EVOLUTION OF A SNOW COVER ALGORITHM FOR THE MODERATE RESOLUTION IMAGING SPECTROMETER (MODIS)

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ABSTRACT

An algorithm for the identification of snow cover is being developed for use with data from the future Moderate Resolution Imaging Spectrometer (MODIS), an Earth Observing System (EOS) instrument. The snow cover algorithm currently employs a series of criteria tests, and a normalized snow difference index (NSDI) that identify snow by its reflectance characteristics in the visible and near-infrared regions, and also discriminates between snow and many types of clouds. The snow cover algorithm is being developed with Landsat Thematic Mapper (TM) data and is also being tested with data simulated from Landsat TM data to match the 500 m resolution of some of the MODIS bands. Satisfactory snow identification results have been obtained on bright snow targets of test images. Testing of the algorithm indicates that performance of the algorithm is affected by scene characteristics such as; extent of snow, terrain, and types and extent of clouds. Refinements will be required to increase the accuracy and reliability of the snow cover product. Also, discrimination of most types of clouds from snow will be possible with the additional spectral bands from MODIS.

INTRODUCTION

Snow is a key component of the global hydrologic cycle and the Earth's radiation budget. Snow covers approximately 30% of the Earth's land surface area seasonally, and about 10% is permanently covered by glaciers (Dozier, 1989). The high reflectivity and low thermal conductivity of snow influence the surface/air heat flux and thus regional and global energy balance. Snow cover is highly dynamic temporally and spatially and represents a changing boundary condition in climate models (Dozier, 1989; Hall, et al., 1990a). The monitoring of snow cover is important to climate modeling and hydrologic cycles. Snow cover has been monitored using the NOAA polar orbiting satellites for about 25 years and maps are produced on a weekly basis (Matson, 1991). The National Operational Hydrologic Remote Sensing Center of the NWS employs both airborne, and satellite data, to produce real time and weekly snow cover products for North America during the snow mapping season. With the future series of Moderate Resolution Imaging Spectrometer (MODIS) instruments on the Earth Observing System (EOS) platforms it will be possible to produce a long time series of snow cover products of the Earth using automated techniques. The research described here is the initial development of a snow cover algorithm for use with MODIS data to generate a global snow cover product using digital data.

MODIS

The MODIS is a NASA instrument designed for study of the biological and physical processes of the Earth and is a component of the EOS. MODIS is an imaging spectroradiometer that will collect data in 36 discrete spectral bands in the electromagnetic spectrum between 0.4 and 14.24 μm. Individual spectral bands will have spatial resolutions of either 250 m, 500 m, or 1 km at nadir. The EOS will be able to repeat coverage of a location on Earth at least every two days. The general objective for the instrument is to provide long term data sets for the study of global processes with emphasis on global climate change. An EOS mission goal is to acquire long term data sets from several successive MODIS instruments with the first launch anticipated for mid 1998.

MODIS data and a group of global survey data products produced from MODIS data will be used by many investigators to study global processes and climate change. One of the global survey data products to be produced with MODIS data is a weekly global snow cover product (NASA, 1991). Several of the MODIS spectral bands correspond in spectral coverage with the TM bands (Table 1) making TM an appropriate sensor to initiate development of the snow product algorithm to eventually be employed with MODIS data. The MODIS instrument has spectral bands that should prove very useful in snow detection. To facilitate snow mapping, the MODIS has a near infrared band (Band 6) centered at 1.640 μm for the purpose of snow and cloud discrimination. The dynamic range of the MODIS bands for the study of land and cloud properties should be great enough to avoid the sensor saturation problems that have been encountered with the Landsat TM sensors when imaging snow at high latitudes and low solar zenith angles (e.g. Dozier, 1989). In addition to the 1.6 μm MODIS band useful for snow and cloud discrimination, MODIS has several thermal bands designed for cloud observation that may also be useful for snow and cloud discrimination in the future (e.g. King et al., 1992).

Table 1. Center wavelengths and spatial resolutions for TM and MODIS spectral bands for the observation of land and cloud properties. (MODIS specifications from Hughes SBRC, April 1992.)

TM Band	MODIS Band	Center Wavelength (μm)		Spatial Resolution (m)	
		TM	MODIS	TM	MODIS
3	1	.66	.659	30	250
4	2	.83	.865	30	250
2	4	.56	.555	30	500
5	6	1.65	1.640	30	500
7	7	2.22	2.130	30	500
6	31	11.45	11.030	120	1000

SNOW REFLECTANCE CHARACTERISTICS

Snow typically has high reflectance in the visible region of the spectrum. Nearly 80% of incident solar radiation may be reflected from fresh snow (Choudhury and Chang, 1981; Hall et al., 1990a). Snow reflectance decreases as snow ages or becomes contaminated by deposition of aerosols, dust, pollen etc. (Warren, 1982; Dozier, 1984) , yet remains much higher than most other surface features. It is the high reflectance characteristics of snow in the visible portion of the spectrum that make it distinguishable from many other surface features. Snow and clouds both have a high reflectance in the visible portion of the spectrum, making discrimination between them difficult in that region. This situation is illustrated in Figure 1, where clouds and snow are both bright and very difficult to distinguish in TM Band 2 . Reflectance from snow depends on solar zenith angle, among other parameters, and at low sun angles at certain times of the year and on slopes exposed to the sun, snow reflectance may saturate TM bands 1, 2, 3, and 4, but is only a severe limitation to use of Bands 1 through 3. Saturation of TM bands 5 and 7 should not occur (Dozier, 1984, 1989).

In the near infrared, snow and clouds have different reflectance characteristics; clouds have high reflectance; snow has very low reflectance. It is this difference in reflectance between snow and clouds at about 1.6 μm that makes it possible to distinguish between the two (Allen et al, 1990; Dozier, 1989; Crane and Anderson, 1984; Bunting and d'Entremont, 1982; Warren, 1982). It is this change in reflectance of snow from the visible to near infrared (Figure 1) that can be exploited to identify snow and discriminate between snow and many types of clouds.

DATA

TM

Landsat 5 TM scenes of the Brooks Range in Alaska acquired on 13 September 1984 (solar zenith 67°) and of the Chugach Mountains in Alaska acquired on 1 August 1985 (solar zenith 47°) have been utilized in this analysis. Both scenes contain mountains with snow cover, glaciers, and clouds. Image subsets 512 x 512 or 1024 x 1024 pixels in size containing snow and clouds in differing amounts were extracted from the scenes for analysis. These scenes were selected for the mixes of snow and clouds occurring in them to develop our algorithm for snow identification and snow/cloud discrimination. A Landsat 4 TM scene of snow and ice covered West Antarctica acquired 12 December 1988 (solar zenith 68°) has also been used for snow/cloud discrimination technique development. This scene has the difficult discrimination situation of thin cirrus clouds over snow.

Landsat TM digital numbers were converted to either effective at-satellite reflectance, or at-satellite temperature. The conversion to reflectance was made because of the desire to work with physically meaningful reflectances rather than digital numbers. The goal is to make identification based on reflectance, with the expectation that some atmospheric correction will be performed in the MODIS processing thus providing surface reflectance measurements. It may be expected that an atmospheric correction may result in an increase in reflectance in the reflective region, 0.4 - 1.0 μm, as compared to the at-satellite measure (Hall et al., 1990b). Reflectance also allows for reasonable comparison of results with other studies. Our analysis uses the at-satellite reflectance values, for comparison of reflectance characteristics of snow, clouds, and other features. The conversion from Qcal digital numbers to radiance (1) to at-satellite reflectance (2) is:

$$L_\lambda = L_{min} + ((L_{max} - L_{min})/Q_{calmax})Q_{cal} \quad (1)$$

$$R = \pi * L_\lambda * d^2 / Solar * \cos\theta \quad (2)$$

L_λ is spectral radiance in a band, L_{min} and L_{max} are spectral radiance at $Q_{cal} = 0$ and $Q_{cal} = Q_{calmax}$, Q_{calmax} is re-scaled radiance in DN, R is unitless effective at-satellite planetary reflectance, d is the earth-sun distance in astronomical units, Solar is the exoatmospheric solar radiance at that wavelength, and θ is the solar zenith angle (Markham and Barker, 1986).

For calculation of at-satellite temperature (3), T is effective at-satellite temperature in degrees Kelvin, K1 and K2 are calibration constants, and L_λ is spectral radiance (Markham and Barker, 1986).

$$T = K2/\ln((K1/L_\lambda) + 1) \quad (3)$$

MODIS Simulated Data

A procedure for simulating MODIS data is presented in brief here. A complete description of the procedure can be found elsewhere in these proceedings (Barker et al., 1992). The simulation procedure approximates the geometrical nature of MODIS data in 250, 500, and 1000 m bands. The simulation procedure begins with TM data, and applies a modulation transfer function for the expected MODIS spatial characteristics, then it generates MODIS radiances, and then calculates at-satellite reflectance. Because the simulated image is still at the TM spatial resolution it must then be re-sampled by a factor of approximately 60 to correspond to MODIS spatial resolution of 500 m. Simulated MODIS data have been generated from TM bands 2 and 5, corresponding to MODIS bands 4 and 6, respectively. The snow algorithm has been applied to this simulated MODIS data.

DISCUSSION AND RESULTS

This snow cover algorithm is being developed as a series of tests based upon reflectance characteristics of snow and reflectance differences among snow and cloud and other surface features. A normalized snow difference index is also employed to identify snow and to aid discrimination of snow from clouds. The logic of development proceeds from assuming an image has the simple case of having a clear view of sunlit snow, and proceeds to discriminate clouds in the image, and also to identify snow that is not directly illuminated by the sun, e.g. in the shadow of mountains. Because of the many possible signatures of snow, we have defined three categories for algorithm results: definitely snow, maybe snow, not snow. Defining these three categories provides a range of estimates of snow cover that can be used to refine the algorithm and identify problem snow situations. The algorithm is performed on every pixel in a scene. Decisions in the threshold tests and the normalized snow difference index are made with a result of true (1) or false (0) returned for each pixel. Results are compiled to generate the snow 'map' product, that identifies three classes; definitely snow, maybe snow, and not snow. A goal is to be able to generate this snow product with an estimate of certainty for each class. These checks for reflectance characteristics have been selected so that the result may have a confidence associated with identification of three classes, definitely snow, maybe snow, definitely not snow. Ability to distinguish snow relies on reflectance differences between regions of the electromagnetic spectrum for snow and between clouds, and surface features.

Analysis has focused principally on the use of TM Bands 2 and 5, located in the visible and short wave infrared portions of the spectrum. These bands have been selected because their spectral coverage corresponds to MODIS bands 4, and 6 at 500 m spatial resolution. Though snow reflectance may occasionally cause saturation in TM band 2, the saturation problem is not expected with MODIS because several visible bands have been designed not to saturate over snow.

The technique of reflectance thresholding presents the problem of applying 'universal' threshold or extrema that are not truly universal; many situations arise where they fail to perform satisfactorily. A common situation where snow is not consistently identified by threshold tests is shaded snow, in areas where snow is shaded by mountains or clouds. Snow in those areas quite often has been observed to not have the high reflectance in the visible that is typical of sunlit snow. An option is to lower the reflectance threshold to try and identify the shaded snow areas but the compromise is that non-snow features may then be identified as snow. In order to evaluate the effect that changing the acceptance threshold had on the results of a reflectance test, the acceptance threshold was changed and the change in result was counted. This was done for each threshold test with acceptance criteria incremented in steps of 0.05 over the acceptance range of 0.0 to 1.0 for several images. It was commonly found that there was about a 10% to 20% change in the number of pixels identified as snow for a 0.05 change in acceptance threshold from the previous threshold result. The spatial result of changing thresholds was observed as an expansion or contraction of snow extent about the perimeters of the snow areas identified in the previous threshold levels, as reflectance threshold acceptance criteria were incremented or de-incremented. This was observed over a wide range of thresholds surrounding the threshold that we interpreted as producing the most acceptable result. At either the high or low ends of acceptance, radical jumps in identified snow area were observed as snow was either eliminated or other features were included in the result. It was observed that the amount of change in snow extent between increments was affected by the amount of snow cover observed in an image, with images having extensive areas of snow cover exhibiting smaller changes than those with lesser observed snow coverage. We observed that there was not an exact or critical threshold for these snow reflectance tests, but that there was a range of acceptable thresholds that corresponded to the best visual interpretations of snow cover.

In the algorithm the first snow reflectance characteristic checked for is that of high reflectance in the visible. High reflectance in the visible bands is a characteristic common to both snow and clouds. The second snow reflectance characteristic checked for is low reflectance at about 1.6 μm. Snow typically has very low reflectance at 1.6 μm, and clouds have a high reflectance. But there are many other surface features that may also have low reflectance at 1.6 μm. Discrimination of cloud from snow is the result of compiling these first two tests if both are true, high visible and low 1.6 μm reflectance, the pixel is identified as not cloud, probably snow, but may be some other surface feature. To further identify snow a normalized snow difference is employed.

To increase our ability to identify snow and slightly decrease reliance on 'universal' thresholds we have defined a normalized snow difference index (NSDI). Snow reflects visible radiation and absorbs near infrared radiation thus, the snow normalized difference is expressed as; NSDI = (reflected visible - absorbed near infrared) / (reflected visible + absorbed near infrared). For TM data we have used TM band 2, visible green, as the reflected visible band and TM band 5, near infrared, because both closely correspond to MODIS band 4 and 6 in spectral coverage, and both MODIS bands have the same spatial resolution (Table 1). The NSDI is then;

$$\text{NSDI} = (\text{TM band 2} - \text{TM band 5}) / (\text{TM band 2} + \text{TM band 5}) \qquad (4)$$

This NSDI is used to key on the characteristic change in snow reflectance between the visible and near infrared spectral regions. Snow will have positive values; snow was commonly found to have NSDI values greater than approximately 0.6. The logic of the snow normalized difference is somewhat analogous to that of the normalized difference vegetation index (NDVI). The NDVI is related to the fact that healthy vegetation absorbs red radiation and reflects near infrared radiation; NDVI = (reflected near infrared - absorbed red) / (reflected near infrared + absorbed red) (Townshend and Tucker, 1984). The similarity of indices is that both are based on a difference in reflectance between a visible wavelength and a near infrared wavelength.

The result of applying the algorithm to the Chugach scene (Figure 1) is shown in Figure 2. The three resulting categories of snow, maybe snow, and not snow correspond well with the interpreted occurrence of those categories. Obviously erroneous results were not observed with this image, but the mix of broken clouds with sunlit and shaded snow below demonstrate a situation where changing the threshold values could result in the area being identified predominately as maybe snow, or cloud, and not be a very accurate representation of the actual situation. Though the snow cover product will probably have

a coarser resolution than the resolution of this early development, it is important to have an understanding of how the algorithm functions at finer resolutions.

A very interesting result of the NSDI was that it identified both sunlit and shaded snow as snow. This result is an improvement over the simple approach of identifying snow simply by reflectance criteria tests which only identifies sunlit snow. Yet, identification of shaded snow was different between images; for the Chugach image (Figure 2) it appears that only the interpreted shaded snow areas were identified, but in the Brooks Range image shaded slopes that were not interpreted as being snow covered were identified as snow covered using the algorithm.

Results have been modest on intensely studied images. For well studied scenes the algorithm can be adjusted to agree very well with interpreted knowledge of snow cover present. The greatest errors have been observed to occur in images with limited snow cover, e.g. less than 10% of the image. Preliminary analysis has demonstrated that similar results are obtained when the snow algorithm is applied to these same scenes generated from MODIS simulated data. Applying the snow algorithm to the MODIS simulated images results in similar percentages of identified snow cover, though some differences do appear they have not yet been thoroughly investigated.

A subset of the Antarctica scene that was nearly total snow cover with the exception of small areas of ice and cirrus clouds was used as a test case for discrimination of cirrus clouds from snow. The cirrus clouds were not discriminated from snow with the algorithm; those cirrus present were identified as snow. It was possible to discriminate the cirrus from snow if TM band 6 (11.45 μm) by use of at-satellite temperature by screening for cloud temperature. This required sampling the cloud temperature and using the average cloud temperature as the screening parameter. Very little transferable success was gained in discriminating cirrus with the data; the algorithm was not able to distinguish some suspected thin cirrus clouds in the Alaska scenes. Also there are other cloud situations such as fog over glaciers (Ormsby and Hall, 1991) and snow cover that should be distinguishable to increase accuracy and confidence in the snow cover product. Because of the potential variable temperature differences between clouds and snow, and our ultimate goal of a automated snow cover algorithm, screening for cloud temperature with a single band will not be acceptable. Some of the potential capabilities of MODIS for distinguishing clouds have been discussed and described by King et al. (1992). In the future, cloud distinguishing techniques for cirrus and other cloud types shall be integrated into the snow cover detection algorithm. A current limitation to implementing cloud distinguishing techniques with TM data is the lack of data over the wavelengths required for these cloud distinguishing techniques and snow detection.

CONCLUSIONS

A snow cover algorithm has been developed that is well suited to specific TM scenes under limited conditions, and the algorithm has been extended to a variety of other scenes with modest success. The use of the thresholding technique poses problems in applying to widely varying remote sensing conditions. This research has found that it is not necessary to have exact reflectance thresholds for snow reflectance but that it is important to be within an acceptable range of values for acceptable results. The greatest success was obtained in identifying sunlit snow cover. Snow cover lying in shade was less consistently identified, though the NSDI demonstrated potential in identifying shaded snow. Snow cloud discrimination was achievable between sunlit snow and some cloud types, with discrimination between other cloud types uncertain. These results indicate that the logic of the algorithm for identifying snow and snow cloud discrimination is reasonable to pursue for use with broad band imaging spectroradiometer data, or similar data, for the purpose of developing the algorithm anticipated to be used to generate a global snow cover product for the future MODIS.

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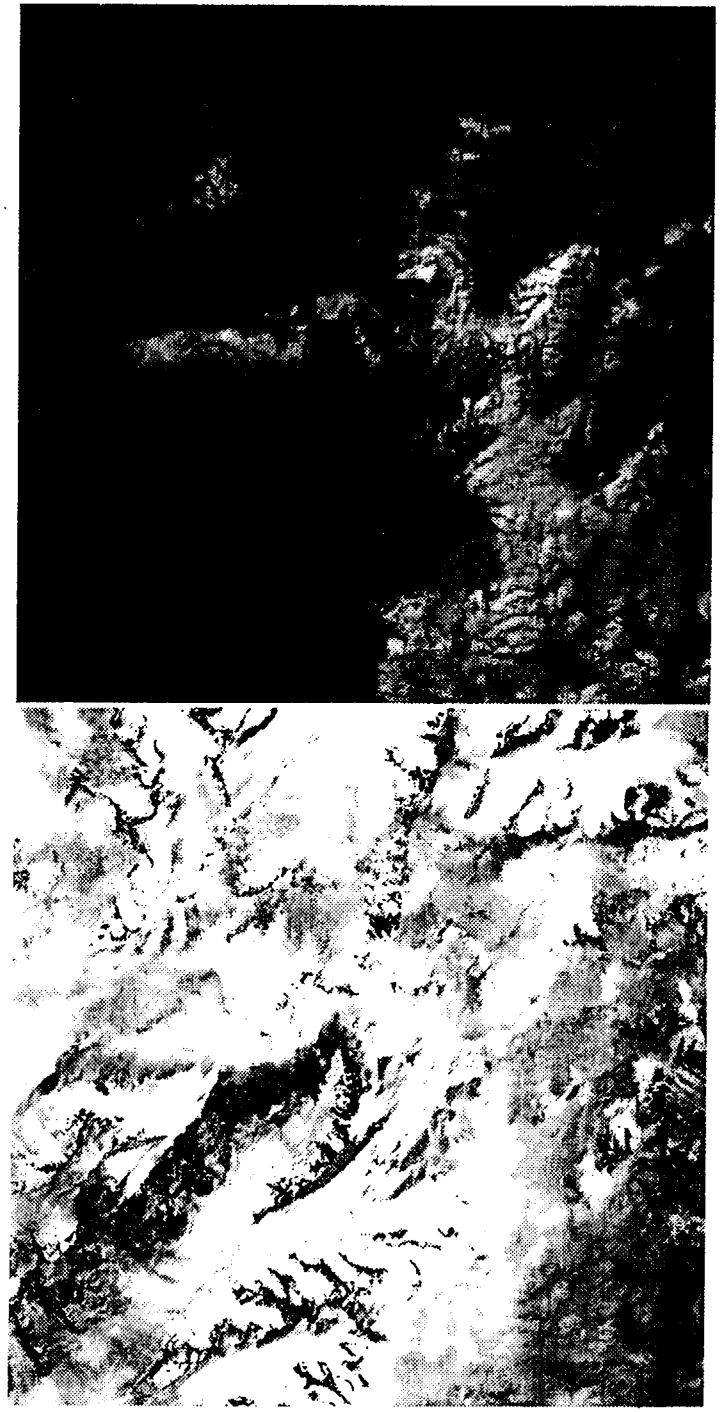

FIGURE 1. Subsets of Chugach TM scene; TM band 2 on the left, TM band 5 on the right. In TM band 2 there is little distinction between clouds and snow, lower left quadrant of image, but the distinction is easily apparent in TM band 5. Also note snow in the shade of the mountains and below and between the clouds in the TM band 2 image.

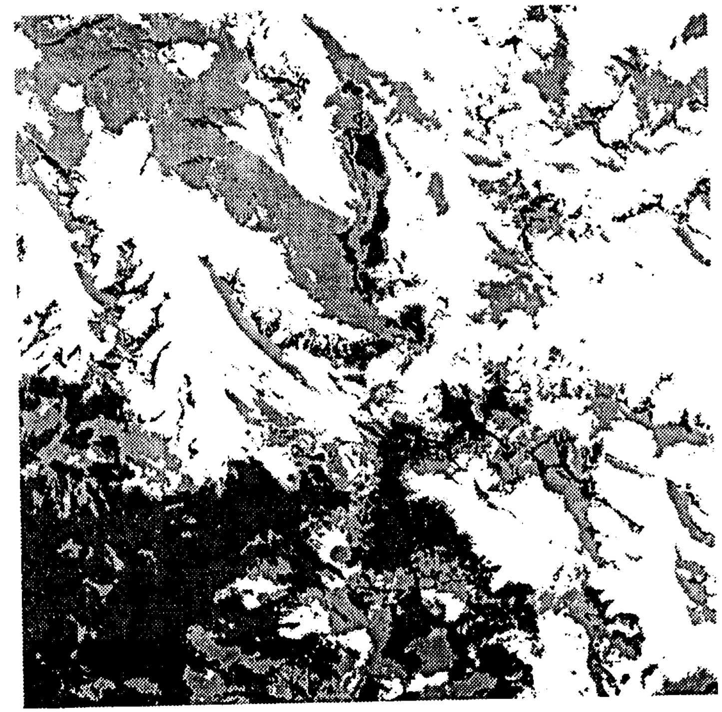

FIGURE 2. Snow cover image resulting from the snow cover algorithm applied to the Chugach scene. White is snow, light gray is maybe snow, and dark gray and black is not snow.

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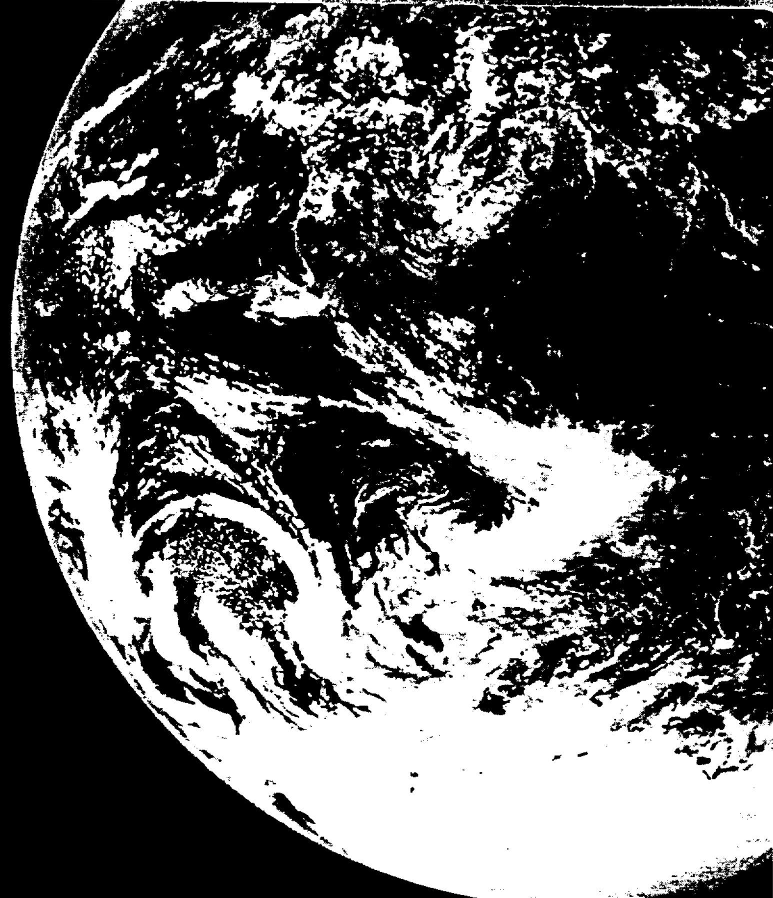

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FOREW

The theme for this year's ASPRS/A *Monitoring Global Change* -- is particu anniversary of the landing of Columbus in and the **International Earth Summit** in F attention on the fantastic changes that hav five centuries, changes that promise to con global mapping and monitoring sciences v they were essential to guide Columbus on these technologies are combining with e sciences to provide critical information ab global environment. A major goal of the provide a forum for the examination, d technological and social challenges represe *monitoring global change*!

Many first-time events will take p Convention. Never before have our socie in conjunction with an ISPRS Congress, an Congress is being hosted by ASPRS i combination of the ISPRS Congress and th make this the largest gathering ever held specialists, photogrammetrists, cartogra managers, technicians, scientists, and engir first time that ASPRS and ACSM have con to host an examination and discussion of issues in the mapping, monitoring and m water, air and other natural resources. T time that several technical plenary session of the convention. In addition, there are sessions (112) than at any previous ASPR premiere event!

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