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Brief Communication

CARMA's MERRA-based caribou range climate database

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Introduction

The CircumArctic *Rangifer* Monitoring and Assessment (CARMA) network's primary goal is to monitor and assess impacts of global change on caribou (*Rangifer tarandus*). One core approach is conducting cross-herd comparisons and contrasts to gauge how herds are similar and how they differ in their responses to climate. By understanding regional climates in which seasonally migratory tundra caribou herds have evolved, we can better assess strategies and mechanisms that *Rangifer* employ to cope with environmental stress. Climate has a strong influence on caribou ecology through its effects on forage growth and availability, its influences on snow conditions, and on insect abundance that can harass caribou and cause changes in caribou movements and redistribution (Griffith *et al.,* 2002; Bergerud *et al.,* 2008; Couturier *et al.,* 2009). We therfore need regional climate datasets that allow direct comparison of environmental attributes across and between continents. Although climate data are available from meteorological stations, those stations are relatively few, unevenly distributed across herd ranges, and often measure climate using different protocols.

An alternative to assessing regional climate based on meteorological stations is NASA's Modern Era Retrospective Analysis for Research and Applications (MERRA) dataset (http://gmao.gsfc.nasa.gov/research/merra/). MERRA was undertaken by NASA's Global Modeling and Assimilation Office with the objectives of placing the observations from NASA's Earth Observing System satellites in a climate context, and improving upon the hydrologic cycle represented in earlier generations of reanalyses (Rienecker *et al.,* 2011). The resolution of the MERRA grid is 1/2 degrees latitude by 2/3 degrees longitude and data are provided on a daily time step for most variables. MERRA was chosen over other datasets because it covers the modern era of remotely sensed data (from 1979 through the present), attempts to address problems with previous reanalysis products, and is focused on the hydrological cycle. Other long-term reanalyses of the Earth's climate have high levels of uncertainty in precipitation and inter-annual variability. MERRA also has better coverage north of 60° than other datasets such as NCEP and data are normally publicly available within a few months.

Methods

Climate data were summarized for 22 herds into as many as 8 polygons for each herd. For most herds separate shapefiles were constructed for five seasons (calving, summer, fall, winter, and spring), for tundra and taiga portions of the range, and for the annual range. For some herds, the two Greenlandic herds and the Iceland reindeer, only the annual range was used as their distribution is small and there is no taiga. For most North American herds, all Greenlandic herds and Iceland reindeer, polygons were determined from radio-collar data (Table 1). Fixed kernel polygons (90% utilization distributions) were produced, using standard settings (href, raster resolution set to 120) from the Rodgers and Carr (1998) Home Range extension for ArcView 3.2a (Environmental Systems Research Institute, Redlands, California, U.S.A.). Collar data were not made available to CARMA for the Beverly and Qamanirjuaq herds. Therefore for those herds older data (pre-1995) were obtained with permission from GNWT-ENR. The basis for the resultant polygons was from work done pulling together surveys, maps, and collar data. Leslie Wakelyn, on behalf of the Beverly-Qamanirjuaq Caribou Management Board (BQCMB), produced seven overall seasonal ranges that were a general amalgamation of the data for 10-25 years over time periods that generally began in the late 1950s and extended to the early 1980s to mid-1990s. Wakelyn's seven seasons were amalgamated to produce polygons for the five seasons used by CARMA. Because there is no history of collaring reindeer in Russia, for the five Russian herds, seasonal polygons were developed by combining seasonal maps produced from aerial surveys by Russian management agencies combined with personal contact to finalize seasonal distributions. To produce the taiga and tundra polygons, a global treeline shapefile was taken from the Circumpolar Arctic Vegetation Map from the Alaska Geobotany Center (http://www.geobotany.uaf.edu/), with the original coverage supplied from (http://www.arcticatlas.org/).

Table 1. The source of range information and time periods they represent for CARMA's 22 migratory tundra herds.

Herd	Source of ranges	Timeframe
Bathurst	Collar data	1996-2009
Ahiak	Collar data	2001-2010
Beverly	Dated survey maps, BQCMB	~1957-1995
Qamanirjuaq	Dated survey maps, BQCMB	~1957-1995
Cape Bathurst	Collar data	1996-2010
Bluenose West	Collar data	1996-2010
Bluenose East	Collar data	1996-2010
Dolphin and Union	Collar data	1996-2006
George River	Supplied Polygons	2006-2009
Leaf River	Supplied Polygons	2006-2009
Teshekpuk	Supplied Polygons	1990-2009
Western Arctic	Collar data	1987-2010
Central Arctic	Collar data	1986-2006
Porcupine	Collar data	1985-2010
Kangerlussuaq-Sisimiut	Collar data	1998-1999
Akia-Maniitsoq	Collar data	1997-1999
Iceland	Collar data	2006-2008
Taimyr	Mapped ranges from figures	Unknown
Yana-Indigurka	Mapped ranges from figures	1980-1990
Sundrunskaya	Mapped ranges from figures	Unknown
Lena-Olenyk	Mapped ranges from figures	Unknown
Chokotka	Mapped ranges from figures	Unknown

While MERRA provides a large number

of climate variables, we chose to download 36 variables to compare between herd ranges (Table 2). These were selected based upon discussions that considered the views of a number of disciplines; they include variables that, at a daily time step, are considered relevant to caribou and also to climatology. MERRA variables were downloaded using the “wget.exe” program from NASA’s website (http://disc.sci.gsfc.nasa.gov/daac-bin/FTPSubset.pl). Mapping boundary box coordinates to download MERRA variables were set to be west -170°, north 82°, south 45°, and east 180° as to cover all possible ranges of the 22 caribou herds. Thirty variables were downloaded from three different MERRA products. Variables (see Table 2 for a description) ps, u850, v850, t850, q850, h1000, h850, u10m, u2m, v10m, v2m, t2m, qv10m, qv2m, and disph were obtained through “Atmospheric Single-Level Diagnostics (tavg1_2d_slv_Nx)”. Variables ts, albedo, albnirdf, albnirdr, albvisdf, and albvisdr were extracted from “Surface and TOA Radiation Fluxes (tavg1_2d_rad_Nx)”. Variables grn, lai, tpsnow, precsno, prectot, snomas, snodp, smland, and frsno were downloaded from “Land Surface diagnostics (tavg1_2d_lnd_Nx)”. The six wind speed and direction variables, ws2m, wd2m, ws10m, wd10m, ws850, and wd850 (Table 2), were calculated from the “u2m” and “v2m” wind component vectors listed above (see

Table 2. MERRA variables downloaded into CARMA’s climate database.

Short Name	Long Name	Unit
albedo	Surface albedo	fraction
albnirdf	Diffuse beam NIR surface albedo	fraction
albnirdr	Direct beam NIR surface albedo	fraction
albvisdf	Diffuse beam VIS-UV surface albedo fraction	fraction
albvisdr	Direct beam VIS-UV surface albedo	fraction
disph	Displacement height	m
Frsno[1]	Fractional snow-covered area	fraction
grn[1]	Vegetation greenness fraction	fraction
h1000	Height at 1000 hPa	m
h850	Height at 850 hPa	m
lai[1]	Leaf area index	m ^ 2 m ^ (-2)
precsno	Surface snowfall rate	kg m ^ (-2) s ^ (-1)
prectot[1]	Total surface precipitation rate	kg m ^ (-2) s ^ (-1)
ps	Time averaged surface pressure	Pa
q850	Q850 Specific humidity at 850 hPa	kg kg ^ (-1)
qv10m	Specific humidity at 10m above displacement[2]	kg kg ^ (-1)
qv2m	Specific humidity at 2m above displacement	kg kg ^ (-1)
smland[1]	Snowmelt rate	kg m ^ (-2) s ^ (-1)
snodp[1]	Snow depth	m
snomas	Snow mass	kg m ^ (-2)
t2m[1]	Temperature at 2m above displacement	°C
t850	Temperature at 850 hPa	°C
tpsnow	Top snow layer temperature	°C
ts	Surface skin temperature	°C
u10m	Eastward wind component at 10m above displacement	m s ^ (-1)
u2m	Eastward wind component at 2m above displacement	m s ^ (-1)
u850	Eastward wind component at 850 hPa	m s ^ (-1)
v10m	Northward wind component at 10m above displacement	m s ^ (-1)
v2m	Northward wind component at 2m above displacement	m s ^ (-1)
v850	Northward wind component at 850 hPa	m s ^ (-1)
wd 850[3]	Wind direction at 850hPa (to North)	degree
Wd10m[3]	Wind direction at 10m above displacement	degree
wd2m[3]	Wind direction at 2m above displacement	degree
ws10m[3]	Wind speed at 10m above displacement	m s ^ (-1)
ws2m[3]	Wind speed at 2m above displacement	m s ^ (-1)
ws850[3]	Wind speed at 850 hPa	m s ^ (-1)

[1] Variables also included in the CARMA dataset
[2] Displacement is the height in meters above the ground at which zero wind speed is achieved because of obstacles such as vegetation
[3] Variable not downloaded from MERRA, but calculated based on MERRA wind components (u,v)

http://mst.nerc.ac.uk/wind vect convs.html for an explanation). The "mean" option box was checked to download daily averaged values. All downloads were saved as NetCDF (Network Common Data Form) files.

In order to extract information stored in these downloads, readings of each variable of each grid points were first extracted using "ncdf" package (Pierce, 2011) in the open source statistical software R (R Development Core Team, 2012). The procedures of extraction are listed as the following: 1) coordinates of the qualified MERRA grid points were obtained through overlaying herd ranges to MERRA grids, 2) median values for each variable among the qualified grid points were further extracted by ranking and locating the 50th percentile of all gridded data, and 3) daily climate files for each year, each herd, and each range were constructed and written into comma-separated values (csv) formatted files. Therefore, each MERRA reading in the database represents the median daily averaged value with its MERRA grid point falling inside or close to the herd range in study. Using median readings instead of mean values within each range avoids making normality assumptions and reduces bias.

All snow variables were considered in snow-years only. A snow-year is defined as starting from the 184th day of the year prior to the 183rd day of the current year. Thus, fall and winter periods of a snow-year consist of 182 days (or 183 days if the year prior is a leap year), and spring and summer periods of a snow-year consist of 183 days. Daily minimum and maximum temperature variables were extracted from the hourly MERRA assimilated temperature data with the following procedures. Hourly maximum and minimum readings were first extracted for each MERRA grid point within the study range. Median readings were then extracted by ranking to locate the 50th percentile.

Based on these 36 variables (Table 2) we then produced a "caribou-relevant" dataset that includes 25 variables for each herd range. Some MERRA variables could be directly used and for others we derived variables based on the MERRA variables for each herd and seasonal range. Equations used to derive the variables were written into R source codes.

1. Snow depth (snodp, m): Equal to MERRA variable snodp.

2. Snow density (snowdensity, $g \cdot cm^{-3}$): Snow mass over snow depth. Snow mass and snow depth are equal to MERRA variables snomas and snodp, respectively.

$$snowdensity = \frac{snomas}{snodp}$$

3. Temperature at 2 meters above ground (t2m, °C): Equal to MERRA variable t2m.

4. Daily minimum temperature at 2 meters above ground (t2m_min, °C): Median reading of the daily minimum temperature from 0:30 to 23:30.

5. Daily maximum temperature at 2 meters above ground (t2m_ max, °C): Median reading of the daily maximum temperature from 0:30 to 23:30.

6. Total surface precipitation (prectot, $kg \cdot m^{-2}$ sec $^{-1}$): Equal to MERRA variable prectot.

7. Daily total surface precipitation (precip_24hr $kg \cdot m^{-2}$ d^{-1}): Total surface precipitation accumulated over 24 hours. Uses MERRA total surface precipitation variable prectot.

$$precip\_24hr = prectot \times 24 \times 60 \times 60$$

8. Snowmelt rate (smland, $kg \cdot m^{-2}$ sec^{-1}): Equal to MERRA variable smland.

9. Fractional snow covered area (frsno, fraction): Equal to MERRA variable frsno.

10. Surface snowfall (i.e., all frozen precipitation; precsno $kg \cdot m^{-2}$ sec^{-1}): Equal to MERRA variable precsno.

11. Number of days with freeze/thaw events (nday_fzthaw, day): Accumulated days from January to December, when t2m_max above 0°C and t2m_min below 0°C.

$$\text{nday\_fzthaw} = \sum_{\text{Jan.1}}^{\text{Dec.31}} I_i\,,\ I_i = \begin{cases} 1 & \text{if t2m\_max} > 0 \text{and t2m\_min} < 0 \\ 0 & \text{otherwise} \end{cases}$$

12. Cumulative growing degrees above 0°C (GDD0_cum, oC): Accumulated daily-averaged values of t2m if t2m > 0°C.

$$\sum_{i=1}^{n} t2m_i$$

13. Cumulative growing degrees above 5°C (GDD5_cum, oC): Accumulated daily-averaged values of t2m if t2m > 5°C.

$$\sum_{i=1}^{n} t2m_i$$

14. Leaf area index (lai, m^2 m^{-2})): Equal to MERRA variable lai.

15. Vegetation greenness fraction (grn, fraction): Equal to MERRA variable grn.

16. Oestrid index (OI, unitless):

$$T = \begin{cases} 1 & \text{if t2m} > 18 \\ 0 & \text{if t2m} < 13 \\ 1 - \dfrac{18 - t2m}{10} & \text{otherwise} \end{cases} \quad W = \begin{cases} 0 & \text{if ws10m} > 9\text{m/s} \\ \dfrac{9 - ws10m}{9} & \text{otherwise} \end{cases}$$

17. Cumulative oestrid index (OI_cum, unitless): Accumulated daily OI from January 1 to December 31.

$$\text{OI\_cum} = \sum_{\text{Jan.1}}^{\text{Dec.31}} \text{OI}$$

18. Mosquito index (MI, unitless):

$$\text{MI} = \text{T} \times \text{W, where,}$$

$$T = \begin{cases} 1 & \text{if t2m} > 18 \\ 0 & \text{if t2m} < 6 \\ 1 - \dfrac{18 - t2m}{13} & \text{otherwise} \end{cases} \quad W = \begin{cases} 0 & \text{if ws10m} > 6\text{m/s} \\ \dfrac{6 - ws10m}{6} & \text{otherwise} \end{cases}$$

19. Cumulative mosquito index (MI_cum, unitless): Accumulated daily MI from January 1 to December 31.

$$\text{MI\_cum} = \sum_{\text{Jan.1}}^{\text{Dec.31}} \text{MI}$$

20. *Surface rainfall* (rainfall, mm·sec^{-1}): Total surface precipitation subtracted by all frozen precipitation, where use MERRA variables prectot and precsno.

$$\text{rainfall} = \mathit{prectot} - \mathit{precsno}$$

21. *Keetch Byram drought index* (KBDI, unitless): (today) = (yesterday) + (today), where DF (drought factor) is calculated following (Keetch & Byram, 1968);

$$\begin{cases} 0 & \text{if } P_t = 0 \text{ and t2m\_max}\ _t \le 6.78; \\ \dfrac{(800 - KBDI_{t-1})(0.968e^{0.0875t2m\_max_t + 1.5552} - 8.3) * 10^{-3}}{1 + 10.88e^{-0.0174 * mean\ annual\ rainfall(cm)}} & \text{if } P_t > 0 \text{ and t2m\_max}\ _t > 6.78; \\ \dfrac{(800 - KBDI_{t-1})(0.968e^{0.0875t2m\_max_t + 1.5552} - 8.3) * 10^{-3}}{1 + 10.88e^{-0.0174 * mean\ annual\ rainfall(cm)}} & \text{if } P_t > 0 \text{ and } \sum P_t \le 0.51cm \\ \dfrac{(800 - KBDI_{t-1})(0.968e^{0.0875t2m\_max_t + 1.5552} - 8.3) * 10^{-3}}{1 + 10.88e^{-0.0174 * mean\ annual\ rainfall(cm)}} - 39.37 \sum P_t & \text{if} P_t > 0 \text{ and } \sum P_t \ge 0.51cm. \end{cases}$$

where, P_t is the 24-hour precipitation, and KBDI (Jan. 1) is set to zero.

22. *Cumulative rain-on-snow* (rainsnow_cum, mm): Accumulated 24-hr rainfall if there is rainfall and snow depth is greater than 0.01 m.

$$\text{rainsnow}_{\text{cum}} = \sum_{i=1}^{t} \text{r ainfall}_i \times 24 \times 60 \times 60, \text{ if } (\text{prectot} - \text{precsno}) > 0 \text{ and snodp} > 0.01$$

23. *Number of days of rain-on-snow* (nday_rainsnow, day): Accumulated number of days with rain-on-snow events.

$$\text{nday\_rainsnow} = \sum_{i=1}^{t} I_i, \text{where} I_i = \begin{cases} 1 & \text{if rain on snow happens} \\ 0 & \text{otherwise} \end{cases}$$

24. *Cumulative freezing rain* (fzrain_cum, mm): Accumulated 24-hr rainfall if there is rainfall and temperature is above 0°C.

$$\text{fzrain\_cum} = \sum_{i=1}^{t} \text{r ainfall}_i \times 24 \times 60 \times 60 \text{if } (\text{prectot} - \text{precsno}) > 0 \text{ and t2m } < 0$$

25. *Number of days with rain-on-snow* (nday_fzrain, day): Accumulated number of days with freezing rain event.

$$\text{nday\_fzrain} = \sum_{i=1}^{t} I_i, \text{where} I_i = \begin{cases} 1 & \text{if freezing rain happens} \\ 0 & \text{otherwise} \end{cases}$$

Discussion

Currently, CARMA has compiled the herd-specific data at the scale of seasonal herd ranges and has distributed the datasets to caribou management agencies. Additionally, CARMA has initiated summary analysis of the key variables. The MERRA dataset, although only including post-1979 data, will allow us to select climate variables to assess large-scale global oscillations which switch between climate phases at approximately decadal timescales. Over decades these large-scale climate patterns are indexed as switches between positive and negative phases and influence caribou ecology (Couturier *et al.,* 2009; Joly *et al.,* 2011).

To make the dataset readily available for CARMA members, these data have been organized into a menu-driven Microsoft Access® database. CARMA's intention is to provide the original dataset and annual updates through its website (www.caff.is/carma). CARMA is undertaking a series of validations by comparing datasets, for example, growing degree-days derived from MERRA data were compared to the Normalized Difference Vegetation Index (NDVI), a variable that has been used to measure "green-up" patterns on caribou range (Griffith *et al.,* 2002). The climate database has also been used to provide driving variables for CARMA's energy-protein model (Russell *et al.,* 2005) and will be central in CARMA's cumulative effects modeling program.

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