SNOW AND ITS DISTRIBUTION

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Summary

Snow is usual for many countries throughout the globe. At the end of winter it covers about 60% of the northern hemisphere land area and 25% of the southern hemisphere land area. One very important parameter is the snow water equivalent (SWE) the distribution of which we investigate through the use of land-based snow survey and remote sensing in different spectral bands.

There are many research results, proposals and applications related to snow cover. But, of a particular importance is the need to answer two questions: (1) how much snow is laying annually and will lie in the future, and (2) what is the impact of snow cover (present and future) on those business areas which are sensitive to climate and hydrology.

In mountains and hills the SWE depends on elevation and slope aspects. Snow cover is distributed over plains mainly according to local factors. Fresh fallen snow is blown from open areas into hollows, while in forests snow accumulation prevails. Interpolated and mapped values of SWE allow for the most reliable prediction of floods. Digital maps of snow cover can be produced from detailed studies and these can be used in the

so-called informative-mapping model.. These maps are drawn by using topography, vegetation, and land use maps.

In winter snow crystals grow within the snow pack and this affects melt water percolation during the spring thaw, and hence the water yield from snow. Snow melt depends on energy exchange within the "snow-atmosphere" system. The main energy factors of the snow melt are solar and long-wave radiation and the energy fluxes, which are defined by measurements in the atmospheric surface layer. Reflectance or surface albedo is also of great importance in regulating snowmelt. The water balance is another way to quantify snowmelt and the water yield from snow. Long-term monitoring indicates declining SWEs, and increasing rainfall during snowmelt seasons especially for the last decade.

Main problem for future investigations is how to retrieve a true picture of snow cover distribution from satellite derived imagery. Applications appear as follows: understanding the influence of climatic changes on snow cover, improvements in flood flow simulation and forecasting, consideration of snow pack as a sink for contaminants, snow retention to provide water for agriculture and to protect water bodies, and snow as a problem for construction engineering.

1. Introduction. Origin of snow pack

The seasonal snow cover that dominates the natural landscapes of Russia and Canada for 4 to 6 months each year is a powerful factor influencing environmental processes and human activity. Snow cover studies have many applications in business and are of great importance in geographical and climate research. These studies include: spring flow forecasting, water projects, calculation of floods and soil freezing for construction engineering, etc. Combating snow drifts on roads and protection of fertile soils against water erosion are almost impossible without reliable snow cover data and information on processes occurring within the snow pack.

Snow crystals originated under different temperature conditions assume different forms: from sparkled needles falling from thin *alto-stratus* clouds in frosty weather to large flakes in the usually mild west European and Japanese winters. By classifying snow crystals, one can find evidence of their thermal history inside a cloud system. Primary snow crystals are destroyed by wind-born drifting, packing them into the snow pack. At the same time, small crystals in deep horizons of the snow pack grow due to so-called *metamorphism* and then look like salt crystals. This depends on the diffusion flux of water vapor through the snow pack.

The snow surface is often covered with a crust created by intense incoming solar radiation. These crusts can stay buried under new fallen snow, so the old snow pack becomes a layered structure. The density or specific weight of "dry" (non-thawing) freshly fallen snow is about 0.06 to 0.10 $g \cdot cm^{-3}$, but this grows gradually to 0.30 $g \cdot cm^{-3}$ by late winter. The extremely arid climate of the Mongolian plains produces such a compact snow pack that it looks like a continuous crust that can be cracked by a footstep like crazing on a floor tile.

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The amount of winter precipitation defines the snow depth or snow thickness only in a general sense, as snow cover generally smoothes out the bumps and hollows of the land surface. Wind-born drifting and re-location of snow are significant aspects of snow storms over the great plains of North America, Siberia and Kazakhstan. In early spring, it melts to create a cavernous surface. In high mountains strong solar radiation can impact the surface of perennial snow pack and create very large ridges of snow inclined according to the incident angle of the sun's rays and with pointed hillocks. Climbers call these snow caps *praying monks*.

Snow evaporates under the influence of solar radiation and sometimes, particularly in extra-arid regions like the Mongolian plains, it disappears almost without any liquid melt water. Evaporation from snow is usually from 10% to 25% of the total snow water content. Snowmelt occurs under the combined effect of sunlight, wind and air temperature. The heat budget is the energy source available for melting. Snowmelt is therefore possible not only with positive air temperatures, but even with negative ones if there is a strong energy flux. Rainfall on the snow surface stimulates snowmelt, particularly in humid climates such as the mountains of Norway, Alaska and western Canada.

2. Methods of snow survey

Region	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
North-west (St. Petersburg)	4 7	12 18	23 32	32 47	33 51	6 18
North (Arkhangel'sk)	11 17	21 38	33 52	42 69	46 73	24 48
Central plain (Moscow)	4 6	12 17	19 33	28 44	30 52	3 6
Upper Volga region (Nizchny Novgorod)	5 7	15 25	31 45	40 58	43 63	
Urals (Ekaterinburg)	10 17	21 38	29 47	39 59	39 62	5 20
Central *chernozem* prairie (Kursk)		6 9	13 20	16 29	17 31	
Mid Volga region (Samara)	4 5	12 21	23 39	27 50	30 63	

Notes:
Names of towns central to the regions are given in parenthesis.
The upper figure in each cell applies to open areas, the lower figure to forested areas.

Source: Kopanev I.D. (1982) Climatic aspects of the snow cover studies. - Leningrad, Gidrometeoizdat, 240 pp. (in Russian)

Table 1. Mean snow depth (cm) over the regions of European Russia

The method for regular (land-based) snow survey was first developed in the late nineteenth century. It consists of regular measurements of snow depth, using a stake, and snow density, using a weighed snow sample. This is taken in a steel cylinder which is pushed carefully into the snow pack and is then lifted without causing any destructive forces on the contained snow. All snow survey routes must be marked by distance, and

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the survey should be carried out regularly (e.g. every 10 days). Only in this way, will the data series obtained be representative of an area and amenable to statistical procedures. As statistical estimation showed, to obtain useful data, the snow pack samples should be regularly located along a survey track of 1 km long for an open area, and 0.5 km under a forest canopy. Based on these data, regional studies were conducted to investigate regional climate and water regimes. As an example, the snow survey data obtained for a long-term period in European Russia are shown in Table 1.

A device known as a *snow pillow* is used to determine the pressure of snow cover on the surface. The pillow itself is a tank with an area of about 10 m^2, made of rubber. It is filled with a mixture of alcohol and fresh water to prevent freezing. The level of the liquid is determined with a float-and-pulley recorder in a well linked to the tank by a tube laid under the soil. Records are repeatedly adjusted during snow surveys.

Another method consists of aerial gamma-survey of the snow surface, based upon extinction of natural terrestrial gamma-rays. This airplane-based method is widely used to detect the snow water equivalent over large river basins throughout European Russia. It was found that gamma radiation from subsurface snow varies, particularly during episodic snowmelts in winter. The snow water equivalent in early spring can be over-estimated by including the melt water accumulated under a deep snow pack. There are also considerable errors as a result of spatial non-homogeneity of the snow cover itself.

In Russia and many other countries, radar precipitation measurements are used to detect snowfall intensities and snow water content. Research was undertaken in the 1980s, in the Central Asian mountains of the former Soviet Union, to derive snow water equivalent by absorption of a space neutron flux within the snow pack. This advanced method was proposed as one of the remote sensing tools for detection of avalanches in high mountains with very deep snow pack.

Snow cover distribution and its dynamics were first detected remotely by the “Tiros” satellite in the mid 1960s, and the global monitoring system has evolved since that time. The Russian Hydro-meteorological Service also uses information and imagery from the home satellites “Meteor” and “Kosmos”. The land surface is continually scanned in visual (0.4 to 0.7 μm) and near infra-red (to 1.3 μm) spectral bands (diapasons). Today the Advanced Very-High Resolution Radiometer (AVHRR) is used as a satellite sensor to study sea ice growth and snow cover extent.

Digital processing of the imagery involves firstly subdivision of an area into snow-covered and bare terrain. By contrasting the picture, one can define, as near as possible, the degree of snow depth using a threshold of the white-gray scale. A question arises as to how snow cover can be distinguished from clouds. It was found that infra-red brightness of snow cover is 60% less than that of clouds that may be as white as snow in the visual spectral band. It is much more difficult to recognize snow hidden by clouds obscuring the land surface. For this, a skillful operator must make a chronological examination of the pictures.

The main problem of how to evaluate the water equivalent of snow by satellite pictures has not yet been resolved. Micro-wave survey is the most suitable method for satellite

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based remote sensing of snow, for instance records of natural radiation of the snow cover in the spectral band from 6 to 37 GHz. This radiation flux correlates well with the snow water equivalent. To detect it more correctly, however, additional factors must be allowed for, such as liquid water content, texture of the snow pack, size of snow crystals, thickness of crusts and snow surface contaminants. Measurements showed that there were temporal variations in micro-wave brightness during the “melt-to-freezing” cycle. As found previously, very moist soil and snow crusts distort back-scattering from the interfaces. This problem has not been fully explored until now and it requires further investigations in snow physics.

Global grid snow cover data are available owing to satellite imagery received every day. The most complete data have been collected at the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado, USA. One of these sources is monthly global snow depth data. They are allocated into grid cells of 4 degrees latitude by 5 degree longitude. Such global grid data sets are too coarse for assessment of snow accumulation at a local scale, e.g. small river basins, but they are very useful for various aspects of climate research, such as updating global climatic and atmospheric circulation models.

3. Global scale distribution

Remote sensing by satellites delivers quite realistic pictures of snow cover distribution at the global scale. By late winter snow extends over almost 60% of the northern hemisphere land mass and about 25% of that in the southern hemisphere. This determines the reflectance of solar radiation or the snow surface albedo, which amounts to 0.80 to 0.90 for fresh fallen snow, while snow-free forest reflects 0.16 to 0.19 of the global solar energy flux. Snow therefore acts as a switchboard for the heat balance of planet Earth, as well as a power forcing the atmospheric circulation.

At the same time, the circulation systems determine the extent and distribution of snow cover. In Europe snow cover expands southwards under the prevailing influence of the so-called western type of circulation. The eastern types tends to make snow cover more persistent in time. This fact results from the close interrelation between atmospheric circulation type, atmospheric water vapor content and precipitation. Thus, the circulation links the components of the hydrological cycle and snow cover, rebuilds heat budget over the Earth surface, and creates temperature anomalies on a global scale.

The satellite imagery showed that the snow covered area over the northern hemisphere varies between 41 and 48 million km^2 in winter, and from 27 to 34 million km^2 in spring. There has been a slight apparent reduction in spring snow cover in recent years, which may be attributable to gradual global warming, presumably as a human impact, leading to earlier snowmelt. In general, however, there are no clear trends in global snow cover. What is clear is that great anomalies take place, such as sudden snowfalls from cold air breaks in late spring and exceptionally long periods with snow near the southern boundaries of the snow covered area in western North America, Central Asia and Asia Minor.

By detailed analysis of satellite imagery and synoptic maps, one may suppose that the snow cover is controlled by weather and, conversely, it affects future weather

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conditions. The anomalies in snow cover distribution over wide regions, e.g. over the Russian plains, create steady temperature anomalies in early spring. These need to be predicted in due time as being of great importance for arable agriculture.

4. Mountainous areas

The climatic snow limit in mountains is the line where perennial snow occurs; this relates to the "accumulation–melting" budget which depends on air temperature, amount of solid precipitation and solar radiation income, over different slopes. So, the mean air temperature at the snow limit T_0 in Norway is equal to +6 ^oC under permanent cloudy sky, and total precipitation is about to 2000 mm. In contrast, in the Chilean Andes with their very high income of solar radiation, $T_0 = -2$ ^oC.

The actual snow limit may not be in a close agreement with the climatic one, because it is a product of continual interrelations between steady climate factors and freaks of weather associated with complex mountain relief. The highest and the lowest altitudes of snow limit are more different in the middle latitudes of the northern hemisphere than anywhere else (see Table 2).

Latitude, degree	80	70	60	50	40	30	20	10
Highest, m a.s.l.	600	1500	2600	3700	5100	6100	5300	4700
Lowest, m a.s.l.	100	300	700	1100	2500	4200	4700	4500

Note: the latitudinal bands are centered around the figures (85 to 75, etc.).

Table 2. Altitudes of snow limit in northern hemisphere mountains

So, in humid western Georgia (the Caucasus Mts.) the snow limit reaches 2500 m and lower, while in the semi-arid mountains of Dagestan it rises to 4000 m above sea level. Skiers can easily appreciate these aspect-related influences from a cable car to Mt. Elbrus in Central Caucasus. Both precipitation and snow water equivalent are usually enhanced with elevation, by 15-25 mm per 100 m height in semi-arid mountain regions such as the Altai Mountains, and by 40-70 mm per 100 m in the humid Italian Alps and by as much as 85 mm per 100 m for the southern slopes of the Caucasus. The highest precipitation is in elevation zones beneath the snow limit. Snow can accumulate rapidly in the relict spruce thickets of the western Georgian slopes, and this can cause snow avalanches of the highest magnitude.

Exposure-related variations in snow water equivalent are also of great importance. They are in fact a "life support system" for wide regions of Central Asia. This is an area of productive agriculture and horticulture: e.g. the cotton, orchards, vineyards, vegetables and well known sweet melons from Bukhara. All this abundance relies on irrigation, using streams fed by snow melt from the Tien Shan ridges. It was found by observation that the runoff yield from May to September from the drainage basin situated at 3400 m a.s.l. on the southern slope of the Tien Shan Mountains is 1300 mm, while the basin of mainly northern aspect and of the same mean elevation produces 2000 mm of melt water and even more.

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Similar effects are revealed by a journey in southern Siberia and Mongolia that depends on a change of atmospheric circulation and affects the local semi-arid climate. There are only dry prairies with sparsely grown larch groves on the south-facing slopes, while on the north-facing slopes, there are pine and fir tree stands that produce good timber. Likewise the American Rocky Mountains (on east- and west-facing slopes respectively) in Idaho, Utah and Wyoming.

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Biographical Sketch

Vladimir A. Shutov was born in August 1950 in a small town of the Kostroma region, Russia. He graduated as a meteorologist in 1972 from the Hydrometeorological Institute, St. Petersburg. Since 1972 he has worked as a hydrologist. From 1974 to 1979 he was the head of the Wetland Research Station *Brusovitsa*, Arkhangelsk region, where he explored water regimes and soil water properties of wetlands.
Since October 1979 he has worked at the Valday Branch of the State Hydrological Institute, as head of the field investigation division, then, since 1984, as senior scientist and then, since 1991, as head of the runoff and hydro-physical research laboratory. He obtained a PhD degree in 1987 for field and theoretical studies of snow cover and water cycle components as modified by snow management measures.

He is currently studying snow cover, precipitation, evapotranspiration and soil water properties, particularly to provide data for runoff computations and forecasting. He conducted much applied research, such as in agricultural climatology, hydrological support of construction engineering and water projects, and in particular, for pipeline engineering in northern European Russia, soil protective agriculture in central Russian plains and flood forecasting for river basins in the southern Urals. At present he is busy processing radar-based precipitation data as applied to engineering hydrology and climate research.

He likes to use a computer both to process scientific data and to create PC-imagery and websites. He has learned English and German, and is interested in history, the international environmental and political problems. He contributed to many nationwide and international conferences, and has published about 60 papers (of which 16 are in English). He teaches students and professionals in hydrology, both in lectures and scientific field trips.

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