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ERDC 6.2 Boreal Aspects of Ensured Maneuver (BAEM)

Evaluation of Modeled and Reanalysis Estimates of Frost Depth through Comparison to Ground Observations

Lynette Barna, Carrie Vuyovich, and Kathleen Jones

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Evaluation of Modeled and Reanalysis Estimates of Frost Depth through Comparison to Ground Observations

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and “Mobility in Peat and Northern Soils”

Abstract

Frozen soils can withstand heavy vehicle loads where the soils would otherwise be too weak. This is important as vehicle mobility models require input of the ground conditions to assess seasonal traffickability. Modeling these frost depths uses the properties of the soil along with any snow cover and air temperature data. Though weather stations with air temperature data are becoming more widespread, station density varies worldwide. Gridded reanalysis products, on the other hand, provide weather data on a global scale.

Our objectives are (a) to evaluate the usefulness of reanalysis data to provide estimates of frost depth and (b) to determine the accuracy of simulated frost depths using either measured or reanalysis air temperature data. We use two one-dimensional models: a coupled heat and moisture flow model that simulates frost and thaw depths throughout the winter and a decoupled heat and moisture model that calculates the maximum frost depth. We compare frost depths determined from measured soil temperatures at stations in North Dakota and Minnesota and reanalysis frost depths with modeled values using both station and reanalysis air temperature data. Modeled frost depths depend more strongly on the depth and density of the snow layer than on the soil properties.

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Preface

This study was conducted for the Assistant Secretary of the Army for Acquisition, Logistics, and Technology under project number 465395, “Boreal Aspects of Ensured Maneuver (BAEM),” which is part of the U.S. Army Engineer Research and Development Center (ERDC) 6.2 Remote Assessment of Infrastructure for Ensured Maneuver (RAFTER) Program managed by Ms. Danielle Whitlow ERDC Geotechnical and Structures Laboratory (GSL). Dr. Sally Shoop was the technical monitor. This work is continuing under project number 471941, “Remote Assessment of Snow Mechanical Properties” and “Mobility in Peat and Northern Soils,” under the Entry and Sustainment in Complex Contested Environments Program managed by Dr. John Rushing, GSL.

The work was performed by the Force Projection and Sustainment Branch (CEERD-RRH) and the Terrestrial and Cryospheric Sciences Branch (CEERD-RRG) of the Research and Engineering Division (CEERD-RR) and the Terrain and Ice Engineering Group of the Remote Sensing / Geographic Information System Center of Expertise (CEERD-RS), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. Harley Cudney was Acting Chief, CEERD-RRH; Dr. John Weatherly was Chief, CEERD-RRG; Mr. Jared Oren was Acting Chief, CEERD-RR; Mr. Stephen Newman was lead for the Terrain and Ice Engineering Group; and Mr. David Finnegan was Chief, CEERD-RS. The Deputy Director of ERDC-CRREL was Mr. David B. Ringelberg, and the Director was Dr. Joseph L. Corriveau.

Dr. Susan Frankenstein and Dr. John Weatherly, CRREL, provided manuscript review comments.

COL Ivan P. Beckman was Commander of ERDC, and Dr. David W. Pittman was the Director.

Acronyms and Abbreviations

BAEM	Boreal Aspect of Ensured Maneuver
CL	Lean Clay
CRREL	Cold Regions Research and Engineering Laboratory
DoD	Department of Defense
ERDC	U.S. Army Engineer Research and Development Center
GSL	Geotechnical and Structures Laboratory
ISRIC	International Soil Reference and Information Center
MERRA-2	Modern-Era Retrospective Analysis for Research and Application Version 2
NDAWN	North Dakota Agricultural Weather Network
NRCS	Natural Resources Conservation Service
SMAP	Soil Moisture Active Passive
SOTER	Soil and Terrain
SOTWIS	SOTER + WISE
SSURGO	Soil Survey Geographic Database
UFC	Unified Facilities Criteria
USDA	U.S. Department of Agriculture
USCS	Unified Soil Classification System
WISE	World Inventory of Soil Emission Potentials

Unit Conversion Factors

Multiply	By	To Obtain
British thermal units (International Table)	1,055.056	joules
degrees (angle)	0.01745329	radians
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
inches	0.0254	meters
miles (U.S. statute)	1,609.347	meters
pounds (mass) per cubic inch	2.757990 E+04	kilograms per cubic meter

1 Introduction

1.1 Background

To support mobility and maneuver activities in all seasons and on regional scales, the Army requires methods to assess the complex interaction between environmental conditions and terrain. Soil temperature and moisture are of interest to the Army because changes in ground strength affect mobility. Frozen soils can withstand heavy vehicle loads and provide major maneuver corridors while wet soils reduce traction and inhibit vehicle mobility. In addition, northern climates contain unconventional soil types with high gravel and organic contents that are not well understood in engineering terms. Global ground-condition data are required to meet Army needs in locations of interest; however, ground observations are very limited. Satellite-based observations (e.g., SMAP [Soil Moisture Active Passive]) provide global coverage but are relatively new and still require validation. Once those observations are validated, many years of observations are required to develop ground-condition climatologies.

1.2 Objective

In this study, we compare frost depths determined from measured soil temperatures at stations in North Dakota and Minnesota, frost depths determined from soil temperatures in a gridded worldwide reanalysis product, and modeled frost depths based on measured and reanalysis air temperature and soil moisture data. The modeled frost depths also require soil property information, which can be obtained from a number of sources. Our goals are to determine (a) the usefulness of reanalysis data for providing global estimates of frost depth and (b) the accuracy of frost depth model estimates based on either station or reanalysis air temperature data.

1.3 Approach

We begin by comparing the observed frost depth time series at one of the North Dakota sites with a simulation of frost and thaw depth by a coupled heat and moisture transport model originally developed for pavement design. This model does not allow users to include a layer of snow on the surface and will therefore compute deeper-than-actual frost depths in settings where snow is not cleared throughout the winter. Therefore, we use for most of the analyses a simpler model that allows a snow layer to be

specified but calculates only the maximum frost depth rather than the winter time series. These frost depths provide critical input into mobility models to understand the seasonal variation of soil conditions in regions of interest.

2 Methods

This study used North Dakota Agricultural Weather Network (NDAWN 2018a) stations as the ground observation network to compare with the Modern-Era Retrospective Analysis for Research and Application Version 2 (MERRA-2) (Global Modeling and Assimilation Office 2017) gridded re-analysis data. The network covers most of North Dakota and western Minnesota. In addition to using soil data from these sources, we also use air temperature data as input to two models to simulate frost depth. We begin by describing the coupled heat and moisture transport model FROSTB and comparing model frost depths with one year of data at Grand Forks, North Dakota (section 2.1). In the following sections we discuss the NDAWN and MERRA-2 data (sections 2.2 and 2.3), the MaxFrst maximum frost depth code (section 2.4), and the Harmonized World Soil Database (section 2.5) that we used for soil texture and density data. A number of other soil databases, including the Soil Survey Geographic Database (SSURGO) (Natural Resources Conservation Service [NRCS], n.d.), are available; but they are less accessible than the Harmonized World Soil Database. Additionally, the relative quality of the soil data in our region of interest from these sources is unknown. We provide in section 3 the results of our comparison between NDAWN and MERRA-2 temperature and moisture profiles and maximum frost depths and our comparison of modeled maximum frost depths. Section 4 is a discussion of these comparisons.

2.1 FROSTB

In the 1990s, researchers at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) developed the coupled heat and moisture model FROSTB to model frost and thaw depths, frost heave, and thaw settlement in pavements (Guymon et al. 1993). This is a one-dimensional model designed for pavement structures in areas of seasonal frost where the subsurface soil freezing and thawing occurs above the water table. A laboratory testing program was devoted to investigating soil frost susceptibility and was used to develop the frost heave and thaw weakening model in FROSTB. The testing program produced an extensive soils database for soil types, as classified by the Unified Soil Classification System (USCS), ranging from gravels to clays. However, the database has limited information on organic silt and organic clay soils and excludes peat soil types. FROSTB has been used to simulate pavement structure designs and to evaluate them to find solutions with a cost-effective long performance life.

FROSTB was one of three models adopted by the Enhanced Integrated Climatic Model to be used for pavement design (Lytton et al. 1989; Larson and Dempsey 1997) and continues to be used as part of the Mechanistic-Empirical Pavement Design Guide released in 2004. This illustrates the continued usefulness of the model and the underlying theory on freezing and thawing processes in multilayered soil structures. Listed below are the underlying assumptions and input parameters of FROSTB with further explanation provided in Guymon et al. (1993):

Assumptions

- FROSTB is intended for seasonally freezing and thawing soils below pavement structures, hence no vegetation or snow on the ground surface.
- Moisture transport in the unfrozen zone is governed by the unsaturated flow equation based upon continuity and Darcy's law.
- Moisture flow is by way of liquid movement; vapor flow is negligible.
- Moisture flow in the frozen zone is negligible, and there is no moisture loss or gain at the frozen soil surface.
- Soil deformation in the unfrozen zone is negligible.
- Soil pore water pressures in the freezing zone are governed by an unfrozen water content factor.
- All processes are single valued (i.e., there is no hysteresis).
- Heat transport in the entire soil column is governed by the sensible heat transport equation, including an advection term.
- Salt exclusion processes are negligible (i.e., the unfrozen water content is constant with respect to temperature).
- Phase-change effects and moisture effects can be modeled as decoupled processes.
- Freezing and thawing can be approximated as isothermal phase-change processes.

- During thawing, settlement in the thaw zone is dominant and consolidation effects are negligible.

Inputs

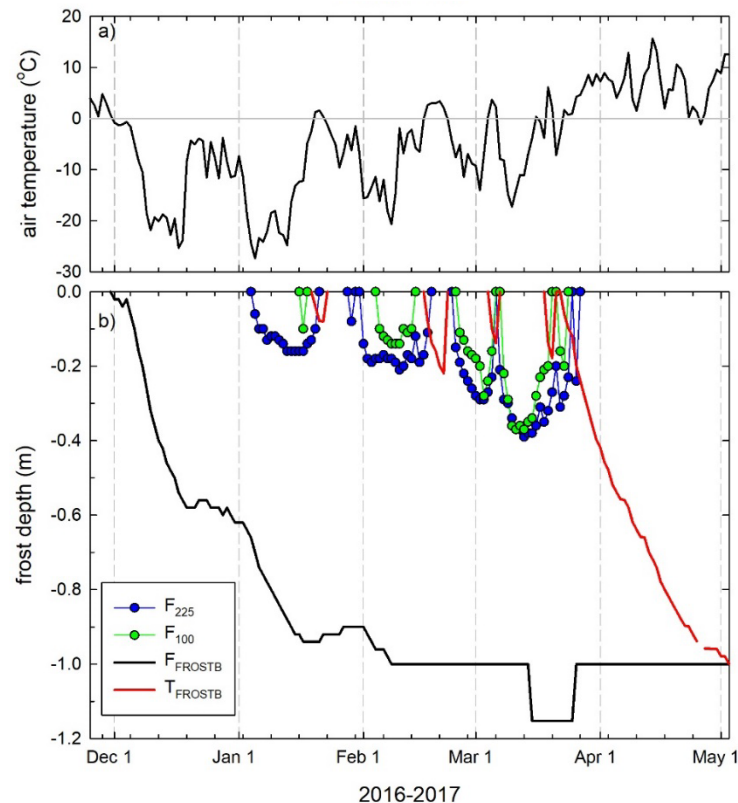
- Dry soil density—The dry density is assumed to be constant through the full depth of the structure. For a specified soil type, the dry density can be obtained from Appendix A in Guymon et al. (1993) or Table 2 in Frankenstein and Koenig (2004).
- Porosity—The soil porosity is determined from the void ratio.
- Soil thermal properties—Values for the heat capacity and thermal conductivity for dry mineral soils are required. Users may specify values. Kersten (1949) performed extensive laboratory testing to determine soil thermal properties on a wide range of soils typical of northern regions. The default values in FROSTB use the relationship established by DeVries (Guymon et al. 1993), which is a volumetric heat capacity of $0.2 \text{ Cal/cm}^3 \text{ }^\circ\text{C}$ ($8.37 \text{ J/m}^3 \text{ }^\circ\text{C}$) and a thermal conductivity of $17.0 \text{ Cal/cm hr }^\circ\text{C}$ ($1.98 \text{ W/m }^\circ\text{C}$).
- Soil moisture properties—The required soil moisture input parameters include the saturated permeability, a hydraulic conductivity multiplier, and an unfrozen water content factor. The hydraulic conductivity multiplier is used to describe the hydraulic conductivity within the soil freezing zone with a default value of 1.0. The unfrozen water content factor is the minimum volumetric unfrozen water content.
- Soil-water characteristics—Parameters to describe the soil-water characteristics are required. The best-fit parameters for the frost heave and thaw settlement submodel are provided by Gardner's function with coefficients A_w and α . There are two parameters for the unsaturated soil permeability function, A_k and β , also from Gardner's function.
- Representation—The soil structure is divided into nodes connected by elements.
- Initial conditions—For each node, initial conditions are given for the pore pressure head, temperature, and ice content.

- Surface boundary conditions—At the surface, daily air temperatures and factors to convert air temperatures to surface temperatures are provided.
- Bottom boundary conditions—A water table is used to define the pore water pressure head. The soil temperature is also specified.

We identified the soil type for the Grand Forks, North Dakota, NDAWN station in this agricultural area as a silty clay loam (NRCS 2017) per the U.S. Department of Agriculture (USDA) textural classification system. Because the soils in FROSTB use the USCS classification system, the silty clay loam is a lean clay (CL) (Garcia-Gaines and Frankenstein 2015). We used the default soil thermal properties. The total thickness of the soil structure was modeled as 6.1 m, chosen to be thick enough to minimize the effects of the assumed 2°C soil temperatures at the bottom boundary on the modeled frost depth. In the upper 1 m, the element length was 0.02 m; and below 1 m, the element length was 0.15 m. The initial conditions reflect the soil structure in a prefreeze state with the temperatures above freezing and no ice content. Two values were used for the factor to convert the average daily air temperature to a surface temperature for bare soil: 0.7 for freezing conditions and 1.8 for thawing conditions in the spring when the average daily air temperature was at or above freezing (DoD 2004; Andersland and Ladanyi 1994). The depth of the water table was estimated to be 0.82 m, consistent with the soil moistures at the beginning of the simulation.

We ran FROSTB with the daily temperature data for Grand Forks during the winter of 2016–2017, using the daily average air temperature beginning 23 November 2016, 7 days prior to the onset of freezing. Figure 1 shows the measured air temperatures along with the FROSTB frost depth (F_{FROSTB}) and thaw depth (T_{FROSTB}) time series and frost depths (F_{100} and F_{225}) calculated from soil temperature data from two thermocouple arrays at the station. The much greater FROSTB frost depths compared to the soil temperatures are likely due in part to the absence of snow cover in the FROSTB simulation. Note also the different frost depths from the two arrays at the site, perhaps attributable to differences in snow cover at the locations of these thermocouple arrays. The differences may also be from local differences in soil type and moisture or may be specific to the arrays themselves.

Figure 1. Winter of 2016–2017 at Grand Forks, North Dakota: (a) air temperature and (b) FROSTB-modeled frost and thaw depths and frost depths from the two soil temperature arrays at the station.



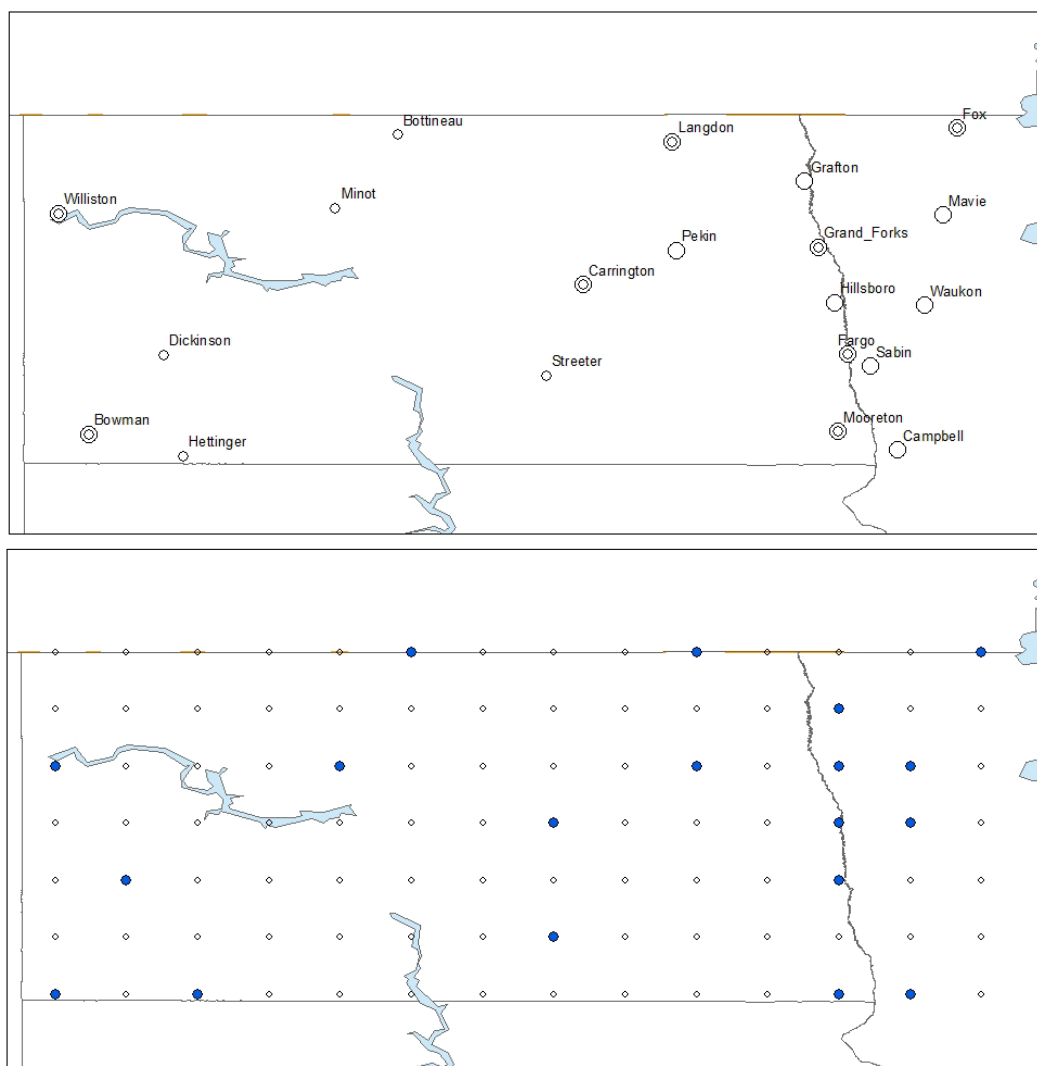
Because snow is not included in FROSTB, we used for the rest of this study a simpler model (MaxFrst) that allows for snow on the ground but calculates only the maximum frost depth. We apply this model to both the NDAWN and MERRA-2 air temperature data and compare the model results from the two datasets with each other and with the soil temperature data from these datasets.

2.2 NDAWN data

NDAWN currently has 91 stations in North Dakota and border regions of Montana and Minnesota with data beginning in 1989 at the original six stations (NDAWN 2018b). Each station is sited to be representative of the weather conditions (with the exception of rainfall) in the surrounding area within a radius of 32 km. At some of the NDAWN stations, both soil data and weather data are measured. Thirteen stations have soil temperature data at up to 14 depths, as deep as 2.25 m, including data for at least the

winter of 2017–2018. Fifteen stations have soil moistures and temperatures at up to six depths, as deep as 1 m, with data for at least the winter of 2017–2018. Figure 2 (top) maps the 20 unique stations, indicating which stations have deep soil temperature and which have soil moisture and temperature data. All stations also have air temperature data. We assume these temperatures are measured at 2 m above the ground surface, which is the standard height for air temperature data. We downloaded the daily average air temperature and the soil temperatures and moistures at 1200 CT.

Figure 2. NDAWN stations and MERRA-2 grid in North Dakota and Minnesota: (*top*) The *large circles* indicate NDAWN stations with soil moisture and temperature data to as deep as 1 m below the ground surface. The *small circles* are NDAWN stations with soil temperature data to depths as deep as 2.25 m. Eight sites marked by *double circles* have both sets of data. All 20 sites have data for at least the winter of 2017–2018. (*bottom*) MERRA-2 grid with *dark blue circles* indicating the grid points closest to each of the NDAWN stations.



2.3 MERRA-2 data

NASA's MERRA-2 is a recent replacement of the original MERRA and includes the assimilation of aerosol observations and improved representations of the stratosphere and cryospheric processes (Gelaro et al. 2017). The data begins in 1980 and extends to the present with a grid spacing of 0.5° (about 50 km) north–south and 0.625° longitudinally. As this reanalysis dataset covers the entire globe, it provides users with weather and soil data in regions where measurements are unavailable. We found the MERRA-2 grid point closest to each of the 20 NDAWN stations (Figure 2, bottom) and downloaded daily average temperatures, soil moistures, and snow-on-the-ground data. Air temperatures are at 2 m above ground and at the ground surface, which is the snow surface when there is snow on the ground. Snow is characterized by the depth and load, from which we calculated the snow density. Soil temperatures are reported as the average for each of six layers, increasing in thickness away from the ground surface. Figure 3 compares the MERRA-2 soil layers and NDAWN deep soil temperature depths. Volumetric soil moistures in MERRA-2 are reported as averages for three overlapping layers: top 0.02 m, top 1 m, and the entire soil profile.

Figure 3. MERRA-2 layers for soil temperatures and NDAWN depths for deep temperature measurements.

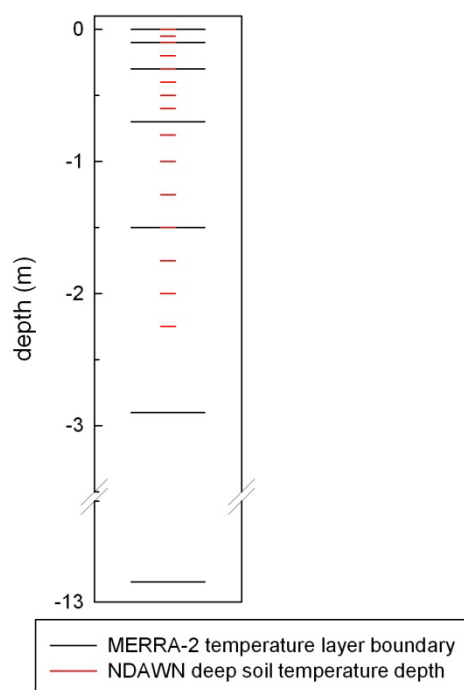


Table 1 lists the NDAWN stations and corresponding MERRA-2 grid points along with the distance between the grid point and the station. Note that Fargo and Sabin are closest to the same MERRA-2 grid point (46, -96.875).

Table 1. NDAWN stations and corresponding MERRA-2 grid points.

NDAWN Station	Latitude	Longitude	Elevation (m)	MERRA-2 Latitude	MERRA-2 Longitude	MERRA-2 Elevation (m)	Distance Between (km)
Bottineau	48.821	-100.760	451	49	-100.625	521	22.2
Bowman	46.200	-103.473	924	46	-103.75	927	30.8
Campbell	46.065	-96.370	306	46	-96.25	320	11.8
Carrington	47.509	-99.132	476	47.5	-99.375	506	18.3
Dickinson	46.895	-102.813	779	47	-103.125	774	26.4
Fargo	46.897	-96.812	275	47	-96.875	283	12.4
Fox	48.878	-95.850	317	49	-95.625	331	21.3
Grafton	48.412	-97.186	244	48.5	-96.875	271	24.9
Grand Forks	47.836	-97.067	258	48	-96.875	273	23.2
Hettinger	46.011	-102.643	841	46	-102.5	796	11.1
Hillsboro	47.353	-96.922	270	47.5	-96.875	280	16.7
Langdon	48.760	-98.345	493	49	-98.125	378	31.2
Mavie	48.121	-95.971	356	48	-96.25	320	24.7
Minot	48.181	-101.308	538	48	-101.25	571	20.5
Mooreton	46.224	-96.895	300	46	-96.875	325	25.0
Pekin	47.808	-98.311	459	48	-98.125	421	25.5
Sabin	46.794	-96.612	280	47	-96.875	283	30.4
Streeter	46.715	-99.450	607	46.5	-99.375	593	24.6
Waukon	47.326	-96.133	355	47.5	-96.25	331	21.3
Williston	48.133	-103.739	650	48	-103.75	653	14.8

2.4 Modeled maximum frost depth

Starting with a Fortran program that calculates maximum frost depth in English units (Cortez et al. 2000), we wrote a front end for the code to run it in batch mode and efficiently process the NDAWN and MERRA-2 data in metric units. This MaxFrst code includes two methods: Unified Facilities Criteria (UFC) 3-130-06 and Modberg, which is supposed to be more precise. The main difference between the methods is the weighted average of the soil properties in Modberg compared to a straight average in UFC 3-130-06.

In the batch mode version there are 30 layers of soil each 4 in. (10.2 cm) thick. The model requires soil texture and soil density data as well as soil moisture. Soil texture is specified as fine or coarse, and we added a medium texture with properties that are the average of the fine and coarse properties. There is a snow layer on top of the soil layers with a user-specified thickness. To calculate the maximum frost depth, F_x , for a winter, the user provides the soil moisture at the beginning of winter; the average annual air temperature, T_{avg} ; the accumulated freezing degree days, F_{DD} ; and the length of the freezing season, L_{fs} .

The snow depth and snow density used are the averages for the freezing season. The effect of snow is primarily to add an insulating layer on top of the soil, which reduces the frost depth. The thermal conductivity of the snow in MaxFrst is set at 0.02 Btu/(hr ft °F) (0.03 W/[m °C]), which is appropriate for low-density snow.

A user-specified factor N_f (similar to the n-factor in FROSTB) multiplying F_{DD} in MaxFrst should be set to 1 if there is snow on the ground and 0.7 if there is no snow. This factor is intended to make the air temperatures represent the temperature at the ground (or snow) surface.

The program iterates to determine the maximum frost depth, using only the number of soil layers necessary. All the input parameters are in metric units and converted to English units in the batch mode front end. The snow depth must be subtracted from the output value to obtain the frost depth in the soil.

2.5 Harmonized World Soil Database

For MaxFrst, we also need soil types, textures, and densities, which were obtained from the Harmonized World Soil Database, version 1.2 (Nachtergaele et al. 2009), for the locations of the NDAWN stations and the corresponding MERRA-2 grid points. These data are available at the Food and Agriculture Organization of the United Nations (2018) and provide a soil texture (coarse, medium, or fine) for the whole soil column, the soil type and density for the top 30 cm of topsoil, and the type and density of the subsoil below on a 30 arc-second rasters (~1 km) grid worldwide. The database provides two dry bulk soil densities (a) based on Saxton et al (1986) and (b) from SOTWIS. SOTWIS is the combination of data from the ISRIC (International Soil Reference and Information Center) SOTER (Soil and Terrain) database (ISRIC 2016a) and taxotransfer rules derived from

the ISRIC WISE (World Inventory of Soil Emission Potentials) database (ISRIC 2016b). The SOTWIS densities were calculated because of the perception that the Saxton density values tend to be too high.

Tables 2a and 2b show the soil properties for the NDAWN stations and MERRA-2 grid points, respectively. In Table 2b, the MERRA-2 points are labeled by their latitude and longitude and are in the same order as the NDAWN points they correspond to.

Table 2a. Soil types, textures, and densities from the Harmonized World Soil Database at the NDAWN stations.

Station	Soil Texture	Soil Type		Saxton Density (g/cm ³)		SOTWIS Density (g/cm ³)	
		Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
Bottineau	medium	silt loam	silt loam	1.35	1.37	1.20	1.36
Bowman	medium	loam	clay loam	1.38	1.33	1.20	1.18
Campbell	fine	clay (light)	clay (light)	1.36	1.36	1.21	1.30
Carrington	medium	silt loam	silt loam	1.35	1.37	1.20	1.36
Dickinson	medium	loam	clay loam	1.38	1.33	1.20	1.18
Fargo	fine	clay (light)	clay (light)	1.21	1.24	1.24	1.35
Fox	medium	loam	clay loam	1.27	1.36	0.15	0.11
Grafton	fine	clay (light)	clay (light)	1.21	1.24	1.24	1.35
Grand Forks	fine	clay (light)	clay (light)	1.36	1.36	1.21	1.30
Hettinger	medium	loam	clay loam	1.38	1.33	1.20	1.18
Hillsboro	fine	clay (light)	clay (light)	1.21	1.24	1.24	1.35
Langdon	medium	loam	loam	1.36	1.36	1.21	1.30
Mavie	medium	loam	clay loam	1.39	1.35	1.28	1.36
Minot	medium	loam	clay loam	1.38	1.33	1.20	1.18
Mooreton	fine	clay (light)	clay (light)	1.21	1.24	1.24	1.35
Pekin	medium	silt loam	silt loam	1.35	1.37	1.20	1.36
Sabin	fine	clay (light)	clay (light)	1.21	1.24	1.24	1.35
Streeter	coarse	sandy loam	sandy loam	1.59	1.54	1.47	1.52
Waukon	medium	loam	loam	1.36	1.36	1.21	1.30
Williston	medium	loam	loam	1.40	1.36	1.40	1.52

Table 2b. Soil types, textures, and densities from the Harmonized World Soil Database at the MERRA-2 grid points closest to each of the NDAWN stations.

Station	Soil Texture	Soil Type		Saxton Density (g/cm ³)		SOTWIS Density (g/cm ³)	
49, -100.625	medium	silt loam	silt loam	1.35	1.37	1.20	1.36
46, -103.75	medium	loam	clay loam	1.36	1.31	1.20	1.20
46, -96.25	fine	clay (light)	clay (light)	1.21	1.24	1.24	1.35
47.5, -99.375	medium	silt loam	silt loam	1.35	1.37	1.20	1.36
47, -103.125	medium	loam	clay loam	1.38	1.33	1.20	1.18
47, -96.875	fine	clay (light)	clay (light)	1.21	1.24	1.24	1.35
49, -95.625	medium	loam	clay loam	1.27	1.36	0.15	0.11
48.5, -96.875	medium	loam	loam	1.36	1.36	1.21	1.30
48, -96.875	medium	loam	loam	1.36	1.36	1.21	1.30
46, -102.5	medium	loam	loam	1.40	1.36	1.40	1.52
47.5, -96.875	fine	clay (light)	clay (light)	1.21	1.24	1.24	1.35
49, -98.125	medium	loam	loam	1.36	1.36	1.21	1.30
48, -96.25	medium	loam	clay loam	1.27	1.36	0.15	0.11
48, -101.25	medium	loam	loam	1.39	1.39	1.29	1.42
46, -96.875	fine	clay (light)	clay (light)	1.21	1.24	1.24	1.35
48, -98.125	medium	silt loam	silt loam	1.35	1.37	1.20	1.36
47, -96.875	fine	clay (light)	clay (light)	1.21	1.24	1.24	1.35
46.5, -99.375	medium	silt loam	silt loam	1.35	1.37	1.20	1.36
47.5, -96.25	coarse	sandy loam	sandy clay loam	1.52	1.41	1.47	1.52
48, -103.75	medium	loam	clay loam	1.38	1.33	1.20	1.18

3 Results

3.1 Comparison of NDAWN and MERRA-2 data

It is useful to compare the NDAWN and MERRA-2 temperature and moisture profiles. The NDAWN stations are supposed to be representative of the weather conditions, with the exception of rainfall, within a 32 km radius. Each MERRA-2 grid point at these latitudes represents a region that is about 50 km by 50 km. Soil temperatures are affected by moisture in the soil, which depends on weather (including rainfall), soil type, and vegetation. As shown by comparing Tables 2a and 2b, soil types are sometimes different at the NDAWN stations and the nearest MERRA-2 grid point. Vegetation information is not provided for either NDAWN stations or the MERRA-2 grid.

Figure 4 compares MERRA-2 and NDAWN air and soil temperatures and soil moistures for the first of each month from September 2017 through June 2018 to capture the evolution from fall to winter to spring at Mooreton, North Dakota, which has both deep soil temperature and soil moisture and temperature data. The NDAWN and MERRA-2 air temperatures at 2 m above ground are similar during these ten months. The biggest difference between the NDAWN and MERRA-2 soil temperatures is in June when the deep MERRA-2 temperatures are significantly lower. The NDAWN soil moistures tend to be wetter than the MERRA-2 moistures and vary significantly with depth, perhaps indicating varying soil properties with depth. Because the MERRA-2 values are averages over the top 2 cm, top 1 m, and entire soil profile, the MERRA-2 moisture variation with depth is subtle. Note that the MERRA-2 moistures are plotted in this figure as though they are in distinct rather than overlapping layers so that the small variation with depth that there is can be seen. Figure 5 is a similar plot for Langdon, North Dakota, north-northwest of Mooreton and at a higher elevation. At Langdon, the January MERRA-2 temperatures near the surface are lower than the corresponding NDAWN temperatures, perhaps because the MERRA-2 grid point is 115 m higher than the Langdon station, but the profiles in June match well. Soil moistures for this location are smaller than for Mooreton, and the NDAWN and MERRA-2 values are more similar than at Mooreton.

Figure 4. Soil temperature and moisture profiles at Mooreton, North Dakota, on the first of each month from 1 September 2017 to 1 June 2018. The profiles also include air temperatures at 2 m above ground and the surface temperature. For MERRA-2, the surface temperature is at the surface of the snow layer, when there is snow.

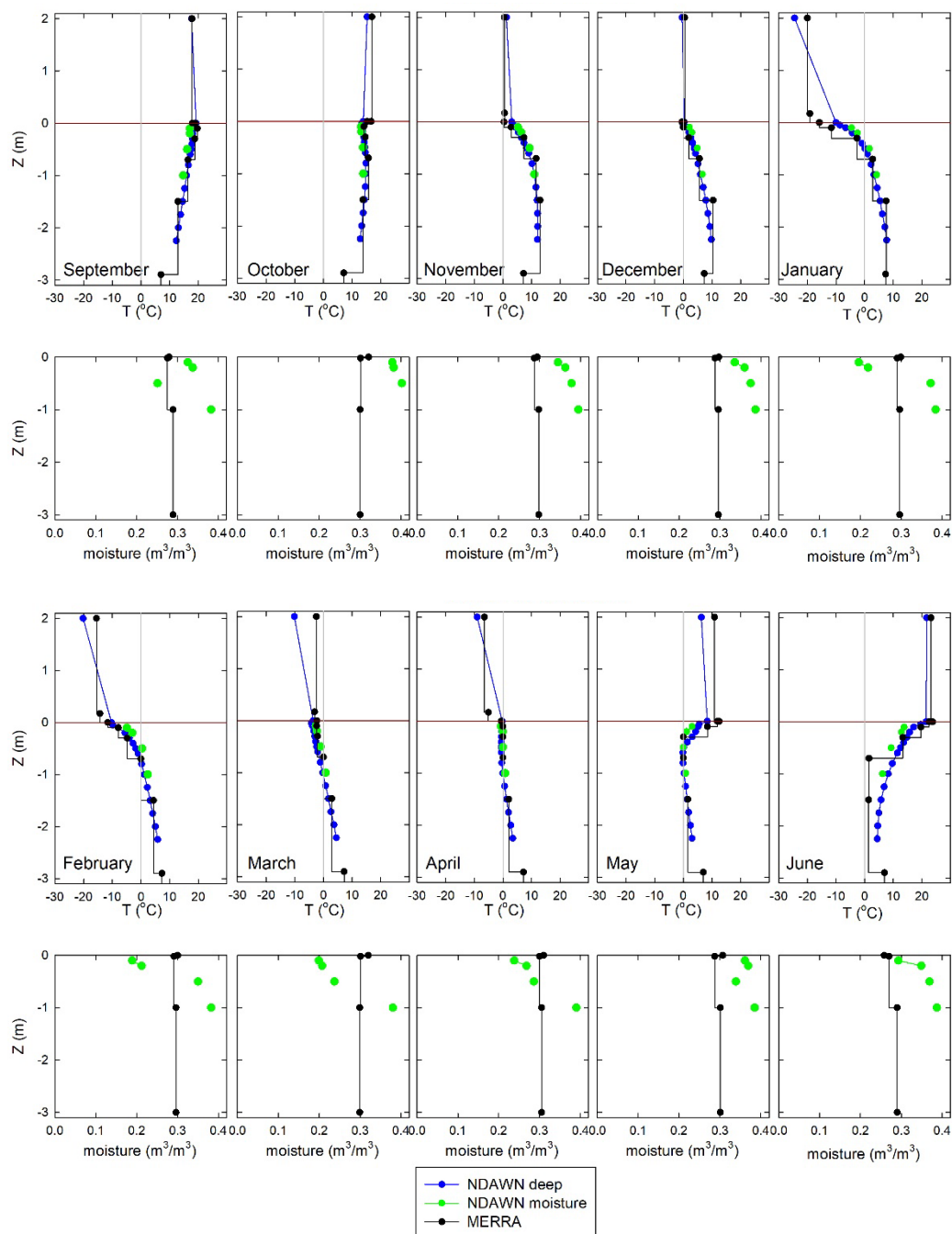


Figure 5. Soil temperature and moisture profiles at Langdon, North Dakota, on the first of each month from 1 September 2017 to 1 June 2018. The profiles also include air temperatures at 2 m above ground and the surface temperature. For MERRA-2, the surface temperature is at the surface of the snow layer, when there is snow.

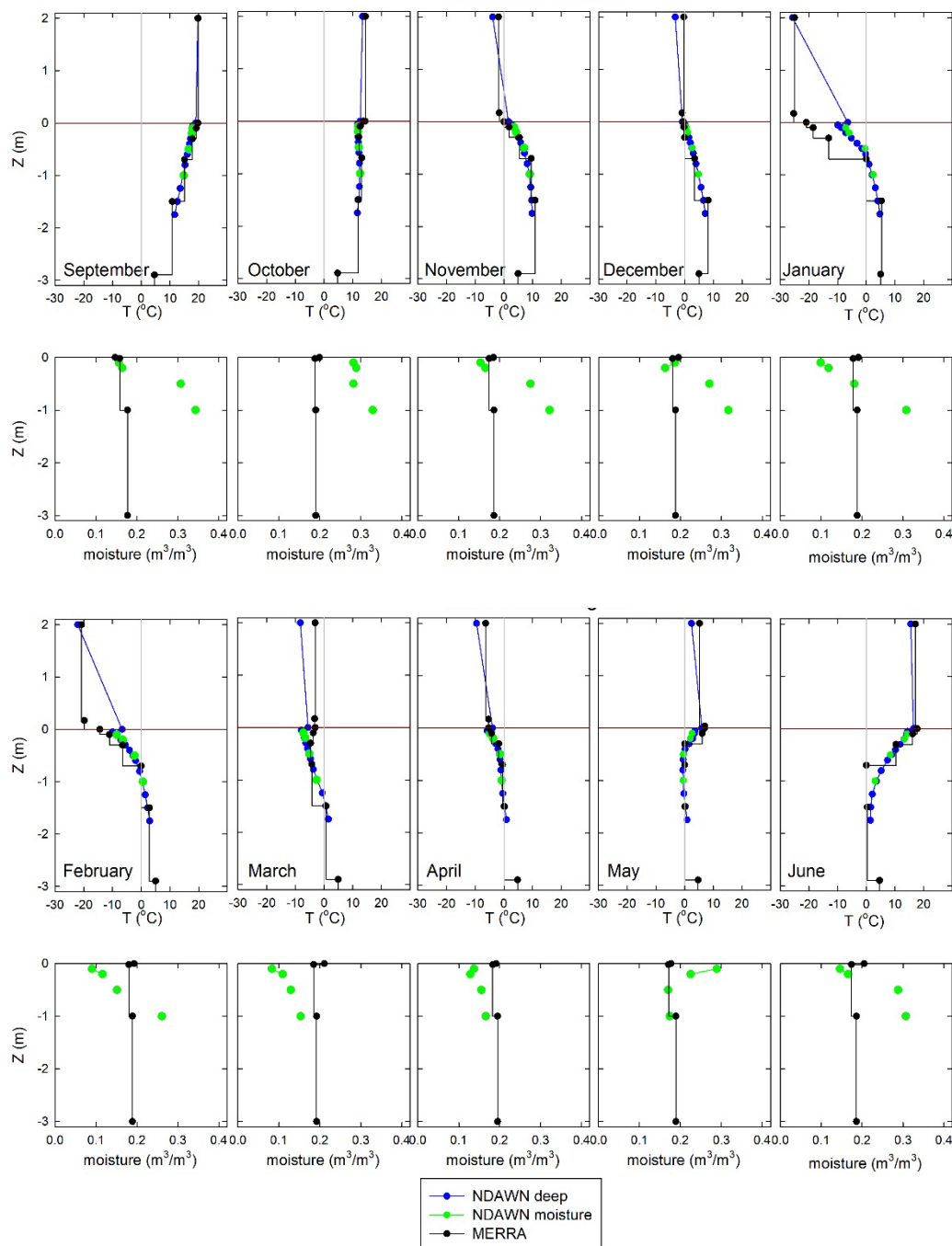


Figure 6 is a comparison of the 1 March 2018 profiles for all 20 NDAWN stations. The available NDAWN data vary from station to station because only some of the stations measure both deep soil temperatures and soil moistures. Users of the NDAWN data are warned that soil moisture data

when the soil is frozen are not valid. Because the top meter of soil is below freezing at most of the stations, the plotted moistures are not generally valid. Figure 7 plots the moistures on 1 October 2017, before the weather turns cold, for the 20 stations.

Figure 6. Temperature and moisture profiles at all 20 NDAWN stations and corresponding MERRA-2 grid points on 1 March 2018: stations 1 through 10.

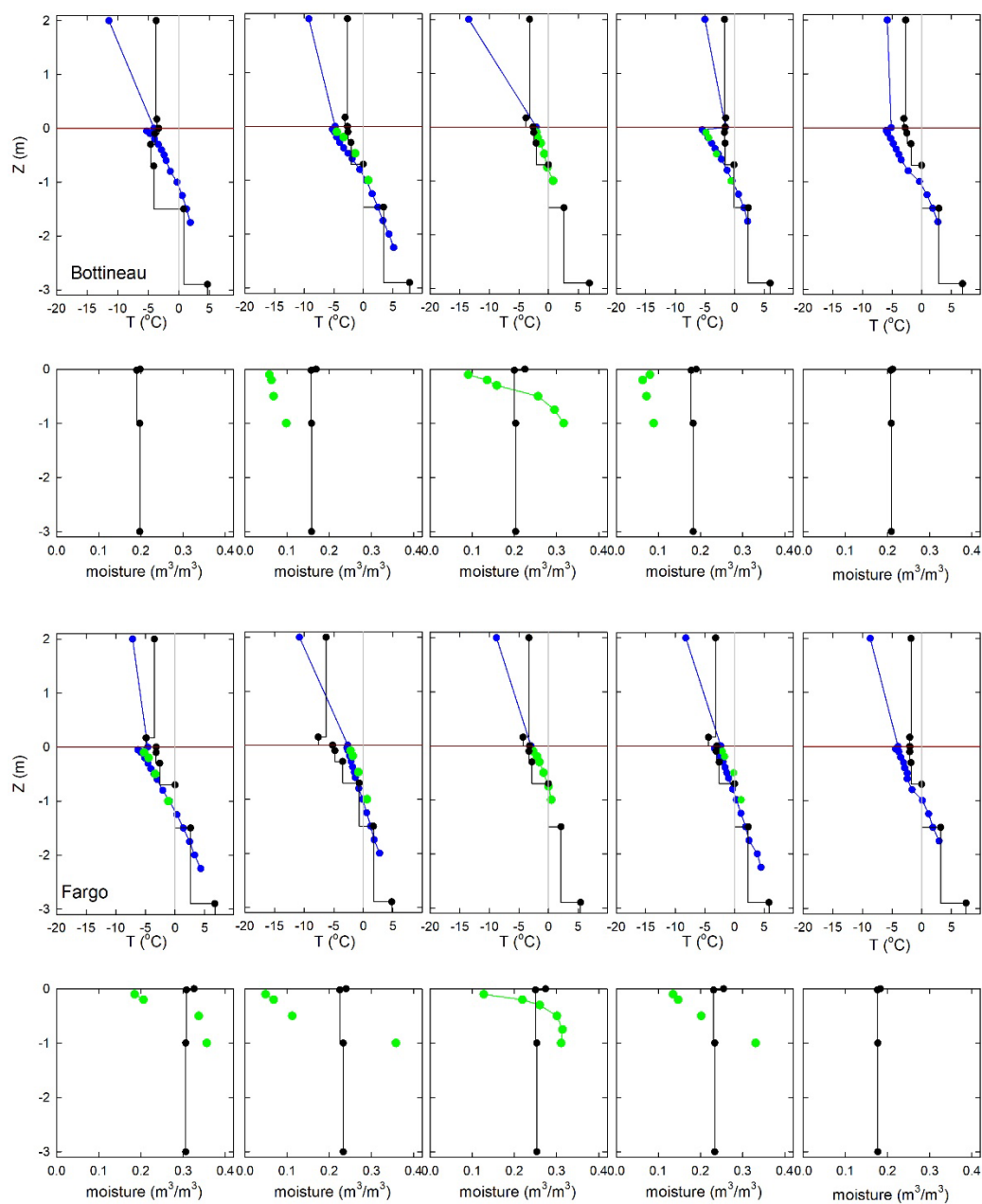


Figure 6 (cont.). Temperature and moisture profiles at all 20 NDAWN stations and corresponding MERRA-2 grid points for 1 March 2018: stations 11 through 20.

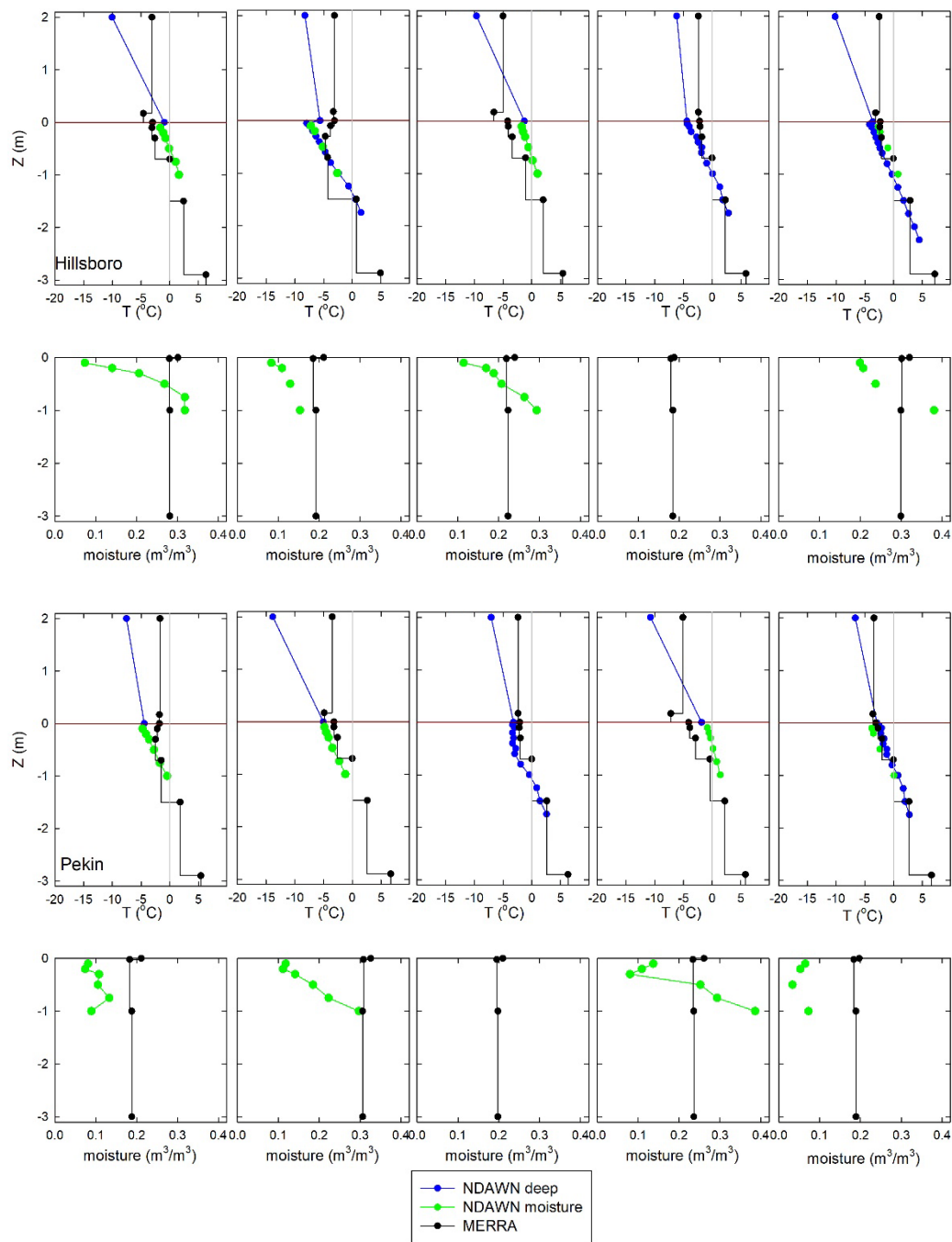
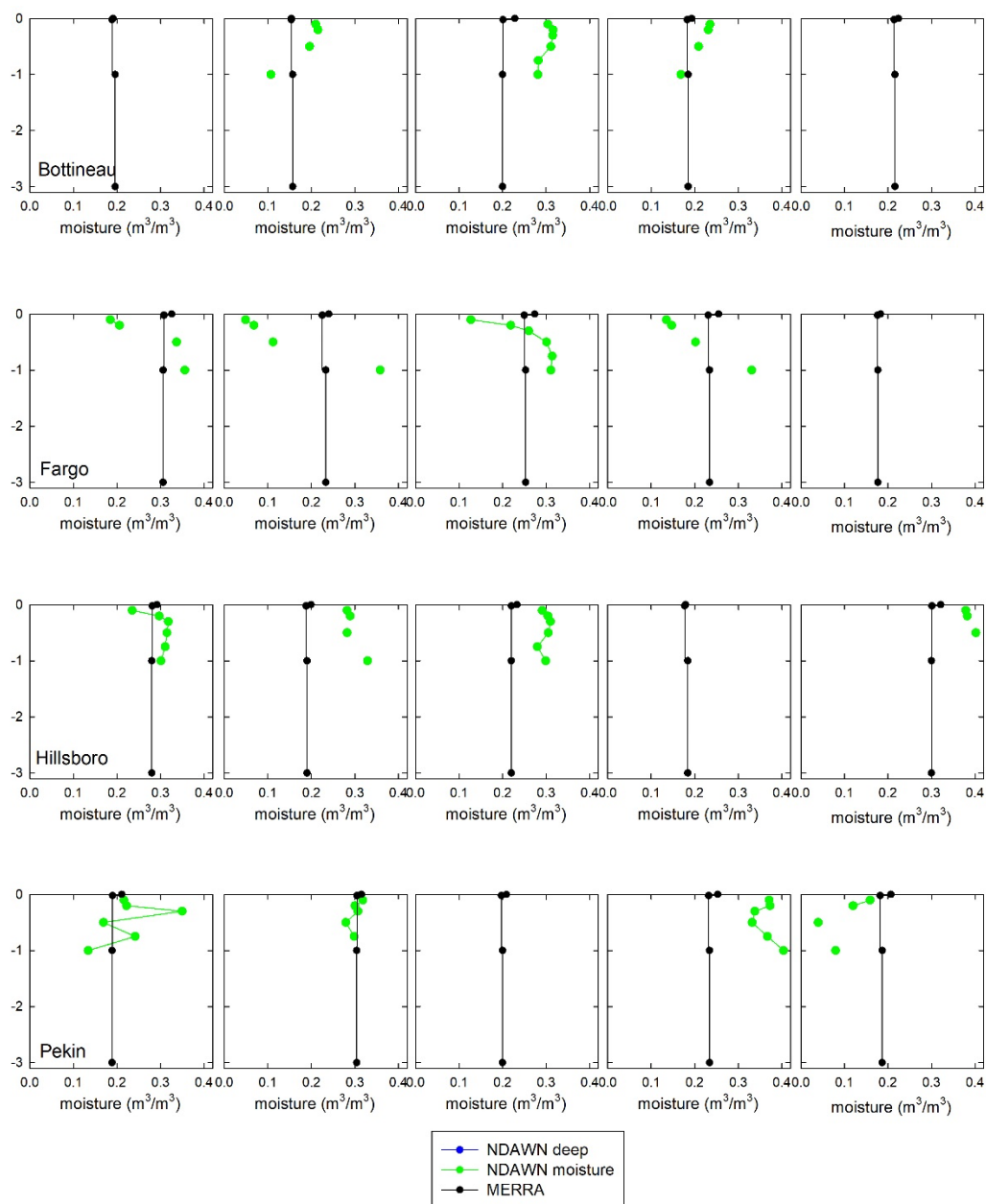


Figure 7. NDAWN and MERRA-2 moisture profiles for 1 October 2017. Both NDAWN and MERRA-2 soil temperatures on this date were typically 15°C down to about 1.5 m.

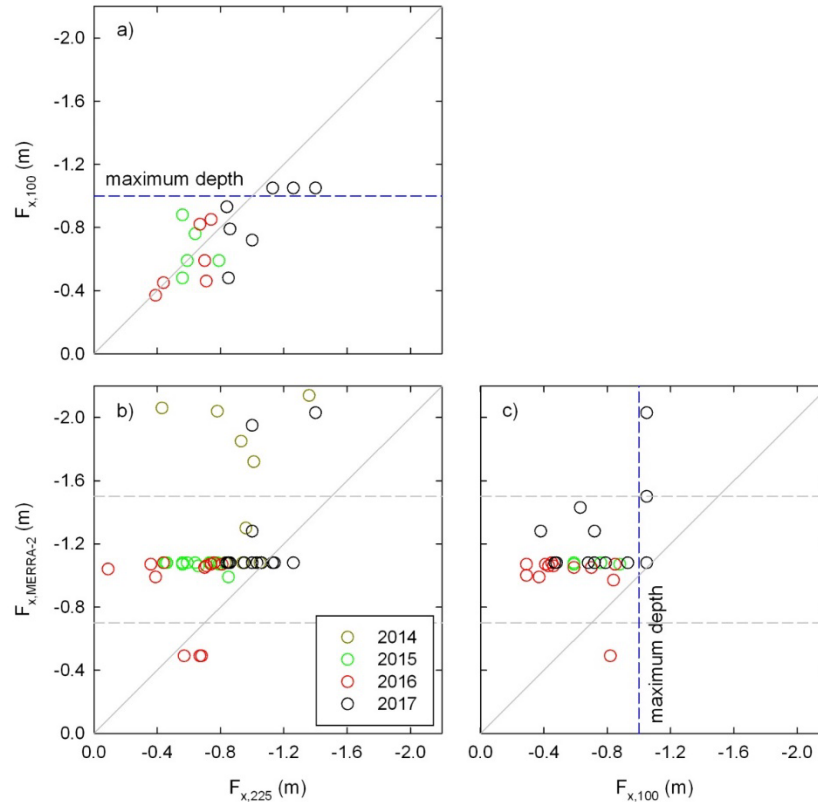


For all the NDAWN stations and the corresponding MERRA-2 grid points, we determined the maximum frost depth for each winter using the deepest depth of the -0.3°C isotherm. At 0°C , the latent heat of fusion might not yet have been removed, and the soil moisture might still be liquid. The maximum depth of the -0.3°C isotherm averages 0.08 m shallower than the 0°C isotherm, with a range from 0.03 to 0.16 m. The soil temperature is sometimes lower than -0.3°C at the deepest depth with data (1 m) at the moisture sites. When that occurs, the calculated frost depth defaults to 1.05 m. For the MERRA-2 points, we assigned the average temperature of the deepest soil layer to the top of that layer (2.9 m below ground surface). For all the other layers, we assigned the average temperature to the middle of the layer. Figure 8 compares for all the available data the maximum frost depths determined by interpolation from the measured soil temperatures from these three sources. Figure 8a compares measurements at the NDAWN sites that have both deep soil temperature and moisture data. Ideally, the frost depths would fall on the diagonal except for the cases with the 1 m limit at the moisture sites (dashed line). A least-squares best fit using the cases where the 1 m limit was not exceeded (16 in three years) results in

$$F_{x,100} = -0.35 + 0.43F_{x,225},$$

where $F_{x,225}$ and $F_{x,100}$ are the maximum frost depths at the deep temperature and moisture sites, respectively. The coefficient of determination $R^2 = 0.35$ for this fit indicates that the maximum frost depth at the deep temperature sites explains only 35% of the variation in maximum frost depth at the moisture sites. Figure 8b and c, which compare the MERRA-2 maximum frost depths with the NDAWN measurements, show a preponderance of MERRA-2 frost depths near 1.1 m. This results from MERRA-2 data with $T = 0^{\circ}\text{C}$ in soil layer 4, extending from -0.7 to -1.5 m, and a higher temperature in layer 5 below. The top and bottom of soil layer 4 are shown as dashed gray lines in the plots.

Figure 8. Maximum frost depths determined from soil temperature data for (a) collocated NDAWN moisture sites (measurements to 100 cm) and deep soil temperature sites (measurements to 225 cm), (b) MERRA-2 vs. deep soil temperature sites, and (c) MERRA-2 vs. NDAWN moisture sites. The *dashed gray lines* in (b) and (c) show the extent of MERRA-2's soil layer 4. The *dashed blue lines* in (a) and (c) show the maximum depth of temperature measurements at the moisture sites.



3.2 Modeled maximum frost depths

We used the Modberg algorithm (DeWalle and Rango 2008) in the MaxFrst Fortran program to model maximum frost depths using NDAWN and MERRA-2 weather data with MERRA-2 snow depths. As discussed in Section 2.4, we determined average snow depths and average snow densities for the duration of the freezing season for each year, calculating both standard and weighted means. There is little variation in the average freezing season snow depths among the grid points and from year to year, so Table 3 shows the average values for 2012 through 2017 for each of the 20 MERRA-2 points along with their standard deviations. Because of the consistency of these values, we used a 17 cm snow depth to model maximum frost depth at all stations and grid points for all years. The corresponding MERRA-2 snow densities are quite low, 100 kg/m³ and smaller. For our initial MaxFrst analyses, we used the default snow thermal conductivity

($k = 0.02 \text{ Btu}/[\text{ft } ^\circ\text{F}]$), which is consistent with a very low-density snow pack. Thermal conductivities of snow are reported in Cote et al. (2012), who compare their results to relationships from Sturm et al. (1997). For snow densities up to about $400 \text{ kg}/\text{m}^3$, the thermal conductivities from those two sources are essentially the same with $k = 0.03 \text{ W}/(\text{m K})$ ($0.02 \text{ Btu}/[\text{ft } ^\circ\text{F}]$) for $\rho = 50 \text{ kg}/\text{m}^3$ and $k = 0.14 \text{ W}/(\text{m K})$ ($0.08 \text{ Btu}/[\text{ft } ^\circ\text{F}]$) for $\rho = 310 \text{ kg}/\text{m}^3$.

Table 3. Means and standard deviations of the mean snow depth for the freezing season for the winters of 2012 through 2017 from MERRA-2.

MERRA grid	Mean (m)	St. Dev (m)
49, -100.625	0.18	0.02
46, -103.75	0.17	0.01
46, -96.25	0.17	0.01
47.5, -99.375	0.17	0.01
47, -103.125	0.16	0.01
47, -96.875	0.17	0.00
49, -95.625	0.17	0.01
48.5, -96.875	0.17	0.00
48, -96.875	0.17	0.00
46, -102.5	0.17	0.01
47.5, -96.875	0.17	0.00
49, -98.125	0.17	0.00
48, -96.25	0.17	0.00
48, -101.25	0.18	0.03
46, -96.875	0.17	0.01
48, -98.125	0.17	0.00
47, -96.875	0.17	0.00
46.5, -99.375	0.18	0.03
47.5, -96.25	0.17	0.01
48, -103.75	0.16	0.01

We specified soil moistures for the model layers based on the values on 1 October. For NDAWN stations without measured soil moistures on that date, we used the MERRA-2 values from the nearest grid point. Table 4 shows the input data (temperature parameters and volumetric moisture) for the NDAWN stations for 2017. Figure 9 compares the modeled maximum frost depths to the maximum frost depths determined from the soil temperature data at the deep temperature and moisture sites for three snow-on-the ground scenarios. The modeled frost depths in (a) and (b) are

for 17 cm of snow on the ground, with $N_f = 1$, with the default snow thermal conductivity in (a) and four times that value in (b). If we instead use a snow depth 25% as deep, modeled frost depths are essentially the same as in (b). The frost depths in (c) result from a simulation with no snow on the ground with $N_f = 0.7$. The simulation that agrees best with the measured frost depths is the one with snow thermal conductivity consistent with $\rho = 310 \text{ kg/m}^3$. Better fits to the observed maximum frost depths would be obtained with a somewhat less insulating layer of snow at many of the NDAWN stations.

We can also compare the modeled NDAWN maximum frost depths with those obtained using the MERRA-2 air temperature data and soil moistures from the corresponding grid points. This comparison is shown assuming 17 cm of snow with density $\rho = 310 \text{ kg/m}^3$ for the winters of 2012 through 2017 in Figure 10. The scatter in maximum frost depths is greatest in 2012 and 2013 with relatively high F_{DD} , with high MERRA-2 compared to NDAWN values in 2013 and relatively low values in 2012.

Table 4. Soil moistures and air temperature parameters for MaxFrst for the winter of 2017–2018.

Station	Volumetric Moisture (top 20 cm)	Volumetric Moisture (below 20 cm)	T (°C)	F_{DD} (°C-day)	L_{fs} (day)
Bottineau	0.17	0.18	2.9	1783	169
Bowman	0.21	0.15	4.9	1145	168
Campbell	0.31	0.30	5.5	1272	165
Carrington	0.23	0.19	4.4	1472	169
Dickinson	0.20	0.19	5.4	1114	167
Fargo	0.36	0.40	5.7	1292	165
Fox	0.21	0.38	2.8	1837	171
Grafton	0.31	0.28	3.9	1601	171
Grand Forks	0.34	0.36	4.6	1519	171
Hettinger	0.17	0.18	5.5	1033	133
Hillsboro	0.27	0.31	4.3	1585	172
Langdon	0.29	0.31	2.8	1821	172
Mavie	0.30	0.30	3.5	1723	171
Minot	0.18	0.18	4.3	1501	169
Mooreton	0.38	0.41	5.4	1275	165
Pekin	0.22	0.22	3.4	1709	172
Sabin	0.31	0.30	5.4	1344	165
Streeter	0.21	0.20	4.3	1450	170
Waukon	0.37	0.36	4.3	1540	165
Williston	0.14	0.06	4.9	1364	163

Figure 9. MaxFrst and measured maximum frost depths at the NDAWN sites for 2017. The *dashed blue line* is the maximum depth of data at the moisture sites. The modeled values in (a) and (b) are affected by a 17 cm layer of snow on the ground for the duration of the freezing season. Thermal conductivity of snow is the default value in the model (0.02 Btu/[ft °F]) in (a) and 0.08 Btu/(ft °F) in (b). The ground is bare in the simulation, resulting in the frost depths in (c).

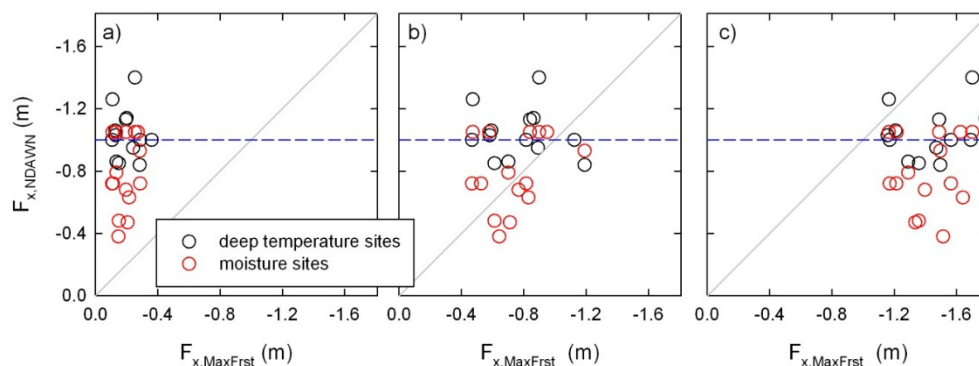
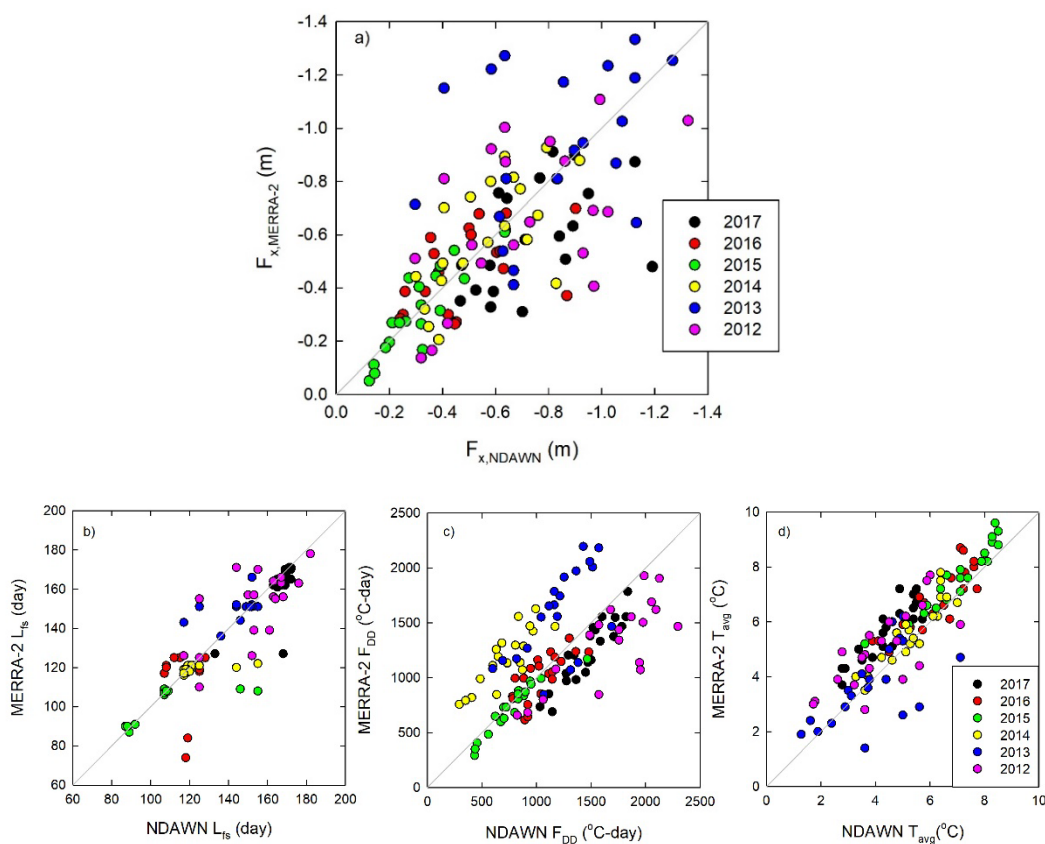
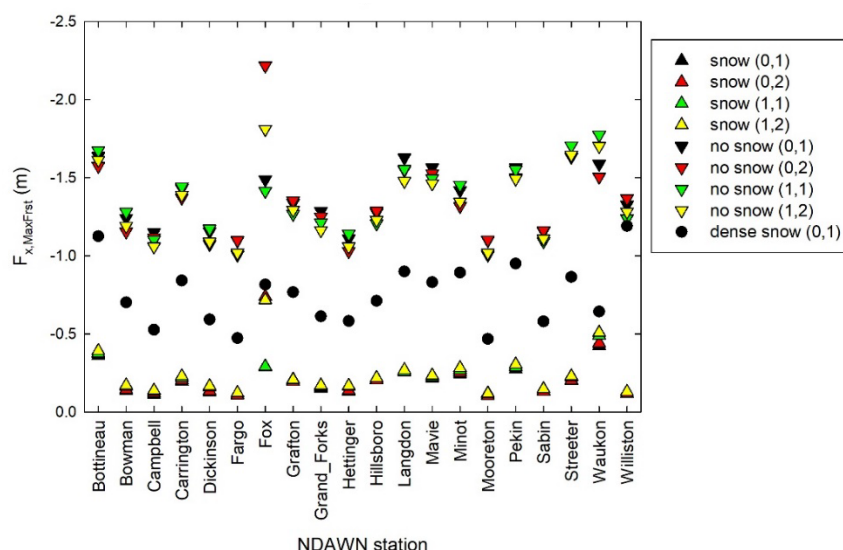


Figure 10. (a) Modeled maximum frost depths compared at NDAWN stations and corresponding MERRA-2 grid for 2012 through 2017 with a 310 kg/m³ snow layer 17 cm deep. The corresponding variation for each year in the temperature parameters used in the model are shown in plots (b) L_{fs} , (c) F_{DD} , and (d) T_{avg} .



Modeled frost depths also depend on the soil density choice in the Harmonized World Soil Database and the solution option chosen in MaxFrst. Figure 11 shows the effect of those choices using data for 2017. Maximum frost depths are shown for each NDAWN station for the four solutions (two soil densities and two solution choices) for no snow and 17 cm of low-density snow. It also shows the intermediate results for Saxton soil densities and the Modberg solution for high-density snow on the ground. Snow on the ground significantly reduces both the maximum frost depths and the effects of the soil density and solution type choices. However, the very low-density SOTWIS soils at NDAWN station Fox still result in a significant increase in maximum frost depth even with an insulating layer of snow on the ground.

Figure 11. Modeled maximum frost depths for the winter of 2017 with the temperature parameters and soil moistures in Table 4, using the two soil density choices and the two solution choices for 17 cm of low-density snow on the ground (Δ) and no snow (∇). The first number in the legend entries indicates the solution choice (0 = Modberg and 1 = UFC 3-130-06), and the second number indicates the soil density choice (1 = Saxton and 2 = SOTWIS). A $\bullet$ indicates results for high-density snow with the Modberg solution and Saxton soil density.



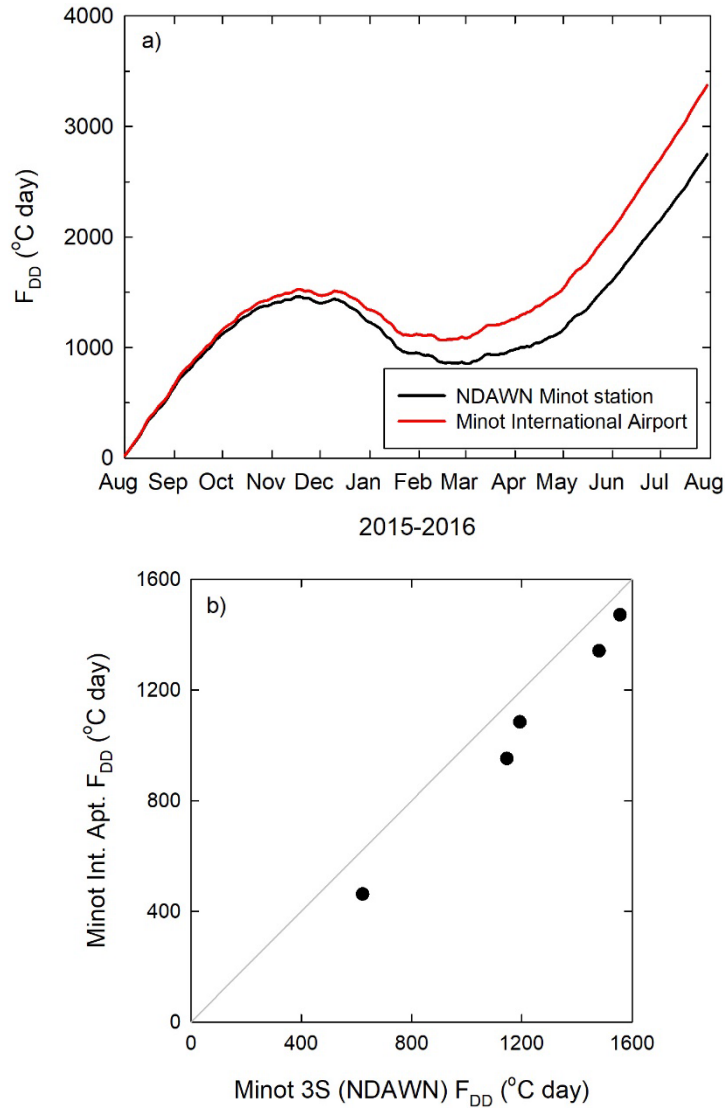
4 Discussion

Our analysis of measured, reanalysis, and modeled frost depths shows significant differences. Differences between soil temperature measurements on very local scales (meters) may be associated with soil variations on that scale. Differences in local weather on the scale of ones to tens of kilometers may cause local variations in frost depths. The distances between the NDAWN weather stations and the closest MERRA-2 grid point are in this range, so the differences we see between the measured and gridded weather parameters may be real. The frost depth can be modeled from weather and soil data. We found that the depth of snow on the ground and the thermal conductivity of the snow have a significant effect on the maximum frost depth determined by MaxFrst. Local soil moisture and snow cover data may be necessary to obtain accurate simulated frost depths. We discuss each of these issues below.

The differences between the maximum frost depths determined from the collocated moisture sites and deep temperature sites seen in Figure 8a might be an indication of the variation in the soil temperature data on a small spatial scale, perhaps due to variations in soil, land cover, moisture, and snow at the NDAWN locations. In an analysis of data from the Oklahoma Mesonet, Godfrey and Stensrud (2008) say that soil temperature depends strongly on soil moisture, which in turn depends on soil texture, which can vary on scales of a few meters or less.

An example of the local variation of weather conditions is provided by comparing the NDAWN Minot station with the weather station at Minot International Airport 7 km to the north-northeast at an elevation of 523 m, which is 15 m lower. For the winter of 2015–2016, F_{DD} at Minot International Airport was 462°C-days compared to 622°C-days at the NDAWN Minot station (Figure 12a). Over recent years, the relative magnitudes of F_{DD} at these two locations have varied as shown in Figure 12b, indicating that Minot International Airport is consistently warmer than the nearby, slightly higher elevation, NDAWN station.

Figure 12. Comparison of F_{DD} at the NDAWN Minot stations compared to Minot International Airport (a) F_{DD} time series for 2015–2016 and (b) total F_{DD} for the winters of 2012–2013 through 2016–2017.



The NDAWN stations are sited to represent the local region within a radius of 32 km, and the MERRA-2 grid points are at a spacing of about 50 km. However, there are significant differences between the modeled frost depths using NDAWN temperature data and modeled values at the nearest MERRA-2 grid point, particularly in years with deep modeled frost depths. Figure 10 shows that the MERRA-2 values of T_{avg} are generally warmer than the NDAWN values while the L_{fs} values tend to agree well, and the MERRA-2 F_{DD} values are greater than the NDAWN values in two years (2013 and 2014) and smaller in two (2012 and 2017). Perhaps these

differences are indicative of local differences in spite of the intention that both datasets represent relatively large areas. Note that Follum et al. (2018) modeled and measured frost depths at six sites in a small, approximately 3 km by 4 km subbasin of a watershed in Vermont and found significantly different results among the sites over an elevation range of 170 m. In comparison, the NDAWN stations are between 12 and 31 km from the nearest MERRA-2 grid point, and the absolute difference in elevation averages 27 m with a range from 3 to 115 m.

The maximum frost depths determined from the 46 station-winters of soil temperatures at the deep temperature sites are significantly different from the maximum frost depths modeled from the air temperature data and snow depths. The modeled values using the high thermal conductivity snow layer are in the same range of depths as the values from the soil temperature data (Figure 9b), but a linear least-squares fit using the data from 2014 through 2017 has $R^2 = 0.13$. For the 28 station-winters of data at the moisture sites with temperature data indicating a frost depth less than 1 m, the results are similar with $R^2 = 0.18$. There are a number of factors that may contribute to this lack of agreement between measured and modeled frost depths:

- We are using snow depth reanalysis data from MERRA-2 that indicates consistent average snow depths during the freezing season in those four years for the grid points corresponding to the 20 stations. The fit might be improved if we had measured snow depth data specific to each site with corresponding density data to determine the local snow thermal conductivity. The variation of snow depth and density over the freezing season also affects the actual frost depth, but that variation is not included in the MaxFrst model.
- Soil textures and densities affect the modeled maximum frost depths. The possible magnitude of that effect is illustrated by the difference in the maximum frost depths obtained using the Saxton and SOTWIS soil densities. At NDAWN station Fox where the SOTWIS density is about 10% of the Saxton density, the modeled maximum frost depth based on SOTWIS is about 0.5 m deeper than with the Saxton soil density, for any amount of snow on the ground. These large soil density differences between Saxton and SOTWIS are not common. However, using soil data from a different database would likely affect the modeled maxi-

imum frost depths. We do not have site-specific soil data, but the differences between the frost depths at the stations with two soil temperature arrays may result from local soil type variations.

- We are characterizing the soil moisture for each winter for the model by the value on 1 October. Significant dry or wet weather after that date and before the ground begins to freeze might change frost penetration. It is also possible that the use of MERRA-2 soil moistures when NDAWN values are not available is contributing to the low R^2 values. A regression between the modeled and measured frost depths at the deep temperature sites using only the 16 station-winters with NDAWN soil moistures increases R^2 to 0.37 while the corresponding value for the 30 station-winters with MERRA-2 moistures is 0.12.
- Ground cover is not taken into account in MaxFrst. Follum et al. (2018) find that the inclusion of insulation by ground cover makes a significant difference in modeled frost depths in their Continuous Frozen Ground Index model. That model does not, however, include soil moisture.

In light of the significant differences between the modeled maximum frost depths and the soil temperature data, it is interesting to determine how they differ in their functional dependence on the air temperature and soil moisture parameters and how well those parameters explain the frost depths. The measured parameters that vary between sites and years are T_{avg} , L_{fs} , F_{DD} , and soil moistures in the topsoil (M_t) and subsoil (M_s). MaxFrst uses those parameters in an iterative calculation to determine the maximum frost depth. We used commercial software TableCurve3D to fit three-parameter equations to the modeled or measured maximum frost depths for pairs of the parameters above and the products F_{DD}/L_{fs} and $F_{DD}T_{avg}/L_{fs}$. For the 80 modeled maximum frost depths from 2014 through 2017, the best fit ($R^2 = 0.97$) with the simplest form is

$$F_{x, \text{MaxFrst}} = 1.24 - 0.0426\sqrt{F_{DD}} + 0.257 \ln M_s.$$

For the 46 maximum frost depths calculated from soil temperatures at the deep temperature stations during those years, F_{DD} and M_s do not explain the variation in F_{NDAWN} . Neither moisture parameter helps determine the measured maximum frost depths in combination with any of the temperature parameters. The best fit ($R^2 = 0.35$) is provided by

$$F_{x,\text{NDAWN}} = -0.55 - 8.67 \times 10^{-8} L_{fs}^3 - 0.0036 \left(\frac{F_{DD}}{T_{avg} L_{fs}} \right)^3.$$

A possible reason for the lack of a fit using the moisture data is the mix of moisture data from NDAWN measurements and MERRA-2 values. Using only the 16 cases with NDAWN moistures the fit improves and soil moisture becomes a significant parameter in determining the maximum frost depth. The best fit ($R^2 = 0.53$) simplest equation is

$$F_{\text{NDAWN}} = -1.17 + 0.00353 T_{avg}^2 - 1.77 M_s^2 \ln M_s.$$

There is no fit using soil moisture for the remaining 30 cases with soil moistures based on MERRA-2 data.

The MaxFrst maximum frost depths at Grand Forks without snow on the ground are consistent with the FROSTB results at Grand Forks. We might get better agreement between measured and modeled frost depths by replacing MaxFrst with FROSTB, which includes heat and moisture transport, if that code could be modified to allow for the inclusion of a snow layer with user-specified thickness and density during the freezing season. Another advantage of FROSTB over MaxFrst for mobility simulations is that it provides the timing of frost penetration and thawing during the season. This enhancement of FROSTB should be considered for future projects.

This project has shown that local differences in soil properties and weather, including accumulated snow, significantly affect maximum frost depths during the winter. Input data to models that calculate frost depth must capture these local variations to obtain values that are accurate enough for vehicle mobility evaluations. Gridded reanalysis weather data is a good supplement to weather station data, filling gaps between stations. Obtaining good soil moisture data is more difficult. While measured maximum frost depths are explained in part by measured soil moistures, MERRA-2 moistures do not contribute to explaining frost depth. Data from SMAP may help to fill this gap.

References

- Andersland, O. B., and B. Ladanyi. 1994. *An Introduction to Frozen Ground Engineering*. New York: Chapman and Hall.
- Cortez, E. R., M. A. Kestler, and R. L. Berg. 2000. "Computer Assisted Calculations of the Depth of Frost Penetration in Pavement-Soil Structures." In *Proceedings, Transportation Systems 2000 Workshop*, 28 February–3 March, San Antonio, Texas, 92–106.
- Cote, J., M. Rahimi, and J.-M. Konrad. 2012. "Thermal Conductivity of Compacted Snow." In *Proceedings, Cold Regions Engineering 2012: Sustainable Infrastructure Development in a Changing Cold Environment*, 19–22 August, Quebec City, Canada, 833–843. American Society of Civil Engineers.
- DeWalle, D. R., and A. Rango. 2008. *Principles of Snow Hydrology*. Cambridge, UK: Cambridge University Press.
- DoD (Department of Defense). 2004. *Calculation Methods for Determination of Depth of Freeze and Thaw in Soil: Artic and Subarctic Construction*. Unified Facilities Criteria (UFC) 3-130-06. Washington, DC: Headquarters, U.S. Army Corps of Engineers. <http://dod.wbdg.org/>.
- Follum, M. L., J. D. Niemann, J. T. Parno, and C. W. Downer. 2018. "A Simple Temperature-Based Method to Estimate Heterogeneous Frozen Ground within a Distributed Watershed Model." *Hydrology and Earth System Sciences* 22:2669–2688. <https://doi.org/10.5194/hess-22-2669-2018>.
- Food and Agriculture Organization of the United Nations. 2018. Harmonized World Soil Database v 1.2. FAO Soils Portal. <http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/>.
- Frankenstein, S., and G. G. Koenig. 2004. *FASST (Fast All-season Soil Strength)*. ERDC/CRREL SR-04-1. Hanover, NH: U.S. Army Engineer Research and Development Center.
- García-Gaines, R., and S. Frankenstein. 2015. *USCS and the USDA Soil Classification System*. ERDC/CRREL TR-15-4. Hanover, NH: U.S. Army Engineer Research and Development Center.
- Gelaro, R, W. McCarty, M. J. Suárez, R. Todling, A. Molod, L. Takacs, C. A. Randles, A. Darmenov, M. G. Bosilovich, R. Reichle, K. Wargan, L. Coy, R. Cullather, C. Draper, S. Akella, V. Buchard, A. Conaty, A. M. da Silva, W. Gu, G. Kim, R. Koster, R. Lucchesi, D. Merkova, J. E. Nielsen, G. Partyka, S. Pawson, W. Putman, M. Rienecker, S. D. Schubert, M. Sienkiewicz, and B. Zhao. 2017. "The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2)." *Journal of Climate* 30:5419–5454. <https://doi.org/10.1175/JCLI-D-16-0758.1>.

- Global Modeling and Assimilation Office. 2017. Modern-Era Retrospective Analysis for Research and Applications, Version 2. National Aeronautics and Space Administration, Goddard Space Flight Center, Global Modeling and Assimilation Office. Last modified 12 December 2017. <https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/>.
- Godfrey, C. M., and D. J. Stensrud. 2008. "Soil Temperature and Moisture Errors in Operational Eta Model Analyses." *Journal of Hydrometeorology* 9:367–387.
- Guymon, G. L., R. L. Berg, and T. V. Hromadka. 1993. *Mathematical Model of Frost Heave and Thaw Settlement in Pavements*. CRREL Report 93-2. Hanover, NH: U.S. Army Cold Regions Research and Engineering Laboratory.
- ISRIC (International Soil Reference and Information Centre). 2016a. Soil and Terrain (SOTER) Database Programme. Wageningen, The Netherlands: International Soil Reference and Information Centre. <https://www.isric.org/projects/soil-and-terrain-soter-database-programme>.
- . 2016b. World Inventory of Soil Emission Potentials (WISE). Wageningen, The Netherlands: International Soil Reference and Information Centre. <https://www.isric.org/projects/world-inventory-soil-emission-potentials-wise>.
- Kersten, M. 1949. *Laboratory Research for the Determination of the Thermal Properties of Soils*. St. Paul, MN: University of Minnesota Engineering Experiment Station. <http://hdl.handle.net/11681/6576>.
- Larson, G., and B. J. Dempsey. 1997. *Enhanced Integrated Climatic Model Version.2.0*. Urbana, IL: University of Illinois at Urbana-Champaign, Department of Civil Engineering. <http://hdl.handle.net/2142/95718>.
- Lytton, R. L., D. E. Pufahl, C. H. Michalak, H. S. Liang, and B. J. Dempsey. 1989. *An Integrated Model of the Climatic Effects on Pavements*. McLean, VA: Federal Highway Administration.
- Nachtergaele, F. H. van Velthuisen, L. Verelst, N. Batjes, K. Dijkshoorn, V. van Engelen, G. Fischer, A. Jones, L. Montanarella, M. Petri, S. Prieler, E. Teixeira, D. Wiberg, and X. Shi. 2009. *Harmonized World Soil Database, Version 1.1*. Food and Agriculture Organization of the United Nations, International Institute for Applied Systems Analysis, International Soil Reference and Information Center—World Soil Information, Institute of Soil Science—Chinese Academy of Sciences, and Joint Research Centre of the European Commission. <http://www.fao.org/docrep/018/aq361e/aq361e.pdf>.
- NDAWN (North Dakota Agricultural Weather Network). 2018a. Home. NDAWN Center. <https://ndawn.ndsu.nodak.edu/>.
- . 2018b. Network Overview. NDAWN Center. <https://ndawn.ndsu.nodak.edu/help-overview.html>.
- NRCS (Natural Resources Conservation Service). n.d. SSURGO/STATSGO2 Structural Metadata and Documentation. Accessed 16 November 2018. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053631.

- . 2017. Web Soil Survey. Last modified 21 August 2017.
<https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm>.
- Saxton, K. E., W. J. Rawls, J. S. Romberger, and R. I. Papendick. 1986. "Estimating Generalized Soil-Water Characteristics from Texture." *Soil Science Society of America Journal* 50:1031–1036.
- Sturm, M., J. Holmgren, M. Koenig, and K. Morris. 1997. "The Thermal Conductivity of Seasonal Snow." *Journal of Glaciology* 43:26–41.

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14. ABSTRACT Frozen soils can withstand heavy vehicle loads where the soils would otherwise be too weak. This is important as vehicle mobility models require input of the ground conditions to assess seasonal traffickability. Modeling these frost depths uses the properties of the soil along with any snow cover and air temperature data. Though weather stations with air temperature data are becoming more widespread, station density varies worldwide. Gridded reanalysis products, on the other hand, provide weather data on a global scale. Our objectives are (a) to evaluate the usefulness of reanalysis data to provide estimates of frost depth and (b) to determine the accuracy of simulated frost depths using either measured or reanalysis air temperature data. We use two one-dimensional models: a coupled heat and moisture flow model that simulates frost and thaw depths throughout the winter and a decoupled heat and moisture model that calculates the maximum frost depth. We compare frost depths determined from measured soil temperatures at stations in North Dakota and Minnesota and reanalysis frost depths with modeled values using both station and reanalysis air temperature data. Modeled frost depths depend more strongly on the depth and density of the snow layer than on the soil properties.					
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