README

Predicting Subsurface Meltwater in the Greenland Ice Sheet with Satellite-based Passive Microwave Observations

This file summarizes the files archived for this project and includes some general information about methods. More complete documentation on the latter topics may be found in the Master's Thesis associated with this work "Extending The Record Of Greenland Ice Sheet Subsurface Meltwater: Exploring New Applications Of Satellite Remote Sensing Data", by Ms. Margeaux Carter. A copy of this thesis has been archived for personal or classroom use only.

Files in this dataset fall into three main categories: modeling microwave brightness temperature (Tb) to test feasibility of the passive microwave technique, prediction of permanent firn aquifers, and other input files supporting these analyses.

1. Modeling microwave emissions of ice and snow using MEMLS

memls_TVC-custom.tgz

MEMLS, the Microwave Emission Model for Layered Snowpacks *(Weismann and Matzler*, 1999), was used to test the feasibility of using passive low frequency microwave (LFM) satellite observations to identify subsurface water (surface lakes, aquifers) in the Greenland Ice Sheet (GIS). A model snowpack was used to test whether the characteristics (frequency, polarization) of the available LFM data could be used to identify subsurface water layers. The representative snowpack is 25 m deep and has twelve layers with thickness, temperature, and density chosen to reflect density profiles of ice cores obtained from snowpacks with perennial firn aquifers (*Koenig et. al.*, 2014), and average winter snow temperature profiles from the Greenland Climate Network (GC-Net) observation station at Swiss Camp (*Steffen et. al.*, 1996). The tested range of liquid water content in the snowpack was chosen to reflect those observed by *Koenig et. al.* (2014).

The official archive for MEMLS is at github.com/akasurak/memls_TVC. Custom files (primarily MATLAB scripts) are archived in the file memls_TVC-custom.tgz.

GC-Net files were acquired from the GC-Net web site (see below) and processed into a single netCDF file containing all stations and variables. This dataset (gcnet.allStationData_d_365.nc) is provided as a courtesy; the GC-Net website should be the source of updates and the official citation.

MEMLS-relevant observations of perennial firn aquifers and buried surface lakes were obtained from the authors (i.e., Forster and Koenig).

2. Predicting Perennial Firn Aquifers (PFA)

Main outcome: AMSRE.2002_2011.refined.PolarizationDifference.nc

Files for the prediction part of this project fall into four groups: original files (binary, hosted by NSIDC), netCDF versions of the original files, Polarization Difference (PD) files, and supporting NCL scripts.

a. Original binary observations obtained from NSIDC

The front end of this analysis begins with the NSIDC dataset "AMSR-E/Aqua Daily EASE-Grid Brightness Temperatures, Version 1" (*Knowles et al 2006;* nsidc.org/data/nsidc-0301). This project settled on using two frequencies, 6.9 and 10.7 GHz, and both horizontal and vertical polarizations. The following file format text is excerpted from the User Guide for this dataset.

Format:

> Files contain flat binary (unformatted) grid arrays, one grid per file. Files are compressed for delivery.
>
> There are 24 brightness temperature data files per day for a given projection: separate data files for each of the 12 channels and the two pass directions per channel. Data are 2-byte unsigned integers, little-endian byte-order, representing temperatures in tenths of kelvins. Data values range from 650 to 3200, with the value 0 indicating missing data.
>
> There are two time files per day for a given projection: ascending and descending passes. Data are 2 byte signed integers, little-endian byte-order, indicating time of data acquisition as minutes since midnight (0:00 UTC) of the date of the enclosing file. The values in the time files range from 0 to 1440, with the value -32768 indicating missing data.

Examples: one day at 6.9 GHz, ascending/descending, horizontal/vertical polarization

```
ID2r3-AMSRE-NL2006001A.v03.06H
ID2r3-AMSRE-NL2006001A.v03.06V
ID2r3-AMSRE-NL2006001D.v03.06H
ID2r3-AMSRE-NL2006001D.v03.06V
```

b. Binary to netCDF

Binary files converted to netCDF using NCL script amsre_chunkBinToNC.ncl. Example:

```
netcdf AMSRE.2006.001_365A.06H {
dimensions:
	day = 365 ;
	south_north = 721 ;
	west_east = 721 ;
variables:
	short Refl(day, south_north, west_east) ;
		Refl:units = "" ;
		Refl:direction = "D" ;
		Refl:frequency = "6 GHz" ;
		Refl:polarization = "H" ;
		Refl:description = "Passive Microwave Reflectance 6 GHz Horizontal" ;
		Refl:_FillValue = -32767s ;
	int time(day) ;
		time:long_name = "time" ;
		time:units = "day of year" ;
	float lat(south_north, west_east) ;
		lat:source_file = "NLLATLSB" ;
		lat:units = "degree_north" ;
		lat:spacing = "25." ;
		lat:description = "25 km EASE grid latitude" ;
		lat:_FillValue = 9.96921e+36f ;
	int south_north(south_north) ;
```

```
        int west_east(west_east) ;
        float lon(south_north, west_east) ;
                lon:source_file = "NLLONLSB" ;
                lon:units = "degree_east" ;
                lon:spacing = "25." ;
                lon:description = "25 km EASE grid longitude" ;
                lon:_FillValue = 9.96921e+36f ;
}
```

These files are provided by year (2002-2011), with four files for each year (6.9 and 10.7 GHz, horizontal and vertical polarization, ascending-only).

c. Polarization Difference

Of the many analyses tested, this is the one that made it into the final thesis. AMSR-E channels at 6.9 GHz and 10.7 GHz are the basis of this approach. At each frequency, the difference between horizontal (H) and vertical (V) polarizations was calculated. Predictions were evaluated versus observations of PFAs (*Forster et al., 2014*) and buried surface lakes (*Koenig et al., 2015*) as well as accumulation and melt intensity derived from the Arctic System Reanalysis. (*Bromwich et. al., 2012*).

Briefly, variables Diff06 and Diff10 from this file are used to classify the ice sheet into four categories: probable firn aquifer, probable buried lake, "overlap" where subsurface liquid water is likely present but type cannot be classified, and "not in range". This effort developed a 10-year (2002-2011) daily prediction dataset.

```
netcdf AMSRE.2002_2011.refined.PolarizationDifference {
dimensions:
        year = 10 ;
        day = 365 ;
        south_north = 85 ;
        west_east = 95 ;
variables:
        int time(year, day) ;
                time:long_name = "time" ;
                time:units = "day of year" ;
                time:_FillValue = -2147483647 ;
        float lat(south_north, west_east) ;
                lat:source_file = "NLLATLSB" ;
                lat:units = "degree_north" ;
                lat:spacing = "25." ;
                lat:description = "25 km EASE grid latitude" ;
                lat:_FillValue = 9.96921e+36f ;
        int south_north(south_north) ;
        int west_east(west_east) ;
        float lon(south_north, west_east) ;
                lon:source_file = "NLLONLSB" ;
                lon:units = "degree_east" ;
                lon:spacing = "25." ;
```

```
        lon:description = "25 km EASE grid longitude" ;
        lon:_FillValue = 9.96921e+36f ;
    float Diff06(year, day, south_north, west_east) ;
        Diff06:units = "K" ;
        Diff06:direction = "A" ;
        Diff06:description = "H-V(6.9 GHz)" ;
        Diff06:long_name = "Polarization Difference 6.9 GHz" ;
        Diff06:_FillValue = 9.96921e+36f ;
    float Diff10(year, day, south_north, west_east) ;
        Diff10:units = "K" ;
        Diff10:direction = "A" ;
        Diff10:description = "H-V(10.7 GHz)" ;
        Diff10:long_name = "Polarization Difference 10.7 GHz" ;
        Diff10:_FillValue = 9.96921e+36f ;
}
```

3. Supporting/related files

A mix of scripts and datasets obtained from external sites and subsequently modified to support our analysis tasks.

i. Related NCL scripts: ncl_scripts.tgz

These NCL scripts support the creation and analysis of the files above. NCL (NCAR Command Language) is available from, and supported by, https://www.ncl.ucar.edu.

ii. Arctic System Reanalysis (ASR): asr30km.fct.2D.2001_2011.mon.nc

In order to better constrain PD as a method of observing retained meltwater, snow accumulation and melt intensity were compared to PD over the 9 years during which AMSR-E was active. Snow accumulation and melt intensity are calculated using Arctic System Reanalysis (ASR) (*Bromwich et. al., 2012*) monthly temperature and dry precipitation values. The ASR is a high resolution (15 km) reanalysis model optimized for the Arctic using the Polar Weather Research Forecasting (WRF) Model and High Resolution Land Data Assimilation systems. Melt intensity is based on Munneke et. al.'s (*2014*) melt intensity which uses Braithwaite and Olesen's (*1985*) positive degree day method. Full details on methodologies are in the thesis.

```
netcdf asr30km.fct.2D.2001_2011.mon {
dimensions:
    year = 11 ;
    month = 12 ;
    y = 81 ;
    x = 86 ;
    easeIX = 8550 ;
    wrfIX = 2 ;
variables:
    double time(year, month) ;
        time:long_name = "time" ;
        time:units = "hours since 1901-01-01 00:00:00" ;
        time:_FillValue = 9.96920996838687e+36 ;
```

```
        float XLAT(y, x) ;
                XLAT:standard_name = "latitude" ;
                XLAT:long_name = "latitude" ;
                XLAT:units = "degree_north" ;
                XLAT:_CoordinateAxisType = "Lat" ;
        float XLON(y, x) ;
                XLON:standard_name = "longitude" ;
                XLON:long_name = "longitude" ;
                XLON:units = "degree_east" ;
                XLON:_CoordinateAxisType = "Lon" ;
        float SnowH(year, month, y, x) ;
                SnowH:_FillValue = 9.96921e+36f ;
        float SWE(year, month, y, x) ;
                SWE:_FillValue = 9.96921e+36f ;
        float SnowIce(year, month, y, x) ;
                SnowIce:_FillValue = 9.96921e+36f ;
        float runoff(year, month, y, x) ;
                runoff:_FillValue = 9.96921e+36f ;
        float precip(year, month, y, x) ;
                precip:_FillValue = 9.96921e+36f ;
        float T(year, month, y, x) ;
                T:_FillValue = 9.96921e+36f ;
        int z(easeIX, wrfIX) ;
                z:description = "wrf grid points nearest EASE2 grid points" ;
                z:long_name = "indices closest to specified LAT/LON coordinate pairs" ;
                z:_FillValue = -2147483647 ;
}
```

iii. GC-Net AWS observations: gcnet.allStationData_1995-2017_d_365.nc

Text files for all GC-Net stations (*Steffen et al, 1996)*, all available years were acquired from the GC-Net web site (http://cires1.colorado.edu/science/groups/steffen//gcnet/) and converted to a single netCDF file. A portion of the metadata is shown here:

```
netcdf gcnet.allStationData_1995-2017_d_365 {
dimensions:
        time = UNLIMITED ; // (8395 currently)
        bnds = 2 ;
        station = 23 ;
variables:
        double time(time) ;
                time:standard_name = "time" ;
                time:bounds = "time_bnds" ;
                time:units = "hours since 1900-01-01 00:00:00" ;
                time:calendar = "noleap" ;
                time:axis = "T" ;
        double time_bnds(time, bnds) ;
        int station(station) ;
```

```
        station:axis = "X" ;
    float StId(time, station) ;
        StId:long_name = "Station Number" ;
        StId:_FillValue = 9.96921e+36f ;
        StId:missing_value = 9.96921e+36f ;
        StId:name = "StId" ;
        StId:var = 1 ;
    float yyyy(time, station) ;
        yyyy:long_name = "Year" ;
        yyyy:_FillValue = 9.96921e+36f ;
        yyyy:missing_value = 9.96921e+36f ;
        yyyy:name = "yyyy" ;
        yyyy:var = 2 ;
    float day(time, station) ;
        day:long_name = "Julian Decimal Time" ;
        day:_FillValue = 9.96921e+36f ;
        day:missing_value = 9.96921e+36f ;
        day:name = "day" ;
        day:var = 3 ;
    float SWD(time, station) ;
        SWD:long_name = "Shortwave Radiation, Down" ;
        SWD:units = "W/m^2" ;
        SWD:_FillValue = 9.96921e+36f ;
        SWD:missing_value = 9.96921e+36f ;
        SWD:name = "SWD" ;
        SWD:var = 4 ;
    float AirT1(time, station) ;
        AirT1:long_name = "TC Air 1 Temperature" ;
        AirT1:units = "degC" ;
        AirT1:_FillValue = 9.96921e+36f ;
        AirT1:missing_value = 9.96921e+36f ;
        AirT1:name = "AirT1" ;
        AirT1:var = 7 ;
    float AirT2(time, station) ;
        AirT2:long_name = "TC Air 2 Temperature" ;
        AirT2:units = "degC" ;
        AirT2:_FillValue = 9.96921e+36f ;
        AirT2:missing_value = 9.96921e+36f ;
        AirT2:name = "AirT2" ;
        AirT2:var = 8 ;
}
```

iv. Observations of surface melting:

mote_GISsurfmelt.2001_2012.nc, mote_TotalSurfMelt_1979_2012.nc

Observations of surface melt occurrence from the "MEaSUREs Greenland Surface Melt Daily 25km EASE-Grid 2.0, Version 1" (*Mote 2014;* https://nsidc.org/data/NSIDC-0533/versions/1) were also archived in modified format (spatially subset and spatially summed).

Surface melt occurrence spatially subset to the Greenland domain, daily resolution:

```
netcdf mote_GISsurfmelt.2001_2012 {
dimensions:
	year = 12 ;
	day = 366 ;
	rows = 90 ;
	cols = 95 ;
variables:
	float surf_melt(year, day, rows, cols) ;
		surf_melt:grid_mapping = "coord_system" ;
		surf_melt:long_name = "Passive Microwave Surface and Near Surface Melt" ;
		surf_melt:valid_range = 50b, 91b ;
		surf_melt:comment = "50: No surface melt, 51: Surface melt, 90: Missing, 91: 
Masked" ;
		surf_melt:flag_values = 50b, 51b, 90b, 91b ;
		surf_melt:flag_meanings = "no_surface_melt surface_melt missing masked" ;
		surf_melt:_FillValue = -99.f ;
	int day(day) ;
		day:long_name = "day" ;
		day:standard_name = "day" ;
		day:_FillValue = -2147483647 ;
	double lat(rows, cols) ;
		lat:_FillValue = -999. ;
		lat:long_name = "latitude of cell center in EASE-Grid-2.0" ;
		lat:units = "degrees_north" ;
		lat:valid_range = -90.f, 90.f ;
		lat:standard_name = "latitude" ;
	double lon(rows, cols) ;
		lon:_FillValue = -999. ;
		lon:long_name = "longitude of cell center in EASE-Grid-2.0" ;
		lon:units = "degrees_east" ;
		lon:valid_range = -180.f, 180.f ;
		lon:standard_name = "longitude" ;
	int Time(year, day) ;
		Time:standard_name = "time" ;
		Time:long_name = "time" ;
		Time:units = "days since 1978-12-31" ;
		Time:axis = "T" ;
		Time:calendar = "gregorian" ;
}
```

Surface melt occurrence across the Greenland ice sheet, daily resolution:

```
netcdf mote_TotalSurfMelt_1979_2012 {
dimensions:
	time = 10769 ;
variables:
	float TotalMelt(time) ;
		TotalMelt:description = "Spatially summed surface melt" ;
		TotalMelt:sum_op_ncl = "dim_sum_n over dimension(s): cols" ;
		TotalMelt:valid_range = 50.f, 91.f ;
		TotalMelt:_FillValue_original = -99b ;
		TotalMelt:comment = "50: No surface melt, 51: Surface melt, 90: Missing, 91:
Masked" ;
		TotalMelt:flag_values = 50b, 51b, 90b, 91b ;
		TotalMelt:flag_meanings = "no_surface_melt surface_melt missing masked" ;
		TotalMelt:_FillValue = -99.f ;
	int time(time) ;
		time:standard_name = "time" ;
		time:long_name = "time" ;
		time:units = "days since 1978-12-31 00:00:00" ;
		time:axis = "T" ;
		time:calendar = "gregorian" ;
}
```

v. Observations of buried liquid water: not archived

Other verification datasets include observations of PFAs (*Forster et al., 2014*) and buried surface lakes (*Koenig et al., 2015*). Contact these authors for these files.

References

Braithwaite, R. J., and O. B. Olesen (1985), Ice ablation in West Greenland in relation to air temperature and global radiation, Z. Gletscherkd. Glazialgeol., 20, 155–168.

Bromwich, D., L. Bai, K. Hines, S. Wang, Z. Liu, H. Lin, Y. Kuo, and M. Barlage (2012), Arctic System Reanalysis (ASR) Project. https://doi.org/10.5065/D6K072B5, Nat. Cent. Atmos. Res., Comp. Inf. Sys. Lab. Boulder, Colo., Accessed 01 Mar 2016.

Forster, R., J. Box, M. van den Broeke, C. Miège, E. Burgess, J. van Angelen, J. Lenaerts, L. Koenig, J. Paden, C. Lewis, S. Gogineni, C. Leuschen, and J. McConnel (2014), Extensive liquid meltwater storage in firn within the Greenland ice sheet, *Nat. Geosci.*, 7, 95-98, doi: 10.1038/NGEO2043.

Knowles, K., M. Savoie, R. Armstrong, and M. J. Brodzik. 2006. AMSR-E/Aqua Daily EASE-Grid Brightness Temperatures, Version 1. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: https://doi.org/10.5067/XIMNXRTQVMOX.

Koenig, L., C. Miège, R. Forster, and L. Brucker (2014), Initial in situ measurements of perennial meltwater storage in the Greenland firn aquifer, *Geophys. Res. Lett.*, 41, 81-85, doi: 10.1002/2013GL058083.

Koenig, L., D. Lampkin, L. Montgomery, S. Hamilton, J. Turrin, C. Joseph, S. Moustafa, B. Panzer, K. Casey, J. Paden, C. Leuschen, and P. Gogineni (2015), Wintertime storage of water in buried supraglacial lakes across the Greenland ice sheet, *The Cryosphere*, 9, 1333-1342, doi: 10.5194/tc-9-1333-2015.

Mote, T. L. 2014. MEaSUREs Greenland Surface Melt Daily 25km EASE-Grid 2.0, Version 1. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: https://doi.org/10.5067/MEASURES/CRYOSPHERE/nsidc-0533.001.

Munneke, P., S. Ligtenberg, M. van den Broeke, J. van Angelen, and R. Forster (2014), Explaining the presence of perennial liquid water bodies in the firn of the Greenland ice sheet, *Geophys. Res. Lett.*, 41, 476-483, doi: 10.1002/2013GL058389.

Steffen, K., J. Box, and W. Abdalati (1996) Greenland Climate Network: GC-Net. http://cires1.colorado.edu/science/groups/steffen/gcnet/order/admin/station.php, Cold Regions Res. and Eng. Lab. Boulder, Colo., Accessed 30 Oct 2014.

Wiesmann, A. and C. Matzler (1999), Microwave emission model of layered snowpacks, *Remote Sens. Env.*, *70*(3), 307-316, doi: 10.1016/S0034-4257(99)00046-2.