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Spaceborne remote sensing for snow hydrology applications

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Abstract Certain satellite-based remote sensing for snow hydrology applications has been very positive, namely, snow areal extent mapping using visible and near-infrared sensors and snow water equivalent using passive microwave techniques. Although certain problems are yet to be solved, very specific applications have become operational. Data from the NOAA-AVHRR sensor are used to produce snow extent maps for about 4000 basins in North America and the data are distributed electronically by the NWS National Operational Hydrologic Remote Sensing Center. At the Canadian Climate Centre, a method has been developed for real time estimation of areal snow water equivalent over the Canadian prairies using microwave brightness temperatures, and the snow water equivalent maps are distributed to operational hydrological forecasters. Current research may also prove fruitful for estimates of snow wetness or active melting, snow albedo and snow grain size. It appears that forthcoming improvements in passive microwave spatial resolution should increase the applicability of the data for snow hydrology. The spectral and spatial resolution of the visible/near-infrared data will also be improved with the launch of EOS/MODIS. Combinations of sensors and integration with other types of data will further improve the suitability of spaceborne data.

Application de la télédétection spatiale à l'hydrologie nivale

Résumé Certaines applications de la télédétection satellitaire à l'hydrologie nivale ont été couronnées de succès en particulier la cartographie du manteau neigeux grâce à des capteurs dans le visible et le proche infrarouge et l'estimation de son équivalent en eau grâce aux micro-ondes passives. Quoique certains problèmes n'aient pas encore trouvé de solution, certaines applications spécifiques sont devenues opérationnelles. Les mesures du capteur NOAA-AVHRR sont utilisées pour établir les cartes du manteau neigeux d'environ 4000 bassins d'Amérique du Nord qui sont distribuées électroniquement par le NWS National Operational Hydrologic Remote Sensing Center. Le Centre Canadien du climat a élaboré une méthode d'estimation en temps réel de l'équivalent en eau du manteau neigeux de la région des prairies qui utilise la température de brillance mesurée par micro-ondes dont les résultats sont distribuées aux prévisionnistes des services d'hydrologie opérationnelle. Les recherches actuelles pourraient se révéler fructueuses pour estimer l'humidité de la neige ou la fonte comme l'albédo et la granulométrie de la neige. Il semble que les prochaines améliorations de la résolution spatiale des micro-ondes passives devraient accroître l'applicabilité de ces données à l'hydrologie nivale. La résolution spectrale et spatiale des données dans le visible et le proche infrarouge

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sera également améliorée avec le lancement d'EOS/MODIS. La combinaison de différents capteurs et l'intégration d'autres types de données devraient améliorer l'adéquation des données télédétectées.

INTRODUCTION

The occurrence of precipitation in the form of snow as opposed to rain typically causes a change in how a drainage basin responds to the input of water. The reason for the modified hydrological response is that snow is held in cold storage on a basin for an extended period of time before it enters the runoff process. During this time, the snow in storage can be augmented by additional snow accumulation, redistributed by wind, changed in its internal structure, and affected by meteorological factors. At the end of the winter storage period, the resultant snowpack is removed from the basin by ablation processes in a compressed period of time, usually ranging from several weeks to several months depending on the amount of snow and the location.

The occurrence of seasonal snow cover on a basin is variable depending on the time of year, weather patterns, moisture sources, latitude, elevation and landscape features. When the seasonal snow cover is deposited on a basin, the distribution of the snow is dominated by different factors depending on the type of basin. In flat, lowland basins, the amount of snow accumulation is primarily influenced by the type and number of winter storms that affect a region and secondarily by terrain and land cover features. In mountain basins, the accumulation of snow is primarily dominated by elevation and secondarily by storm track and landscape features. In basins where wind is an important factor, the snow can be transported and redeposited so that original deposition patterns can be drastically modified. In Spring, when the snow leaves a basin, the pattern of disappearance is generally the same from year to year, although the timing is affected by the weather and amount of snow accumulation in various parts of the basin. In many mountain basins, snow can still be accumulating at high elevations when it is already disappearing from the lower elevations.

Once the seasonal snow cover has been established in a basin the snow itself undergoes various transformations or metamorphism with time. This includes a general decrease of surface albedo, a fluctuation of snow grain size, and an eventual increase in snowpack liquid water until snowmelt appears at the bottom of the snowpack. Other changes associated with these metamorphic changes are a progressive warming of the snowpack, an increase in snow density, a settling or decrease in snow depth (if unaffected by new snow), and an increase in internal snowpack strength, at least up to the appearance of liquid water in the snowpack. The degree to which these processes are active in snowpacks in the mountains as opposed to the plains varies considerably.

There is such a vast difference in the physical properties of snow and other natural surfaces that the occurrence of snow on a drainage basin can cause significant changes in the energy exchange. As a result of its high albedo, snow reflects a much higher percentage of incoming solar shortwave radiation than snow-free surfaces (80% for relatively new snow *vs* 15% for snow-free vegetation). This causes a large difference in energy absorption and subsequent thermal heating. In the longwave region of the spectrum, snow absorbs and emits radiation very efficiently, in contrast with other natural surfaces. Additionally, the low thermal conductivity of snow sharply reduces heat exchange between the ground and the atmosphere so that snow serves as an insulating blanket. This insulating effect can allow sharp temperature gradients between the ground and air which contribute to changes in the crystal forms in the snowpack.

In the Spring the snowpack undergoes rapid transformation which involves bringing the snowpack temperature to an isothermal situation at 0°C and satisfying the snowpack liquid water holding capacity. When both of these conditions have been met, the snowpack is in a ripe condition and the absorption of additional energy will produce snowmelt. This process takes place at various rates depending on aspect, slope, elevation, vegetation cover and atmospheric conditions. Once snowmelt is occurring, runoff increases rapidly and most of the snow disappears from the basin within a period of several weeks, although this period can be compressed to several days for a shallow prairie snowpack.

The use of remote sensing in snow hydrology has received increasing emphasis as an understanding of the capabilities of the various remote sensing methods has been gained. The four major electromagnetic spectral bands useful for remote sensing of snow are gamma rays, visible and near-infrared, thermal infrared and microwaves. The literature shows that although the microwave band has the most potential, the visible and near-infrared band has been utilized for the most useful applications. The gamma ray band is only useful from low aircraft altitudes because of atmospheric absorption. The thermal infrared band is limited in potential and useful applications to date. The following discussion will concentrate mostly on remote sensing applications from satellite altitudes.

AREAL SNOW DISTRIBUTION FROM SPACE

The areal extent of the snowpack is an extremely useful snow hydrology and climate variable for a number of reasons. In hydrology, the extent and location of the snowpack provides a definition of where snowmelt can possibly occur in a basin. For hydrological models, it provides the coordinates of where the model snowmelt algorithms should be applied. Knowledge of the areal extent of the snowpack also defines where in the basin large amounts of incoming solar radiation are reflected and where large amounts are absorbed. This difference in albedo is also important for regional and global climate studies. Energy and moisture exchanges are vastly different in snow covered and snow free areas which lead to resulting differences in local climate. These large differences in surface characteristics lead to large scale effects that need to be considered in general circulation modelling.

Snow cover extent from space has been available since the early 1960s with the advent of visible and near-infrared sensors on meteorological satellites (Popham, 1968). For hydrological purposes, however, the optimum combination of spatial resolution and frequency of observation never seems to be available. High resolution data with pixels on the order of 30 m or less are usually available on a very infrequent period of observation, such as every 16 days assuming no cloud interference. The ability to observe daily snow extent with the National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer (NOAA-AVHRR) has been available on a continuous basis since 1972 (Rango, 1986). One daylight overpass, subject to cloudiness, is available each day at about 1 km resolution. In polar regions, several passes per day are possible because of overlapping coverage. This 1 km resolution can be termed moderate, but is generally too coarse for detailed hydrological research purposes, i.e. in basins or sub-basin areas less than 200 km^2 (Rango *et al.*, 1985). However, the resolution of 1 km is suitable for hydrological applications over large areas and for most climatological applications. Even at this temporal resolution, clouds can obscure the ground for extended periods. At times like this, the advantages of assured observations from microwave sensors can be appreciated. At present, passive microwave observations of snow extent are available and assured once every 1-2 days from the Special Sensor Microwave/Imager (SSM/I) sensor on the Defense Meteorological Satellite Program (DMSP) weather satellite because of its cloud penetration capability. Once again, in polar regions the frequency of coverage is higher because of overlap. Unfortunately, while frequency of observation is high, the spatial resolution is very poor (about 25 km) compared to visible and near-infrared data. This limits the applications to very large area hydrology and climate studies. When resolution eventually improves so that this type of passive microwave data can be used for basin snow cover mapping, other problems such as penetration of precipitating weather systems, wetness in the surface layer of the snowpack and gaps in data coverage will have to be solved.

Planned future developments will change the temporal and spatial resolution of satellite sensors. At high resolutions, the spatial resolution will improve slightly from the 10-30 m range, but frequency of coverage will remain poor except when pointable sensors can be used to get several days of daily coverage in favourable parts of the satellite orbit. The NOAA-AVHRR will continue daily 1 km coverage, and it is expected to be supplemented by the Earth Observing System-Moderate-Resolution Imaging Spectroradiometer (EOS-MODIS) with similar frequency of coverage and spatial resolution except when the 250-500 m resolution of MODIS is utilized (Running *et al.*, 1994; Hall *et al.*, 1995). Improved resolution in the passive microwave, with sensors similar to SSM/I, is planned with 8 km resolution at 0.8 cm wavelength available in the EOS timeframe (Asrar & Dozier, 1994; Asrar & Greenstone, 1995) and the Russian PRIRODA multifrequency remote sensing satellite programme (Russian Academy of Sciences, 1995). After the year 2000 there is a projected capability to produce the passive microwave data at 1-2 km resolution.

Examples of operational readiness

Because areal snow cover extent data have been available since the 1960s, various investigators have found many useful applications. A team of scientists from a variety of US Government agencies developed plans in the early 1980s for operational snow mapping by the US National Weather Service (NWS) for hydrological purposes. In 1986, NWS adopted these plans and proceeded to develop operational remote sensing products, mostly for snow hydrology. The most widely distributed products of the NWS National Operational Hydrologic Remote Sensing Center (NOHRSC) are periodic river basin snow cover extent maps from NOAA-AVHRR and the Geostationary Operational Environmental Satellite (GOES). Digital maps for about 4000 basins in North America are produced about once per week and are used by a large group of users including the NWS River Forecast Centers and individual water authorities. On about 10% of these basins, the mapping is done by elevation zone (Carroll, 1995). Data distribution is possible in real time through a variety of electronic methods such as the Internet and with the assistance of Geographic Information Systems. The 1 km resolution of the product makes it useful on basins or sub-areas greater than 200 km^2 in area (Rango *et al.*, 1985), and various users employ the data to assist in hydrological forecasting using models. NOHRSC products are continually under development, and the latest products and services can be accessed by visiting their World Wide Web homepage at http://www.nohrsc.nws.gov.

Norway has also been using satellite snow cover data for planning of hydroelectric power generation since 1980. This approach is a simple digital ratioing which is converted to a percentage of snow cover by pixel in the study basin (Andersen, 1991; 1995). NOAA-AVHRR has again been used as the data source for this system because of its daily coverage. Snow cover maps are produced for the various basins, and snow cover by elevation zone in a basin is also a product. The data are now input to snowmelt runoff models for the prediction of streamflow (Andersen, 1995).

Some good examples of operational application of snow extent data are found in India. Initially Ramamoorthi (1983; 1987) started to use NOAA-AVHRR data in a simple regression approach for empirical forecasts of seasonal snowmelt runoff in the Sutlej River Basin (43 230 km^2) and the forecasts were extended to other basins. Ramamoorthi (1987) also decided to use satellite data as input to a snowmelt runoff model for shorter term forecasts. This idea was developed by Kumar *et al.* (1991) and satellite data were input to the Snowmelt Runoff Model (SRM) for use in operational forecasts of daily and weekly snowmelt runoff on the Beas (5144 km^2) and Parbati (1154 km^2) Rivers in India. Apparently because of the isolation of these remote basins the only way forecasts can be made in this region is with the use of remote sensing data.

Another type of operational snow areal extent product is the monthly hemispherical snow maps produced for climatological applications. These hemispherical charts have made use of both GOES and NOAA-AVHRR with resolution of 1.1-8.0 km. These snow maps were made by hand and although the snowline is somewhat crude, they provide a relatively long data set extending back to the early 1970s. They have been found to be useful for trend analysis in snow climatological studies by Robinson & Frei (1995). They are produced operationally by the NOAA Climate Analysis Center.

Challenging problem areas

Despite the fact that the various snow cover extent products are operational, separation of snow from clouds and cloud cover obscuration of the snowpack are still problems because the major data source is visible and near-infrared data. Countries in northern latitudes report that clouds cause major problems in accurately determining snow cover even though they still use the visible snow extent data operationally. A good example is the largest hydropower company in Norway, Statkraft, which uses snow extent maps from NOAA-AVHRR on an operational basis as input to their hydropower production planning but can go for several weeks at a time without a cloud-free image (Andersen, 1995). They would like high resolution microwave data for penetrating clouds in order to make the system more reliable. Although the resolution of active microwave sensors is very acceptable, as will be seen, detection of the snow itself with radar is very much a problem. Such hydropower companies would be very happy to use passive microwave data to penetrate clouds and make simple snow cover extent measurements. Very little adaptation would be required if the passive microwave resolution was on the order of NOAA-AVHRR or about 1-2 km. Even data with a resolution of 5 km used in conjunction with NOAA-AVHRR would be very useful. Some methods to extrapolate visible snow mapping from cloud-free to cloud-covered areas have also been developed (Lichtenegger *et al.*, 1981; Baumgartner *et al.*, 1986) and can be used in partly cloudy situations. Such methods use digital topographical data and assume that pixels with equal elevation, aspect and slope have the same relative snow coverage over all the basin. Such approaches allow some snow cover data to be generated in a way similar to replacing missing data in a conventional precipitation record, and, as such, it is a better approach than assuming zero.

Spatial resolution is sometimes raised as a drawback to satellite snow extent data, especially by researchers with distributed hydrological models. The closer a model evolves towards operational use, the less stringent the need for high resolution data. One-kilometre data from NOAA-AVHRR or GOES have found many operational snow applications because they are available in real time and can be used in a number of operational models and basins. Only very special situations will merit the use of data with resolutions below 1 km and will require a firm commitment to more expensive data processing.

Another real problem is that visible satellite data do not lead to snow water equivalent. There are times when snow extent is not enough. However, when a simple snowmelt model is being applied, all one needs to do is keep track of where the snowpack exists in order to apply the snowmelt equations in the appropriate parts of the basin. Because not much more than 5-6 cm of snow water equivalent per day can be melted under extreme conditions (Stepphun, 1981), the location of the seasonal mountain snowpack cannot change very quickly. If measurements can be obtained once per week, snow extent is sufficient for snowmelt simulation and forecasting. However, remote sensing of snow water equivalent is an important objective in other snow hydrology situations. Additionally, more frequent observation may be required on the prairies where the shallow snowpack can change much more rapidly.

SNOW WATER EQUIVALENT MAPPING FROM SPACE

It is important to know areal water equivalent in a basin for arriving at snowpack volume estimates. Observations of just the snow cover extent are not enough because it has been shown that a large areal extent can sometimes be associated with a small snowpack volume and vice versa. Remote measurements of the water equivalent provide the third dimension that allows better estimates of expected seasonal runoff volume. In addition, most snowmelt runoff models do not accept snow cover extent and, instead, require a point measurement or estimate (based on precipitation and temperature data) of snow water equivalent. A remote sensing measurement of areal snow water equivalent could most likely be substituted for the point snow water equivalent in snowmelt runoff models with some modifications to the models. Some study will be required to determine if such a substitution is straightforward or whether these snowmelt runoff models will all have to be recalibrated for use with actual areal data.

Climate modellers also maintain that snow cover extent is not enough for their purposes. Rather they also need to know average snow water equivalent so that they can estimate how long snow cover will affect the energy and moisture exchange at the land surface. Resolution requirements are not nearly as stringent as those for similar applications in hydrology.

In the measurement of snow water equivalent, there are only two types of data that can be used over relatively large areas – passive microwave and active microwave. Passive microwave data have been available on a regular basis from satellites since 1972 when Nimbus 5 with the Electrically Scanned Microwave Radiometer (ESMR) sensor on board was launched (Hall & Martinec, 1985). Subsequent Nimbus satellites had ESMR and Scanning Multispectral Microwave Radiometer (SMMR) sensors and these were followed by DMSP satellites with the SSM/I sensor starting in 1987 (Goodison & Walker, 1995). Different frequencies were available on the different satellites but 37 and 18 or 19 GHz were found to be most useful (Goodison & Walker, 1995). All spatial resolutions of the various instruments have been poor, namely, 25 km or greater. Frequency of observation, however, has been once every few days depending on latitude. Because of the poor resolution, most of the attempts to use passive microwave data to estimate snow water equivalent have been limited to flat and relatively homogeneous terrain. The studies that have been reported employ some sort of empirical relationship between snow water equivalent (or snow depth) and microwave brightness temperature (one or two bands) (Rango *et al.*, 1979). In addition to having importance for snowmelt runoff forecasting, the data generated would also be important for estimating agricultural water supplies and potential winter kill of wheat.

When active microwave sensors were planned to fly on a variety of satellites in the 1990s – e.g. European Remote-Sensing Satellite (ERS), Japanese Earth Remote-Sensing Satellite (JERS), Canadian Radar Satellite (RADARSAT) and the Russian ALMAZ – there was much enthusiasm for using these high resolution (about 25 m) data for measuring snow water equivalent, particularly in mountain regions. This enthusiasm was premature because the active microwave wavelengths were not optimized for snow measurements. In fact, in dry snow situations which prevail for most of the snow accumulation season, these sensors could not even detect the presence of the snow. When the snowpack becomes wet during the melt season, there is enough scattering of the radar wave so that some information on snowpack can be obtained, but it is usually too late in the runoff season to be useful for hydrology. Some innovative investigators have made creative use of the polarization of bands and multiband processing to see hints of the dry snow signature and snow wetness (Shi, 1995), but there are no plans to have the appropriate polarization and number of bands in space. Furthermore, there are no plans for flying an active radar around the optimum 0.8 cm wavelength in the future. As a result, there is little hope of making active radar into a useful and operational tool for snow mapping of any kind, so one is left to rely on the passive microwave techniques.

Examples of operational readiness

Investigators at the Canadian Climate Centre have taken the early research results and developed techniques useful for operational application of passive microwave data. Using both SMMR and SSM/I data, they have developed a method for real time estimation of areal snow water equivalent over the Canadian prairies using a vertically-polarized brightness temperature gradient (Goodison & Walker, 1995). The real time maps of snow water equivalent have been used by operational hydrological forecasters. Based on input from operational personnel, further development led to a wet snow indicator to discriminate between areas of wet snow and snow free land (Walker & Goodison, 1993). Because the Canadian prairies are open and extremely flat, the poor resolutions of SMMR and SSM/I are less of a problem than in more mountainous areas.

The SSM/I data are being archived and distributed in Boulder, Colorado, USA, at the National Snow and Ice Data Center (NSIDC). The coverage is global and the brightness temperatures in an Equal Area SSM/I Earth Grid

(EASE-Grid) are available since 1989 on CD-ROM (Armstrong *et al.*, 1995). Additionally, NSIDC is also registering SMMR data to the same EASE-Grid. This makes available a time series of passive microwave brightness temperatures for the period 1978-1994. Applications in both snow hydrology and climatology are envisioned for this data set as it grows.

Challenging problem areas

The most significant problem standing in the way of effective snow water equivalent mapping from space is a poor resolution at present in the passive microwave. This is about to change as some new passive microwave instruments will be flown that should improve resolution at about 0.8 cm wavelength from the existing 25 km to the projected 8 km. The first improvement should occur in 1996 when the PRIRODA instrument package is flown on the MIR space station (Russian Academy of Sciences, 1995). Although it is purely a research program, it will give investigators currently experienced with the 25 km capabilities the first chance to compare the improved resolution advantages over study areas previously used such as the Canadian Prairies (Rango *et al.*, 1979; Goodison *et al.*, 1990), US high plains (Foster *et al.*, 1980), and the Upper Colorado River basin (Chang *et al.*, 1992). These investigators will be well suited to evaluating the incremental improvement and will be able to use the PRIRODA data to prepare for similar 8 km passive microwave data to be available from the EOS Multifrequency Passive Microwave Radiometer (MPMR) scheduled to be launched in the year 2000. Both the PRIRODA sensor and MPMR will obtain 8 km resolution by using a much larger antenna than currently used for SSM/I. MPMR, however, will provide global coverage whereas PRIRODA will have coverage limited to 53°N and S.

Although not an approved project at the moment, the technology exists to provide even further improved passive microwave resolutions with the Interdisciplinary Commercial Environment Surveillance Thinned Aperture Radiometer (ICESTAR). This new technology would provide 1-2 km resolution at 18 and 37 GHz frequencies sometime in the first decade of the 21st century. This is another major improvement because the resolution will be compatible with the operational NOAA-AVHRR sensor, and many of the users of the visible snow cover data could easily adapt to use the new data. Much needs to be done to make ICESTAR a reality, but the existence of the technology is reassuring to users of the current SSM/I and related data who are hoping for better resolutions. It is the next logical advancement to make the passive microwave data more widely used.

Another problem is the presence of liquid water in the snowpack which causes the microwave brightness temperature to rise to the point that it appears like snow-free land. The microwave emission characteristics are changed significantly and no quantitative determination of snowpack depth or water equivalent is possible. By monitoring the dry snow water equivalent continuously, the occurrence of melting and a wet snowpack is easy to detect. Where such continuous monitoring is not possible, Walker & Goodison (1993) have devised a wet snow indicator to discriminate between wet snow and snow free areas in agricultural environments based on the difference between 37 GHz vertical and horizontal brightness temperatures. Although quantitative determinations of snow water equivalent in the wet snow area are no longer possible, it is usually not critical for the following reasons. If intermittent winter melt is recurring, the snow will "reappear" when cold temperatures cause the water to freeze. If the wet snow occurs in the Spring, the last dry snow water equivalent determination is usually very close to the maximum snow accumulation.

The problems with forest obscuring the snowpack is potentially more serious. A forest canopy over a snowpack will tend to attenuate the microwave signal from the snowpack while at the same time producing a forest microwave emission. This makes estimates of snow water equivalent much less certain. Goodison & Walker (1995) suggest that this effect causes underestimation of snow water equivalent by as much as 50% compared to open agricultural areas. In extremely dense forest areas, the apparent snow water equivalent can drop to zero where a significant snowpack exists. There is a definite need to find a method to correct for the effect of forest cover on the passive microwave snow signature. Some initial empirical attempts at correcting for the forest or vegetation cover effect on the microwave signature of the snowpack (Hall *et al.*, 1982; Chang *et al.*, 1991; Foster *et al.*, 1991) need to be expanded.

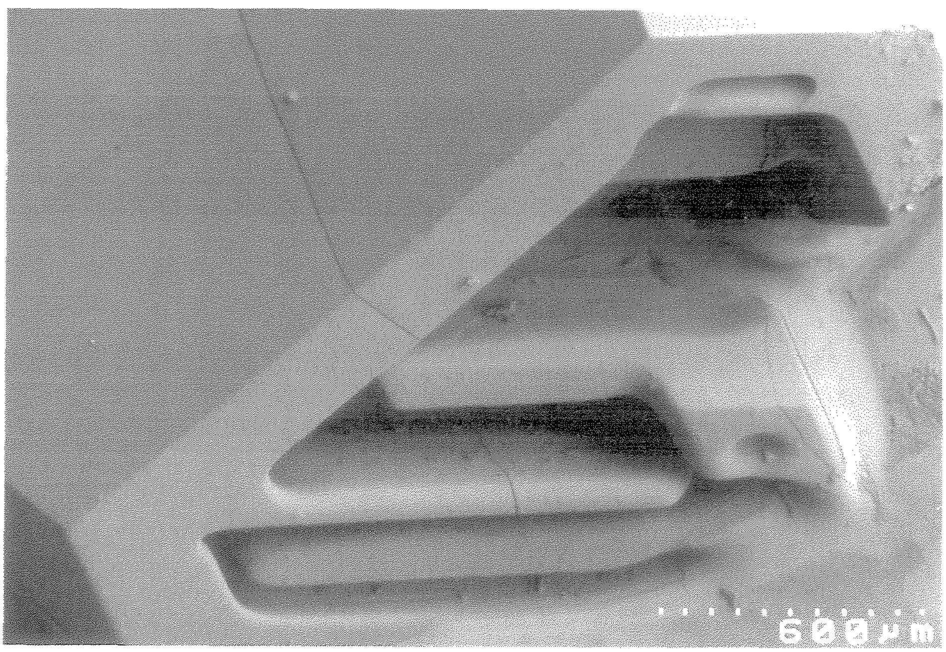

Fig. 1 Intricate, hollow depth hoar crystal from Ester Dome, Alaska obtained from the middle layer of the snowpack (Magnification 50×; bar = 0.6 mm).

A number of investigators have been using algorithms based on passive microwave data to extract snow water equivalent from a dry snowfield. Josberger *et al.* (1996) have reported erroneous snow water equivalent values obtained by their algorithm in locations where depth hoar crystals of fairly large size made up a significant amount of the snowpack. In the regions of well developed and large depth hoar crystals, much more snow was estimated than was actually there. Large snow grains scatter more than small grains. It is apparent that some correction factor or modification to the algorithms must be made to account for abnormal snow grain size distributions as suggested by Armstrong *et al.* (1992). New techniques of observing snow grains with scanning electron microscopy (SEM) may provide better microwave radiative transfer modelling for snow water equivalent estimates. Figure 1 shows a depth hoar crystal obtained in Alaska and imaged with low temperature SEM. Figure 2 shows clusters of grains in a liquid water matrix obtained from a melting snowpack. Figure 3 shows the close packing of small snow crystals by wind effects. A new data base on snow crystal visualization and measurement is currently being assembled (Rango *et al.*, 1996) using SEM techniques and will be incorporated into microwave methods for estimating snow water equivalent.

Theoretically, a number of the problems mentioned for passive microwave remote sensing could be solved by using active microwave remote sensing. The resolution of active microwave techniques is inherently much better than that of passive microwave techniques, namely, on the order of metres rather than kilo-

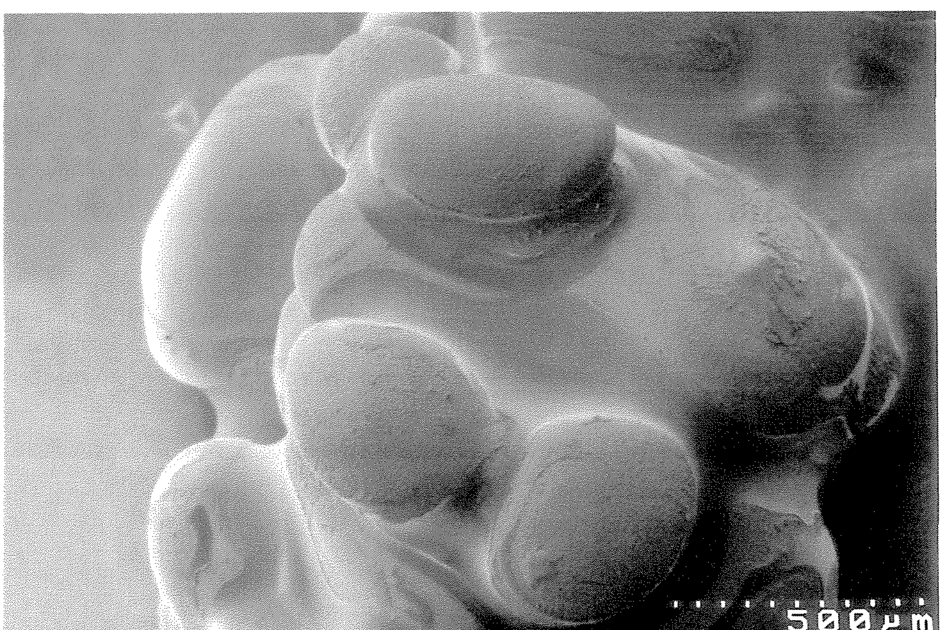

Fig. 2 Cluster of nearly spherical snow grains from the surface layer of a melting snowpack at Loveland Pass, Colorado. The surface layer is saturated with liquid water which loosely holds the snow grains in a cluster (magnification 60×; bar = 0.5 mm).

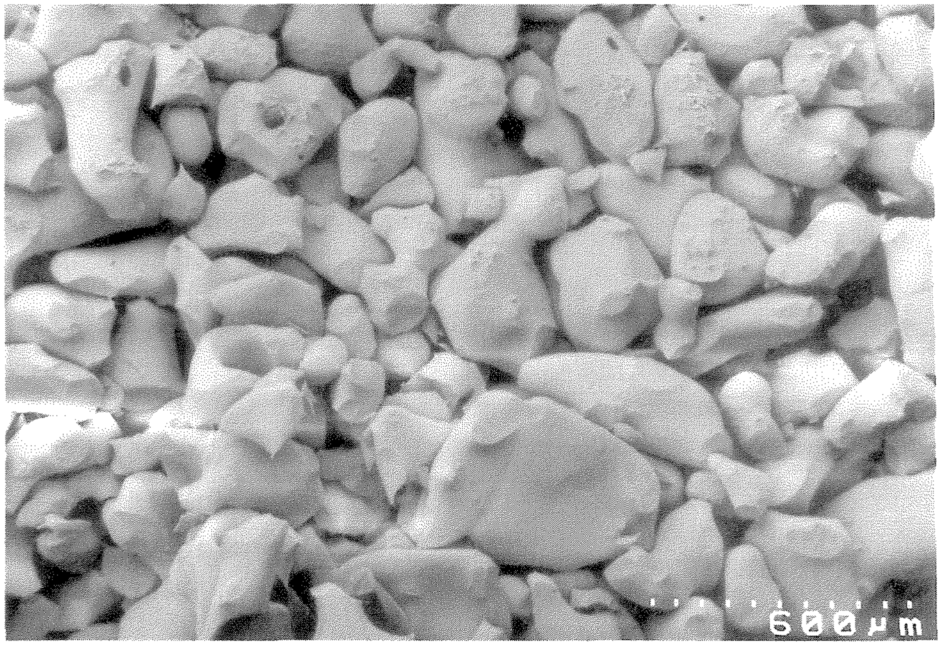

Fig. 3 Sample of tightly-packed snow grains from wind slab snow obtained on the North Slope near Prudhoe Bay, Alaska (magnification 50×; bar = 0.6 mm).

metres. Because wet snow is more easily seen with radar remote sensing, active microwave techniques should be able to extract the snow water equivalent of wet snow. It should also be possible to make measurements of snowpack characteristics in forested areas by using the high resolution of the radar to make measurements in forest openings. But for the most part, all of these potential improvements will not be realized because the appropriate active microwave wavelength and polarizations will not be available. 37 GHz would be the optimum radar frequency for snow, but it is not available now or in the future. Even though there is some potential at longer wavelengths if appropriate polarizations and frequencies are combined, there is no plan to fly the appropriate combinations in the future. As a result, active microwave remote sensing of snow will remain a very complex research problem that will frustrate those who need operational remote sensing of the snowpack. Most emphasis should be placed on the development and improvement of the passive microwave techniques.

REMOTE SENSING OF OTHER SNOW VARIABLES

Temperature

This is one property for which the thermal infrared portion of the spectrum has some advantages. Indeed the monitoring of the surface temperature of the snowpack may have some direct application to delineating the areas of the snow cover where melt may be occurring. If the snow surface temperature is always below 0°C, no melt is occurring. If the snow surface is at 0°C during the daytime and below 0°C at night, the melt-freeze cycle is occurring but it is uncertain whether melt water is being released at the bottom of the snowpack. If the snow surface stays at 0°C both day and night, then it is highly likely that the snowpack is isothermal and that melt is occurring and being released at the base of the snowpack. Much research needs to be done to determine whether thermal infrared remote sensing can play a useful role in assisting in snowmelt runoff modelling and forecasting.

Wetness

Detection that the snowpack is wet, at least at the surface, can be done with a variety of sensors. The near-infrared region experiences a reduction in reflectivity when liquid water is in the snow. Green & Dozier (1995) have shown that a spectral band centred at 1.0 μm can be used to separate liquid water from ice in the snowpack. As mentioned above, when the thermal infrared records 0°C both night and day, it is likely that liquid water is in the snowpack. As the passive microwave emission is greatly affected by liquid water, microwave techniques can be used to identify the initiation of melt metamorphism in the snowpack. As a result of the presence of liquid water, wet snow causes a higher dielectric loss in the microwave frequencies resulting in a high microwave emissivity, much in excess of dry snow. A passive microwave radiometer measures a pronounced jump in the brightness temperature when even a small amount of liquid water is produced in a dry snowpack. For small percentages of liquid water in the snowpack, there may be a quantitative relationship between liquid water content and brightness temperature (Stiles *et al.*, 1981). Active microwaves have also shown a potential for measuring snow wetness (Shi, 1995).

Snow albedo

The albedo of the snow surface changes with time as grain sizes change and surface impurities collect on the snow. Remote sensors collect only a small portion of the light reflected by the snow, i.e. the light reflected towards the sensor in the specific electromagnetic band of the sensor. The albedo, on the other hand, is made up of light reflected in all directions off the snow over all portions of the electromagnetic spectrum. As the bidirectional reflectance distribution function has not been investigated thoroughly, it is extremely difficult at present to take one remote sensing reflectance measurement and deduce the albedo from it. In a general way, one can say that the albedo decreases in the visible region as more impurities reach the snow surface and in the near-infrared as the size of individual grains or clusters of grains increases. As this is what happens as the snow season progresses, remote sensors see this general decrease in albedo with time. Remote sensing techniques, as yet, have not yielded the total bidirectional reflectance distribution function or albedo. Work such as that by Dozier *et al.*, (1988) is necessary eventually to enable effective albedo measurements in a variety of land covers and terrain types.

Bidirectional reflectance measurements of snow covered surfaces like forests and meadows have been obtained from airborne spectroradiometers (Hall *et al.*, 1993). It is likely that the MODIS instrument scheduled to fly on the EOS platform in the late 1990s can be used to obtain snow albedo measurements from space.

Grain size

Grain sizes in the snowpack are difficult to measure by remote sensing. Microwave emission is strongly influenced by the grain size, as was shown by Chang *et al.* (1982). However, it is difficult to distinguish between different grain sizes and the number of snow grains. As yet there is no dependable way to quantify grain size with microwave measurements. Research with visible and near-infrared reflectivities have established surface layer optical ice grain radii, but evidence is lacking on how this value relates to physical grain size (Dozier, 1987). The largest sensitivity of snow reflectance to grain size occurs in the near-infrared wavelengths (1.0-1.3 μm) where no current satellite sensors make measurements (Dozier, 1989). Nolin & Dozier (1993) have used aircraft spectroradiometer data in the near-infrared at 1.04μm and an inversion technique to get estimates of near surface layer snow grain size. If one can relate these grain sizes to physical measurements of the snowpack grain sizes, it appears that grain size measurement capabilities could increase in the late 1990s with the launch of the MODIS which will have the appropriate near-infrared wavelength.

DISCUSSION

The two potentially most useful spectral bands for snow hydrology applications are the visible/near-infrared and the microwave. The visible/near-infrared applications for mapping snow cover are widely accepted and in some cases vastly underrated in importance. For snowmelt runoff forecasting, regular and reliable monitoring of the changing snow cover extent, when combined with a good snowmelt model, can replace the need for remote sensing of snow water equivalent, a much harder problem to solve. Additionally, with selection of appropriate bands in the visible/near-infrared, there is a strong potential that definitive information on snowpack liquid water, albedo, and grain sizes can be derived. The launch of the MODIS instrument in the late 1990s should provide sufficient spectral resolution for these potentials to be realized.

In the passive microwave region, there is the strong potential that areal remote sensing of snow water equivalent will be possible, especially as the resolution of sensors shrinks from 25 km to 8 km and perhaps even smaller. In addition to this capability, the passive microwave has the advantage of nighttime observations as well as an all-weather ability to penetrate clouds. The complexity of active microwave remote sensing of snow makes the potential in this area much less than that of the passive microwave.

Combinations of two different remote sensors can at certain times increase the information available about the snowpack. As an example, a method has been developed in Finland which combines several different approaches to measuring or estimating snow water equivalent (Kuittinen, 1989). Ground-based point measurements of water equivalent were made as usual about twice a month. One airborne gamma ray flight was made at the beginning of the snowmelt season to give line transect values of snow water equivalent. All available NOAA-AVHRR satellite images in the Spring are used to provide areal snow water equivalent estimates based on a relationship between the percentage of bare spots in the snow cover and snow water equivalent (Kuittinen, 1989). The point, line and areal snow water equivalent values were used with a method of correlation functions and weighting factors, as suggested by Peck *et al.* (1985), to determine an areal value based on all data. Evaluations in the Finland study have shown that the error of the estimate of areal snow water equivalent is less than 3.5 cm (Kuittinen, 1989). Carroll (1995) also developed a system which combines ground-based snow observations and airborne gamma ray snow water equivalent observations to yield gridded snow water equivalent values. Satellite areal extent of snow cover data are used to constrain the snow water equivalent interpolations to regions where snow cover is present.

In hydrology, deterministic models are commonly used for simulations, forecasts, and future projections for planning. At present, only a few models directly incorporate remote sensing inputs (e.g. Kite, 1991; Martinec *et al.*, 1994). More models need to incorporate areal remote sensing data including snowmelt runoff models. The simple areal extent of snow cover is calculated in many distributed models but is not accepted as an input variable. Now that such data can be provided, these models need to use the real data along with the calculated data rather than continue to rely solely on data calculated internally in the model. Areal snow water equivalent data are required by several models, but are not yet ready to be provided operationally. However, they will be forthcoming shortly, either directly from microwave data or from combinations of sensors (Kuittinen, 1989; Carroll, 1995). Deterministic models need to prepare to use these real data rather than to continue to use snow accumulations derived from point precipitation data which have been commonly shown to have inherent errors associated with precipitation gauge collection deficits and poor coverage with increasing elevations. If redesign of existing models or development of new models is required, it should be remembered that simple modelling approaches receive much more widespread application than complex approaches with about the same amount of error in simulations or forecasts (Naef, 1981; Loague & Freeze, 1985).

CONCLUSIONS

Snow cover extent mapping can be done operationally with visible satellite imagery. The launch of EOS/MODIS with improved spectral and spatial resolution should improve snow extent mapping but also allow advances in the areas of snow wetness, snow albedo, and snow grain size estimation. Better techniques need to be developed to improve snow cover mapping under cloudy conditions.

Microwave techniques for snow water equivalent monitoring are somewhat promising. Active microwave techniques are greatly hindered by non-optimum wavelengths and polarizations and complex geometries with little hope for future improvement. Passive microwave techniques are already used for operational snow water equivalent maps in large flat areas where the existing 25 km resolution is not so much a problem. The launch of EOS/MPMR will improve resolution to 8 km with hopes that subsequent satellites will have even better resolutions. This extends the applications for areal snow water equivalent determination and contributes to solving the problem of snow extent mapping under cloudy conditions.

It is recommended to combine and integrate data from different remote sensors and various types of low altitude and ground measurements. Studies along these lines have shown that the result is more areal information content than available from any one data source. Areal snow extent and areal snow water equivalent thus obtained should be suitable for input to deterministic hydrology models.

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