# Digital extraction of snowline based on flow path analysis

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**Abstract:** In this paper, a digital identification method for a snowline is presented. The method takes into consideration that the lower limits of a perennially snow-covered area should only be deduced through contrasting with other limits. Thus, a method based on hydrological analysis was introduced to extract the snowline. Based on the digital elevation model (DEM) of the study area and the result of snow cover monitoring, the lowest point covered with snow could be recorded in one flow path. Through loop statements, all of the lowest points were determined by comparing the snow altitude in every flow path. The lowest points were then joined sequentially, according to the real landform, and shaped into snowlines. In addition, a method of computing the average annual snowline was analyzed. This method based on hydrological analysis can effectively avoid the influence of naked areas in snow cover, and shows promising results for the calculation of the lower boundary of a perennially snow-covered area. Spatial-temporal dynamics of snowlines can also be analyzed by the proposed method. The digital identification method presented here is effective at identifying a snowline, and could be helpful in rapid information extraction of a large-scale area.

**Key words:** snowline, flow path, digital extraction

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## 1 INTRODUCTION

As one of the most active and unstable natural factors (Xu & Tian, 2000), snow cover is an extremely sensitive indicator of climatic variability, and has received much attention (Feng & Li, 2000). Spatial-temporal distribution information of snow cover is important for water resource management and for evaluating the effects of climate change. Changes in snow cover have great significance in hydrology and climatology at the global scale as well as the local scale (Turpin *et al.*, 1997; Kerr & Sugden, 1994).

As the zero-balanced surface of solid rainfall (Yan & Zeng, 1985), a snowline can be defined as the lower limit of the perennially snow-covered area in natural landscapes, and it is a geographic element as important as a tree line, a periglacial line, or a soil line (Wu, 1989; Cheng, 1984; Mengel *et al.*, 1988). In China, because of the diversity and complexity in topography, there is great climatic dissimilarity in the transmeridional direction. Primarily due to the effect of the Tibetan plateau, the snowline is shaped into an annular distribution in the Tibetan area (Jiang *et al.*, 2002; Jiang, 1991). Accordingly, the latitudinal zonality of the snowline is changed or disturbed. Regarding snowlines in particular regions, except for latitudinal zonality effects, the altitude of a snowline would also depend on the local temperature, precipitation, and topography, etc. Accordingly, all of these impacts enhance the spatial complexity of the snowline distribution (Kerr & Sugden, 1994).

Traditionally, snowline distribution data have been acquired from relief maps, or ascertained from field surveys (Wu, 1989). Due to data limitations and incomplete information on snowline distribution, often the snowline of a whole mountain or the snowline at a regional scale is represented by a single point. However, single points obviously cannot accurately reflect the spatial variety of snowlines. Alternatively, handwork could be used for traditional snowline mapping, but this takes much time and effort. Therefore, it is difficult to update snowline data for a broad scale area.

With the development of remote sensing (RS), the technology of snow cover monitoring has rapidly moved from qualitative to quantitative. At present, remotely sensed images have already proven useful as a data source for snow cover (Li *et al.*, 2007; Hao *et al.*, 2008). Nevertheless, whether data are collected through field surveys or from RS images, handwork is still relied upon to outline the snowlines. There is still no effective method for digitally extracting a snowline.

Currently, much information about snow cover can be ob-

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tained using image processing technology. Many ways to extract snow cover information are now available (Li *et al.*, 2007; Hao *et al.*, 2008; Liang *et al.*, 2007). Difficulties in digital extraction of snowlines are presently primarily focused on how to extract the lower altitudinal boundary of a perennially snow-covered area automatically from the snow cover data. This is the basis for calculating the position and elevation of a snowline and, from that, the averaged annual snowline etc. However, because of the discrete spatial distribution of snow cover above the snowline (Klein & Isacks, 1999), many bare areas in snow cover also exist. At the same time, bare areas would also be created in the process of image processing due to the influence of hill shading. Consequently, not all of the borderlines of snow cover would be considered as snowlines. Therefore, the border detection method cannot be used directly to extract a snowline. Methods such as mathematical morphology are also not appropriate, as the lower boundary may be changed while filling the bare area. Moreover, there are still some difficulties in comparing and describing the annual variance of a snowline, and in determining the spatial distribution of the average snowline. Accordingly, in this paper, a digital identification method for defining a snowline is discussed that is based on the combination of the GIS spatial analysis and remotely sensed images.

## 2 METHODS

The snowline is defined as the lower limit of the perennial snow on the landscape, as well as the lower borderline of the perennial snow area (Yan & Zeng, 1985; Jiang *et al.*, 2002), above which there is perpetual snow and ice. However, the area above a snowline is not always covered by snow or ice. There are plenty of naked areas with no snow above the snowline. Therefore, current edge-detecting methods cannot be used directly for snowline extraction, as the some of the borderlines are the boundaries of naked areas other than the lower limit of the perennial snow area. From another point of view, we know that the lower borderlines are made up of points that are the lowest points on every downhill direction of the perennial snow cover. If snow-points in the lower borderline of snow cover were all located, the snowline could be naturally determined. Thus, extraction of a snowline can be switched to finding the locations of all the lower snow-points at the beginning. Consequently, calculating the lowest snow-points for every downhill direction and linking the continuous lines are the nodes and keys for digital snowline extraction.

Considering that the lower altitudinal snow-point is a relative concept that can only be fixed by contrasting it with other points, the first step of snowline extraction is to locate the positions of all the included points in a comparison calculation process. For any pixel in a snow-cover image, there are eight pixels around it, but which of these eight points should be chosen and used for contrast is the key question. Therefore, only if the comparing direction is clarified and the locations of included points are ascertained, would there be a possibility of ransacking every pixel throughout the image and discovering the snowlines. On the condition that the snow area is an inclined plane with a single aspect, all of the positions of lower altitudinal points can be located directly by comparing elevations from one pixel to another on every corresponding vertical direction. However, the real landform, which is characterized with three-dimensional complex topography, is often far from a single inclined plane. Although the real landform could be separated into various planes in some fashion, the pixels in different planes are not directly comparable with each other because of the different positions, ranges, and aspects in their distribution. Moreover, the real topography cannot be separated into planes that extend from the bottom to the top of a mountainous area. Accordingly, the process used to extract lower altitudinal snow-points in a single aspect plane cannot be extrapolated and applied directly to real circumstances.

In this paper, a new method, based on hydrologic flow-path analysis, is presented for extracting lower altitudinal snow-points. For any position in a snow-covered region, a flow-path traverses it that runs from higher elevations to lower elevations. Consequently, the flow-path forms a natural flow-path line. Because there is a unique downstream flow direction from any position, which simply reflects the relationship of upward and downward among points located on the flow-path line, the line could therefore be used to define a comparison direction. Thus, once the line of the flow-path is defined, and the comparison direction is fixed, the lower altitudinal snow-point can be easily extracted owing to the location of points that participate in the comparison calculation. Consequently, in the end, the snowline will be extracted automatically, based on the above assumption.

As shown in Fig.1, the shaded area represents the snow-covered area, and the other parts are areas with no snow. Similar to the real condition, whereby naked regions often occur within the snow cover, there are also two hollow areas in the shaded area. As shown in Fig.1(a), we can see that the occurrence of a naked area complicates the shape of borderlines of snow cover, and it was difficult to separate the lower borderline directly from all other borderlines due to a three-dimensional complex geomorphology.

The method we developed in this paper is indicated in Fig. 1(b). As mentioned above, the main aim of this method was to extract every snow-point in the lower borderline of snow cover. In Fig. 1(b), *C* was a random point in the lower borderline of snow cover, and the dashed lines were used here to express one of the random flow-paths that passed through *C*. As shown by the map, there would be intersecting points when flow-paths pass across the borderlines, regardless of whether the borderline was of naked area or not. Given that the intersecting points are *A* and *B*, we can determine that *A* and *B* are points in the borderline of a naked area, while point *C* was located in the lower borderline of a snow covered area. In order to locate all of the points that form the lower borderline, it is necessary to find a method for distinguishing the points in the lower borderline of snow cover from the points in the borderline of a naked area. In Fig. 1, this means determining how to extract the random point *C*. From the viewpoint of water flow, at least one flow-path must pass through any point in the snowline, such as *C*. It is obvious that *C* is the lowest snow-point in all of the flow-paths that passed through *C*, even though there are other intersecting points such as *A* and *B* in the flow-paths. Accordingly, the method based on flow-path analysis could avoid the influence of the naked areas, and differentiate snow-points in the lower borderline from other points in the snow cover. By calculating all flow-paths that passed through a snow-covered area, we could locate all of the lower snow-points in downhill directions of the perennial snow cover. Snowlines could then be created from the linking of the extracted lower snow-points.

Once the lower borderline of snow cover was extracted, the average elevation and the average or undermost borderline could then be calculated from borderlines of snow cover. By stacking the extracted results from multi-temporal remote sensed images, and then calculating separately for every flow-path, the average altitude, extremes, and the amplitude of variation could be easily calculated. This method thus provides convenience in analyzing the annual and interannual changes in snowlines. In this paper, the drainage area of the Yarkent River was selected as an example to test the above approach and its corresponding process. Considering that the area was too broad and it was difficult to exhibit the details clearly, we chose a random area (as shown in Fig. 2) as a sample to exhibit the data processing.

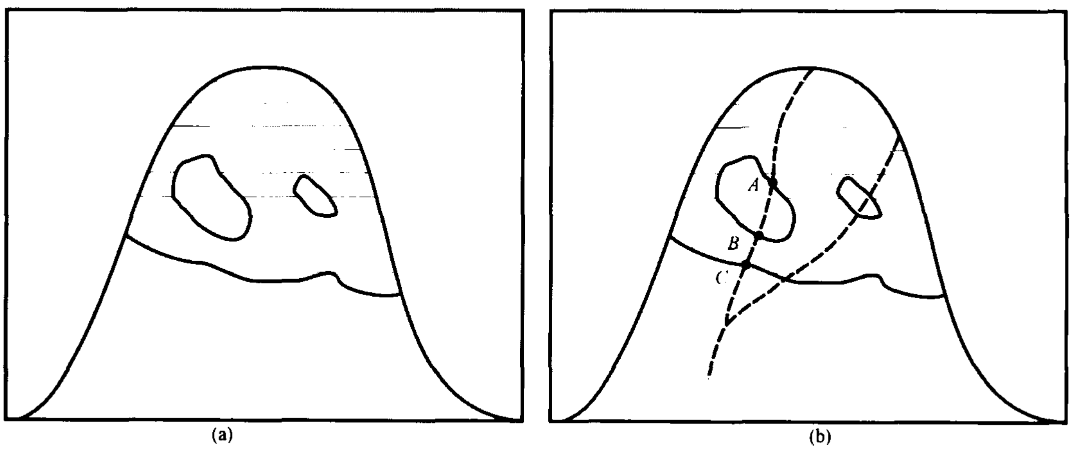


Fig. 1 Sketch map of a snowline extraction method based on flow-path analysis

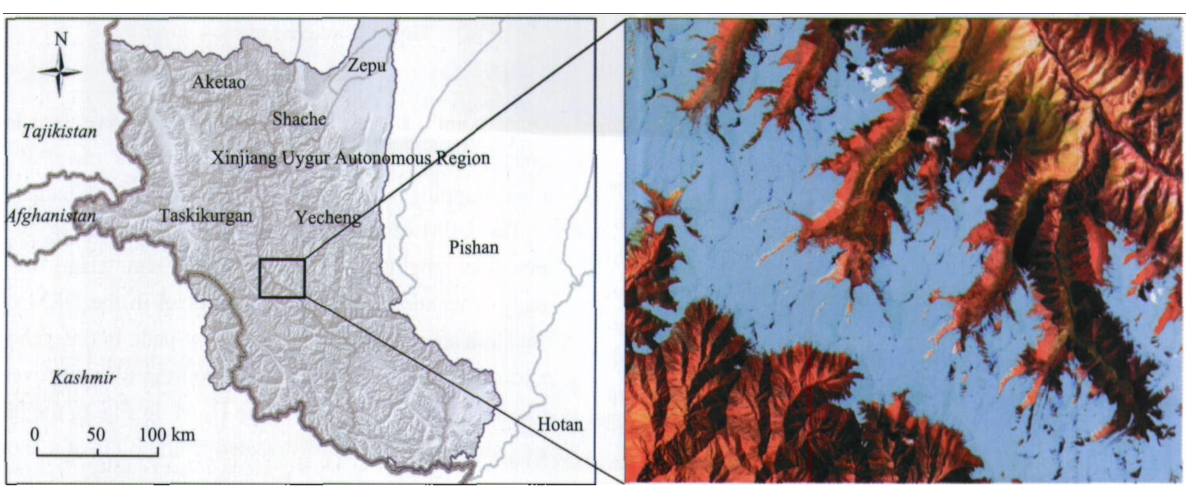


Fig. 2 Study area with the sampling location

## 3 DIGITAL SNOWLINE EXTRACTION

In general, the process of snowline extraction consisted of four steps. The first step was to obtain the spatial distribution information of snow-cover by remote sensing. Secondly, we had to calculate the lower points of the snow-covered areas according to the assumption previously discussed. Then, the lower points were joined together and this created a snowline according to a real landform. Finally, we calculated the averaged annual snowlines.

The digital elevation model of Yarkent River basin area used in this paper is the three arc second data from the Shuttle Radar Topography Mission (SRTM). After projection transformation, the raster size of the DEM was approximately 83m in the study area. The remotely sensed data used here are Landsat TM and ETM+ images taken in summer. In order to spatially match with DEM, the images were resampled to a lower resolution of 83m, which is the same size as DEM. According to the analysis raster size and the scale of mapping, the multi-source data including images and DEM were all projected to a Gauss-Kruger projection.

### 3.1 Remote sensing of snow-cover

Due to the difficulties in catching the characters of snow distribution and dynamics by traditional methods, remote sensing was selected and gradually developed into one of the basic tools of monitoring snow cover, owing to its good performance in temporal and spatial dimensions. Presently, the NOAA/AVHRR database is still the main source for information regarding long time series data of snow cover (Feng *et al.*, 2000; Li, 2004). In addition, some other data, such as SMMR, SSM/ I , SAR and ER, which included both optical and microwave remote sensing, have been successfully applied in snow cover monitoring. These data are applied widely in the monitoring that involves distribution, depth, water balance, etc. As the main aim of this paper is to discuss and validate the new method of snowline extraction, only the TM and ETM+ images from the summers of 1990 and 2000 are used. As the images are all cloudless, there is no interwoven phenomenon between clouds and snow. Thus, a supervised classification method was used to extract snow-cover without prior cloud detection. The extracted snow-cover resulting from images of the sample region in 1990 is shown in Fig. 3. The yellow area represents the snow-covered area, with some naked patches within it. If the edge-detecting method is used directly to compute the snowline, we obtain an inaccurate result, as shown in Fig.4. Clearly, some of the extracted lines in the result are neither lower altitudinal borderlines nor snowlines.

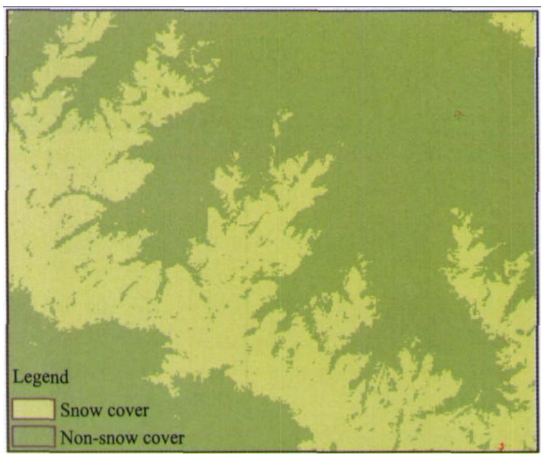


Fig. 3 Snow-covered area from a TM image from 1990

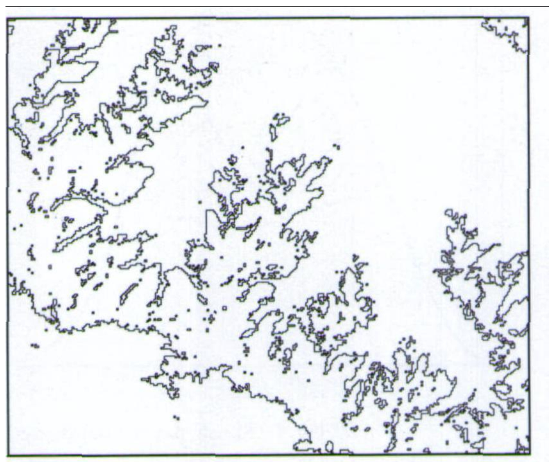

Fig.4 Borderline of snow cover

### 3.2 Lower snow-point extraction

Extraction of lower snow-points was the key step in the process of digital extraction of a snowline. The first step was to calculate the flow-path, pixel by pixel, and to make a judgment whether the flow-path passed through snow-covered area or not. If there were snow-points located on the flow-path, their elevations would be recorded sequentially. When the flow-path reached the boundary of the study area, the lowest snow-point was located and recorded as one point in the lower borderline of snow cover, through comparing all of the elevations of recorded snow-points in the flow-path. According to the above calculation, every lowest snow-point could be located through the circulation algorithm and a traversal search.

The above process was accomplished using Arc Macro Language (AML) and other functions in ArcGIS. The sinks on DEM were filled in with the FILL function. The function of "flowdirection" was used to calculate the flow-directions of every pixel. The flow-path was then created by integrating the "costpath" command and other functions. Thereafter, the location of the lowest snow-point on a flow-path could be fixed through the "zonal" calculation. Functions in ArcGIS, such as "selectpoint", and a circulation algorithm were used to search every pixel of the snow-covered area in a traversal way, to avoid skipping over any snow-point on any flow-path.

The DEM of the sampled area is shown in Fig. 5, with an elevation ranging from 3254m to 6034m. Using the spatial analysis technologies in GIS, any pixel in the DEM could be used as a source point to create a flow-path. In order to generate a corresponding flow-path, every point in a snow-covered area was sorted out and cast over the DEM. In Fig. 6, the blue lines are parts of the flow-paths created from points of a snow- covered area. The lines extend from a snow-point in a snow- covered area to the boundary of the sampling area. Through overlay analysis, elevations of all points in one line were read from the DEM, and the lowest snow-point in every flow-path was located directly by elevation comparison. After the flow-paths were all generated and calculated, all of the lowest altitudinal snow-points were subsequently created. The result of the extraction of the lowest altitudinal snow-points is shown in Fig. 7. All of the extracted lowest snow-points of the sampling area were designated by red colored points. From Fig. 7, we can determine that the extracted points effectively describe the real

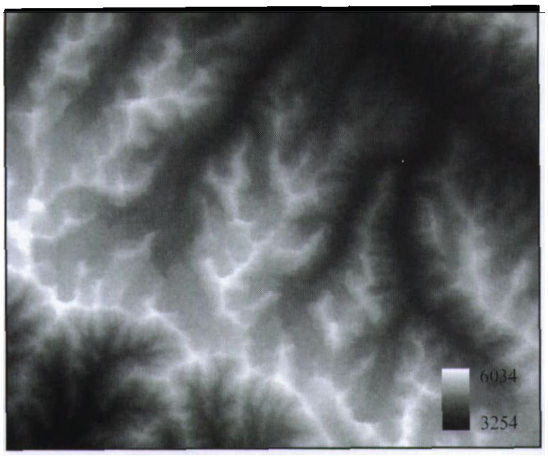


Fig. 5 DEM of the sampling area


Fig. 7 Lower points of a snow-covered area from the digital extraction

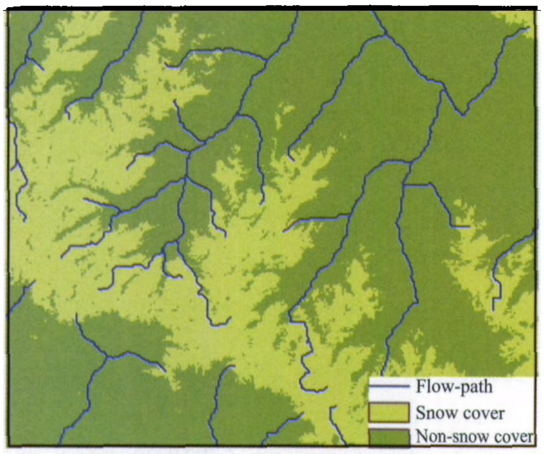


Fig. 6 Flow-path generation of the sampling area

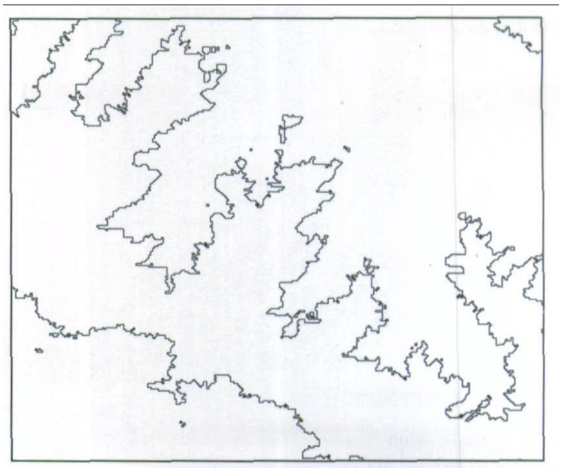

Fig. 8 Digitally extracted snowline

location of the lower snow-cover borderline, without being affected by the naked areas in the snow-covered area.

### 3.3 Linking snow-points to snowlines

When all of the lower altitudinal snow-points of the covered area were extracted, the next step was to join the points to form continuous lines and to shape to snowlines. From Fig. 7, we notice that the extracted lower altitudinal snow-points are often clustered into curved shapes in a spiccato fashion. In most cases, the lowest points were sequentially spatial and abutted onto each other. In these circumstances, the sequential points that were adjacent to one another in spatial could be directly shaped into uninterrupted lines by raster vectorizing. However, discrete points occurred with no adjacent points or with only one adjacent point. When the extracted flow-path was coincident with a section of the lower borderline of a snow-covered area, discrete points were found because only the lowest point in the path-flow had been recorded. Other factors such as data accuracy and spatial matching errors would also add to the possibility of discrete points. As a result, lines became interrupted at the discrete points, which caused disagreement with the facts of the real distribution of the snowline. In order to generate a continuous snowline, the discrete points should be joined sequentially according to the real landform. Since the discrete points appeared when the flow-path coincided in position with the lower borderline of the snow-covered area, it was reasonable to link any two discrete points by flow-paths that passed through them. Moreover, discrete points could be spatially joined in turn by the link-lines from the flow-path, which were naturally consonant with the real topography. Combining these two different ways of linking sequential points and the discrete points, the extracted lower snow-points were accordingly joined. As shown in Fig. 8, the lowest snow-points in all of the flow-paths were successfully linked and shaped to continuous snowlines.

### 3.4 Averaged snowline calculation

The average snowline was regarded as the mean line of the lower borderlines of the perennially snow-covered area for several years. Accordingly, it could be acquired by calculating the average elevation of the annual snowlines in a designated period. Previously, it was difficult to compare and average elevations everywhere among different snowlines. However, the average snowline could be extracted from by the flow-path analysis method, as described above. The first step in calculating the average snowline was to extract all of the annual lowest snow-points from multi-temporal remotely sensed images. All of the multi-temporal lowest snow-points were then overlaid to form a single coverage. Afterwards, the flow-paths that sourced from all of the points in the single coverage were generated from DEM. By separately recording the elevations of all of the points in every flow-path, the averaged position of the lowest snow-points in every flow-path could be located. In the end, the average snowlines were created by linking all of the points of the averaged position. The linking method was the same as that used to extract the annual snowline. According to the above steps, the average snowline of the Yarkant river basin was calculated from images taken in 1979, 1990, and 2000. As Fig. 9 shows, the spatial distribution of the snowline in a broad scale could be digitally extracted.

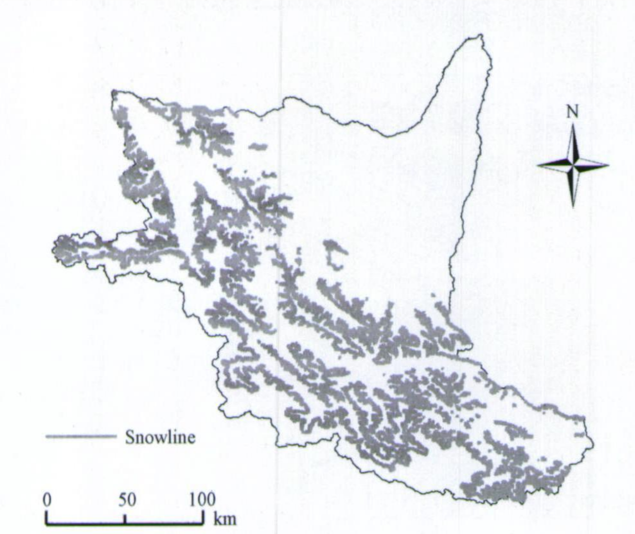


Fig. 9 Average snowline of the Yarkant river basin calculated from images taken in 1979, 1990, and 2000

## 4 ANALYSIS OF THE RESULTS

The steps described for digital extraction were derived from the definition of the concept of snowlines. By analyzing the snowline from the concept of the water flow phenomena, the snowline was digitally extracted by means of comparison of every flow-path. Comparing Fig. 4 and Fig. 8, we see that the edge-detecting method could not be applied directly in snowline extraction, due to the disturbing influence of naked areas in the inner portions of the snow-covered area. The method discussed in this paper avoids the influence of naked areas on snowline extraction, and provides a result that is in accord with the real status.

Since the method based on flow-path analysis could link counterpoints at different elevations, and show ubiety information, it provided the possibility to quantitatively compare the snowlines at different times. Changes in the snowline at any position in the study area could be measured by calculating multi-temporal snow-points on every flow-path. Moreover, the spatial patterns of snowline changes could also be mapped based on this method.

However, due to factors such as data accuracy and spatial match errors, a possibility that small blocks of snow would fall just on the lower reaches of a path-flow, where the elevations are far below snowlines, would infrequently arise. Once these small snow blocks were recognized, the results of digital extraction of snowlines were greatly influenced, as all of the comparison calculations were realized based on flow-paths. Accordingly, the data should be verified at the beginning. Error would be also introduced during the connection of discrete lower snow-points, despite the fact that the method mostly represents the real condition. Thus, it is better to compare the lower snow-points directly, rather than with snowlines, for the analysis of changes among multi-temporal snowlines.

## 5 CONCLUSION AND DISCUSSION

Spatial patterns of snowlines are complicated and subject to change, due to the intricate interactions between climate and landforms. There is still a scarcity of automatic methods for digital extraction of a snowline at present. The new method discussed in this paper, regarding this question, is based on the analysis of the phenomenon of water moving down mountains. By comparing the elevations of snow-points on every flow-path, the lower snow-points of a snow-covered area were located and connected into snowlines. Using this method in the process of snowline extraction, the influence of naked areas in the inner regions of the snow-covered area can be effectively avoided. Combined with data processing of remotely sensed images, the method could be used to calculate the lower limit of a perennially snow-covered area and to extract the average snowlines rapidly in a broad scale. This may lay the groundwork for future study on the spatio-temporal changes of snowlines.

For the above method, there are still inadequacies in the snowline extraction due to the great spatial complexity. The method is susceptible to the inaccuracy of the flow-path. Large errors would appear once snow-points appear just in the lower reaches of the flow-paths; therefore, it is necessary to verify the data in advance. In addition, inaccuracy might also arise from the process of linking discrete lower snow points. Restricted by the coarse resolution of the DEM in this paper, the accuracy of the results of snowline digital extraction was not particularly high. In conclusion, as a tentative method, the procedure described in this paper behaved well as a means of digitally extracting a snowline, even though it still requires further fine tuning.

## REFERENCES

Cheng G D. 1984. Problems on zonation of high-altitude permafrost. *Acta Geographica Sinica*, **39**(2): 185—193

Feng X Z and Li W J. 2000. Research on the methods of obtaining satellite snowcover information. *Journal of Image and Graphics*,

**5**(10A): 836—839

Hao X H, Wang J and Li H Y. 2008. Evaluation of NDSI threshold value in mapping snow cover of MODIS. *Journal of Glaciology and Geocryology*, **30**(1): 132—138

Jiang F C, Wu X H, Wang S B and Fu J L. 2002. Characteristics of space distribution of the climatic snowline in China. *Journal of Geomechanics*, **8**(4): 289—296

Jiang Z X. 1991.Trend surface analysis of the existent snowline in West China. *Chinese Geographical Science*, **1**(1): 62—69

Kerr A and Sugden D. 1994. The sensitivity of the south Chilean snowline to climatic change. *Climate Change*, **28**(3): 255—272

Klein A G and Isacks B L. 1999. Spectral mixture analysis of Landsat Thematic Mapper images applied to the detection of the transient snowline on tropical Andean glaciers. *Global and Planetary Change*, **22**: 139—154

Li B L, Zhang Y H and Zhou C H. 2004. Snow cover depletion curve in Kaidu river basin, Tianshan Mountains. *Resources Science*, **26**(6): 23—29

Li S M, Yan H and Liu C. 2007. Study of snow detection using FY-2C satellite data. *Journal of Remote Sensing*, **11**(3): 406—413

Liang J, Zhang X H and Wang J. 2007. Exploration for the algorithm of snow cover mapping based on NDVI background field. *Journal of Remote Sensing*, **11**(1): 85—93

Mengel J G, Short D A and North G R. 1988. Seasonal snowline instability in an energy balance model. *Climate Dynamics*, **2**(3): 127—131

Turpin O C, Ferguson R I and Clark C D. 1997. Remote sensing of snowline rise as an aid to testing and calibrating a glacier runoff model. *Phys. Chem. Earth*, **22**(3—4): 279—283

Wu X H. 1989. A preliminary study on existing snowline timber line and their relations in southeastern part of the Qinghai-Xizang Plateau. *Journal of Glaciology and Geocryology*, **11**(2): 113—124

Xu X K and Tian G L. 2000. Dynamic distribution and Albedo change of snow in China. *Journal of Remote Sensing*, **4**(3): 178—182

Yan Q S and Zeng Z X. 1985. Geomorphology. Beijing: China Higher Education Press

# 基于水流路径分析的雪线数字提取

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**摘 要**: 基于水流路径分析的思路, 提出一种雪线自动提取方法。该方法利用对水流路径上积雪覆盖信息逐像元对比, 记录最下点位置形成积雪区下边缘点, 顺次连接各点形成雪线; 在此基础上, 探讨了多年平均雪线的求算。研究表明, 该方法可避免雪盖内部积雪空缺区域对下边缘线提取的影响, 较好地提取积雪区的下边缘线, 初步实现了雪线的数字提取; 并可较为方便地进行多个时期雪线的时空变化对比分析。利用该方法并结合遥感影像数据, 可为大范围雪线时空分异信息的快速、准确提取与分析奠定基础。

**关键词**: 雪线, 水流路径, 数字提取

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## 1 引 言

积雪作为地表极为活跃且具有多重属性的自然因素(徐兴奎 & 田国良, 2000), 其空间分布与变化是地学科学家关注的焦点之一。从流域雪盖到区域性乃至全球雪盖的变化具有重要的水文学和气候学意义(冯学智等, 2000; Turpin 等, 1997; Kerr & Sugden, 1994)。雪线是固态降水的零平衡面(严钦尚 & 曾昭璇, 1985), 作为常年积雪区的下界, 雪线与森林线、高度多年冻土下界线(冰缘线)和山地寒漠土上界线(土壤线)等界线同为重要的自然地理要素(吴锡浩, 1989; 程国栋, 1984; Mengel 等, 1988)。在中国, 由于地形复杂, 气候在东西方向存在十分明显的差异, 尤其是青藏高原的存在, 使得现代地形雪线在青藏高原地区呈环状分布, 改变或破坏了雪线的纬度地带性分布规律(蒋复初等, 2002; Jiang, 1991)。对于区域的雪线, 其分布高度还决定于局域气温、降水量和地形等多种因素, 增加了雪线空间分布的复杂性(Kerr & Sugden, 1994)。

传统雪线分布数据主要依据地形图、结合实地考察确定。因数据量少、信息不完整, 常用单个点来代表整个山体或区域雪线分布高度, 难以系统反映雪线空间分布规律。其绘制也主要借助手工完成, 对凡有现代冰川分布的图幅, 定出高度的变化区间, 取雪线平均高度(中值)点在地理底图上图幅面积的中点, 然后绘制等值线, 即得区域雪线高度等值线(吴锡浩, 1989)。随着遥感数据时、空与光谱分辨率不断提高以及相应的图像处理技术的不断发展, 积雪信息提取从定性发展到定量化, 为积雪动态研究提供了大量基础数据(李三妹等, 2007; 郝晓华等, 2008)。无论是通过实际考察还是结合遥感图像, 目前这两种方法在绘制雪线时仍需依靠手工勾绘。对于大范围的雪线精确绘制, 上述方法较为繁琐, 目前尚缺乏雪线自动提取的相关研究。

鉴于目前积雪遥感监测方面研究成果, 雪盖范围提取技术较为成熟(梁继等, 2007; 李三妹等, 2007; 郝晓华等, 2008), 雪线自动提取的关键和难点主要在于如何由遥感监测结果求算常年积雪区的下边缘线, 从而得到雪线位置和高度, 进而求算多年平均

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雪线等其他指标。由于雪线以上冰雪常常非连续分布(Klein & Isacks, 1999)，雪盖内部常存在许多地表裸露区域，同时在积雪遥感提取过程中，因地形及山体阴影等影响，提取结果也会产生大量空白区域。这些空白地区其边缘并非雪盖的下边缘线，其边界不能指示雪线位置，单纯基于边缘提取的方法不能较好地提取出雪线。基于数学形态学的算法虽可以填充内部小块不连续区域，但改变了冰雪分布本来的边缘状况，也不适合用于较为精确的雪线自动提取。另外，对于多年积雪变化，如何对比描述其年际变幅、求取多年平均雪线的空间分布等指标也是难点。鉴于此，本文基于 GIS 空间分析技术并结合遥感资料，尝试提出一种雪线数字提取思路和方法，为相关研究提供支持。

## 2　雪线数字提取思路

雪线是常年积雪区的下界，即常年积雪区域的下边缘线(严钦尚 & 曾昭璇，1985；蒋复初等，2002)。由于区域地形地貌等因素的影响，雪线之上地域并非处处为积雪覆盖，雪盖内部常常存在大量积雪空缺区域，其边缘非积雪区下边缘线，因此单纯基于边缘提取的方法难以较好地进行雪线提取，还需对常年积雪区的下边缘线进行准确识别。下边缘线是雪盖在各方向的下坡最低点的连线，因此如何在不受空白区影响的情况下，求取积雪区在各下坡方向上的每一最低点成为雪线提取的关键。

最低点是通过与其他点的对比求取的，困难在于对比对象的确定。在积雪区遥感图像中，对积雪区任意一栅格点，该点究竟应该同哪些栅格进行对比从而确定最低点、并由此最终遍历所有栅格是一个难以确定的问题。如积雪区为一单向倾斜坡面，则只需沿山体走向在垂直于坡向的方向上进行逐栅格对比，即可找出每一最低点。由于实际地形的复杂多样，山体并非理想斜面，很难将真实的山体划分为多个由山底至山顶单一倾向的斜面，因此分坡向进行最低点判断的方法难以实现，需要寻求新的思路。

本文基于对水文现象的分析，提出一种转换思路尝试解决上述问题，即以水滴运移的角度看待雪线提取问题。区域上任意位置的积雪，每一点上会有一条通过此点的水滴流路经过，该路径从山顶到山脚、由较高海拔到较低海拔，形成自然的上下比对路线。对比线路确定后，线路上所有积雪点的对比对象就较为明确，最低点也相对容易求算。基于上述思路，本文提出一种基于水滴运移思路的雪线自动提取方法。

如图1，有灰线部分为积雪区，积雪区内部两个小斑块代表空白区，其余部分为非积雪区，虚线为水流路径。某一水流路径与积雪区内空白区域的交点分别为 $A$、$B$，与积雪区下边缘线的交点为 $C$。要提取积雪区的下边缘线，即需避开积雪内部空白区的影响、并准确找出组成下边缘线的每一点。以上述流路进行分析，虽该流路穿过空白区、并与边缘线有多个交点，但只需在该线路上找出所有积雪点中的海拔最低点，即可定出雪线与该流路交点 $C$ 的位置。而积雪区内部空白区域边缘线与流路的交点 $A$、$B$，由于其海拔高度较 $C$ 点为低，在求算过程中不会对结果有所影响，从而自然地避免了空白区对雪线提取的干扰。对于组成地形雪线的每一点，必定有一条流路经过该点。对区域内每一条流路进行分析计算，即可提取出积雪区在各下坡方向上的所有最低点，从而构成雪盖下边缘线。

一期的雪盖下边缘线提取出来后，由于比对路线得以确定，同理可进行多期图像下边缘线平均高程或最低高程等的求算。将多幅影像提取的结果相

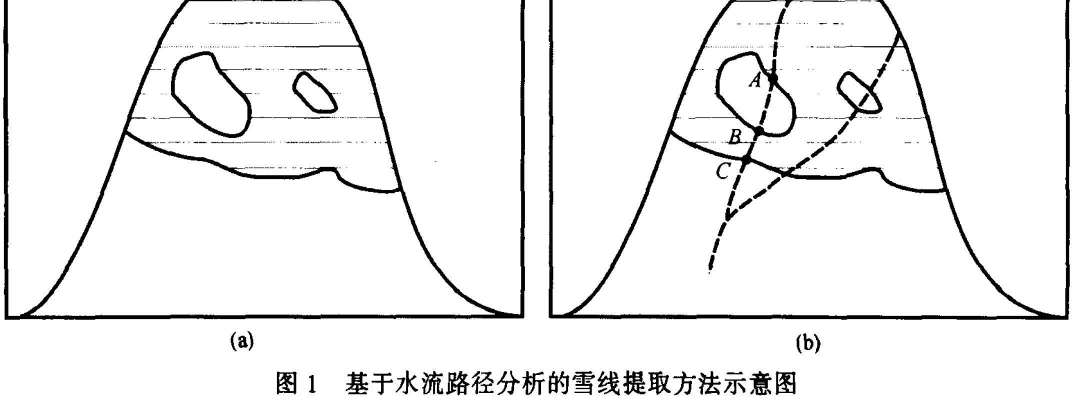


图 1　基于水流路径分析的雪线提取方法示意图

叠加，在每一流路上分别计算，即可较为容易地计算出多期雪盖下边缘的最低值、平均值及变幅等，从而进一步分析雪线空间位置年际空间变化。本文以昆仑山叶儿羌流域为例，对该思路的实现方法及步骤进行实践。由于流域范围较大，为便于雪线提取过程的细节表现，在文中任意选取流域中一小矩形区域作为样区，如图 2，进行方法说明。

## 3 雪线数字提取

分 4 个过程进行雪线数字提取。首先是积雪分布的遥感监测，以获取积雪空间分布信息；根据提出的雪线提取思路，求算积雪区下边缘点；然后由下边缘点生成下边缘线；最后计算多年平均雪线。所用数字高程模型(DEM)为叶儿羌流域 SRTM (Shuttle Radar Topography Mission) 3″数据，经投影转换后，在本研究区其栅格大小为 83m；遥感资料为 Landsat TM 和 ETM+夏季数据，均重采样至较低分辨率 83m，与 DEM 数据栅格大小一致。考虑栅格大小及成图比例尺，多源数据均统一投影至高斯-克吕格投影(Gauss-Kruger)。

### 3.1 雪盖遥感提取

由于积雪的分布和动态特征，遥感方法以其宏观、时效等方面的优势逐渐成为对其监测的基本工具。目前中国长时间序列的雪盖状况监测主要是应用 NOAA/AVHRR 数据，其处理已有大量的研究成果(冯学智等，2000；李宝林，2004)。除光学遥感外，SMMR、SSM/Ⅰ、SAR 和 ERS 等微波遥感数据也广泛应用于雪盖分布、水量平衡、积雪深度等信息提取中。作为方法探索，选取 1990, 2000 年 2 个时期夏季的 TM、ETM+数据为例，对所提出的雪线数字提取方法进行实践和说明。上述影像为研究区夏季无云图像，没有考虑云雪混分现象，采用监督分类即可较好地实现积雪范围提取。以样区为例，其 1990 年 TM 积雪范围提取结果如图 3。黄色部分表示积雪区，其内部可见有很多小块非积雪区域。基于雪盖遥感提取结果，采用单纯边缘提取方法所得到的积雪区边缘线如图 4。

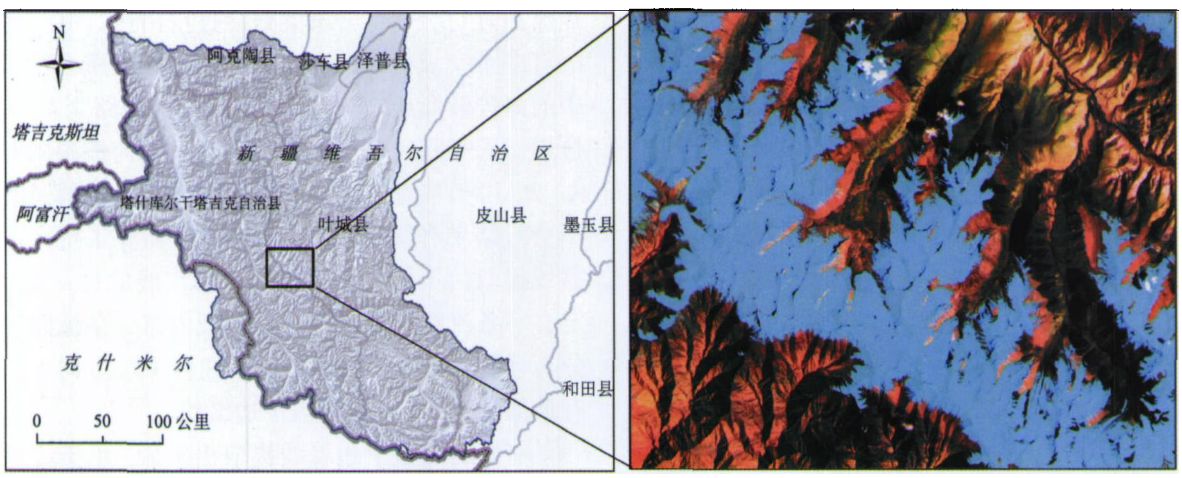


图 2 研究区示意图


图 3 样区雪盖遥感提取

图 4 积雪区边缘线

### 3.2　积雪区下边缘点求算

积雪区边缘最低点求算就是针对研究区内的每一点，计算水流路径，如该路径通过冰雪覆盖地区，记录该流路上有冰雪覆盖的每一点的高程值，当水滴运移到最下游出口时，对比该路径上所有记录的冰雪高程，将其最低点记录下来作为积雪区下边缘上的点。针对积雪覆盖区的任意一位置，按照上述方法依次进行对比，即可求出积雪区边缘的最低点。

上述过程可在 ArcGIS 软件中利用相关函数和 AML 宏语言实现。主要过程如下：首先对研究区 DEM(图 5)预处理，利用 FILL 函数进行洼地(Sink)填充，然后利用 Flowdirection 函数计算流向；选取积雪区上的一点，借助 Costpath 等函数生成水流路径，并在该路径上利用 Zonal 相关统计函数计算冰雪最低点，记录该点位置。

利用循环语句及 Selectpoint 等相关函数遍历积雪区的每一栅格，实现对经过积雪区每一条水流路径的逐条统计，记录下各流路上每个有积雪的最低栅格点。如图 6，蓝线表示积雪区部分栅格点所生成的水流路径，当积雪区所有栅格点水流路径生成并逐条计算完毕后，该区域中积雪区的各下边缘点就得以识别并保存下来。经过上述步骤计算，积雪区各下边缘点栅格得以求出，在此以红色在图 7 中示出。由图 7 可见，所求出的下边缘点避开了雪盖内部非积雪区的影响，能够较好地反映积雪区的下界。

### 3.3　积雪区下边缘线求算

积雪区各下边缘点求算出来后，将各栅格点下坡边缘依次连接形成积雪区的连续下界。由图 7 可见，红色栅格所标示的下边缘点在空间上断续相连。空间相邻的栅格点可形成自然的连线，难点在于不连续之处。不连续之处主要源于积雪空间分布、数据精度及误差等方面因素。若要形成连续的边缘线，需依据地形按照实际空间分布状况将上述边缘点顺次相连。由于本文采用了水滴运移的思路和流路对比的方法，在比较过程中只记录流路下坡方向

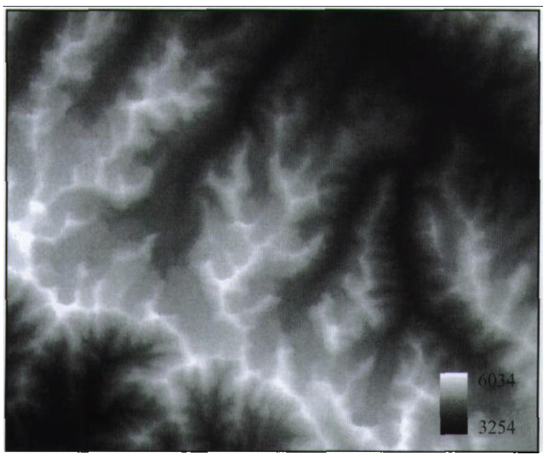


图 5　样区数字高程模型

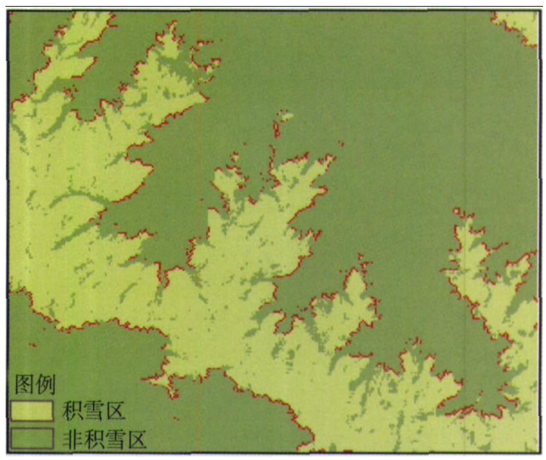


图 7　积雪区下边缘点提取结果

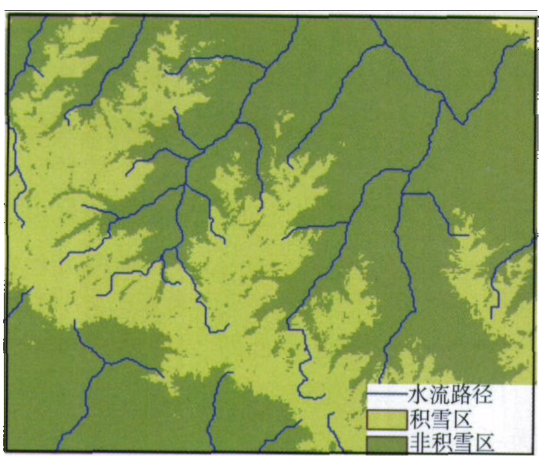


图 6　样区水流路径生成示意图

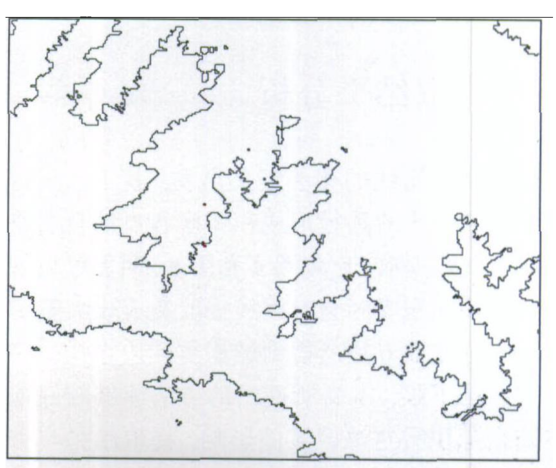

图 8　雪线自动提取结果

的最低点，如下边缘线某段与同一流路重合，在该处即会产生不连续。因此对于下边缘栅格点空间不连续之处，可利用通过该段的流路进行连接。本文利用上游最低流路进行连接，可保证连线切合于实际地形，并实现下边缘点在空间上的顺次连接。如图 8，黑线为积雪区下边缘各点顺次相连而形成的下边缘线。

### 3.4 多年平均雪线求算

将由多年遥感图像提取的积雪区下线求解平均值，此平均值的连线即为多年平均雪线。多年平均雪线的空间分布及其高程仍可借助上文提出水流路径的方法进行求解。将不同期遥感图像求出的积雪区最低点进行叠加，在相应 DEM 上求算水流路径，依次记录各流路上积雪点的平均高程，找出该平均高程在流路上的对应位置点，将各点相互连接即可形成多年平均雪线。图 9 为利用 1979, 1990, 2000 三个时期夏季的 MSS, TM, ETM+遥感影像，按照上述方法求取的叶尔羌流域平均雪线。

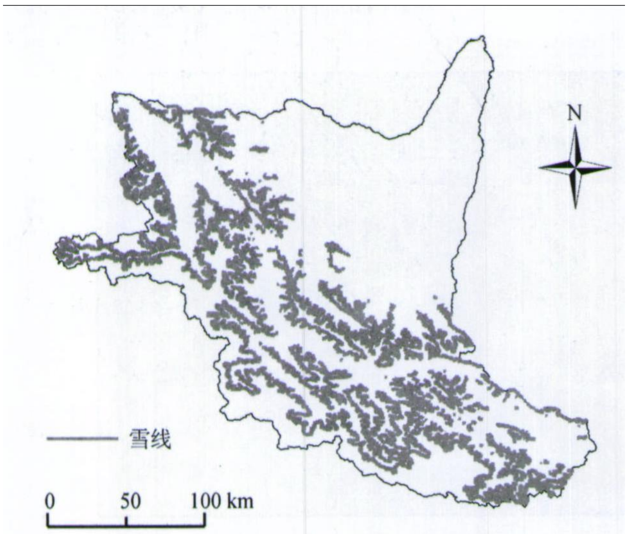


图 9 叶尔羌流域平均雪线(1979, 1990, 2000)

## 4 雪线提取结果分析

上述步骤从雪线的相关定义出发，基于水滴运移的思路、利用水流路径形成积雪区各点的自然对比路线进行雪线提取。比较图 4 和图 8，明显可见雪盖内部的小块非积雪区会对雪线提取造成较大影响，基于单纯边缘提取方法所得到的积雪区边缘线很多并非积雪区的下限；本文所提出的方法能够较好地避免雪盖内部积雪空缺区域的影响，提取结果与雪线实际分布较为吻合。

由于基于水流路径的分析可以建立不同时期雪线各点间的空间对应关系，根据每一流路上不同期雪线上点的变化，可以得出研究区每一点位处的雪线高程变化状况，因此还可以用于分析不同时期雪线的变幅及空间格局变化状况，为相关研究提供较为详细的雪线空间变异基础资料。

因空间数据精度及配准误差等原因，在非常年积雪区的下游水流路径上会存在不合理的小块暂时性积雪，而由于本文利用水流路径进行上下对比，这些下游流路上的积雪会对其上的提取结果造成影响，因此需预先对数据进行检查处理。另外，因积雪空间分布、数据精度及误差等方面原因，下边缘点在空间上并非处处相连。对栅格点空间不连续之处，本文连接上游最低流路而形成下边缘线，虽可与实地地形相符，但在这一过程中可能带来误差。因此在雪线的多时期空间分析过程中，直接利用下边缘点数据进行对比计算可能精度更好。

## 5 结论与讨论

由于气候与地貌因素的综合作用，各地雪线空间分布复杂多变，目前尚缺乏较好的雪线自动提取方法。本文基于水滴运移的思路，提出一种雪线数字提取思路及相应方法。利用对流路上积雪覆盖信息逐像元进行对比，记录最下点位置并形成积雪区的下边缘线。该方法可较好地去除雪盖内部积雪空缺区域对下边缘线提取的影响，利用该方法并结合遥感影像可求算常年积雪区的下界、计算多年平均雪线等，可为大范围雪线时空分异信息的快速、准确提取与分析奠定基础。

因雪线空间分布的复杂性，本文提出的基于水流路径分析的雪线数字提取尚有许多不足之处。本文根据水流路径进行上下对比，提取结果对水流路径上的误差较为敏感，如果下游流路因数据误差等原因而存在不合理的小块积雪，将对上游提取结果产生较大影响，因而在雪线提取前，需对所采用数据进行检查处理；在顺次连接雪盖下边缘点为下边缘线的过程中，可能引入误差，目前尚未有更好方法解决这一问题；受目前资料所限，文中所用数字高程模型比例尺较小。此外，本文作为一种方法探索，还需进一步验证和检查，需要针对不同地区、不同遥感数据源进行实验，对现有方法中的不足之处进行改进。

## REFERENCES


Cheng G D. 1984. Problems on zonation of high-altitude permafrost. *Acta Geographica Sinica*, **39**(2): 185—193

Feng X Z, Li W J and Bai Y C. 2000. Research on the methods of obtaining satellite snowcover information. *Journal of Image and Graphics*, **5**(10A): 836—839

Hao X H, Wang J and Li H Y. 2008. Evaluation of NDSI threshold value in mapping snow cover of MODIS. *Journal of Glaciology and Geocryology*, **30**(1): 132—138

Jiang F C, Wu X H, Wang S B and Fu J L. 2002. Characteristics of space distribution of the climatic snowline in China. *Journal of Geomechanics*, **8**(4): 289—296

Jiang Z X. 1991.Trend surface analysis of the existent snowline in West China. *Chinese Geographical Science*, **1**(1): 62—69

Kerr A and Sugden D. 1994. The sensitivity of the south Chilean snowline to climatic change. *Climate Change*, **28**(3): 255—272

Klein A G and Isacks B L. 1999. Spectral mixture analysis of Landsat Thematic Mapper images applied to the detection of the transient snowline on tropical Andean glaciers. *Global and Planetary Change*, **22**: 139—154

Li B L, Zhang Y H and Zhou C H. 2004. Snow cover depletion curve in Kaidu river basin, Tianshan Mountains. *Resources Science*, **26**(6): 23—29

Li S M, Yan H and Liu C. 2007. Study of snow detection using FY-2C satellite data. *Journal of Remote Sensing*, **11**(3): 406—413

Liang J, Zhang X H and Wang J. 2007. Exploration for the algorithm of snow cover mapping based on NDVI background field. *Journal of Remote Sensing*, **11**(1): 85—93

Mengel J G, Short D A and North G R. 1988. Seasonal snowline instability in an energy balance model. *Climate Dynamics*, **2**(3): 127—131

Turpin O C, Ferguson R I and Clark C D. 1997. Remote sensing of snowline rise as an aid to testing and calibrating a glacier runoff model. *Phys. Chem. Earth*, **22**(3—4): 279—283

Wu X H. 1989. A preliminary study on existing snowline timber line and their relations in southeastern part of the Qinghai-Xizang Plateau. *Journal of Glaciology and Geocryology*, **11**(2): 113—124

Xu X K and Tian G L. 2000. Dynamic distribution and Albedo change of snow in China. *Journal of Remote Sensing*, **4**(3): 178—182

Yan Q S and Zeng Z X. 1985. Geomorphology. Beijing: China Higher Education Press


## 附中文参考文献


程国栋. 1984. 我国高海拔多年冻土地带性规律之探讨. 地理学报, **39**(2): 185—193

冯学智, 李文君, 柏延臣. 2000. 雪盖卫星遥感信息的提取方法探讨. 中国图象图形学报, **5**(10A): 836—839

郝晓华, 王建, 李弘毅. 2008. MODIS雪盖制图中NDSI阈值的检验. 冰川冻土, **30**(1): 132—138

蒋复初, 吴锡浩, 王书兵, 傅建利. 2002. 中国气候雪线空间分布特征. 地质力学学报, **8**(4): 289—296

李宝林, 张一驰, 周成虎. 2004. 天山开都河流域雪盖消融曲线研究. 资源科学, **26**(6): 23—29

李三妹, 闫华, 刘诚. 2007. FY-2C积雪判识方法研究. 遥感学报, **11**(3): 406—413

梁继, 张新焕, 王建. 2007. 基于 NDVI 背景场的雪盖制图算法探索. 遥感学报, **11**(1): 85—93

吴锡浩. 1989. 青藏高原东南部现代雪线和林线及其关系的初步研究. 冰川冻土, **11**(2): 113—124

徐兴奎, 田国良. 2000. 中国地表积雪动态分布及反照率的变化. 遥感学报, **4**(3): 178—182

严钦尚, 曾昭璇. 1985. 地貌学. 北京: 高等教育出版社