3B.6 SNOWPACK VARIABILITY AND CHANGE ACROSS THE MIDDLE EAST AND NORTH AFRICA WITH A VIEW TO HYDROLOGIC IMPACTS

M. Neil Ward[1,2,*] and David A. Robinson[2]
[1]Independent Scholar, Basking Ridge, New Jersey;
[2]Department of Geography, Rutgers University, Piscataway, New Jersey

1. INTRODUCTION

Mid-latitude snowpacks are an important dynamic component of regional climates and, often, they form a key societal resource as well, delivering water during the melt season that can be used immediately or stored for future use (Barnett et al. 2005). While hemisphere-wide snow trends and some regional systems have been carefully studied (Robinson and Dewey 1990; Groisman et al. 1994; Déry and Brown 2007; Derksen and Brown 2012; Thackeray et al. 2016; Cayan 1996; Mote et al. 2005; Shi et al. 2013), a number of key regional systems have received less attention. An example is the Middle East, which is a region historically sensitive to climate variability and change, and which contains snowpacks that have been shown to be important inputs to regional water resources (Mankin et al. 2015), as well as, influencing regional climate patterns.

Focusing on the Middle East (and the smaller snowpacks of northwestern Africa), this work aims to document climatological snowpack development and recession, and begin to assess variability and change, with specific reference to timing in the annual cycle, and potential implications for water resources (as well as other societal impacts, such as flash flooding).

2. DATA

The work is drawing on a range of data sources, including satellite-based products, station data, and model reanalyses.

For satellite-based snow products, the Interactive Multisensor Snow and Ice Mapping System (IMS, Helfrich et al. 2007; Helfrich et al. 2012) is a daily snow cover extent product that has a strength in its combination of moderate length (1999-present) *and* relatively high resolution (~24 km). It is a professional best estimate analysis derived primarily from visible satellite products, but over time, has included additional satellite products and other data sources. Since 2004, there is also a 4 km resolution product (this has started to be analyzed in the context of this overall study, but results are not reported here). For most analyses reported here, the daily 24 km product has been analyzed at 5-day intervals (i.e., pentad resolution). The last day of a given 5-day period is taken as indicative of the just completed pentad. For example, Pentad 1 is given by the IMS data for January 5th (taken as indicative of January 1st - 5th).

For station data, the Global Historical Climatology Network – Daily (GHCN) is drawn upon for observations of snow depth, precipitation and temperature (Menne et al. 2012). For a range of fields, NCEP/NCAR reanalysis Version 1 is used (Kalnay et al. 1996), with results presented here confined to snowfall. Subsequent work plans to draw on other reanalysis products as well.

3. SNOW COVER EXTENT CLIMATOLOGY

The typical mid-winter snow cover extent across the Middle East and North Africa (MENA) is documented in Fig. 1 using the IMS product. Regional snow cover extent indices have been studied for the areas bounded by the gray boxes on Fig. 1, namely (i) Northwestern Iran and Southern Caucasus (NWIC), including the Zagros Mountains and (ii) Eastern Turkey (ETKY) including the Taurus Mountains. In addition, smaller-scale indices quantify snow variations in (i) the mountains of Lebanon and (ii) the Atlas Mountains of northwestern Africa. The separation of the NWIC and ETKY domains is based on synoptic interpretation, visual inspection of typical snow cover extent maps, and support from spatial analysis techniques (see initial results in Section 5).

For much of the MENA region, winter generally corresponds to the peak in annual cycle of precipitation as well as snowfall and snow cover extent, as mid-latitude weather systems penetrate the region, in contrast to summer, when the region is closer to the descending branch of circulation from tropical precipitation such as associated with the Indian monsoon. There are some nuances in the winter precipitation maximum related to proximity to major water bodies (e.g., Black Sea, Mediterranean Sea, Caspian Sea), as well as orography; and the sharpness of the winter maximum is generally greater in southern parts of the region, being less influenced by mid-latitude climate features (e.g., Sariş et al. 2010; Raziei et al. 2014).

Snow cover extent indices calculated with the 24 km IMS product for the Lebanon and Atlas Mountains domains (domains marked on Fig. 1) have showed good relation with reanalysis circulation products, and lay the basis for further work on these

* *Corresponding author:* Neil Ward, c/o Department of Geography, Rutgers University, Piscataway, NJ 08854-8054; e-mail: neil.ward@rutgers.edu

systems with the 4 km IMS product, which better resolves the spatial details in these smaller domains. For the remainder of this paper, the more regional scale domains of ETKY and NWIC are focused upon (Fig. 2 shows the orography of these domains, along with GHCN station network for snow depth). Analyzing 1999-2016, it is found that for both NWIC and ETKY, the peak snow cover extent typically occurs in late January, and usually becomes near-zero by late June (Fig. 3). The decay rate is initially somewhat faster for NWIC. The mean late-January extent for NWIC is slightly less than that for ETKY (275,000 km^2 versus 325,000 km^2), however, the interannual variation for both domains is very large, with both regions ranging from about 450,000 km^2 to 125,000 km^2 (a slightly higher range is found for NWIC). By early April, mean extent declines to about 50,000 km^2 for NWIC and 100,000 km^2 for ETKY. In early April, interannual variability is still large for NWIC (ranging 130,000-15,000 km^2) and especially for ETKY (ranging 250,000-15,000 km^2). These variations and the implied melt patterns can be expected to have significant implications for local and regional water resources, including drainage into the Tigris-Euphrates river system.

4. IMS EXTENT AND STATION DEPTH INDICES

Regional area-average index calculation for IMS snow cover extent is relatively simple: summing over the target domain, the area of cells referenced as snow-covered is calculated for the given pentad. Time-series are analyzed in terms of km^2 of coverage and also, for ease of comparison with GHCN depth indices, the IMS coverage indices are normalized to have a mean of 0 and standard deviation of 1 over the 1999-2016 period.

Systems have been developed to analyze station snow depth for a target day in the annual cycle, including drawing on temperature and precipitation data to help inform on days that have zero snow depth. For comparison with the IMS pentad indices, the GHCN depth indices target the last day of the comparable pentad (e.g., January 5 for Pentad 1). Networks of approximately 20 stations are identified with sufficient data in mid-winter for both ETKY and NWIC, and are analyzed from 1981 to present (see Fig. 2 for typical mid-winter station networks).

Considering a target pentad *p*, the index value *I* for year *t* is given by:

$$I_t = \frac{\sum_{i=1}^{n} \frac{d_i - \mu_i}{\sigma_i}}{n} \quad (1)$$

Where d_i is the reported snow depth for station i in year t, μ_i and σ_i are the mean and standard deviation of available snow depth values for station i over the base period (usually taken as 1981-2016 to allow best estimates of these quantities), and n is the number of stations with a pentad snow depth value in the given year t.

Because reports of snow depth are usually intermittent and contain no 0-depth values, considerable analysis and experimentation is required in applying Equation (1). Details are in the Appendices, and just a qualitative description is provided here. Each station is assessed for snow depth for the target date (e.g. January 5, if the index is to represent Pentad 1). For the target date, a snow depth observation is accepted up to a maximum of 10 days prior to the target date. If there are no depth observations in this window, then it is necessary to assess if snow depth is zero. Method 1 assumes a true zero depth if there is evidence of the station reporting snow depth values +/- 30 days from the target date. When this practical system is applied, very good agreement is found between the GHCN depth and IMS extent indices. While IMS analysis has over time increasingly drawn on a larger variety of input products, it is believed that station data have only input in the most recent analysis version, which means only 2015 and 2016 may have some station input (S. Helfrich, personal communication, 2017). For the majority of the period analyzed (1999-2014) the comparison is believed strongly independent. Clearest results are found for mid-winter through spring, and these are focused upon here. Typically, IMS and GHCN pentad indices during mid-winter correlate at about r=0.7 (for both ETKY and NWIC domains, slightly higher for ETKY), with little sensitivity to the choice of analysis parameters across sensible ranges (e.g., changing the window to accept a snow depth observation from 10 days to 5 days). The degree of match is encouraging from the perspective of confidence in the data. It is also encouraging because it suggests the snow spatial extent in these regions also covaries strongly with depth, which indicates that it should be possible to combine the IMS and station depth data to contribute to integrated estimates of snowpack (depth * extent), key for implications of melt water entering water resource systems in spring.

Trend patterns also broadly agree between the GHCN and IMS indices. Generally weak or very small downward trends are found in mid-winter over Pentads 1-10 for ETKY. To summarize this, the indices for Pentads 1-10 have been averaged together, and re-normalized over 1999-2016 (Fig. 4a). The averaging reduces noise further and the correlation between the two indices rises to over r=0.9. For Pentads 11-18, generally stronger downward trends are observed (Fig. 4b).

The method 1 for inserting zeros appears to be practical and effective, but it was judged desirable to develop a more physically based system to check results. For this, all GHCN daily station reports October-April were consulted for instances where snow depth was reported on the previous and current day (allowing calculation of snow depth change) and daily average temperature and precipitation were also available for the current day. This permits the calculation of mean snow depth change as a function of temperature and precipitation categories (see Fig. 5). Various improvements may be envisaged, such as making the look-up table a function of elevation as well. Tests suggested the overall results (Fig. 5) relatively robust for initial application (with some small adjustment moving from mid-winter to spring, see Appendix 2 for details). To apply the look-up table, the closest depth observation D prior to the target date is identified (up to a maximum of 60 days prior to the target date). The snow depth is then modelled (using daily temperature and precipitation data to inform daily snow depth change, based on Fig. 5), starting with the depth observation D, stepping forward in time up to the target date. A model estimate of 0 depth for the target date results in 0 depth being used in the analysis. Applying this system to the ETKY data, reproduces results (Fig. 6) that are broadly comparable to those produced with Method 1 (Fig. 4).

Analyses have also been undertaken for the NWIC domain. A look-up table for this domain (not shown) was similar in overall structure, although reflecting slightly more continental nature to the climate. Overall, trend results were similar to ETKY, although the stronger spring declines are found to begin earlier in this NWIC domain. Thus, the NWIC indices for Pentads 1-5 are quite stationary (Fig. 7a) while for Pentads 6-12, relatively strong declines are found in both the snow extent and snow depth indices (Fig. 7b). The earlier decline for the NWIC indices, starting in February, may have implications for water resource impacts, such that declining input to water resource systems starts first from the NWIC domain, and is then extended in time through spring by the later declines in the ETKY domain.

5. INITIAL SPATIAL ANALYSIS RESULTS

A broader goal of the work is to analyze the space-time structure of snowpack evolution during the snow season. As an initial step in building analysis methodology, and to provide context for the choice of ETKY and NWIC index domains, some initial VARIMAX rotated Principal Component Analysis (PCA) results are presented here, drawing on this well-established method for assessing covarying regions in a space-time dataset.

Results reported here focus on the mid-winter January-February (JF) period. For the IMS data for each cell, the number of pentads N_y that are snow-covered in the JF period in year y are calculated. Cells that tend to always be snow-covered, or that tend to always be snow-free, are removed from the analysis, thereby only considering the “active” cells. The remaining series of N_y are then subjected to PCA. For initial assessment here, just the first two principal components (PCs) are rotated, to assess how well the ETKY and NWIC domains are delimited, although results with larger number of PCs lead to similar conclusions. To interpret the PC maps (Figs. 8a,b), it should be noted that the blank areas inside the ETKY and NWIC domains represent cells that were removed from the analysis due to a tendency to always be snow-covered (e.g., northeastern parts of Turkey) or always be snow-free (e.g., southwestern part of NWIC domain). Rotated PC1 captures variability in the NWIC domain, though not extending strongly into the Southern Caucasus. Rotated PC2 captures the ETKY domain. Analyses of other variables (e.g., precipitation, surface temperature, not shown) tends to also support this separation. For example, for reanalysis snowfall (Figs. 8c,d), the separation is clearly reproduced, though the order of the PCs is reversed. This reversal may be related to the substantial removal of ETKY cells in the ETKY IMS domain, such that it is easier for the NWIC mode to explain most variance in the IMS analysis, as well as, for some variance from the southern Caucasus domain to leak into the ETKY mode. Overall interpretation of PCA results with multiple variables suggests that the southern Caucasus part of the NWIC domain has some substantial independent variance, such that subsequent analyses may also consider indices for the southern and northern part of NWIC separately.

6. SUMMARY

Snow cover extent climatologies have been studied. For the Middle East, area extent is substantial and varies greatly from year to year. GHCN-daily indices of snow depth agree well with interannual variability in IMS snow cover extent over the ETKY and NWIC domains. Spatial patterns of variation agree well, including drawing on snowfall in the NCEP/NCAR reanalysis. The widely observed Northern Hemisphere spring snow cover decline is found for Middle East indices, with implications for regional water resources. This can be further quantified, including through snow-hydrology models. The IMS product at 4 km resolution is starting to be analyzed for the Atlas Mountains and Lebanon snow cover, which also varies greatly from year to year, with implications for hydrology.

It is planned to further develop these analyses with data from other satellite-based and reanalysis-based products. The overall assessments reported here and ongoing, are considered to form a basis for underpinning risk assessments of snow-related societal impacts today, as well as providing a baseline for assessments of possible future changes.

APPENDIX 1: GENERATING REGIONAL AVERAGE SNOW DEPTH INDICES FROM STATION DAILY SNOW DEPTH DATA

GHCN index Method 1: Missing Data Pattern is used to infer zero snow depth

For results shown in this paper, the following procedure was followed:

Step (i): For a given year, if there is no snow observation for the target date, seek the nearest observation before, up to a maximum of 10 days before the target. Initially, +/- 5 days was applied. This was found to be inferior, probably because it is vulnerable to large errors whenever a depth observation is strongly influenced by a substantial snow event occurring after the target date.

Step (ii): If no observation is found in step (i), we need to assess if the reason for no depth observations is that the true depth is actually zero. A simple method was implemented which looked to see if there were any snow observations +/- 30 days of the target date. If there was at least 1 snow observation, then the snow depth for the target date was assumed to be zero. Otherwise the snow depth value is set to missing.

The above system was applied to all stations with some snow depth data 1981-2016 in a given domain (here, either ETKY as in Fig. 2a or NWIC as in Fig. 2b).

To qualify for contributing to a pentad series 1981-2016, a station was required to have at least 14 years with a pentad value in the period 1981-2016. For qualifying stations, the regular mean standardized anomaly procedure was applied, i.e.:

a) Each station is transformed into standardized units, by removing the mean and dividing by the standard deviation. So each station has a mean of zero and a standard deviation of 1 over 1981-2016.

b) The area-average depth index for a given year is the average of the available station standardized anomalies.

The trend of these indices has been calculated. This guided over which pentads to make lower temporal resolution indices for summaries. To create an index for Pentad 1 to Pentad 10, the standardized unit area-average index values for each Pentad 1 through 10 are averaged together. To avoid outliers, if a pentad series value was contributed to be a single station, then it was set to missing. Note, for NWIC, there are no depth reports for Jan 1999 to the end of the snow season, so these index values are all missing and comparison with IMS is over 2000-2016.

Finally, for a clear comparison with the IMS standardized series (as shown in Figs. 4, 6, 7), the GHCN averaged pentad indices are re-normalized to have mean 0 and standard deviation 1 over 1999-2016.

It is planned to experiment with other normalization systems, given that the snow depth data contain 0s and are strongly skewed. For example, the percentile rank in the observed distribution may be used. However, especially when averaged over multiple pentads (e.g., Figs. 4, 6, 7), the above normalization system appears adequate for an initial comparison with IMS snow cover extent variability.

GHCN index Method 2: Snow Depth Model Look-up Table is used to infer zero snow depth

These indices are constructed in an identical way to Method 1, except the insertion of zero depth observations is made in a more sophisticated way. First, station-days are identified (in the window October 2nd to April 30th) that satisfy the following, where d is the target day: non-missing values of snow depth for d-1 and d, precipitation for d, and average temperature for d (similar results were found substituting average temperature with minimum or maximum temperature). For ETKY there are about 15,000 such cases available (with about 1% of cases removed due to outliers clearly not representative and likely erroneous). For NWIC, there are about 5,000 such cases (again removing about 1% of cases for outliers). The mean snow depth change is then calculated for categories of average temperature and precipitation. This delivers a two-dimensional look-up table to integrate forward snow depth, based on each day's temperature and precipitation. Figure 5 illustrates the ETKY look-up table (see Appendix 2 for adjustment of the look-up table as a function of annual cycle).

For making the snow depth analysis, Step (i) for the index Method 1 is identically followed. Then, if there is no snow depth observation available, the record is searched to see if there is a snow depth observation within the previous 60 days. Initializing the model with the closest snow depth observation to the target date, the look-up table is applied based on available daily temperature and precipitation data, to step forward the snow depth from its observed value, up to the target date. If the model estimates 0 depth for the target date, then 0 depth is assumed. If the model estimates non-0 depth, then the snow depth value is set to missing for this date (an alternative could be to actually use the model's snow depth estimate for the target date, but for now, we just focus on identifying zero depths with the model).

In applying the above procedure, a system is required for handling missing values of daily temperature and precipitation while the model is stepping forward from the date of the observed snow depth, to the target date. After some experimentation, an initial minimum requirement was for precipitation and temperature to both be present on at least 50% of the days in the period from the snow depth observation to the target date. If this was not satisfied, snow depth for the target date was set to missing. However, if this was satisfied, then the mean change in snow depth is calculated for the available pairs of precipitation and temperature. This is assumed to be representative of the period over which the model will run, and this mean depth change is applied for the days with missing precipitation and temperature.

Once the snow depth analysis is completed for a given pentad, then the exact same procedure is applied as described above to arrive at area-average standardized series.

APPENDIX 2: ADJUSTING THE SNOW DEPTH LOOK-UP TABLE FOR ANNUAL CYCLE

It can be expected that, for example, for a given mean temperature, melt rates may be higher in spring than in winter, and the daily change in snow depth in the look-up table should be adjusted accordingly. Analysis of the data suggest this is indeed seen moving from winter to spring (and is systematic for temperature categories, but not obviously so for precipitation).

Little systematic change could be seen from fall to winter. For simplicity in this initial implementation, the basic temperature/precipitation look up table is only adjusted based on temperature, and fall is pooled together with winter. A base look-up table for October-April (e.g., Fig. 5) is therefore adjusted following the empirical shift required for (i) October-February, (ii) February-March, (iii) March-April. This produced smoothly evolving adjustments. The October-February look-up is applied for October 1st to February 14th, the February-March look-up is applied for February 15th to March 14th, and the March-April look-up is applied for March 15th to the end of the snow reporting season.

REFERENCES

Barnett, T. P., J. C. Adam, and D. P. Lettenmaier, 2005: Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, **438**, 303–309, doi:10.1038/nature04141.

Cayan, D. R.,1996: Interannual climate variability and snowpack in the western United States. *J. Clim.*, **9**, 928-948.

Danielson, J. J., and D. B. Gesch, 2011: Global multi-resolution terrain elevation data. U.S. Geological Survey Open-File Report 2011–1073, 26pp.

Derksen, C., and R. Brown, 2012: Spring snow cover extent reductions in the 2008–2012 period exceeding climate model projections. *Geophys. Res. Lett*., **39**, L19504, doi:10.1029/2012GL053387.

Déry, S. J., and R. D. Brown, 2007: Recent Northern Hemisphere snow cover extent trends and implications for the snow-albedo feedback. *Geophys. Res. Lett.*, **34**, L22504, doi:10.1029/2007GL031474.

Groisman, P. Y., T. R. Karl, R. W. Knight, and G. L. Stenchikov, 1994: Changes of snow cover, temperature, and radiative heat balance over the Northern Hemisphere. *J. Clim.*, **7**, 1633–639.

Helfrich, S. R., et al., 2007: Enhancements to, and forthcoming developments to the Interactive Multisensor Snow and Ice Mapping System (IMS), *Hydrological Processes* **21**, 1576-1586.

Helfrich, S. R., M. Li, and C. Kongoli, 2012: Interactive Multisensor Snow and Ice Mapping System Version 3 (IMS V3) Algorithm theoretical basis document version 2.0 Draft 4.1. NOAA NESDIS Center for Satellite Applications and Research (STAR), 59 pp.

Kalnay, E., et al., 1996: The NCEP/NCAR 40-Year reanalysis project. *Bull. Amer. Meteor. Soc.,* **77**, 437–471.

Mankin, J. S., D. Viviroli, D. Singh, A. Y. Hoekstra, and N. S. Diffenbaugh, 2015: The potential for snow to supply human water demand in the present and future. *Environ. Res. Lett.*, **10**, 114016.

Menne, M. J., I. Durre, R. S. Vose, B. E. Gleason, and T. G. Houston, 2012: An overview of the global historical climatology network-daily database. *Journal of Atmospheric and Oceanic Technology*, **29**, 897-910. DOI: 10.1175/JTECH-D-11-00103.1

Mote, P. W., A. F. Hamlet, M. P. Clark, and D. P. Lettenmaier, 2005: Declining mountain snowpack in western North America. *Bull. Amer. Meteor. Soc.,* **86**, 39-49.

Raziei, T., J. Daryabari, I. Bordi, and L. S. Pereira, 2014: Spatial patterns and temporal trends of precipitation in Iran. *Theor. Appl. Climatol.,* **115**, 531-540.

Robinson, D. A., and K. F. Dewey, 1990: Recent secular variations in the extent of northern hemisphere snow cover. *Geophys. Res. Lett.*, **17**, 1557–1560.

Sariş, F., D. M. Hannah, and W. J. Eastwood, 2010: Spatial variability of precipitation regimes over Turkey. *Hydrol. Sci. J*., **55**(2), 234-249.

Shi, X., S. J. Déry, P. Y. Groisman, and D. P. Lettenmaier, 2013: Relationships between recent pan-Arctic snow cover and hydroclimate trends. *J. Clim*., **26**, 2048-2064.

Thackeray, C., C. Fletcher, L. Mudryk, and C. Derksen, 2016: Quantifying the uncertainty in historical and future simulations of Northern Hemisphere spring snow cover. *J. Clim*., **29**, 8647–8663.

FIGURES

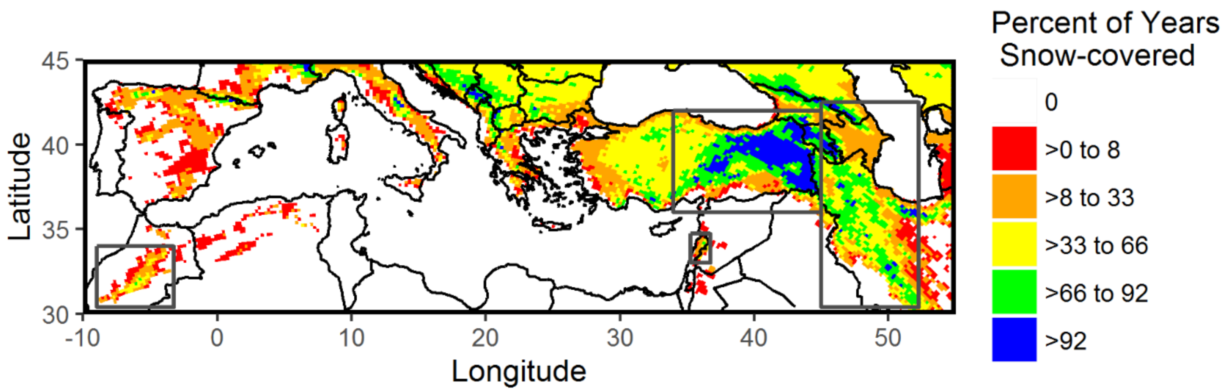
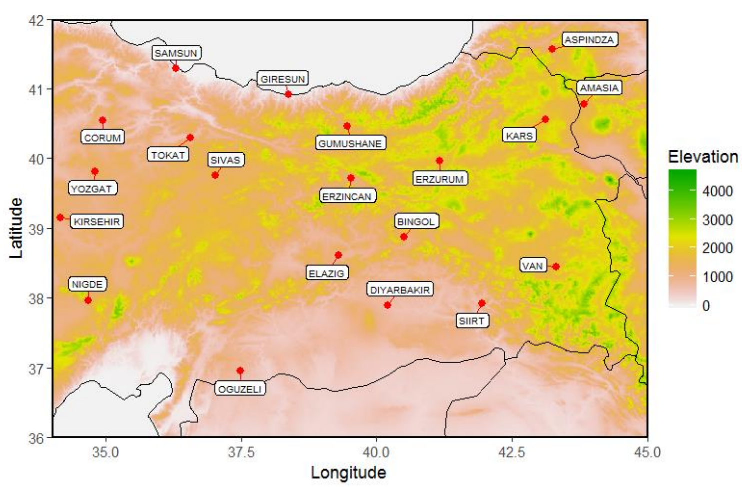


Figure 1. Climatological Snow Cover Extent 1999-2016 from IMS 24 km resolution product for January 31st. The area-average domains analyzed in the paper are shown by the dark grey rectangles for Northwestern Iran / Southern Caucasus (NWIC), Eastern Turkey (ETKY), Lebanon, and Atlas Mountains of northwestern Africa.



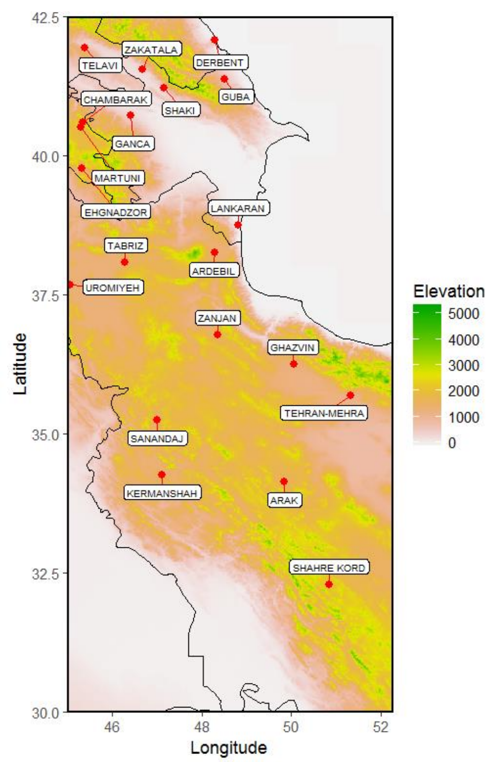


Figure 2. GHCN-Daily stations contributing to typical area-average snow depth index in mid-winter for (a) Eastern Turkey (ETKY) domain (left panel) and (b) Northwestern Iran / Southern Caucasus (NWIC) domain (right panel). Elevation (meters) is from the USGS GMTED2010 product at 30 arc-second resolution (Danielson and Gesch 2011).

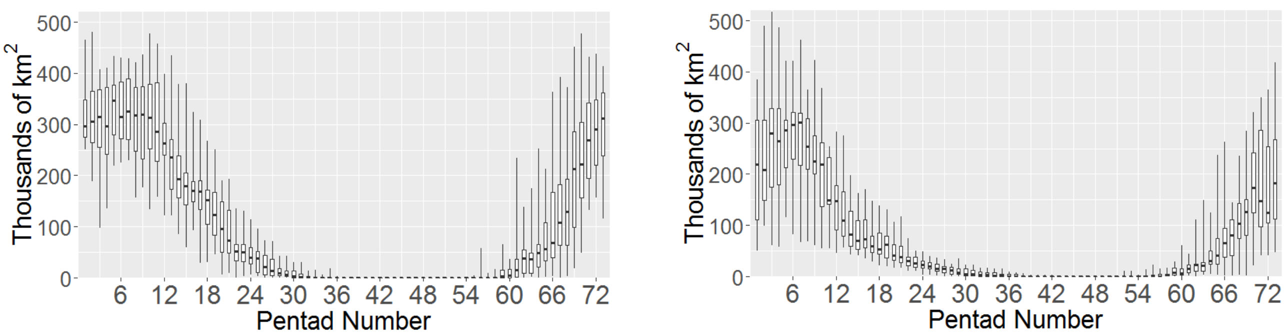


Figure 3. Climatological snow cover extent for each 5-day period (pentad) in the annual cycle, for (a) ETKY (left panel) and (b) NWIC (right panel). The box-whisker plots show the median, inter-quartile range and absolute range of snow cover extent observed for each pentad in the 1999-2016 period.

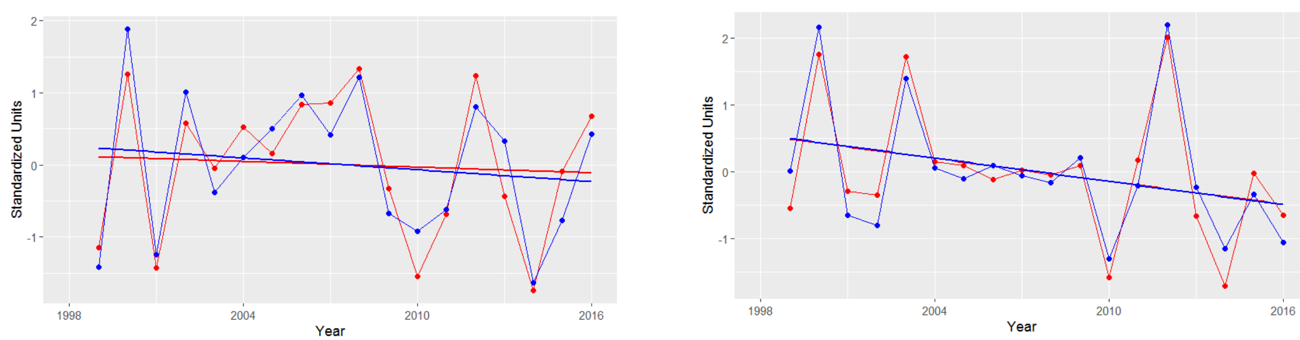


Figure 4. For the ETKY domain, standardized snow cover extent from the IMS data (red) and snow depth from GHCN stations (blue). Results are averaged for (a) Pentads 1 to 10 (i.e., January 1st - February 19th) (left panel), and (b) Pentads 11 to 18 (i.e., February 20th - March 31st) (right panel). For the calculation of GHCN indices, zero snow depth days were inferred using method 1 (see text and Appendix 1). Correlation between the red (IMS) and blue (GHCN) lines is r=0.91 (left panel) and r=0.94 (right panel).

Figure 5. Look-up table for snow depth change (from previous day to current day) depending on the current day's observed rainfall and temperature category. Based on about 15,000 daily sets of observations in the ETKY domain for all available observations in October to April.

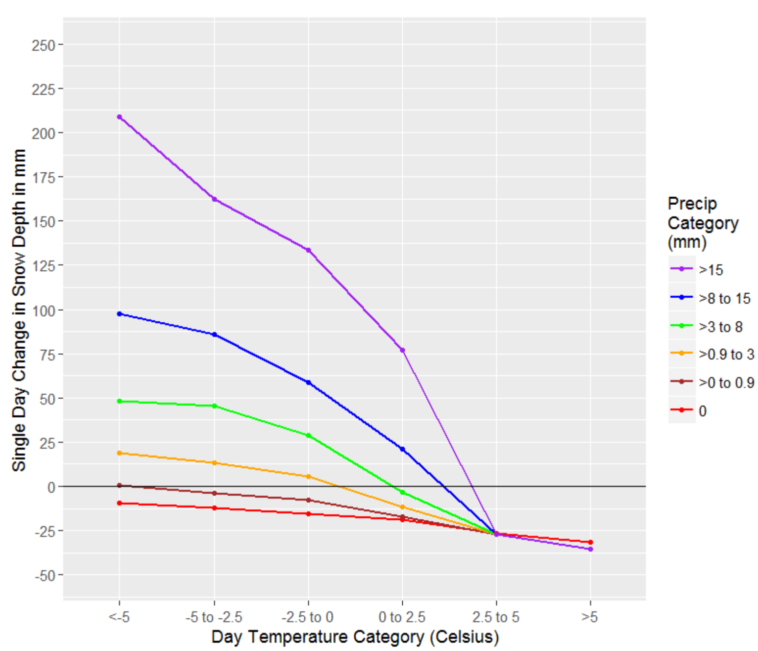


Figure 6. Same as Fig. 4 but for the GHCN indices, zero snow depth days are inferred from method 2 (i.e., applying the look-up table, Fig. 5). Correlation between the red (IMS) and blue (GHCN) lines is r=0.88 (left panel) and r=0.90 (right panel).

Figure 7. Same as Fig. 6 but for the NWIC domain and for the averaging periods: (a) Pentads 1 to 5, i.e., January 1st - 25th (left panel) and (b) Pentads 6 to 12, i.e., January 26th - March 1st (right panel).

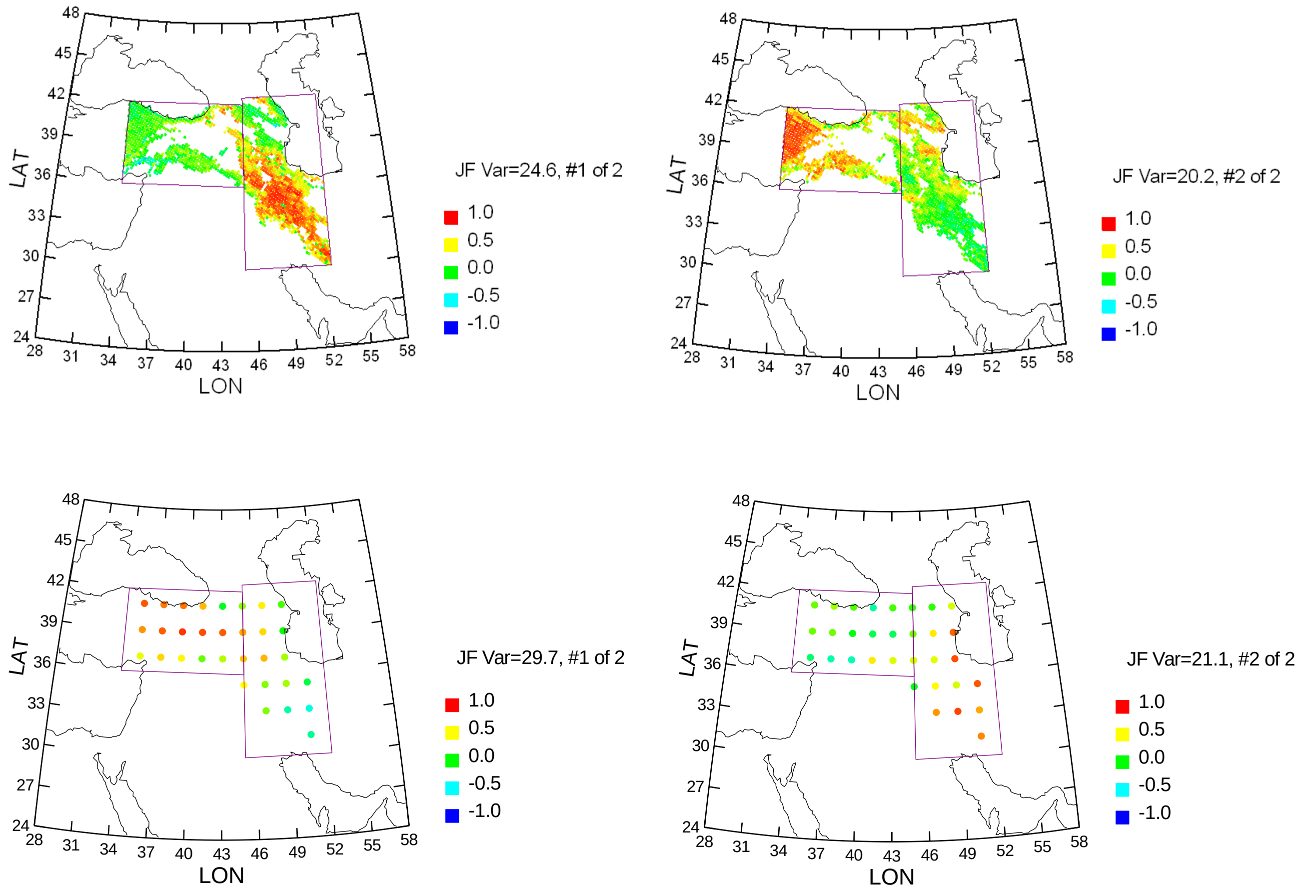


Figure 8. Rotated (VARIMAX) Principal Components (PCs) for January-February (JF) 1999-2016: (a) Rotated PC1 of snow cover extent from IMS data (top left panel) and (b) Rotated PC2 (top right panel); (c) Rotated PC1 of JF snowfall from NCEP/NCAR reanalysis version 1 (bottom left panel) and (d) Rotated PC2 (bottom right panel). Both PC analyses identify an Eastern Turkey mode (PC2 for IMS, PC1 for reanalysis snowfall) and a Northwestern Iran / Southern Caucasus mode (PC1 for IMS, PC2 for reanalysis snowfall). The percentage of total variance explained by each mode is given by “Var” in each panel.