Variation of snow water resources in northwestern China, 1951—1997 *

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Abstract An observation study is carried out on snow mass amount estimate in northwestern China by using microwave derived snow depth charts employing data from SMMR in conjunction with daily snow depth, density and snow cover duration records for 46 ground climate stations. Spatial patterns, seasonal cycle, and interannual variation of snow cover are discussed. Results show that snow cover is the second largest water supply over the arid northwestern China, and unlike most other areas in the world, northwestern China did not experience any decrease in snow cover since 1987. Secular trends reveal systematic increase in snow mass and durations. Analysis of snow cover-climate relationship indicates that gradual increase in snow cover is primarily in response to increase in snow season precipitation.

Keywords: northwestern China, snow water resources, spatial and temporal variability.

Northwestern China (fig. 1), one of the most important snow-cover areas in China, is selected for this study. Two-fifths of stable snow cover area in China is located there[1], and one-third of snow resource in China is distributed in this region[2]. Since this region suffers from a serious deficit of water resource and experiences frequent catastrophic drought episodes, the main water supply is snow melt water. Snow cover, as a cryospheric component, is considered to be particularly sensitive to regional and global climate change. In the context of global warming, changes in snow mass, snow cover extent and duration take on great significance. And it is generally believed that decrease in snow cover is in response to CO_2-induced global warming. Global snow cover monitoring showed a reduction of hemispheric snow cover after 1987[3], earlier disappearance of spring snow cover[4—7], and a considerable desiccation of the soil in the mid-latitude arable areas. Aizen et al.[8] reported a decrease in snow resources in the west Tianshan Mountains. But there are important regional exceptions. Precise airborne laser altimetry and satellite radar altimetry surveys revealed a thickening in Greenland ice sheet between 1978 and 1993[9—11]. Observation from Russian stations found a fairly consistent increase in winter snow depth in most of the Arctic continental regions[12]. Surface mass balance measurements indicated that the accumulation rate increased in Antarctic ice sheet[13]. Trend estimates show that the increase in Tibetan snow depth is a systematic development over the past 40 years[14]. A high-resolution GCM (T106) simulation of Antarctic mass balance change demonstrates that a great increase in snow accumulation without melt is projected in the next century[15]. Fully coupled atmosphere-ocean GCMs simulation predicts that a 1—2℃ rise in global mean temperature by 2100 would increase the global mean precipitation by about 3% or more. And precipitation is expected to

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increase in higher and mid latitudes, particularly in winter[16]. At present, the response of snow cover to global warming is yet in debate. It is clear only that both precipitation and temperature affect the snow cover, but their aggregate impacts remain unsolved.

1 Snow cover data

1.1 Challenge to large-area snow resource study

Assessment of natural variation in snow resources requires reliable high-spatial-resolution snow depth and density data covering a sufficient time. However, up to now the operational NOAA satellite-derived snow cover chart refers only to snow cover extent on $2° \times 2°$ coarse grid cells. Thus no information on snow depth or snow water equivalent is attainable. Measuring microwave radiation provides snow depth information regardless of sky conditions, which provides a potentially invaluable means of monitoring snow resource conditions. The NASA scanning multichannel microwave radiometer (SMMR) passive microwave satellite snow depth data are arranged in a $0.5° \times 0.5°$ grid scale. Although SMMR snow depth data are good for snow resource storage estimate, 10-year record is still too short for us to know the long-term variation and trends of snow storage. Station data offer longer time series of snow depth, density, and duration, but spatial coverage is frequently less than optimal, especially in high mountainous areas, where station data are sparse. And there may be some problems in data quality. Nevertheless, when attention is paid to quality control and selection of a station network, station-derived estimates of snow cover might be accurate and reliable. Following "World Snow Watch" recommendation, satellite SMMR and ground station-derived regional snow cover data were integrated in this study.

1.2 Utility of SMMR pentad snow depth data

Satellite-borne passive microwave sensors have been recognized as an important means of monitoring snow cover. The SMMR, on board the Nimbus 7, is a five-frequency dual-polarized microwave radiometer. The frequency 37-GHz sensor with a spatial resolution of 25 km is the most widely used for snowpack monitoring. The intensity of microwave radiation thermally emitted by snow is measured and expressed as brightness temperature (T_B). T_B is spatially averaged for each $0.5° \times 0.5°$ latitude-longitude grid cell and retrieved to snow depth by snow parameter retrieval algorithm developed by Chang et al.[17]. NASA SMMR snow depth data were compiled for six-day periods from 1978 to 1987. For the purpose of this study the complete 10-year data over the study area are used. However employing a single global algorithm to extract snow signal from SMMR data does not accurately monitor snow cover over western China. NASA algorithm was tuned for a uniform snow field with moderate snow depth over low elevation regions, with a snow density of $0.3\ g \cdot m^{-3}$ and a mean snow grain size of 0.3 mm which is the avevage value for many snow pits from the Colorado River basin. Over western China snow cover is predominantly shallow, patchy, and frequently of short duration[18]. It is therefore necessary to calibrate the SMMR snow product with ground station record and visible satellite imagery. We compared SMMR data with DMSP Operational Linescan System (OLS) shortwave images and daily snow depths reported by 175 weather stations over northwestern China. A regional snow parameter retrieval algorithm was developed to account for the effect of the atmospheric conditions, and snow cover extent adjustment for shallow and patchy snow area under the support of GIS[19].

$SD = 2.0\ (T_{18H} - T_{37H}) - 8$ for the plateau,

$SD = 2.0\ (T_{18H} - T_{37H}) - 6$ for high mountains,

$SD = 1.59\ (T_{18H} - T_{37H}) - 3$ for low mountains, rolling hills and basin,

where SD is the snow depth in cm; T_{18H} and T_{37H} are the horizontally polarized brightness temperature for the SMMR 18 and 37 GHz radiometers. By applying the regional algorithms the SMMR derived snow data correspond much better with the "ground truth" over northwestern China.

1.3 Snow and other climatic data from ground meteorological stations

Out of the 175 synoptical stations available in the study region, 94 are primary meteorological stations. Snow cover data include daily snow depth, pentad snow density with snow depth $\geqslant 5$ cm, and number of snow cover days. The data span the period 1951—1997. Since the stations are irregularly spaced and the data vary with length and temporal completeness, we use a subset of 46 best stations by selecting one station for 38 $2° \times 2°$ grid cells each with lengthy records, without station relocation and record missing. And an additional 8 high-elevation (2 000—4 000 m asl) stations were added to account for orographic effects on snow distribution. The snow cover year was defined as from September to next August. The station point records are integrated over the snow cover year and space to derive the regional time series of snow cover information as well as snow season surface air temperature and precipitation. We believe that with regard to large scale area averages, biases and errors associated with point specific station data are minimized to such an extent that meaningful snow cover and climate signals can be extracted.

2 Snow storage and its spatial pattern and annual cycle

Accurate monitoring of snow water storage over northwestern China is essential for understanding the amount and location of stored frozen water in the form of snow cover and its spatial variation and the patterns of water release by melting. Snow water storage, or snow water equivalence is given by the simple approach:

$$W = \rho h s,$$

where W represents the pentad snow storage on each of the 1 007 $0.5° \times 0.5°$ grid cells over northwestern China; h and s denote pentad snow depth and snow area extent respectively, which are obtained by the revised SMMR algorithms during the period between 1978 and 1987; ρ is pentad snow density recorded at 36 primary weather stations. The results show that during the maximum winter snow periods in 1978—1987, the mean snow water storage reaches 361.0×10^8 m^3 over northwestern China, being 38.2% of the annual mean runoff in the region. In the 361.0×10^8 m^3, 211.6×10^8m^3 is in North Xinjiang, 130.5×10^8 m^3 in South Xinjiang, and 18.9×10^8 m^3 in Qilian Mountains. This has clear economic impacts in arid northwestern China, where it is vital for sustaining agriculture water supply in spring.

Figure 1 shows that snow water storage varies spatially between large mountains and basins. Snow storage is concentrated in six large mountain systems in northwestern China. The highest snow depth (50—60 cm) is found in Altay Mountains, the second highest (40—50 cm) occurs in the Tianshan Mountains, Pamir and Karakorum Range, the third highest (20—30 cm) in the Kunlun Mountains, and only 10—20 cm in the Qilian Mountains. Besides, the depth of 20—50 cm is seen in the Elgis Basin, the Ili Basin, and the plain at the northern foot of Tianshan Mountains.

Snow storage exhibits considerable spatial fluctuations. The above-mentioned snowy areas are af-

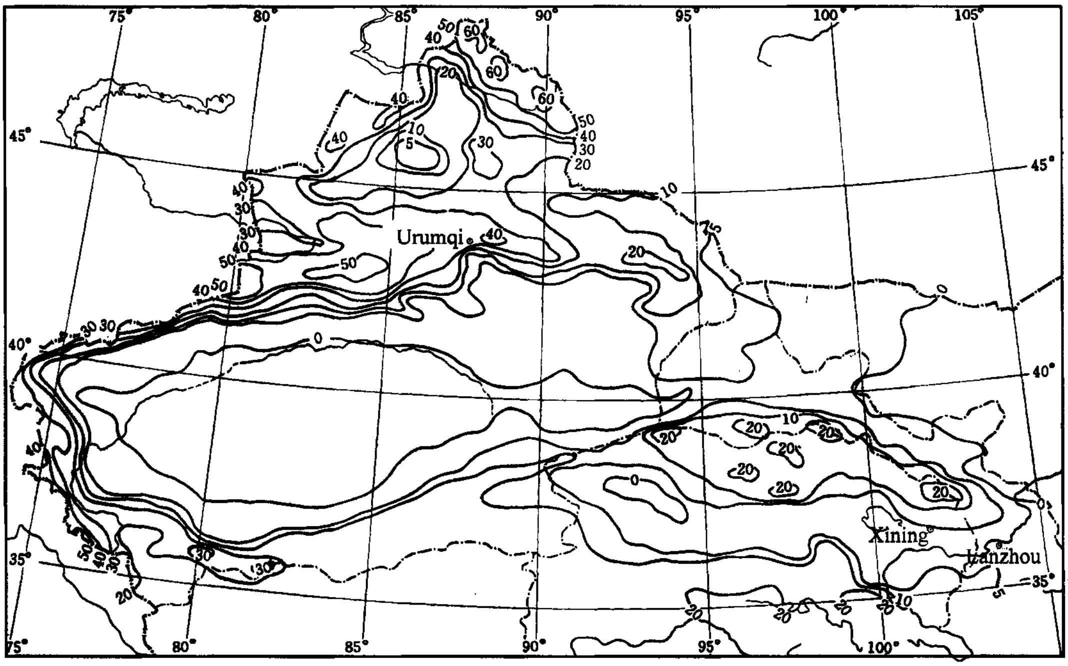

Fig 1. Spatial pattern of snow depth (cm) over northwestern China during winter snow maxima estimated by SMMR between 1978 and 1987.

fected by substantial year-to-year variations in snow depth by as much as 40—50 cm. In the Junggar Basin, the annual anomaly reaches 50—60 cm, as in some winters there was no snow cover there. It is in those areas that fluctuation of snow storage dominates interannual variation of snow storage.

The normal annual cycle of snow water storage over northwestern China derived from SMMR 10-year observation demonstrates that snow storage is predominantly a winter phenomenon. Snow storage begins accumulating in mid November. It increases to a late February or early March peak, followed by a rapid decline until early April. The ablation season is only as long as one month. The characteristics of late peak and short ablation period are beneficial to humans, especially for overcoming spring droughts.

3 Variation and secular trends of snow storage

The development of long-term homogeneous time series is a crucial step in examining natural variation of snow storage. In homogeneous time series variations are caused only by climate. The determination of homogeneity could be made by intercomparison of time series.

Figure 2 shows that any year-to-year fluctuations experienced by the snow duration time series show up in the SMMR snow storage time series as well. And a strong correlation ($r = 0.59$) exists between the two. So, they are relative homogeneous time series. The same also holds true for highly correlated ($r = 0.72$) time series of snow duration and annual cumulative daily snow depth (see lines 1 and 2 in fig. 3). The comparison results prove that three snow time series constructed in this study have the ability to accurately represent the true variation of snow storage over arid northwestern China.

SMMR pentad snow storage time series (see top in fig. 3) are characterized by high interannual

Fig. 2. Intercomparison of annual number of snow cover days created from a 46-station network and annual cumulative pentad snow storage estimated by SMMR in Xinjiang. 1, Annual cumulative pentad snow storage; 2, annual number of snow cover days.

variability. For instance, peak amounts of snow storages between heavy snow winter and light snow winter have great difference of 70×10^8 m^3. In some winter the peak was delayed by about one month, and sometimes it appeared earlier by half a month. The broad peak lasted for 72 d while the sharp peak for only 30 d. The highly variable nature of snow storage is principally responsible for the anomalies in spring runoff as well as seasonality of river flow.

The long-term variation of snow cover durations and that of snow depth over Xinjiang between 1951 and 1997 are depicted in fig. 3 as annual summaries. Both of them demonstrate that throughout the record there are six occasional periods where two or more consecutive years are above or below the half century mean. Periods above the mean: 1958/1959—1959/1960, 1975/1976—1977/1978 and 1984/1985—1987/1988; periods below the mean: 1961/1962—1965/1966, 1973/1974—1974/1975 and 1980/1981—1983/1984. The highest year was 1987/1988, and the lowest year was 1967/1968. Noteworthy years of anomalous snow storage include very high snow year 1959/1960, and very low snow year in 1973/1974. In the late 1960s and early 1970s, snow was the lowest in the second half of the 20th century. The variations indicate an alternating occurrence of heavy and light snow periods which superimposed on small positive trend. Snow storage fluctuated around the mean and the anomalies do not appear to be outside the range of natural variation. Neither other snow regimes nor rather abrupt change happened. And no continuation of recent snow minima that began in the late 1980s to the early 1990s as well as early disappearance of spring snow cover was found. Only from the end of 1980s a longer-lived decrease in snow cover was evidenced, but not so great as the three previous snow-deficit years.

Snow cover responds to both winter precipitation (snowfall) and temperature variations. To diagnose the climate influences on snow cover over northwestern China, we conducted a multiple linear regression analysis. The area averaged time series of annual snow duration and annual cumulative daily snow depth were related to area-averaged snow season total precipitation and surface air temperature time series during the period between 1951 and 1997. The resulting regression equations are given by

$$S_n = 0.4975\,P_s - 4.5142\,T_s + 35.2,$$

$$S_d = 20.8551\,P_s - 150.284\,T_s - 738.8,$$

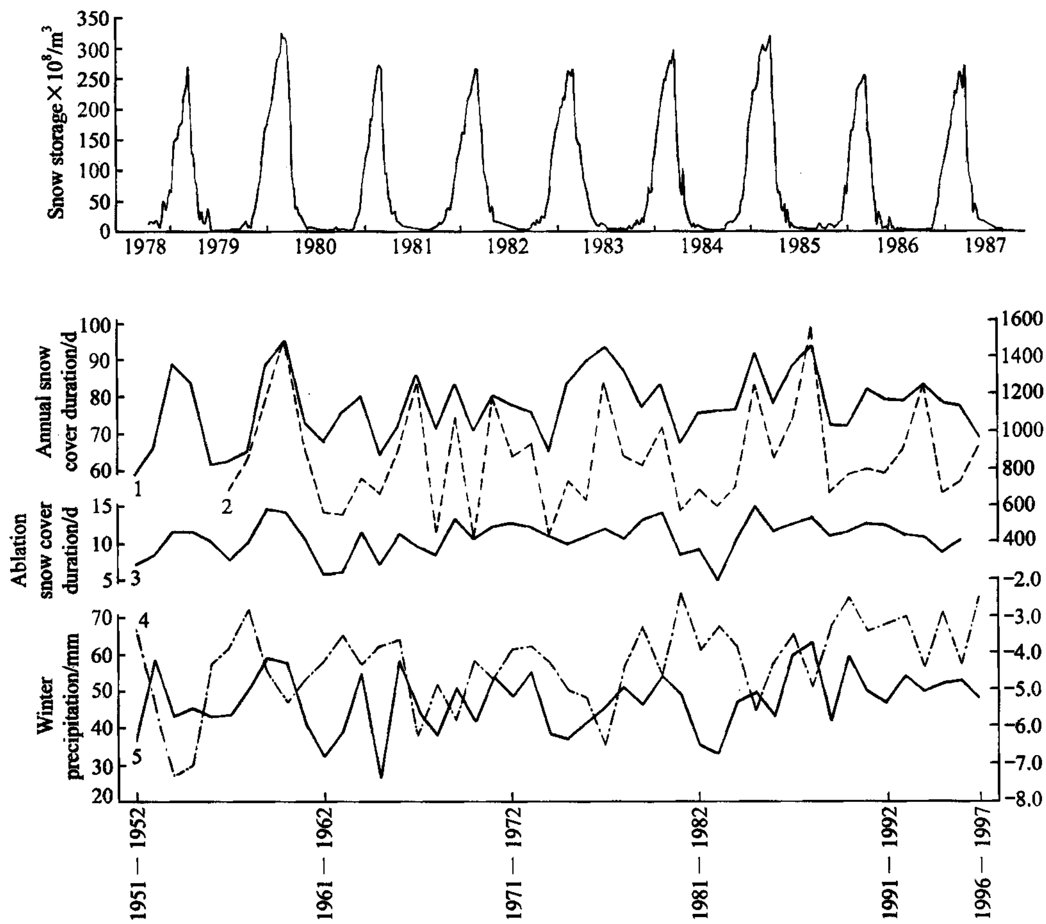

Fig 3. Time series of snow cover and climate in Xinjiang for SMMR pentad snow storage (top); annual number of snow cover days (bottom line 1); annual cumulative daily snow depth (bottom line 2); number of snow cover days in ablation period (bottom line 3); winter snow season temperature (bottom line 4); and winter snow season precipitation (bottom line 5).

where S_n and S_d are the annual snow duration (annual number of snow cover days) and the annual cumulative daily snow depth respectively; P_s represents the total precipitation in cool season; T_s denotes the surface air temperature during snow season. The multiple regression coefficients are 0.70 and 0.81 respectively. The year-to-year snow cover fluctuation was found to be fundamentally tied to the precipitation and the temperature interannual variations. A significant portion of the variances were able to be explained by the corresponding precipitation and temperature variations. While snowfall is always entered as a positive coefficient and cool season temperature as a negative one, annual cumulative snow depth is more closely linked to the snowfall variability and snow cover duration is more closely linked to the temperature. However cool season total precipitation and surface air temperature are not correlated with each other over northwestern China.

Testing for long-term trend in snow cover of the large-scale dimensions is also critical for identifying interactions between climate and snow cover. Here a statistical model consisting of a possible trend plus correlated noise are fitted to the snow and climate time series. This plausible statistical approach is

$$Y_t = a + bt + E_t,$$

where Y_t represents the climate parameters in year t; E_t is the deviation from a straight line, and is assumed to be a stationary zero mean process. Whether the changes in time series are approximated by a linear trend, or E_t are serially correlated, and the random trends are presented in the time series, a deterministic trend can be detected by using three trend testing approaches of autoregressive moving average model (ARMA), least squares fitting, and different average[20,21]. Results of trend estimates for five time series are listed in table 1. The increases in annual and ablation season snow duration as well as annual cumulative daily snow depth are systematic developments as evidenced by the presence of deterministic trends which are statistically significant at the 0.01 significance level. Both snow cover duration and depth exhibited a gradual increase. Although increasing rates are small, they are statistically different from zero. Annual snow cover duration, ablation season snow cover duration and annual cumulative snow depth increased by 8.9 day, 1.6 day and 20.8 cm respectively during the past 50 years.

Table 1 Three trend estimates based on slope ARMA (ρ) process, least squares fitting and different average

Time series	Trend testing approach			
	b_{ARMA}	b_{LS}	b_{AV}	ρ autocorrelation coefficient
Annual snow cover duration	+0.0221	+0.0214	+0.0276	0.2821
Snow cover duration in ablation season	+0.0153	+0.0150	+0.0135	0.1972
Annual cumulative daily snow depth	+0.0018	+0.0018	+0.0016	0.0200
Cool season surface air temperature	+0.0318	+0.0324	+0.0246	0.4182
Cool season total precipitation	+0.014 7	+0.014 4	+0.010 2	0.191 0

Trend estimates of snow cover, cool season total precipitation and surface air temperature reveal that large-scale systematic increases in snow cover duration and snow water storage are accompanied by statistically significant increases in total precipitation of $+0.12\ \mathrm{mm \cdot a^{-1}}$ and surface air temperature of $+0.03℃ \cdot \mathrm{a}^{-1}$ during snow cover season. However, the positive correlation between snow cover and cool season precipitation is stronger (+0.60) than the negative correlation (−0.5) between snow cover and winter surface air temperature. And the increased winter temperatures are still well below freezing. Therefore, snowfall has great influence and becomes most important climate variable for determining long-term trend of northwestern China snow cover.

4 Summary and discussion

Owing to the serious impacts of global warming on snow cover, understanding snow water storage variation and quantifying the relationship between snow cover and climate over the arid northwestern China, where much of the water supply is from snowmelt runoff, have aroused much attention.

In this study, the variation of snow water storage and its interactions with cool season total precipitation and surface air temperature have been examined for the period between 1951 and 1997 by using SMMR pentad snow depth data in conjunction with daily snow cover records and monthly temperature and precipitation data for 46 selected meteorological stations across northwestern China.

Significant snow water storage in northwestern China is delineated. Considerable spatial characteristics of the snow storage variation are observed. And a long-term temporal variation of snow cover is documented. On average, snow storage peaks at the end of a winter at about $361.0 \times 10^8\ \mathrm{m}^3$. Alsence of the rapid decrease in snow cover after the 1970s as well as earlier disappearance of spring snow cover reported by a number of studies which are all based on the post 1972 period of NOAA satellite data. This 20-year period is insufficient for characterizing snow cover variability. Our long-term station observations provide valuable insights into the nature of snow cover variations.

Recently, association of snow cover with precipitation and temperature has gained attention for estimating regional snow cover response to global warming. These estimates including ours must be interpreted with some caution. The standard rain gauges currently being used worldwide undercatch true snowfall. It is possible that because winter precipitation data have been biased, the actual relationship between snow cover and precipitation could not be obtained.

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