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ERDC 6.2 Boreal Aspects of Ensured Maneuver (BAEM)

A Comparison of Frost Depth Estimates from Ground Observations and Modelling Using Measured Values and Reanalysis Data for Vehicle Mobility

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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).

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A comparison of Frost Depth Estimates from Ground Observations and Modelling Using Measured Values and Reanalysis Data for Vehicle Mobility

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ABSTRACT: Frozen soils can withstand heavy vehicle loads and provide major maneuver corridors in locations where the soils are otherwise too weak to support the loading conditions. Vehicle mobility models require input of the ground conditions to assess seasonal trafficability. Increasingly, measured air temperatures from weather station locations are becoming more widespread, however they lack a global gridded coverage. Similarly, ground profile measurements, such as soil temperature and moisture, are significant inputs to estimate depths of frost. New data products, such as gridded reanalysis data provides weather and soil data on a gridded global scale. This study compared frost depths determined from measured soil temperatures at stations in North Dakota and Minnesota with frost depths determined from soil temperatures from NASA's Modern Era Retrospective Analysis for Research Application Version 2 (MERRA-2). The objectives of the study were to evaluate the usefulness of the MERRA-2 data to provide estimates of frost depth, and to determine the accuracy of estimated frost depths from modelling using either measured air temperatures or reanalysis air temperature data. To estimate the maximum frost depth a one-dimensional decoupled heat and moisture flow model was used. Differences in estimated frost depth resulted from modelling when compared to the measured soil temperatures. These differences are likely due to the influence of a snow layer. The properties of the snow layer play an important role in estimating the depth of frost. Improved material properties of the snow layer are needed to more accurately estimate the depth of ground freezing.

KEY WORDS: Frost depth, global scale, mobility, modelling, reanalysis data.

1 INTRODUCTION

Methods are needed to assess the complex interaction between environmental conditions and the terrain to support vehicle mobility and maneuver activities in all seasons and on regional scales. Frozen soils can withstand heavy vehicle loads thus providing potential major maneuver corridors. Conversely, thawing or wet soils reduce soil strength and inhibit traction for vehicle mobility. These changes in soil strength are driven by the state of the ground, primarily soil temperature and soil moisture, in response to the seasonal climate. State of the ground computer models require ground condition data, however, while the number of ground observing stations continues to grow, the overall areas of coverage remain limited. Satellite-based observations providing global coverage are relatively new and still require validation. Once those observations are validated, many years of observations are required to develop ground condition climatologies.

In this study, frost depths determined from field sites that measured air and soil temperatures are compared with frost depths determined from a gridded worldwide reanalysis data product, and with frost depths modeled using the measured air and soil temperatures. The measured air and soil temperatures were from agricultural field sites located in the upper Midwestern United States. The National Aeronautics and Space Administration's (NASA) Modern Era Retrospective analysis for Research and Application Version 2 (MERRA-2) was the source for the gridded worldwide reanalysis data. A one-dimensional computer model was used to estimate the maximum depth of frost. Additional details are given in Barna et al. (in prep). There were two goals for the study, first to determine the usefulness of reanalysis data to provide estimated frost depths, and determine the accuracy of modelled frost depth using either measured station or reanalysis air temperature data. In regions of interest, the depth of frost is a critical input parameter into mobility models to understand the seasonal variation of soil conditions and soil strength.

2 APPROACH

The ground-based data used in this study came from stations within the North Dakota Weather Network (NDAWN) in the upper Midwest covering North Dakota and portions of western Minnesota (NDAWN 2018). The global gridded reanalysis data was from NASA MERRA-2. Both of these data sources provided the soil parameters and air temperature values used as input into the computer model to estimate the maximum depth of frost.

2.1 Weather and Soil Data

NDAWN consists of 91 stations located throughout North Dakota and along the border regions of neighboring states of Montana and Minnesota. With the exception of rainfall, each station within the network was sited to represent the weather conditions in the surrounding area within a radius of 32 km. All NDAWN stations collect air temperature data, some stations have weather histories dating back to 1989, and a number of stations are also instrumented to collect subsurface soil data to a maximum depth of 2.25m. This study used air and soil data from 20 stations with data collected through the winter of 2017-2018(Figure 1 top).

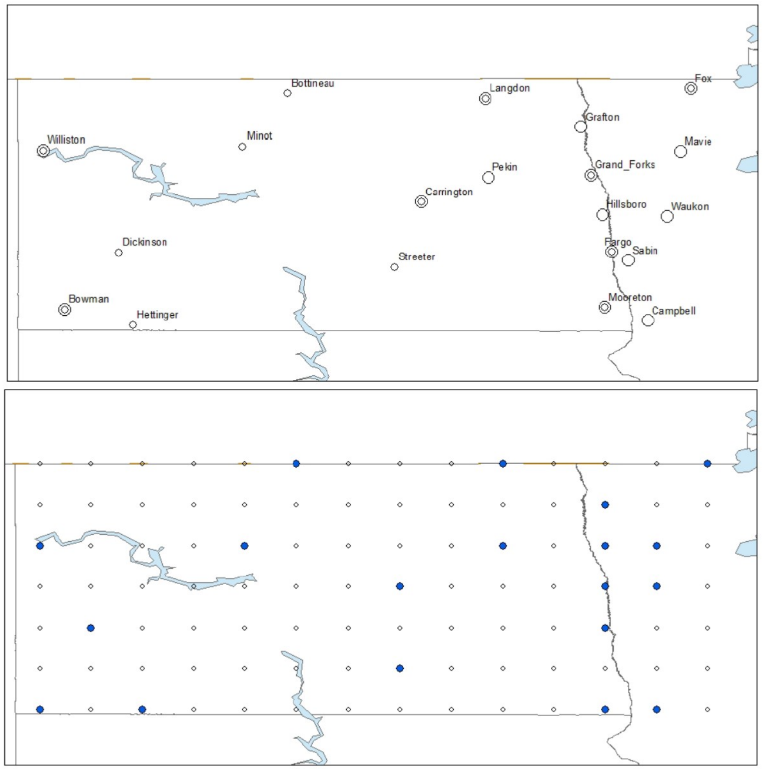

Figure 1. NDAWN stations and MERRA-2 grid in North Dakota and Minnesota: (*top*) the *large circles* indicate NDAWN stations with soil moisture and temperature data to 1 m. depth. The *small circles* are NDAWN stations with soil temperature data to 2.25 m depth. Eight sites marked by *double circles*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

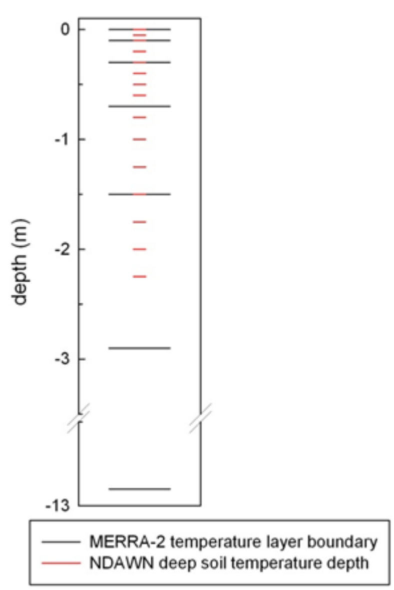

Figure 2. Soil temperature profile for MERRA-2 and instrumented NDAWN stations to 2.25m depth.

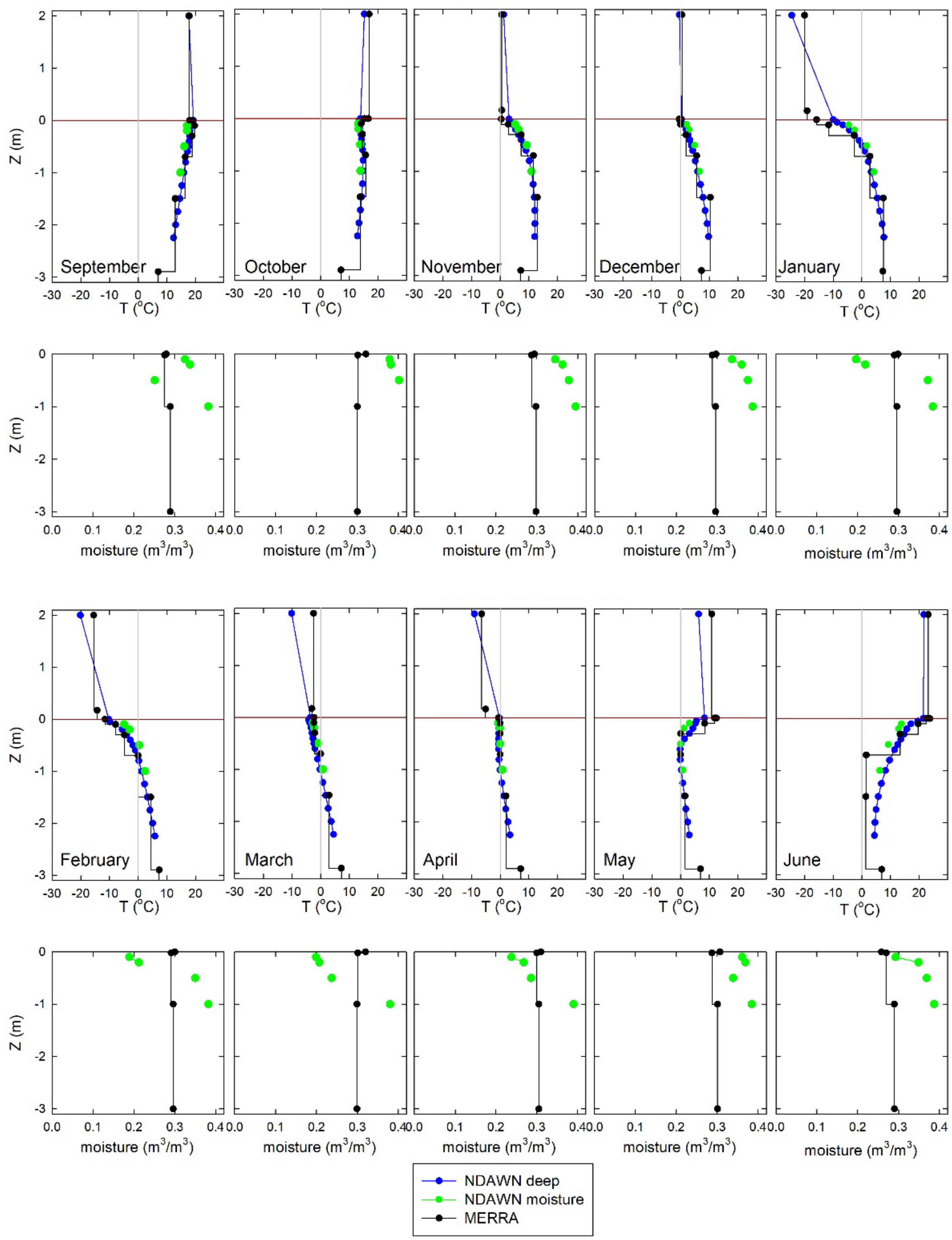

Figure 3. Soil temperature and moisture profiles at Mooreton, North Dakota, on the first of each month from 1 September 2017 to 1 June 2018. The profiles also include air temperatures at 2 m above ground and the surface temperature. For MERRA-2, the surface temperature is at the surface of the snow layer, when there is snow.

The MERRA-2 reanalysis dataset provides global coverage at a grid spacing of approximately 50 km (0.5°) in the north-south direction and 0.625° longitudinally (Global Modeling and Assimilation Office 2017), thus providing weather and soil data in areas otherwise unavailable. The MERRA-2 dataset is a revised version of the original

MERRA dataset, beginning in 1980 and includes the assimilation of modern hyperspectral radiance and microwave observations, and GPS-Radio Occultation datasets (Gelaro et al. 2017). Daily average temperatures, soil moisture, and snow depth data were downloaded for the nineteen grid points closest to the selected NDAWN stations (Figure 1 bottom). The distance between the NDAWN station and MERRA-2 grid point ranged from 11 to 31 km. Air temperatures from the MERRA-2 dataset are available at 2m above the ground surface and just above the ground surface. When a snow layer is present, the near-ground temperatures measure the snow surface.

The profile of the soil temperature for both NDAWN and MERRA-2 is illustrated in Figure 2. MERRA-2 subsurface soil temperatures are reported as the average value over each of six layers, where each layer increases in thickness. The locations of the NDAWN soil temperature sensors to a depth of 2.25 m are also shown in Figure 2. Within the soil profile, average volumetric soil moisture content values are reported within overlapping layers extending from the top to depths of 0.02 m, 1 m, and 13 m. Figure 3 compares the NDAWN and MERRA-2 air and soil temperatures, and soil moisture values with depth at Mooreton, North Dakota from September 2017 to June 2018.

2.2 Maximum frost depth computer model

The computer model to estimate the maximum frost depth (MaxFrst) is one-dimensional and based on the modified Berggren solution for heat flow (Andersland and Ladanyi 1994, Cortez et al. 2000, DoD 2004). The model decouples the subsurface heat and moisture flow simplifying the input values to freezing season parameters (average annual air temperature, average cumulative freezing degree days, and length of the freezing season) and soil parameters (soil type, gravimetric moisture content, and dry density). The model is capable of including an overlying snow layer. Air temperatures are converted to ground surface temperatures through the n-factor. Values of 0.7 and 1.0 were used to represent bare soil and a snow layer, respectively.

3 RESULTS

The estimated maximum depth of frost for the NDAWN sites is shown in Figure 4 (a-c). The effect of a 17 cm thick snow layer and the snow thermal conductivity value is shown in 4a and b. The default value for thermal conductivity of the snow layer in the model is 0.03 W/m-°C corresponding to a low-density snow pack and resulting maximum frost depth (Figure 4a). In Figure 4b, the thermal conductivity value of the snow layer is modified to 0.14 W/m-°C to reflect a higher-density snowpack (Cote et al. 2012, Sturm et al. 1997).

Figure 5 compares the estimated maximum frost depth for NDAWN stations and MERRA-2 air temperatures and soil moisture values at corresponding locations for the time period 2012 to 2017. A 17 cm thick snow layer using a density of 310 kg/m^3 was also included. The variation in the annual temperature parameters used in the model are shown in Figure 5 *bottom*. The parameters include the length of the freezing season (L_{fs}), the annual cumulative freezing degree days (F_{DD}), and average annual air temperature (T_{avg}).

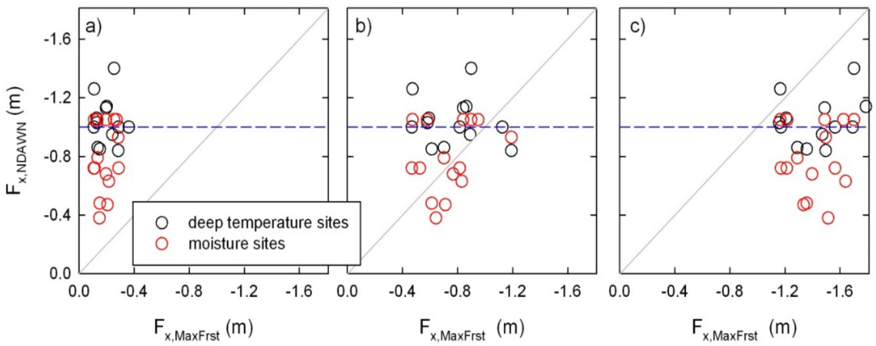

Figure 4. MaxFrst and measured maximum frost depths at the NDAWN sites for 2017. The *dashed horizontal line* is the maximum depth of data at the moisture sites. The modeled values in (*a*) and (*b*) are affected by a 17 cm layer of snow on the ground for the duration of the freezing season. The frost depths in (c) represent a bare ground condition.

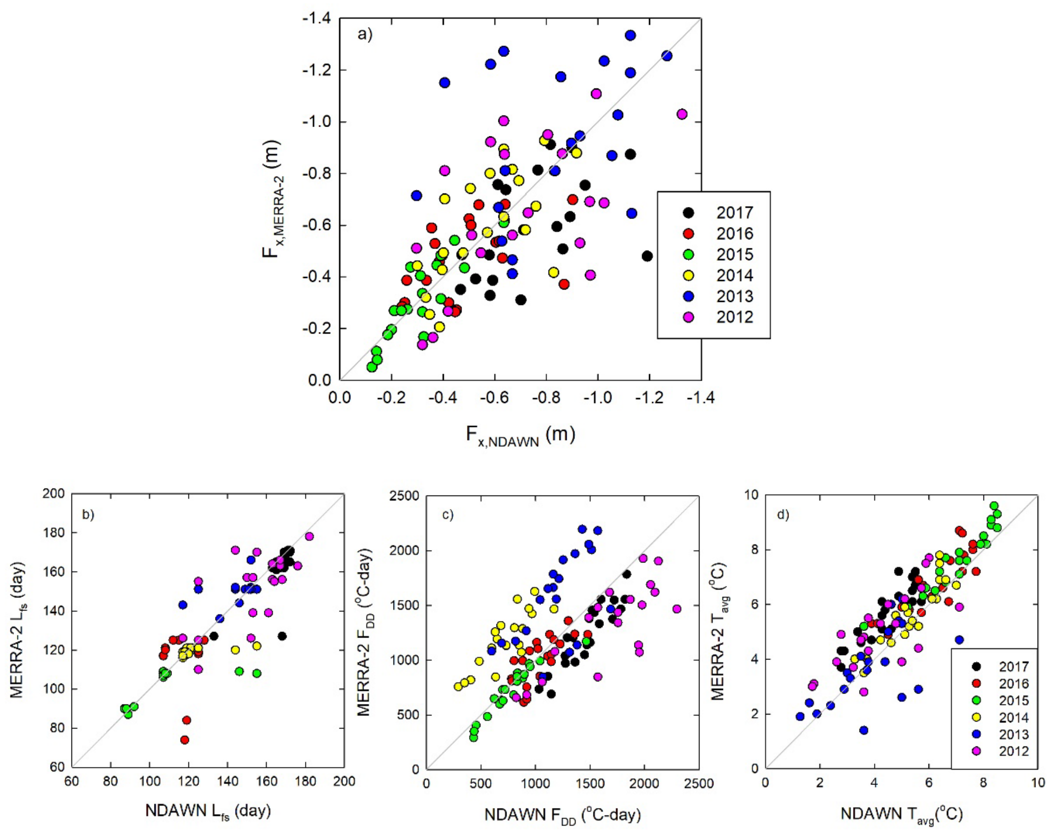

Figure 5. (a) Modeled maximum frost depths compared at NDAWN stations and corresponding MERRA-2 grid for 2012 through 2017 with a 310 kg/m^3 snow layer 17 cm

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}.

4 CONCLUSIONS

In this study, frost depths determined from field sites that measured air and soil temperatures, and volumetric soil moisture are compared with frost depths determined from a gridded worldwide reanalysis data product, and with frost depths modeled using the measured air and soil temperatures. We found significant differences in frost depths between measured, reanalysis data, and modelled results.

Weather and soil data are critical inputs to estimate frost depth. The differences in frost depth may be attributed to variations between local conditions, either weather or soil, and those conditions over a larger scale.

This study showed that variations in weather, soil properties, presence of a snow layer, and snow layer properties significantly affect the maximum depth of frost penetration during the winter. Weather and soil property data obtained from ground-based systems are favored to reanalysis datasets. However, reanalysis weather datasets do augment ground-based datasets in locations where no data is otherwise available. Measured subsurface soil conditions are difficult to obtain and the utility of reanalysis data is limited. To reasonably estimate frost depths needed to estimate soil strength, mobility modelling requires improvements to the soil and snow properties.

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14. ABSTRACT

Frozen soils can withstand heavy vehicle loads and provide major maneuver corridors in locations where the soils are otherwise too weak to support the loading conditions. Vehicle mobility models require input of the ground conditions to assess seasonal trafficability. Increasingly, measured air temperatures from weather station locations are becoming more widespread, however they lack a global gridded coverage. Similarly, ground profile measurements, such as soil temperature and moisture, are significant inputs to estimate depths of frost. New data products, such as gridded reanalysis data provides weather and soil data on a gridded global scale. This study compared frost depths determined from measured soil temperatures at stations in North Dakota and Minnesota with frost depths determined from soil temperatures from NASA's Modern Era Retrospective Analysis for Research Application Version 2 (MERRA-2). The objectives of the study were to evaluate the usefulness of the MERRA-2 data to provide estimates of frost depth, and to determine the accuracy of estimated frost depths from modelling using either measured air temperatures or reanalysis air temperature data. To estimate the maximum frost depth a one-dimensional decoupled heat and moisture flow model was used. Differences in estimated frost depth resulted from modelling when compared to the measured soil temperatures. These differences are likely due to the influence of a snow layer. The properties of the snow layer play an important role in estimating the depth of frost. Improved material properties of the snow layer are needed to more accurately estimate the depth of ground freezing.

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