson et al., 1997; Klene et al., 2001), numerical simulation (Hinzman et al., 1998), analytical expressions (Shiklomanov and Nelson, 1999), and stochastic modeling (Anisimov et al., 2002). Spatial time series of ALT have been developed over an extensive period (Shiklomanov and Nelson, 2002). Permafrost-related research is ongoing at both sites.

Fieldwork for this study was performed in the Kuparuk river basin in July 2001, August 2001, June and August 2002, and in June and August, 2003.

6.2.1 West Dock

West Dock lies within the Prudhoe Bay Oilfield in the Arctic Coastal Plain physiographic region (Wahrhaftig, 1965), and near the northern terminus of the Dalton Highway (Figure 6.1). The site occupies a 1 km$^2$ area centered on 70° 22’ 30.2” N, 148 ° 32’ 57.8” W. Initiated as part of the Arctic Flux Study (Weller et al., 1995), this location is one of seven core Alaskan sites in the Circumpolar Active Layer Monitoring (CALM) program. The embedded “CALM grid” consists of a series of 121 steel stakes driven into permafrost at 100 m intervals, the locations of which were determined by precise optical survey. The site is near the coast, with elevation ranging from 2 to 5 m. Terrain consists of partially drained thaw lake basins, separated by areas of intervening “uplands” underlain by ice-wedge polygons. Plant communities consist of moist graminoid and prostrate dwarf-shrub tundra. According
to the US Soil Taxonomy, the soil material is primarily Typic Hemistel (Soil Survey Staff, 1999).

![Image](image.jpg)

Figure 6.1 Coastal plain site located in West Dock, Alaska. The site encompasses a drained thaw-lake basin (right) and an “upland” tract between lake basins (left). Photo by J. Little, summer, 2002.

DGPS investigations at West Dock were conducted within two 1 ha subunits of the CALM grids. The base station is located less than 1 km away at an elevation of approximately 3 m, as shown in Figure 4.2. A frost-defended benchmark composed of threaded ready rod was inserted vertically to a depth of two meters in the silty, ice-rich substrate and anchored with large-diameter plate washers. A lubricated outer sleeve, composed of PVC pipe, surrounds the upper portion of metal rod to prevent heave-induced movement. Vertical elevation of the benchmark was established with static DGPS. The benchmark was used for classical surveying purposes.

Nelson et al. (1999) found that the most substantial spatial variations in active-layer thickness at West Dock, and at the nearby Betty Pingo CALM grid, occurred over distances of 100-300 m, a consequence of the pattern of drained thaw.
lake basins in the area. Variations at shorter separation distances were of substantially smaller magnitude.

### 6.2.2 Flux Plot 3 (Sagwon Uplands)

Flux Plot 3 (69° 26’ 00.3”N, 148° 40’ 12.3”W, 240-245 masl) is situated in the Sagwon uplands, atop a hill 1 km west of the Dalton Highway (Figure 6.2). The site is situated in the northernmost section of the Arctic Foothills physiographic province (Wahrhaftig, 1965). The DGPS base station benchmark was cemented into a small-diameter hole drilled in a sandstone outcrop located approximately 3 km away, at an elevation of 308 m (Figure 4.3). DGPS investigations were conducted within the 1 ha Flux Plot using a sampling design incorporating a nested hierarchical sampling scheme (Nelson et al., 1999).

The Flux 3 site is located in a transition zone between moist acidic tundra and moist nonacidic tundra, a result of past glaciation (Walker et al., 1998). The site is comprised of moist nonacidic tundra containing patchy vegetative cover and numerous frost boils (Figure 6.2). More detailed descriptions of the site are provided by Nelson et al. (1997) and Klene et al. (2001).

Unlike the West Dock site, active-layer thickness varies substantially across very short horizontal distances (e.g., 1-3 m), a situation attributed to the influence of frost boils and the patchy vegetation (Nelson et al., 1999). Thaw depth sampled at 441 grid nodes (5 m intervals) within the plot showed significant variation (25 cm to over 80 cm), likely due to the relatively thin organic mat and lack of a dominant moss (Sphagnum) at acidic sites, promoting heat flux downward (Shiklomanov and Nelson, 2003).
Figure 6.2  Rover antenna atop a platform target amongst tundra tussocks at Flux Plot 3, Brooks Range foothills, northern Alaska. Tundra tussocks (a.k.a. vegetation tussocks) are a characteristic periglacial feature. Tundra tussocks, as shown in the picture are closely spaced together. Photo by J. Little, summer 2002.

6.3 Temporal Changes in Frost Heave and Thaw Settlement: Barrow, Alaska

The third research site used in this study is located near the Arctic Ocean at a series of plots installed by the U.S. Army Cold Regions Research and Engineering Lab (CRREL) near Barrow, Alaska (Figure 6.3). Barrow, the northernmost settlement in the United States, lies in the Arctic Coastal Plain physiographic province (Wahrhaftig, 1965).

The CRREL Plots were established in the early 1960s to facilitate a comprehensive program of permafrost research, including terrain analysis, active-layer measurements, thermal observations, and ice content. The plots are arranged along an east-west trending linear transect within the Barrow Environmental Observatory (BEO) east of the village of Barrow. The subset of plots used in this study are situated at (at 71° 19’ 17.6” N, 156° 36’ 29.3” W). Elevations on the
nearby Barrow 1 km$^2$ CALM grid range from near sea level to 7.5 m. The BEO has low relief. A drained thaw lake (Central Marsh) in the west and a polygonized “upland” to the east are separated by a north-south trending, beach ridge. The 10 m by 10 m CRREL Plots used in this study are located east of the beach ridge and encompass wet sedge tundra and low centered ice-wedge polygons. The beach ridge consists of sandy gravel while the upland is characterized by moist and wet meadow tundra (Barrow Arctic Science Consortium, 2002). An overview of the Barrow study area is provided in Figure 6.3.

The CRREL Plots were chosen for this study because of their accessibility (less than 3 km from a road) and to make use of results from intensive studies performed in the 1960s (Brown and Johnson, 1965; Brown, 1969; Lewellen, 1972). By comparing data obtained in 2002 and 2003 with those collected nearly 40 years earlier, a temporal dimension is added to the problems addressed in this thesis. Comparison of absolute elevations collected in the early 1960s with those from the early 21st century will, in theory, provide information about long-term changes in response to aggradation or degradation of ground ice. Conceptually similar work has been performed on moisture (ice) content (Hinkel et al., 1996; Miller et al., 1998) and active-layer thickness (Nelson et al. 1998b) at the Barrow CRREL Plots.
The CRREL Plots at Barrow were surveyed precisely during the early 1960s, as were a series of frost boils nearby. Details are provided by Brown and Johnson (1965). DGPS was conducted at CRREL Plots 34, 37, 40 and 44 (10 m by 10 m plots), within the 1 km² BEO CALM grids and near the 2100 m transect (the C-line) oriented from east-northeast to west-southwest (Figure 6.3). The C-line and surrounding BEO are characteristic of the vegetative cover, climate, and soil
conditions of the Barrow region. Figure 6.4 is a photo of CRREL Plot 37, showing the characteristic terrain and a rapid static survey. Figure 6.5 is a picture of Piling 2 (wooden post), surveyed in 1964 (Brown and Johnson, 1965) and resurveyed in 2003 for comparative purposes. The DGPS base station, established by UNAVCO in 2002 (Figure 6.6), and used in this study, is located at the Barrow Arctic Science Consortium (BASC) building. The base antenna is located on a telephone pole against the east side of the building. The CRREL-Plot study was conducted in August 2002 and in June and August, 2003.

**Figure 6.4** Photo of CRREL Plot 37. Photo shows a rapid static survey of Plot 37, corner two (37-2), using Trimble 5700 and a bipod, June 2003. Platform targets were installed August 2003. CRREL Plots are 100 m², outlined in black in this photograph. Orange pin flags mark the location of each survey location. The terrain is typical of the CRREL Plots. Photo taken by David Zaks of BASC.
Figure 6.5  Piling 2. The wooden post was used as a benchmark in this study and in the early 1960s (Brown and Johnson, 1965). Photo courtesy of Dave Zaks.

Figure 6.6  Barrow Arctic Science Consortium (BASC) base antenna located on top of telephone pole on the east side of the BASC building. Base station is located within the building. This base station was used in the CRREL-Plot portion of this study. Photo by J. Little June 2003.
Chapter 7

SAMPLING AND ANALYTIC METHODS

Heave and thaw can vary substantially in both time and space. Total heave per year varies from over 30 cm in highly frost susceptible areas on Alaska’s North Slope to 9-20 cm in the Mackenzie River Delta, an area with similar physiographic characteristics as the West Dock, Alaska (Mackay et al., 1979). Extreme values of heave at a set of bridge pilings in Siberia amounted to 3.3 m in one year (Davis, 2001). Table 2.1 describes total heave per year in various cold regions.

There is little quantitative information, however, about the variation of heave and settlement across geographic space, except within very small areas (e.g., 10 x 10 m). One of the goals of this thesis is to determine the scale of variation of heave and thaw across a series of representative study sites on Alaska’s North Slope. Despite the spatial sampling techniques available in such closely related fields as soil science (Webster and Oliver, 1990), previous studies of heave and thaw have resulted in simple summary statistics such as total heave per year, as shown in Table 2.1. Because most of these studies were conducted at point locations, and the degree to which these field sites are representative of larger areal units is not known. Review of literature indicates there has not been an attempt to formally assess the spatial variability of heave and thaw at multiple scales.
7.1 Sampling Designs

Several studies on Alaska’s North Slope (Mueller, 1996; Nelson et al., 1998a,b, 1999; Gomersall and Hinkel, 2001; Klene et al., 2001; Hinkel and Nelson, 2003) have shown that processes governing active-layer thickness (ALT) operate at several spatial scales, and that the dominant scales are radically different in the Arctic Coastal Plain and the Arctic Foothills. Embedded within tundra landscapes are several sources of spatial periodicity (regularity), each operating at a different geographic scale. These include tundra tussocks, first-order drainage networks (water tracks), frost boils, ice-wedge networks, and drained thaw-lake basins. Further details can be found in the references cited above, and in Shiklomanov and Nelson (2003).

A central tenet of this thesis is that, as is the case with ALT, knowledge about the spatio-temporal variability of heave and settlement processes can best be obtained through spatial sampling. As a first approximation, it is reasonable to propose that the sources of variation are similar to those governing active-layer thickness.

A great variety of spatial sampling designs is available, including simple random, stratified random, systematic, transect-based, and stratified systematic unaligned. Comprehensive reviews of spatial sampling have been provided by Dixon and Leach (1978) and Thompson (1992). Fagan (1995) conducted a comparative study of the performance of these four spatial sampling designs on the 1 km2 CALM grids in northern Alaska. Fagan’s work was focused on ascertaining the most efficient and accurate method for obtaining summary (descriptive) statistics of active-layer thickness, and made use of both field and simulated data. Repeated sampling of simulated data sets, into which several levels of spatial periodicity (regularity) were constructed, indicated that the systematic stratified unaligned (SSU) design yielded
marginal improvement in accuracy over its purely systematic counterpart. The additional time and effort required to implement the SSU design in the field, however, led to the conclusion that the systematic design provided a reasonable compromise between accuracy and collection efficiency.

Owing to discrepancies between sampling interval and spatial regularities, none of the sampling designs investigated by Fagan (1995) could be used to generate mappable data at all of the Alaskan CALM grids. Nelson et al. (1998a) discussed these problems in the context of spatial autocorrelation. Nelson et al. (1999) implemented an integrated set of procedures known as Nested Sampling and Analysis (Webster and Oliver, 1990) or NSA, which uses intensive hierarchical areal sampling, in conjunction with analytic procedures rooted in nested analysis of variance, to ascertain the spatial scale(s) at which variability is maximized. Gomersall and Hinkel (2001) adopted a similar strategy using a linear sampling design, and obtained results nearly identical to those of Nelson et al., 1999). NSA is, therefore, a useful tool that can be used to guide the construction of subsequent sampling programs.

The integrated conclusion derived from the studies outlined in the preceding paragraphs is that systematic sampling at widely spaced (e.g., 100 m) intervals is inadequate to resolve spatial variability in the Arctic Foothills physiographic province owing to the closely spaced nature of tundra tussocks and water tracks. In the Arctic Coastal Plain province, contrasts in ALT between drained thaw lake basins and intervening tundra “upland” are so great that 100 m sampling intervals are adequate to obtain data for mapping purposes.
7.2 Nested Sampling and Analysis (NSA)

Nested Sampling and Analysis (NSA) has been applied successfully in soil science (Webster and Oliver, 1990), geography (Moellering and Tobler, 1972), geology (Krumbein and Slack, 1956), and recently in geocryology (Nelson et al., 1999; Gomersall and Hinkel, 2001). Depending upon the feasibility of implementing the measurement techniques, NSA is adaptable across any range of geographic scale (Krumbein and Slack, 1956).

In geostatistics, NSA is based on subdividing a population (e.g., physical area) into two or more levels or stages, creating a hierarchy (Webster and Oliver, 2001). The physical area is sampled at multiple spatial scales (levels or stages), with each stage representing a different distance between observation points. This “nested scheme” allows for the determination of variance at each stage (Webster and Oliver, 1990; Webster and Oliver, 2001). The survey area is divided into stages 1 through m. As m increases (e.g., stage 1 to 2 and 2 to 3), the distance between points decreases. A single observation represents variation at all stages, including unresolved variance at the first stage (Webster and Oliver, 2001). In this study, at each sampling point, a positive magnitude (frost heave) or negative magnitude (thaw settlement) was recorded, along with active-layer thickness.

7.21 NSA Field Implementation: West Dock and Flux Plot 3

In a manner similar to Webster and Oliver (1990 and 2001), Nelson et al. (1999), and Gomersall and Hinkel (2001), a balanced four-stage nested sampling system was implemented at West Dock and Flux Plot 3. Stage 1 consisted of four primary centers, 30 m apart. At Stage 2, a substation was located along a compass direction that was determined from a pseudorandom number generator and was
positioned 10 m from the primary center. At Stage 3, two observation points were located in a random direction from the primary center and the substation and were positioned 3 m apart. At Stage 4, every point was replicated in a random direction 1 m away. Bifurcation at the four levels of hierarchy provided eight sampling points at each primary station and a total sample size at West Dock and Flux 3 of 32 (Webster and Oliver, 2001). A dendrogram depicting the organization of the sampling design is shown in Figure 7.1.
Figure 7.1  Dendogram (a), depicting four levels of nesting. The maximum and minimum lag separation for this study are 30 m and 1 m, respectively. (b) Spatial arrangement of sampling points shown to the right.

7.22 NSA Calculations

NSA procedures are an explicitly spatial implementation of nested analysis of variance (ANOVA) (Webster and Oliver, 2001). ANOVA calculations consist of determining: 1) sums of squares, 2) degrees of freedom, 3) mean squares, 4) F-tests and 4) cumulative percentage of variance. In this study, 2001 and 2002 ANOVA results were calculated using a FORTRAN program developed by F. E.
Nelson (Nelson et al., 1999). The 2003 ANOVA data were calculated using the SAS program developed by Jerome Braun of the Statistics Laboratory at the University of California Davis (Braun, personal communication, 2005) and J.D. Little. The analysis is performed using PROC NESTED, a program specifically designed for hierarchical analyses (Braun, personal communication, 2005).

Sums of squares represent the variation of all observation points at a particular site (Webster and Oliver, 2001). First, the mean and variance of all four levels at each primary center were calculated. The equation for variance ($S^2$) is given by:

\[
S^2 = \frac{\sum (a_i - \bar{a})^2}{N-1}
\]

(7-1)

where $N = $ number of observation points, $\bar{a} = $ mean of all observation points at each primary center, $a_i = $ value at the $i^{th}$ level, and $(a_i - \bar{a})$ is the deviation from the mean for each value (Webster and Oliver, 2001). The results from the aforementioned equation were applied to equation 7-2 in order to determine the Sum of the Squares Between stages (SSB):

\[
SSB = \sum_{i=1}^{k} n_i (\bar{a} - \bar{A})^2
\]

(7-2)
where \( k = \text{number of stages (e.g., 4)} \), \( n_i = \text{number of samples at each primary center (e.g., 8)} \), \( \bar{a} = \text{mean of observational points for each primary center} \), and \( \bar{A} = \text{grand mean, or average of all observation points (Webster and Oliver, 2001)} \). Because there were four stages in this study, SSB was repeated for the second (SSB_2), third (SSB_3), and fourth primary center (SSB_4). The following equations were used to determine SSB_m:

\[
SSB_m = \sum_{i=1}^{n_1} n_1 n_i (\bar{a}_i - \bar{A})^2
\]

\[
SSB_2 = \sum_{i=1}^{n_1} \sum_{j=1}^{n_2} n_2 n_{ij} (\bar{a}_{ij} - \bar{A}_i)^2
\]

\[
SSB_3 = \sum_{i=1}^{n_1} \sum_{j=1}^{n_3} \sum_{k=1}^{n_3} n_3 n_{ijk} (\bar{a}_{ijk} - \bar{A}_{ij})^2
\]

\[
SSB_4 = \sum_{i=1}^{n_1} \sum_{j=1}^{n_4} \sum_{k=1}^{n_3} \sum_{l=1}^{n_4} (\bar{a}_{ijkl} - \bar{A})^2
\]

The total sums of squares (SST) can be found by applying equation 7-7.

\[
SST = SSB_1 + SSB_2 + SSB_3 + SSB_4
\]
The second step was to determine the number of degrees of freedom, or the number of values that can vary freely (Webster and Oliver, 2001). The following equations were used to calculate the degrees of freedom at each stage:

\[
\begin{align*}
\text{Stage 1: } & n_1 - 1 \quad (7-8a) \\
\text{Stage 2: } & n_1 (n_2 - 1) \quad (7-8b) \\
\text{Stage 3: } & n_1 n_2 (n_3 - 1) \quad (7-8c) \\
\text{Stage 4: } & n_1 n_2 n_3 (n_4 - 1) \quad (7-8d)
\end{align*}
\]

where \( n \) was the number of subdivisions at each stage (i.e., \( n_1 = 4 \) and \( n_2 = n_3 = n_4 = 2 \) representing bifurcation at each stage) (Nelson et al., 1999).

Mean squares (MS) were used to determine the statistical significance within each level in the hierarchy (Webster and Oliver, 2001). MS were determined by dividing the sums of squares by the appropriate degree of freedom. For example, to determine the mean squares at stage \( m \) (MSB\(_m\)), the following equation was used (Webster and Oliver, 2001):

\[
\text{MSB}_m = \frac{SSB_m}{\text{Degree of freedom at stage } m} \quad (7-9).
\]

To determine if the mean squares were significant, F-tests were employed. F-tests are determined by taking the ratio of mean squares (e.g., MSB\(_1\) with MSB\(_2\) and MSB\(_2\) with MSB\(_3\)) with the appropriate degree of freedom (Nelson et al., 1999). Following Nelson et al. (1999), the F-test employed a significance level of 0.1 to lessen the chance of Type II errors. Type II errors are statistical decision errors that occur when a false null hypothesis is not rejected (Webster and Oliver, 2001). A
significance level of 0.1 makes it easier to reject the null hypothesis of no difference between levels (Nelson, personal communication, 2005).

To facilitate the graphical interpretation of the results, “reconnaissance variograms” were produced, illustrating the cumulative proportion of the variance at stage $m$ against the sampling point separation distance (Nelson et al., 1999). The cumulative percentage of variance was calculated for each stage, beginning with the last:

\[ \text{Cumulative Variance}_{b} = \frac{SSB_{b}}{SST} \quad (7-10a) \]

where $b =$ last stage. The cumulative percentage of variance for the second through the last stage is given by:

\[ \text{Cumulative Variance}_{b-1} = \frac{SSB_{b} + SSB_{b-1}}{SST} \quad (7-10b). \]

Cumulative percentage of variance for the third to the last stage was determined by:

\[ \text{Cumulative Variance}_{b-2} = \frac{SSB_{b} + SSB_{b-1} + SSB_{b-2}}{SST} \quad (7-10c). \]

Subsequent stage(s) were calculated following this pattern.

7.3 Pearson’s Correlation Coefficient

Pearson’s Correlation Coefficient $(r)$ is used to assess the linear relationship between two measured variables, $x$ and $y$. It is sometimes referred to as Pearson’s product-moment coefficient of linear correlation, as has been described by
Till (1974). Values of $r$ can vary from $-1$ to $+1$. An $r$ value of $+1$ means that there is a perfect linear relationship, a value of $-1$ means that there is perfect antipathy or perfect negative correlation, and a value of $0$ indicates no relation between $x$ and $y$. In this study, the relationship between heave/settlement and active-layer thickness (ALT) were calculated using Pearson Correlation Coefficient. To do so, a simple Microsoft Excel document was created (Till, 1974; Klene, personal communication, 2005; and Dretzke 2005), and the following equations were used:

$$
r = \frac{\text{CSCP}}{[(\text{CSSX})(\text{CSSY})]^{1/2}}
$$

where
- CSCP (corrected sum of cross products) = $\Sigma xy - \Sigma x \cdot \Sigma y / n$,
- $n$ = number of samples,
- CSSX (corrected sum of squares of $x$) = $\Sigma x^2 - \Sigma x \cdot \Sigma x / n$,
- and CSSY (corrected sum of squares of $y$) = $\Sigma y^2 - \Sigma y \cdot \Sigma y / n$.

Correlation results were assessed for their statistical significance ($\alpha$) using the paired samples t-test (Dretzke 2005) in Microsoft Excel. The significance level ($\alpha$) was set at 0.05.

### 7.4 Reduced-Major Axis Line

The relationship between heave, settlement, and ALT was examined by developing reduced major axes (Till, 1974). The reduced major axis (RMA) procedure incorporates the results from Pearson’s correlation coefficient and is used when there is not a cause/effect relationship between two variables, as is the case with heave, settlement and ALT (Nelson, personal communication, 2005; Till, 1974). If there were a cause/effect (causal) relationship between the two, then a linear regression would be implemented. RMA results in a line that runs in between those produced by linear regression of $x$ on $y$ and $y$ on $x$, and through the point where they cross (Klene, personal communication, 2005). The RMA equation partitions the
distance between the data points and the RMA line (error) equally between x and y (Nelson, personal communication, 2005).

A simple Microsoft Excel document was created to determine the RMA between heave/settlement and ALT as described in Till (1974). To confirm these results a tool called linear fit within the program PAST (PAlaeontological STatistics) was used (Hammer et al., 2006). The following simple mathematical equations were used to determine RMA:

\[ y = a + bx \quad (7-12a) \]

where the slope, \( b \), is \( s_y/s_x \), \( s_y \) is the standard deviation of \( y \), and \( s_x \) is the standard deviation of \( x \). The sign of the slope is given by that of the correlation coefficient \( r \) as determined in eq. 7-11. The intercept \( a \) is found by:

\[ a = (\text{mean of } y \text{ in sample}) - b \times (\text{mean of } x \text{ in sample}) \quad (7-12b) \]
	hereby providing a reduced major axis line.
8.1 Detecting Frost Heave/Thaw Settlement with DGPS: Kuparuk River Basin

During the summers of 2001 through 2003 DGPS was used to monitor the vertical positions of 32 platform targets, arranged in a nested hierarchical sampling design at West Dock and at Flux Plot 3 (Nelson et al., 1999). Classical surveying was implemented in the summers of 2002 and 2003 at West Dock to assess the effectiveness of DGPS for monitoring vertical movement. The salient aspects of the DGPS and surveying equipment can be found in Appendix B. Results are represented through the use of data plots and descriptive statistics in Tables 9.1 and 9.2, and in Figures 9.1 to 9.5. Results indicate that, as hypothesized, DGPS is able to measure heave and thaw effectively and accurately at the centimeter-scale in tundra environments.

8.2 Spatial Components of Heave/Thaw and Heave/Thaw/ALT: Kuparuk

The analytic portion of NSA, corresponding to Equations 7-1 to 7-10, was implemented by adapting an existing FORTRAN program developed by F. E. Nelson (Nelson et al., 1999) and using the SAS program developed by Jerome Braun of the Statistics Laboratory at the University of California Davis (Braun, personal communication, 2005) and J. Little. Results are represented numerically in Tables 9.3 to 9.6 and graphically in Figures 9.6 through 9.9.
The “reconnaissance variograms” of Figure 9.6 through 9.9 indicate that, as hypothesized, there is great similarity in the spatial patterns of heave, subsidence, and active-layer thickness within the study areas over the two orders of magnitude of geographic scale constructed into the experimental design.

8.3 ALT and Heave/Thaw Correlation

Measurement of ALT and surface ground movements were conducted at West Dock and Flux Plot 3. This was accomplished by inserting a 1-cm diameter steel rod to the depth of mechanical resistance (Mackay, 1977b; Nelson and Outcalt, 1982; Nelson et al., 1998b). If ALT is measured without tracking changes in elevation, the possibility exists that consolidation accompanying penetration of thaw into an ice-rich transient layer may disguise the increased ALT values (Nixon and Taylor, 1998; Nelson et al., 2004; Shur et al., 2005). Statistical analysis of heave/settlement and ALT data can provide information about covariation between these parameters. Pairwise relations between heave, settlement, and active-layer thickness were examined by developing reduced major axes (Till, 1974), a procedure based on the Pearson correlation coefficient using equation 7-12. Pearson correlation coefficient and reduced major axis results are summarized in Table 9.7. Figure 9.10 through 9.17 are scattergrams that show the relationship between heave/thaw.

Pearson correlation coefficient were determined at both the West Dock and Sagwon locations using Equation 7-11 and data from all 32 points at each site. Each correlation was assessed for its statistical significance. Two types of correlations were made:

Method 1) the August ALT and following-winter frost heave. For example, August ALT values from the previous year (e.g., 2001) and elevation
differences between June of the present year (e.g., 2002) and August of the previous year (e.g., 2001). This gives the correlation between last year's ALT and the heave that took place during the winter of 2001-02. This will provide a total of two correlations at West Dock and two at Flux Plot 3 since data were obtained over the period July 2001 through August 2003.

Method 2) August ALT and that summer’s thaw settlement. For example, August ALT values from the current year (e.g., 2002) were correlated with the elevation differences between August and June of the present year (e.g., 2002). This gives the correlation between this year's ALT and the subsidence that took place during the summer of 2002. This procedure provides two correlations at West Dock and two at Flux Plot 3 since data were obtained over the period July 2001 through August 2003.

8.4 Temporal Changes in Frost Heave and Thaw Settlement: Barrow, Alaska

Beginning in August 2002, DGPS technology was used in an effort to compare the microrelief and surface elevations taken in 1962 through 1964 by Brown and Johnson (1965) on two Cold Regions Research and Engineering Lab (CRREL) Plots within the Barrow Environmental Observatory (BEO) (Figure 6.4). Very few permafrost studies have compared sets of precise elevation measurements that are separated by four decades. Results may determine if settlement has occurred at the two CRREL Plots since the 1960s, which could indicate climate-warming impacts.

Mean surface elevations were measured at CRREL Plots 34 and 37 by implementing post-processed continuous kinematic DGPS in August 2002, generating 135 and 120 points at CRREL Plots 34 and 37, respectively. A polar bear shortened the August 2002 survey, resulting in an absence of data for CRREL Plot 40 and 44.
Post-processed continuous kinematic DGPS records data at varying sync times (1-5 s) resulting in decreased accuracy, especially with the Trimble 4700 equipment used in this study. Both plots were surveyed continuously every two meters, providing average surface height. The CRREL Plots were originally surveyed in the summer of 1964 using classical surveying techniques (Brown and Johnson, 1965).

In June 2003 this project began incorporating newer GPS equipment, the Trimble 5700 DGPS (Appendix B). To improve survey accuracy in 2003, rapid static DGPS was used at the CRREL Plots during June 2003. Trimble 5700 equipment and RTK were employed at the CRREL Plots August 2003, as RTK surveying with the 5700 can achieve results comparable to those from the 4700 in rapid static mode. RTK constitutes a major improvement, as it can save significant amounts of time. Rather than continuous surveying, five targets were inserted at the four corners and middle of CRREL Plots 34, 37, 40 and 44. Data obtained in 1962/63 and from 2003 used the same benchmark, Piling 2, shown in Figure 6.5. Results are summarized in Table 9.8.
9.1 Detection of Frost Heave and Thaw: Kuparuk River Basin

9.1.1 West Dock, Alaska

Results from West Dock indicate that DGPS has the ability to resolve vertical movement resulting from frost heave and thaw settlement (Little et al., 2003a,b). Figure 9.1 shows heave and subsidence relative to an arbitrary datum of 0 cm, stipulated at the beginning of the survey during the summer of 2001 at West Dock. An average surface heave of 1 cm was recorded in June 2002, even though the initial observations were recorded July 2001 instead of August, the typical period of maximum thaw on Alaska’s North Slope. Maximum heave and subsidence of 6.7 cm and 2 cm, respectively, were measured with rapid static DGPS in June 2002 at West Dock (Figure 9.1). The June 2002 survey showed that three-fourths (24 of 32) of the targets had experienced heave. During August 2002, a rapid static DGPS survey indicated a mean decrease (subsidence) of approximately 4 cm, compared to June 2002 (Figure 9.1). Ninety-one percent (29 of 32) of the targets indicated subsidence by August 2002. June 2003 results indicate a mean heave of approximately 4 cm as compared to August 2002 (Figure 9.1). Ninety-four percent (30 of 32) of the targets showed surface uplift June 2003. August 2003 indicated mean subsidence of 3.6 cm, with a standard deviation of 4.4. Ninety-four percent (30 of 32) of the targets
subsided from their June 2003 elevations. Summary statistics for West Dock, beginning July 2001, are given in Table 9.1.

The application of DGPS as the exclusive measurement technique has been called into question by the U.S. Army Corps of Engineers (1996), who suggested that traditional surveying techniques (e.g., differential leveling or profile leveling) should be applied in conjunction with DGPS. Most recently, the US Army Corps of Engineers (2003) recommend the use of differential leveling as a control check in combination with DGPS for greatest accuracy. To determine the degree of agreement between DGPS and traditional survey techniques for measurement of frost heave and thaw settlement, UDPG compared results at West Dock from profile leveling with rapid static and stop-and-go kinematic DGPS. Profile leveling conducted in August 2002 detected mean subsidence of 2 cm as compared to June 2002 (Table 9.1b and Figure 9.2). Results indicated that rapid static DGPS yields results similar to profile leveling and with much better accuracy than stop-and-go kinematic DGPS. Traditional surveying during June 2002 averaged approximately 1 cm higher than rapid static DGPS measured a few days earlier, yet stop-and-go kinematic was 5 cm higher (Figure 9.2). In addition, during August 2002, classical surveying resulted in 28 of 32 (88%) targets indicating subsidence, in close agreement with the 29 of 32 (91%) for rapid static DGPS. Only 22 of 32 (68%) suggested settlement for stop-and-go kinematic DGPS. Results from June 2003 indicate mean heave of 3.2 cm, less than one cm lower than rapid static (Figure 9.3). Due to fog, only 28 of 32 targets were surveyed traditionally. Of the 28, all indicated heave. Figure 9.4 compares rapid static and profile leveling during August 2003. Mean subsidence of 6 cm was recorded, and a little over 2 cm recorded with rapid static. Of the twenty-eight targets
available for comparison, all recorded settlement. Stop-and-go kinematic results for this measurement period are not available due to accidental loss of data during download.

Table 9.1 Descriptive summary statistics at West Dock July 2001 through August 2003 (cm). Table 9.1a show rapid static results at West Dock. Table 9.1b shows results from profile leveling. Mean heave or subsidence (sub) is indicated in column 2. Between July 2001 and June 2002, there was a mean heave of 1 cm. Column 3 indicates standard deviation. Column 4 and 5 show the percentage of points that heaved or subsided during the dates given to the left. The sixth and seventh columns indicate maximum heave and subsidence for the given time. Values greater than and less than zero indicate heave and subsidence, respectively.

a. Rapid Static at West Dock, Alaska

<table>
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<tr>
<th>Date</th>
<th>Mean (cm)</th>
<th>Standard deviation</th>
<th>% heave</th>
<th>% sub.</th>
<th>Max. sub. (cm)</th>
<th>Max. heave (cm)</th>
<th>Sample size</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>1.7</td>
<td>75 %</td>
<td>25 %</td>
<td>1.5</td>
<td>6.7</td>
<td>32</td>
</tr>
<tr>
<td>June02 – Aug02</td>
<td>-4.3</td>
<td>3.9</td>
<td>9 %</td>
<td>91 %</td>
<td>15.5</td>
<td>0.5</td>
<td>32</td>
</tr>
<tr>
<td>Aug02 – June03</td>
<td>4</td>
<td>3.7</td>
<td>94 %</td>
<td>6 %</td>
<td>0.9</td>
<td>17</td>
<td>32</td>
</tr>
<tr>
<td>June03 – Aug03</td>
<td>-3.4</td>
<td>4.4</td>
<td>6 %</td>
<td>94 %</td>
<td>15.5</td>
<td>10.2</td>
<td>32</td>
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</tbody>
</table>

b. Traditional Surveying at West Dock, Alaska

<table>
<thead>
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<th>Mean (cm)</th>
<th>Standard deviation</th>
<th>% heave</th>
<th>% sub.</th>
<th>Max. sub. (cm)</th>
<th>Max. heave (cm)</th>
<th>Sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug01–June02</td>
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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>32</td>
</tr>
<tr>
<td>June02 – Aug02</td>
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<td>72 %</td>
<td>3.7</td>
<td>6.6</td>
<td>32</td>
</tr>
<tr>
<td>Aug02 – June03</td>
<td>3.1</td>
<td>1.9</td>
<td>100 %</td>
<td>0 %</td>
<td>None</td>
<td>10</td>
<td>28</td>
</tr>
<tr>
<td>June03 – Aug03</td>
<td>-6.2</td>
<td>2</td>
<td>0 %</td>
<td>100 %</td>
<td>12.5</td>
<td>None</td>
<td>28</td>
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</table>

UNAVCO (2006) and Trimble (2005) provided equations to determine vertical error for both DGPS techniques. The estimated error for rapid static DGPS, in centimeters, can be found by applying Equation (4-1). With baseline length of 1 km or less at West Dock, the estimated vertical error is 1.6 cm. Vertical error in
centimeters can be estimated for stop-and-go kinematic DGPS using Equation (4-2). Estimated vertical error at West Dock for stop-and-go kinematic DGPS was 2.1 cm. The close agreement between rapid static DGPS and profile leveling at West Dock confirms that frost heave and thaw settlement can be detected successfully using rapid static DGPS. As part of a continuing project, the vertical component of each target was measured with DGPS during the summers of 2004 and 2005, and will be reported elsewhere.
Figure 9.1  Box-whisker plot from rapid static DGPS survey at West Dock. An arbitrary elevation of 0 cm was stipulated in summer 2001. Rapid static DGPS was able to resolve heave (June 2002 and 2003) and thaw subsidence (August 2002 and 2003) at West Dock, Alaska. Vertical movement above and below zero cm indicates heave and thaw, respectively. In this and subsequent figures, the middle bar in the box represents the median, the upper and lower ends of the box represent the lower and upper quartile, and the upper and lower ticks indicate minimum and maximum vertical movement (cm).
Figure 9.2  Box-whisker plot from traditional surveying vs. rapid static and stop-and-go kinematic DGPS, August 2002 at West Dock, Alaska. An arbitrary elevation of 0 cm was stipulated in summer 2001. Rapid static DGPS compared closely to traditional surveying. Vertical movement above and below zero cm indicates heave and thaw, respectively.
Figure 9.3  Box-whisker plot comparing results from traditional surveying with rapid-static DGPS at West Dock between August 2002 and June 2003. An arbitrary elevation of 0 cm was stipulated in summer 2001. The mean for both surveys varied by less than 1 cm. Vertical movement above and below zero cm indicates heave and thaw, respectively.
Figure 9.4  Box-whisker plot comparing results from traditional surveying with rapid-static DGPS at West Dock between June 2003 and August 2003. An arbitrary elevation of 0 cm was stipulated in summer 2001. Vertical movement above and below zero cm indicates heave and thaw, respectively.

9.1.2 Flux Plot 3

Results from Flux Plot 3 also indicate that DGPS has the ability to resolve vertical movement resulting from frost heave and thaw settlement. Table 9.2 summarizes the descriptive data from Flux Plot 3 from August 2001 through August
2003. Figure 9.5 shows heave and subsidence relative to an arbitrary datum of 0 cm, stipulated at the beginning of the survey during August 2001 at Flux Plot 3. Average surface heave of 2 cm was recorded with rapid static DGPS in June 2002, relative to August 2001. Twenty-four targets (75%) showed heave and five (15%) showed little to no change during June of 2002. Maximum heave and subsidence of 8 cm and 9 cm, respectively, were measured with rapid static DGPS in June 2002 (Figure 9.5).

During August 2002, a rapid static DGPS survey indicated a mean decrease (subsidence) of approximately 5 cm, relative to June 2002 (Figure 9.5). Ninety-one percent (29 of 32) of the targets indicated subsidence by August 2002. June 2003 results indicate mean heave of approximately 8.5 cm as compared to August 2002 (Figure 9.5). In June 2003, 94% (30 of 32) of the targets showed heave at the surface. Due to a technical error, only 16 of 32 targets were surveyed in August of 2003. The technical error was caused by the improper use of newer DGPS equipment (Trimble 5700), a consequence of the author’s neglect to sufficiently practice and ask for Trimble 5700 training. Every target surveyed showed subsidence, with mean settlement of 4 cm and standard deviation of 5.1 (Figure 9.5).

Trends in surface elevation at Flux Plot 3 can also be discerned from data collected using rapid static DGPS between August 2001 through 2003. Between August 2001 and 2002 the data indicate net subsidence, with average surface elevation lowering of 1.5 cm. Between August 2002 and 2003 no significant change occurred. Using the 16 points surveyed in August 2003 for comparison, overall subsidence of slightly more than 2 cm resulted.

The estimated error for rapid static and stop-and-go kinematic DGPS, in centimeters, can be found by applying Equations (4-1) and (4-2). With baseline length
of 3 km at Flux Plot 3, the estimated rapid static vertical error is 1.6 cm. Estimated vertical error at Flux Plot 3 for stop-and-go kinematic DGPS is 2.1 cm.

Table 9.2  Descriptive summary statistics at Flux plot 3 for August 2001 through August 2003 (cm). Mean heave or subsidence (sub) is indicated in Column 2. Between August 2001 and June 2002, there was a mean heave of 1.9 cm. Column 3 indicates standard deviation. Columns 4 and 5 show the percentage of points that heaved or subsided during the dates given to the left. The sixth and seventh columns indicate maximum heave and subsidence for the given time. Values greater than and less than zero indicate heave and subsidence, respectively.

Rapid Static at Flux Plot 3, Alaska

<table>
<thead>
<tr>
<th>Date</th>
<th>Mean (cm)</th>
<th>Standard deviation</th>
<th>% heave</th>
<th>% sub.</th>
<th>Max. sub. (cm)</th>
<th>Max. heave (cm)</th>
<th>Sample size</th>
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<tbody>
<tr>
<td>Aug 01-June 02</td>
<td>1.9</td>
<td>3.6</td>
<td>78 %</td>
<td>15 %</td>
<td>8.7</td>
<td>8.3</td>
<td>32</td>
</tr>
<tr>
<td>June 02 - Aug 02</td>
<td>-3.3</td>
<td>4.8</td>
<td>12 %</td>
<td>88 %</td>
<td>11</td>
<td>17</td>
<td>32</td>
</tr>
<tr>
<td>Aug 02 - June 03</td>
<td>5.4</td>
<td>4.3</td>
<td>91 %</td>
<td>6 %</td>
<td>6.4</td>
<td>15.1</td>
<td>32</td>
</tr>
<tr>
<td>June 03 - Aug 03</td>
<td>-4.06</td>
<td>5.1</td>
<td>0 %</td>
<td>100 %</td>
<td>23.5</td>
<td>None</td>
<td>16</td>
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</table>
Figure 9.5  Box-whisker plot results from rapid static DGPS survey at Flux Plot 3. An arbitrary elevation of 0 cm was stipulated in August 2001. Rapid static DGPS was able to resolve heave (June 2002 and June 2003) and thaw subsidence (August 2002 and August 2003) at Flux Plot 3, Alaska. Vertical movement above and below zero cm indicates heave and thaw, respectively.
9.2 Spatial Variability of Frost Heave/Thaw Settlement, and ALT: Kuparuk River Basin

9.2.1 West Dock, Alaska

At West Dock, in response to controls exerted by drained thaw lakes and networks of ice wedge polygons, frost heave varied at scales similar to thaw depth (e.g., 10 m or more). Table 9.3 provides a summary of ANOVA statistics for frost heave and thaw at West Dock for each field season, July 2001 through August 2003. The cumulative proportion of the total variance at each stage is given. In Figure 9.6, variance components for West Dock are plotted against the distance between points. The “reconnaissance variograms” visually display the scales at which variations occur.

The largest component of variance on the coastal Plain occurs over separation distances of 30 m or more. The important factors responsible for this result include: 1) relative homogeneity as a result of the level terrain at the microscale, and 2) heave/thaw differences associated with moisture differences between the drained thaw lake basin (Targets 1-1 through 2-8) and the adjacent “upland” (Targets 3-1 through 4-8).

Figure 9.6 shows that most of the frost heave/thaw variation along the coastal plain occurs at “local” scales involving separation distances of 10 m or more. Although analysis of variance indicates that nearly all scales make contributions to the total variance (Table 9.3), on average, more than 50% occurs at 10 m or more. The main departure occurred between July 2001 and August 2001, which indicated more variance at the micro scale (3 m), most likely as a result of the late survey date (July).

This investigation also shows that the active-layer thickness (ALT) variation at West Dock is similar to that reported by Nelson et al. (1999) and Gomersall and Hinkel (2001) study of active-layer thickness along the coastal plain.
Table 9.4 provides summary ANOVA statistics of ALT at West Dock for each field season, beginning in July of 2001. Figure 9.7 is a reconnaissance variogram representing active-layer thickness data (ALT). It shows that most ALT variation on the coastal plain occurs at the local scale (10 m or more), the same as heave/thaw. These results support an assertion by Nelson et al. (1999) that effective sampling within this physiographic province does not require a large number of closely spaced observations.
West Dock Frost Heave/Thaw Settlement

Figure 9.6  “Reconnaissance variograms” (cumulative variance represented on the y-axis sampled against sampling-point separation) for nested samples of frost heave and thaw at West Dock. Note dissimilar trend between Flux Plot 3 graph (Figure 9.8) and with the exception of July 2001 to August 2001, a similar pattern within this site.
Figure 9.7  Reconnaissance variogram of active layer thickness at West Dock.
Table 9.3 ANOVA summary statistics of frost heave and thaw at West Dock, July 2001 through August 2003.

a. West Dock frost heave and thaw (July2001/Aug2001)

<table>
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<th>Stage</th>
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<th>Sums of Squares</th>
<th>Mean Squares</th>
<th>Cumulative %</th>
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c. West Dock frost heave and thaw (June 2002/Aug2002)

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e. West Dock frost heave and thaw (June 2003/Aug2003)

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Table 9.4 ANOVA summary statistics of ALT at West Dock, June 2002 through August 2003.

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a. West Dock Active Layer (July 2001)

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c. West Dock Active Layer (Aug 2002)

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d. West Dock Active Layer (June 2003)

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e. West Dock Active Layer (Aug 2003)
9.2.2 Flux Plot 3

At Flux Plot 3, frost heave varied over shorter distances (e.g., 0 – 3 m) as the vegetative cover varies over shorter distances. Table 9.5 provides ANOVA summary statistics of frost heave and thaw at Flux Plot 3 for each field season, beginning August 2001. The cumulative proportion of the total variance at each stage is given. In Figure 9.8, variance components for Flux Plot 3 are plotted against distance between sampled points.

Unlike the coastal plain, nearly all of the variation in frost heave and thaw at Flux Plot 3 occurs at the microscale (1 to 3 m); this is shown clearly in Figure 9.6 (West Dock) and 9.8 (Flux Plot 3). Every time period sampled shows that more than 70% of the variance is contained in sampling intervals less than 1 m. This is a result of 1) large differences attributable to tundra tussocks, occurring at distances less than one meter, and 2) complex drainage and soil moisture regime patterns, typical of the foothills physiographic province and its irregular topography. The results are similar to those found in studies by Nelson et al. (1999) and Gomersall and Hinkel (2001) of active-layer thickness in the Arctic Foothills physiographic province of north-central Alaska.

Table 9.6 provides ANOVA summary statistics of the active layer at Flux Plot 3 for each field season, beginning August 2001. Figure 9.9 is a reconnaissance variogram that represents active layer thickness data (ALT) at Flux Plot 3. At Flux Plot 3, active layer thickness varied over shorter distances (e.g., 0 – 3 m) than on the coastal plain, as did vegetative cover. This is similar to the frost heave/thaw settlement variation at Flux Plot 3, and to the conclusion of Nelson et al. (1999).
These results indicate that effective sampling in the Foothills physiographic province requires intensive or specialized sampling designs. Such designs must account for the peaks in variability existing at multiple scales.
Figure 9.8  Reconnaissance variograms for nested sampling of frost heave and thaw of Flux Plot 3. Note dissimilar trend between West Dock graph (Figure 9.6), but similar pattern within this site.
Figure 9.9  Reconnaissance variogram of active layer thickness at Flux Plot 3.
Table 9.5  ANOVA summary statistics of frost heave and thaw settlement at Flux Plot 3 August 2001 through August 2003.


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b. Flux 3 frost heave and thaw (June 2002/August 2002)

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d. Flux 3 frost heave and thaw (June 2003/August 2003)

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Table 9.6 ANOVA summary statistics of ALT at West Dock, June 2002 through August 2003.

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b. Flux 3 Active Layer (June 2002)

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9.3 Active-Layer Thickness and Heave/Thaw Correlation: Kuparuk River Basin

9.3.1 West Dock, Alaska

The investigation showed that Pearson Correlation Coefficient calculations of heave/thaw vs. active-layer thickness result in weak (<0.35) to moderate (0.35 to 0.65) correlation. Table 9.7 provides a summary of heave/thaw and ALT correlation, its statistical significance (p-value of 0.05), and reduced major axis (RMA) analysis. Figure 9.10 through 9.13 are scattergrams that show the relationship between heave/thaw and ALT at West Dock.

The Pearson Correlation Coefficient and reduced major axis were calculated following the methodology outlined by Till (1973) and Klene (personal communication, 2005). Correlation calculations at West Dock indicated a weak (<0.35) to moderate (0.35 to 0.65) correlation between ALT and heave and settlement using method: 1) the August ALT and following winter frost heave and 2) the August ALT and that summer’s thaw settlement. There was virtually no correlation (0.18) between ALT and heave during the first year (July 2001 ALT and elevation differences between June 2002 and July 2001) using method 1 (August ALT and following Winter Heave). This may be attributable to the fact that ALT was recorded in July of 2001 instead of August 2001. Figure 9.10 is a scattergram that shows the relationship between July 2001 ALT and the following winter’s heave. Moderate positive correlation (0.47) was found for the second year (August 2002 ALT and elevation differences between June 2003 and August 2002) using method 1 (August ALT and following Winter Heave). Figure 9.11 is a scattergram that shows the relationship between August 2002 ALT and the following winter’s heave. The results obtained using method 2 (August ALT and that summer’s thaw settlement) indicated a
moderate negative correlation of –0.39 during the first freeze/thaw cycle (August 2002 ALT and elevation differences between June 2002 and August 2002) as well as the second cycle (August 2003 ALT and elevation differences between June 2003 and August 2003). Figure 9.12 and 9.13 are scattergrams that show the relationship between August 2002 and 2003 ALT, respectively, and that summer’s thaw settlement. All ALT and heave/thaw correlations at West Dock were statistically significant ($\alpha = 0.05$).

Results indicate that the lack of a close correspondence between ALT and heave/settlement may be a result from the many factors controlling the ground thermal regime (e.g., edaphic, snow cover, etc.).
Figure 9.10 Scattergram of July 2001 ALT and following winter’s heave at West Dock. Reduced Major Axis (RMA) Line is included. Figure 9.10 through 9.17 were made using the linear fit tool within the software program called PAST (Hammer et al., 2006).
Figure 9.11 Scattergram of August 2002 ALT and following winter’s heave at West Dock. Reduced Major Axis (RMA) Line is included.
Figure 9.12  Scattergram of August 2002 ALT and that summer’s thaw settlement at West Dock. Reduced Major Axis (RMA) Line is included.
Figure 9.13  Scattergram of August 2003 ALT and that summer’s thaw settlement at West Dock. Reduced Major Axis (RMA) Line is included.

9.3.2 Flux Plot 3

Pearson Correlation Coefficient calculations of heave/thaw vs. active-layer thickness result in weak to moderate correlation. Reduced major axis (RMA) were also calculated. Table 9.7 provides a summary of correlation and their statistical significance, as well as RMA. Figure 9.14 through 9.17 are scattergrams that show the relationship between heave/thaw and ALT at Flux Plot 3.
Pearson Correlation Coefficient and Reduced major axis were calculated following (Till, 1973) and Klene (personal communication, 2005). Correlation calculations at Flux Plot 3 indicated even weaker correlation between method 1 and 2: 1) August ALT and following Winter Heave and 2) August ALT and that summer’s thaw settlement. A weak negative correlation of 0.25 occurred during the first year (August 2001 ALT and elevation differences between June 2002 and August 2001) using method 1 (August ALT and following Winter Heave). A slightly stronger negative correlation of 0.27 occurred during the second year (August 2002 ALT and elevation differences between June 2003 and August 2002) using method 1 (August ALT and following Winter Heave). Figure 9.14 and 9.15 are scattergrams that show the relationship between August 2001 and 2002 ALT, respectively, and the following winter’s heave. Results from method two (August ALT and that summer’s thaw settlement) indicated virtually no correlation (-0.15 and -0.13, respectively) during the first freeze/thaw cycle (August 2002 ALT and elevation differences between June 2002 and August 2002) and the second cycle (August 2003 ALT and elevation differences between June 2003 and August 2003). Figure 9.16 and 9.17 are scattergrams that show the relationship between August 2002 and 2003 ALT, respectively, and that summer’s thaw settlement. All ALT and heave/thaw correlations at Flux Plot 3 were statistically significant ($\alpha = 0.05$), except the second cycle of August ALT and that summer’s thaw settlement.

The weak correlation at Flux Plot 3 between ALT and heave/settlement may be a result of edaphic factors, snow cover, and topoclimatology.
Figure 9.14 Scattergram of August 2001 ALT and following winter’s heave at Flux Plot 3. Reduced Major Axis (RMA) Line is included.
Figure 9.15 Scattergram of August 2002 ALT and following winter’s heave at Flux Plot 3. Reduced Major Axis (RMA) Line is included.
Figure 9.16  Scattergram of August 2002 ALT and that summer’s thaw settlement at Flux Plot 3. Reduced Major Axis (RMA) Line is included.
Figure 9.17 Scattergram of August 2003 ALT and that summer’s thaw settlement at Flux Plot 3. Only 16 points on the y-axis were determined as a result of human error. Reduced Major Axis (RMA) Line is included.
Table 9.7  Tables 9.71a and 9.72a depict correlation and Reduced Major Axis Lines (RMA) for ALT (e.g., August 2002) and the following Winter Heave (e.g., elevation differences between August 2002 and June 2003) at West Dock and Flux Plot 3, respectively. Tables 9.71b and 9.72b show the calculated correlation between a summer’s ALT (e.g., August 2002) and thaw settlement (e.g., elevation difference between June 2002 and August 2002) at West Dock and Flux Plot 3, respectively. The Pearson correlation coefficient and reduced major axis (RMA) were determined based upon the protocol of Till (1974) and are shown in Equations (7-11) and (7-12), respectively. Each correlation was assessed for its statistical significance (NS = Not significant, S = Significant).

### 9.71a) West Dock: August ALT and following Winter Heave

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<th>Time Period over which Elevation Δ were measured</th>
<th>Correlation (r)</th>
<th>P-value (0.05)</th>
<th>Reduced Major Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>July 2001</td>
<td>July 2001 to June 2002</td>
<td>0.18</td>
<td>S</td>
<td>$Y = -5.4 + 0.2X$</td>
</tr>
<tr>
<td>August 2002</td>
<td>August 2002 to June 2003</td>
<td>0.47</td>
<td>S</td>
<td>$Y = -8.6 + 0.2X$</td>
</tr>
</tbody>
</table>

### 9.71b) West Dock: August ALT and that summer’s Thaw Settlement

<table>
<thead>
<tr>
<th>Time period (ALT)</th>
<th>Time Period over which Elevation Δ were measured</th>
<th>Correlation (r)</th>
<th>P-value (0.05)</th>
<th>Reduced Major Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>August 2002</td>
<td>June 2002 to August 2002</td>
<td>-0.39</td>
<td>S</td>
<td>$Y = -8.9 - 0.3X$</td>
</tr>
<tr>
<td>August 2003</td>
<td>June 2003 to August 2003</td>
<td>-0.39</td>
<td>S</td>
<td>$Y = 9.0 - 0.2X$</td>
</tr>
</tbody>
</table>

### 9.72a) Flux Plot 3: August ALT and following Winter Heave

<table>
<thead>
<tr>
<th>Time period (ALT)</th>
<th>Time Period over which Elevation Δ were measured</th>
<th>Correlation (r)</th>
<th>P-value (0.05)</th>
<th>Reduced Major Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>August 2001</td>
<td>August 2001 to June 2002</td>
<td>-0.25</td>
<td>S</td>
<td>$Y = 30.8 - 0.4X$</td>
</tr>
<tr>
<td>August 2002</td>
<td>August 2002 to June 2003</td>
<td>-0.27</td>
<td>S</td>
<td>$Y = 21.9 - 0.36X$</td>
</tr>
</tbody>
</table>

### 9.72b) Flux Plot 3: August ALT and that summer’s Thaw Settlement

<table>
<thead>
<tr>
<th>Time period (ALT)</th>
<th>Time Period over which Elevation Δ were measured</th>
<th>Correlation (r)</th>
<th>P-value (0.05)</th>
<th>Reduced Major Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>August 2002</td>
<td>June 2002 to August 2002</td>
<td>-0.15</td>
<td>S</td>
<td>$Y = 11.5 - 0.4X$</td>
</tr>
<tr>
<td>August 2003</td>
<td>June 2003 to August 2003</td>
<td>-0.13</td>
<td>NS</td>
<td>$Y = 43.9 - 1.0X$</td>
</tr>
</tbody>
</table>
9.4 Temporal Variation of Frost Heave and Thaw Settlement: Barrow, Alaska

Preliminary results from Barrow during June and August 2003 indicate possible ground subsidence when compared to the report of Brown and Johnson (1965).

Table 9.8a provides data comparing June 21, 2003 rapid static survey (Trimble 5700) with Brown and Johnson’s July 1964 traditional survey of CRREL Plots 34, 37, 40, and 44. Comparisons were based on the height of Piling 2, located near the CRREL Plots, surveyed in 1964 and 2003. Rapid static DGPS was conducted at five targets at each plot. Each CRREL Plot showed surface subsidence (Plots 37, 40, and 44) except CRREL Plot 34, which indicated a mean rise of 36 cm. At all four CRREL Plots mean subsidence was 5.8 cm as compared with 1964. The estimated error for rapid static DGPS while using the Trimble 5700, in centimeters, can be found by applying equation 4-5.

Preliminary data from August 2003 (RTK study using Trimble 5700) was consistent with June 2003. Table 9.8b provides data comparing August 14, 2003 with July 1964. Compared with July 1964, surface subsidence was reported in August 2003 at each CRREL Plot (37, 40, and 44) except CRREL Plot 34, which indicated a mean rise of 20 cm. Mean subsidence at all four CRREL plots August 2003 was 2.8 cm using RTK DGPS. The estimated error for RTK DGPS while using the Trimble 5700, in centimeters, can be found by applying equation 4-6. Although all four CRREL Plots are within an area with the highest concentration of non-sorted circles in the Barrow area (Brown & Johnson, 1965), CRREL Plot 34 exhibits different physical characteristics than CRREL Plot 37, 40, and 44. These differences provide a plausible explanation as to the conflicting results at CRREL Plot 34. For example, CRREL Plot...
34 has the: 1) lowest plot elevation as shown in Table 9.8 and in the Brown and Johnson (1965) C-line elevation profile; 2) lowest maximum depth of thaw from 1962 through 1963 (Brown and Johnson, 1965) and 1991 through 1993 (Brown and Nelson, 1998); 3) greatest surface microrelief variation as shown in Figure 15 of Brown and Johnson (1965); and 4) may be partially or entirely in a basin resulting in increased soil moisture content and ice segregation. Although speculative, CRREL Plot 34’s unique physical characteristics may have resulted in surface uplift as oppose to surface subsidence as evident at CRREL Plots 37, 40, and 44.

Four CRREL Plots were surveyed August 2002 using a Trimble 4700 rover and post-processed continuous kinematic DGPS. Operational error and animal disturbance resulted in a lack of representative data in August of 2002. On August 29, a close encounter with a polar bear led to immediate survey arrest. Reports of additional polar bears in the vicinity of the BEO continued to put a hold on surveying until September 1, 2002 (Oberbauer, 2005). On September 1, post-processed continuous kinematic DGPS surveying was conducted at the four CRREL Plots. Results were not usable, possibly as a result of increased ionospheric disturbance and/or poor satellite geometry, a complication with DGPS work outlined by Tait et al. (2005).

A) Rapid Static DGPS Results

<table>
<thead>
<tr>
<th>Location</th>
<th>Elevation Change (1964 vs. June 2003) $^{1,2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top of piling 2</td>
<td>- 14 cm</td>
</tr>
<tr>
<td>Ground surface/piling 2 interface</td>
<td>- 50 cm</td>
</tr>
</tbody>
</table>

CRREL plots: July 1964 vs. June 2003

<table>
<thead>
<tr>
<th>Location</th>
<th>July 1964 elevation $^{2,3}$</th>
<th>June 2003 elevation $^{4}$</th>
<th>Elevation Change (1964 vs. June 2003) $^{1,2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRREL plot 34</td>
<td>3.19 m</td>
<td>3.55 m</td>
<td>+ 36 cm</td>
</tr>
<tr>
<td>CRREL plot 37</td>
<td>3.79 m</td>
<td>3.59 m</td>
<td>- 20 cm</td>
</tr>
<tr>
<td>CRREL plot 40</td>
<td>3.97 m</td>
<td>3.78 m</td>
<td>- 19 cm</td>
</tr>
<tr>
<td>CRREL plot 44</td>
<td>4.30 m</td>
<td>4.10 m</td>
<td>- 20 cm</td>
</tr>
<tr>
<td><strong>AVERAGE</strong></td>
<td></td>
<td></td>
<td><strong>-5.8 cm</strong></td>
</tr>
</tbody>
</table>

B) RTK DGPS Results

CRREL plots: July 1964 vs. August 2003

<table>
<thead>
<tr>
<th>Location</th>
<th>July 1964 elevation $^{2,3}$</th>
<th>August 2003 elevation $^{4}$</th>
<th>Elevation Change (1964 vs. June 2003) $^{1,2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRREL plot 34</td>
<td>3.19 m</td>
<td>3.39 m</td>
<td>+ 20 cm</td>
</tr>
<tr>
<td>CRREL plot 37</td>
<td>3.79 m</td>
<td>3.69 m</td>
<td>- 10 cm</td>
</tr>
<tr>
<td>CRREL plot 40</td>
<td>3.97 m</td>
<td>3.47 m</td>
<td>- 10 cm</td>
</tr>
<tr>
<td>CRREL plot 44</td>
<td>4.30 m</td>
<td>4.19 m</td>
<td>- 11 cm</td>
</tr>
<tr>
<td><strong>AVERAGE</strong></td>
<td></td>
<td></td>
<td><strong>-2.8 cm</strong></td>
</tr>
</tbody>
</table>

1 Negative value represents surface subsidence.
2 2003 data in Geoid 99 Alaska coordinates (masl), standardized using the top of piling 2. 1964 data in NAD27 coordinates (masl).
3 Data collected from Bob Lewellen survey in the 1960’s as reported in Brown (1965).
4 Data collected using a Trimble 5700. RTK was employed August 2003 and rapid static DGPS was used June 2003.
Chapter 10

CONCLUSIONS AND RECOMMENDATIONS

This thesis presents evidence that Differential Global Positioning System (DGPS) surveys have considerable potential for monitoring frost heave and thaw subsidence in landscapes underlain by ice-rich permafrost. Prospects for the continued use of a DGPS survey include the measurement of many geomorphic phenomena. Technology has improved steadily since the survey of 2001 through 2003, making DGPS measurements easier and faster to conduct. A global DGPS permafrost network will provide monitoring of warming-induced thaw settlement, potentially reducing damage to buildings and roads.

Hierarchical sampling, and nested sampling and analysis, indicate that frost heave and thaw settlement variations are similar to those of active-layer thickness (ALT) studies, in accord with reports by Nelson et al. (1999) and Gomersall and Hinkel (2001). Further studies in the Kuparuk River Basin may provide information concerning an appropriate sampling scheme for the development of a global DGPS permafrost network.

Debate continues regarding the reliability of the active-layer thickness as an indicator of climate change (Nixon and Taylor, 1998). In part, this skepticism can be traced to the fact that temperature increases resulting from regional warming will
degrade permafrost, causing settlement of the ground. The CALM program uses
graduated steel rods to measure the active layer depth in Kuparuk, but this technique
may not yield accurate-assessment of long-term changes if thaw settlement in the
transient layer is occurring, and heave/settlement measurements are part of procedures
recommended under the CALM II program (Nelson et al., 2004). Although simple
thaw tubes anchored in permafrost provide a stable reference for thaw settlement
measurement (Nixon, 2000), the device cannot be used to assess spatial variability. In
contrast to previous investigations, the present study used DGPS to determine if thaw
settlement or frost heave has occurred since the 1960s in Barrow, Alaska (Brown and
Johnson, 1965), thereby potentially providing information on the transient layer’s role
in climate change. As described below, this protocol was able to compare ground
surface elevations between 1964 and 2003.

10.1 Measuring Frost Heave/Thaw Settlement with DGPS: Kuparuk River Basin

10.1.1 Conclusion

Evidence acquired at West Dock and Flux Plot 3 in the Kuparuk River
basin confirms that DGPS is able to measure heave and thaw effectively and
accurately at the centimeter-scale, and in tundra environments, substantiating
Hypothesis 1 (section 5.2). Frost heave and thaw was detected by using carrier-phase,
post-processed rapid static DGPS at West Dock, Alaska. The accuracy of the
measurements was verified by the close vertical correspondence between classical
leveling techniques and rapid static DGPS. At West Dock using rapid static DGPS,
heave was observed at 24 of 32 targets (75%) during June of 2002 and 29 of 32 targets (91%) the following year (June 2003), as illustrated in Figure 9.1. Subsidence was observed at 29 of 32 (91%), and 30 of 32 (94%) targets during August 2002 and 2003, respectively, at West Dock using rapid static DGPS. Heave was observed at 24 of 32 targets (75%) during June of 2002 and 30 of 32 targets (94%) during June of 2003 at Flux Plot 3 (Figure 9.5). Subsidence was observed at 29 of 32 (91%) and 16 of 16 (100%) targets during August 2002 and 2003, respectively, at Flux Plot 3 using rapid static DGPS. In contrast to rapid static DGPS, the use of kinematic DGPS resulted in increased error.

We conclude that Differential GPS/target methodology is a viable strategy for detecting frost heave and thaw settlement. The advantages of DGPS over previous techniques (e.g., use of frame-and-rod instruments) include its high degree of accuracy and automatic placement of surveys within well-established geodetic coordinate systems. DGPS provides a method to measure thaw settlement resulting from melting ground ice at the base of the active layer and, as such, can be useful for tracking changes in permafrost induced by a warming climate. The thaw of ice-rich permafrost may constitute a very significant consequence of global warming for humans, as it can result in considerable elevation changes (greater than 0.5 m) and severe damage to buildings and roads.

While accurate and comparatively easy to use, there are drawbacks to DGPS. These include high costs, target reinsertion difficulties, and the physical demands described in Section 4.5. DGPS entails significant time requirements compared to traditional leveling techniques when surveying small areas. For example, classical leveling requires 5-30 seconds to collect data, while rapid static DGPS
requires approximately eight minutes or more. However, DGPS has the potential to measure large regions much more rapidly than classical methods. Moreover, a new generation of DGPS instruments collect data at much higher rates than the equipment used in this study (Trimble, 2006).

The heave and subsidence targets described in this thesis minimize changes to the natural environment and are unlikely to be adversely affected by flooding, cold weather, snow, or animal disturbance. The DGPS/target methodology may be applied at various scales, depending upon time considerations. Although the present investigation did not measure frost heave and thaw in all, or even most potential applications in permafrost environment, this study’s results indicate that DGPS technology could be employed in for the solution of a variety of periglacial problems. Advances in GPS technology have been rapid over the past decade. New equipment and future developments will decrease time requirements and costs, the largest constraint on widespread implementation of DGPS technology in geocryology operating at the time fieldwork for this study was carried out.

10.1.2 Recommendations and Future Studies

Although time consuming, a DGPS network and the use of AutoGypsy software is required to improve the accuracy of the measurements obtained at West Dock and Flux Plot 3. This requires base station occupation for a minimum of 12 hours and occupation of at least three targets for 12 hours.

Compared to rapid static DGPS, improved DGPS equipment may provide similar or improved accuracy while requiring far less time. Trimble 5700 base and rover receivers have the potential to measure a vertical change of 1 cm using real time kinematic (RTK) DGPS. If RTK surveying turns out to be as accurate as rapid static,
it would allow points to be measured in 5-15 seconds, rather than requiring 8 or more minutes. This would greatly increase the number of potential sampling points per unit of time. It is highly recommended that a comparative study between RTK and rapid static be conducted in order to address these issues. Such a study could be conducted at the Barrow Environmental Observatory (BEO) as the permanent base station and Trimble 5700 equipment is available there.

There is an ever-growing demand to monitor the effects of global warming on ice-rich terrain, at a global scale, through a monitoring network such as CALM (Nelson et al., 2004). To do so, a continuous DGPS (CDGPS) network and/or DGPS network is recommended in combination with satellite technology in order to monitor and warn of thermokarst development (Nelson et al., 2001). Although Hedling et al. (2001) reported that continuous DGPS was unfeasible due to serious logistical problems, with increased and improved technology and sufficient financial support, the author hypothesizes that it is viable. A global DGPS permafrost network potentially will reduce thermokarst damage and government and private business from loses economically.

10.2 Spatial Variability of Frost Heave and Thaw Settlement: Kuparuk River Basin

10.2.1 Conclusions

Frost heave and thaw settlement show patterns of similar spatial variation to those of active-layer thickness at West Dock and Flux Plot 3 because they are controlled by a similar process suite, affirming our hypothesis. The largest component of variance along the coastal plain occurs at local scales (distances of 10 m or more) as shown in Figure 9.6. The factors responsible for this result include: 1) the relative
homogeneity of edaphic factors as a consequence of the level terrain on the microscale, and 2) heave/thaw differences associated primarily with the local scale, between the polygonalized upland (Targets 3-1 through 4-8) and the drained thaw lake basin (Targets 1-1 through 2-8). These results indicate that effective sampling does not require large numbers of closely spaced observations (1 m) on the coastal plain, a conclusion that is similar to those described by Nelson et al. (1999) and Gomersall and Hinkel (2001) in their studies of active-layer thickness along the coastal plain.

In contrast to the coastal plain, nearly all of the variation in frost heave and thaw at Flux Plot 3 in the Arctic foothills occurs on the microscale (1 to 3 m), a factor that is shown clearly in Figure 9.8. Every time period sampled shows that more than 70% of the variance is contained in sampling intervals of less than 1 m. This is a result of: 1) large differences attributable to tundra tussocks, occurring at distances less than one meter, and 2) complex drainage and soil moisture regime patterns, typical of the foothill and its irregular topography. The present conclusions are similar to those expressed by Nelson et al. (1999) and Gomersall and Hinkel (2001) in their investigations of active-layer thickness in the Foothill’s of North-Central Alaska.

The close correspondence with the findings of Nelson et al. (1999) and Gomersal and Hinkel (2001) have significant implications as future sampling strategies, since they imply that interpolation efforts based on spatial analytical or remote sensing methods are quite feasible in some landscapes, but less so in others. Information about the spatial variability of various geomorphic landscapes facilitates effective sampling. Knowledge of locations and regions with a high spatial variability allow one to determine where more intensive sampling should occur and regions where very few measurements should be taken, thus saving time and money. Nested
sampling and analysis could be used in the development of a heave/thaw monitoring program covering large areas (e.g., North Slope of Alaska).

### 10.2.2 Recommendations and Future Studies

Investigation of the spatial variability of heave and subsidence is the first of a two-stage sampling strategy. The second stage, not addressed directly in this thesis, is to use this information to implement an appropriate monitoring protocol over extended areas and lengths of time. Future implementation of a regional (e.g., > $10^5$ m) heave and settlement monitoring system depend upon knowledge gained through additional nested sampling and analysis studies over small areas (e.g., $10^0$ to $10^2$ m) in the Kuparuk River basin. It is suggested that future sampling occur in the upper Kuparuk River basin, specifically at Toolik Lake, because the glaciated Arctic Foothills contain both moist acidic and nonacidic tundra. Toolik Lake Field Station is relatively easy to access. It is also recommended that sampling continue at West Dock and Flux Plot 3. However, at Flux Plot 3, results indicate that effective sampling in the Foothills physiographic province requires specialized sampling designs that must account for the peaks in variability existing at multiple scales.

The second stage of the two-step sampling strategy will use the information about scale variability (step 1) to implement an appropriate sampling procedure that will facilitate extensive monitoring of heave and thaw (step 2). This will allow the development of monitoring in regions that have similar physiographic characteristics.
10.3 ALT and Heave/Thaw Correlation

10.3.1 Conclusions

A total of eight correlation calculations at West Dock and Flux Plot 3 indicated a weak to moderate relation between the following methodologies: 1) August ALT and following Winter Heave and 2) August ALT and that summer’s thaw settlement, thereby rejecting Hypothesis 2. The strongest correlation of August ALT and that summer’s thaw settlement were at West Dock, where a moderate positive correlation of 0.47 occurred during the second year (August 2002 ALT and elevation differences between June 2003 and August 2002) using method 1 (August ALT and following Winter Heave). Otherwise, correlation values at Flux Plot 3 and West Dock using both data types ranged from 0.18 to 0.39, with the weakest correlations being at Flux Plot 3. All ALT and heave/thaw correlations at West Dock and Flux Plot 3 were statistically significant ($\alpha = 0.05$), except the second cycle of method 2 at Flux Plot 3.

The lack of close correspondence between ALT and heave/settlement may be a consequence of edaphic factors, vegetation patterns, snow cover or microclimatic factors. The annual frost cycle is controlled by the ground thermal regime (temperature variations in the soil), which is controlled by the topoclimatic and by vegetation, snow cover, moisture content and soil properties. These factors affect the spatial variation of heave and settlement. Preliminary results indicate that ALT is not directly related to heave and settlement. In other words, ALT may be the same at two locations but show significant variation in heave and settlement as a result of edaphic factors, topoclimatology, and snow cover.

The weaker correlation at Flux Plot 3 is likely attributable to greater variation in frost heave and thaw at the microscale (1 to 3 m). It is similar to the
greater variation found by Nelson et al. (1999) and Gomersall and Hinkel (2001) in their study of active-layer thickness in the Foothills of north-central Alaska, and that described in this thesis.

Spatial variability results between ALT and heave/settlement appear similar at West Dock and Flux Plot 3, but the direct correlation of ALT and heave/settlement on a one-to-one basis are not very strong. This result is similar to that of Hinkel and Nelson (2003), who found the correlation between organic thickness and ALT on a one-to-one basis are not very strong.

Current ALT probing protocol involves probing of the ground surface at random directions approximately 5-20 cm from the DGPS target. It is possible that frost heave/thaw settlement and ALT may show characteristics of anisotropy. In other words, heave/thaw measurements made in one direction differ from the measurement made in another direction. Thus, an ALT at a random direction away from the DGPS target will indicate an ALT not characteristic of the DGPS target. For example, probing often occurred near or on hummocks (10-50 cm in diameter). If the target was located on the hummock, and probing occurred on non-hummocky terrain, ALT and heave/thaw would likely show a weak correlation. If the target and the ALT were taken at the same location one would expect a larger ALT and increased heave as compared to non-hummocky terrain (Davis, 2001). Since ALT probing did not occur at the DGPS target, heave/thaw and ALT correlations were weak to moderate. If ALT probing occurs at the DGPS target, the author hypothesizes that the correlation between ALT and heave/thaw would increase.
10.3.2 Recommendations and Future Studies

The correlation between ALT and heave/settlement may improve if the ALT and heave/settlement probing protocol is modified. To avoid disturbing the ground, probing did not occur at the precise location of the platform target. Instead, it took place from a few cm (5 to as much as 25 cm) away from it. Significant variation of the soil and vegetation occur over this micro-scale. Further experiments that probe at the platform and incorporate a modified ALT, heave/settlement protocol are suggested (e.g., by probing at the platform target). It is also recommended that measurements of heave and settlement be made at standardized times (e.g., on the North Slope during the second week of June and the last week of August).

10.4 Temporal Changes in Frost Heave and Thaw Settlement: Barrow, Alaska

10.4.1 Conclusions

Preliminary results from Barrow, and a comparison with the report of Brown and Johnson (1965), indicate that ground subsidence since the 1960s may have occurred. Comparisons were based on the height of Piling 2, located near the CRREL Plots, surveyed in 1964 and 2003. Compared with July 1964, surface subsidence was reported August 2003 using RTK and rapid static GPS at each CRREL Plot (37, 40, and 44), with the exception of CRREL Plot 34. At all four CRREL Plots, the mean subsidence during June of 2003 compared to July of 1964 was 5.8 cm. Mean subsidence at all four CRREL Plots during August of 2003 was 2.8 cm using RTK DGPS. However, recent findings by Tait et al. (2005) suggest that the use of a wooden benchmark (Piling 2) may not be an accurate method of monitoring long-term subsidence. Thus, there is not clear evidence that thaw settlement has occurred over a multi-decadal period, neither refuting nor substantiating Hypothesis 3 (section 5.2).
The use of a wooden benchmark (Piling 2) has been called into question by Tait et al. (2005), who suggest that ground rods (metal) should be used as a benchmark to monitor long-term subsidence in areas of continuous permafrost. However, the disadvantage of using metal ground rods is due to the high thermal conductivity of metal compared to wood. Ground rods are used to ground electrical systems for protection against lightning. These two plus meter steel rods are coated with solid aluminum or high tensile copper. Over a 17-year period (1987-2004), differential leveling in the Mackenzie River Delta (Inuvik, Canada) indicated that ground rods established at a depth of 9 meters moved vertically only 5-10 mm (Tait et al., 2005).

10.4.2 Recommendations and Future Studies

Based on the recent findings by Tait et al. (2005), it is recommended that a benchmark of alternative design be established at a depth of approximately 9 m (if possible) within a meter of Piling 2 (CRREL Plots). With the continued use of DGPS surveying and the installation of a new ground rod benchmark at the CRREL Plots, monitoring of vertical surface movements are likely to improve. A comparative study is recommended to ascertain the vertical changes at Piling 2 and the alternative benchmark over a two to four year time period. Depending on the degree of vertical difference between Piling 2 and the alternative benchmark, conclusions can be made regarding the amount of thaw settlement that has occurred since the 1960s. With incorporation of alternative designs for benchmarks at the CRREL Plots and further data collection, preliminary results from summer 2003 can be used to assess the transient layer’s role in climate change.
If an alternative design for benchmarks is deemed viable after a two to four year period, it is recommended that it be used in an expanded DGPS thaw settlement-monitoring program. DGPS measurement of thaw-induced settlement should be conducted in areas with large magnitude change potential. Locations most vulnerable to these effects include the immediate Arctic coast, Tibet, and the interior regions of Russia. Along the Arctic Coast, coastal erosion is a concern in locations like Barrow and population centers in Russia, including Igarka, Dudinka, and Tiksi (Nelson et al., 2001). The cities of Yakutsk and Noril’sk, located in the interior of Russia, are at high risk for settlement in a global warming scenario (Nelson et al., 2001).

As technology advances, DGPS results will continue to improve and provide the highest-quality data. Remote sensing is making rapid technological gains, and will likely be used with increased frequency in conjunction with DGPS (JPL, 2006). DGPS constitutes the current recommended approach for monitoring cryogenic phenomena and promises to be utilized for many years.
REFERENCES


Lovick J, Li S, Romanovsky V. 2002. Fusion of Radarsat SAR interferograms with other image and geological data sets to establish temporal, spatial and physical behaviors of the active layer at Sagwon, Alaska. EOS Transactions American Geophysical Union 83(47), F261.


Appendix

APPENDIX A-DGPS BASE STATION SET-UP

Base station receiver set up for the TRIMBLE 4000 involves connecting the base antenna to the receiver, connecting the solar panels to the batteries and the batteries to the receiver as shown in Figure 4.2 and 4.3 (UNAVCO, 2006). Thereafter, programming of the base station receiver is accomplished. After turning the receiver power on, verify proper operation by clicking on STATUS, then checking the power strength bars, the icon representing the tracking of satellites, and the UTC time. Downloading of old data should occur prior to a new survey, if this was done, delete all unnecessary files through CONTROL. In SESSIONS, create a new station identification code. Set the elevation mask to an appropriate setting (e.g., UDPG used 100 most often). The measurement sync time (e.g., 30 seconds for rapid static and 5 seconds for stop and go kinematic DGPS), number of minimum satellites (e.g., 4), and the antenna height (e.g., 0 m) requires manual input (UNAVCO, 2006). Press ACCEPT once the base station receiver is ready to survey. Surveying with the Trimble 4000 can last up to eight hours or more depending on the number of rechargeable batteries available. The total time required to set up the base station for an experienced user under good weather conditions is approximately one-half hour.
## APPENDIX B-DGPS SURVEY EQUIPMENT SPECIFICATIONS

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Survey type</th>
<th>Vertical error ($\xi_v$) (\text{BL} = \text{baseline length (cm)})</th>
<th>Location implemented</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trimble 4000\textsuperscript{1} base</td>
<td>DGPS-Static</td>
<td>$\xi_v = 0.5 \text{ cm} + 10^{-6} \text{BL}$</td>
<td>Kuparuk</td>
</tr>
<tr>
<td>Trimble 4700\textsuperscript{2} Rover</td>
<td>DGPS-Post-processed rapid static or “fast static”</td>
<td>$\xi_v = 1.5 \text{ cm} + 10^{-6} \text{BL}$</td>
<td>Kuparuk</td>
</tr>
<tr>
<td>Trimble 4700\textsuperscript{2} Rover</td>
<td>DGPS-Post-processed stop and go kinematic (or continuous)</td>
<td>$\xi_v = 2 \text{ cm} + 10^{-6} \text{BL}$</td>
<td>Kuparuk and briefly in Barrow</td>
</tr>
<tr>
<td>Trimble 4700\textsuperscript{2} Rover</td>
<td>DGPS-Real time kinematic</td>
<td>$\xi_v = 5 \text{ cm} + 10^{-6} \text{BL}$</td>
<td>Not used</td>
</tr>
<tr>
<td>Trimble 5700\textsuperscript{3} Base</td>
<td>DGPS-Post-processed rapid static or “fast static”</td>
<td>$\xi_v = 0.5 \text{ cm} + 10^{-6} \text{BL}$</td>
<td>Barrow</td>
</tr>
<tr>
<td>Trimble 5700\textsuperscript{3} Rover</td>
<td>DGPS-Real time kinematic</td>
<td>$\xi_v = 0.5 \text{ cm} + 10^{-6} \text{BL}$</td>
<td>Barrow</td>
</tr>
<tr>
<td>Philadelphia rod &amp; optical level\textsuperscript{4}</td>
<td>Classical Surveying-Profile leveling</td>
<td>$\xi_v = +/- 0.1 \text{(y/1.6)}^{1/2}$</td>
<td>West Dock, Kuparuk</td>
</tr>
</tbody>
</table>

Note: Performance specifications are based on implementing rover surveys with a permanent benchmark. The specifications are for use with a Trimble 4000 or 5700 as a permanent benchmark.

\textsuperscript{1} Additional Trimble 4000 specifications can be found online at GFZ (2005).  \textsuperscript{2} Additional Trimble 4700 specifications can be found online at Trimble (2005).  \textsuperscript{3} Additional Trimble 5700 specifications can be found online at UNAVCO (2005).  \textsuperscript{4} To determine vertical error, the distance between the optical level and the Philadelphia rod is represented by y (km) (McCormac, 1999).