ASSESSMENTS OF SNOW COVER INDEX AS A CLIMATE CHANGE INDICATOR: STEP 1 PROPOSE OF TESCI (TIME EQUIVALENT SNOW COVER INDEX)

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Abstract

In this study a short review of climate literature and standardization of climate observation methodology - adopted from the World Meteorological Organization - is presented. Snow properties used to provide climate indexes internationally are examined in the presence of the Greek observation capabilities and archives related with these properties. A methodology to create a high-quality index for snow coverage based only in satellite earth observation data, is presented, taking into account data availability and remote sensing techniques for seasonal snow extend calculation. A case study for the implementation of the proposed quality index in the mountain of Pindos is also presented. Prerequisites for the development of a time series of the proposed index as climate change indicator in the area of Olympus Mountain is discussed in relation with planned earth observation missions of the European Space Agency.

This study has been driven by the need to identify engineering inputs and/or constraints for the required spaceborne instruments as a mean to improve/optimize the end-to-end instrument design from space operation to data products.
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References
Abbreviations
ASTER = Advanced Spaceborne Thermal Emission Reflection Radiometer
CHRIS = Compact High Resolution Imaging Spectrometer
CNES = Centre National d’Etudes Spatiales
DEM = Digital Elevation Model
EOS = Earth Observation Satellite
ERS = European Remote Sensing Satellite
E.S.A = European Space Agency
ETM = Enhanced Thematic Mapper
IPCC = Intergovernmental Panel on Climate Change
L1R = Level 1 Radiometrically
MIR = Mid Infrared
MODIS = Moderate Resolution Imaging Spectroradiometer
NDSI = Normalized Difference Snow Index
NDSII = Normalized Difference Snow Ice Index
NIR = Near Infrared
NOAA = National Oceanic and Atmospheric Administration
NSIDC = National Snow and Ice Data Center
SAR = Synthetic Aperture Radar
SC = Snow Cover
SLC = Scan Line Corrector
SPOT = Satellite Pour l'Observation de la Terre
SWE = Snow Water Equivalent
T.E.S.C.I. = Time Equivalent Snow Cover Index
TM = Thematic Mapper
U.S. = United States
U.S.G.S = United States' Geological Survey
WMO = World Meteorological Organization
Rationale

Snow cover exerts a significant influence on the heat balance of the earth and acts as a major source of thermal inertia within the total climate system. Snow properties time series of regularly observations along with other climate indexes play an important role in a better understanding of the climate system and in detecting climate fluctuations from the normal conditions.

1. Climate, Climate System, Climate Controls, Climate Normals and Climate Change

1.1 Climate

Climate is defined as the average or collective state of the earth's atmosphere at any given location or area within a specified period of time. Climate of an area is determined over periods of many years and represents the general weather characteristics of an area or locality.

1.2 Climate system

The climate system consists of the atmosphere, the hydrosphere\(^1\), the surface lithosphere and the biosphere. Although climate is solely essentially related to the varying states of the atmosphere, the other parts of the climate system also have a significant role in the climate forming process, mainly through the interactions among them and the atmosphere.

1.3 Climate drivers

The climatic Drivers are the several factors that cause the variation of climatic elements from place to place and from season to season. The same basic factors that effect weather in the atmosphere also determine the climate of an area. These drivers, acting in different combinations and with varying intensities act upon temperature, precipitation, humidity, air pressure, and winds to

\(^1\) comprising the liquid water distributed on and beneath the earth surface, as well as the cryosphere, i.e. the snow and the ice on and beneath the surface
produce many types of weather and therefore climate. The following four factors largely determine the climate in every region.

a. Latitude (General atmospheric circulation and Weather systems)

b. Land and water distribution (e.g Continental - Mediterranean Climates)

c. Topography (over land, climates may vary radically within very short distances because of the altitude and the variations of the land forms. The altitude of an area exerts a considerable effect on the local climate. Significant influence in the climate is the mountainous terrain type, especially when having long high mountain-chains that act as climatic dividers. These obstacles deflect the tracks of cyclones and block the passage of air masses in the lower levels. If the pressure gradients are strong enough to force the air masses over the mountains, the forced ascent and descent will modify the air masses to a great extent - thus modifying the climate on both windward and leeward sides.

d. Ocean currents. (e.g. Thermal Surface Circulation)

1.4 Climate Normals

One of the basic purposes of the World Meteorological Organization (WMO) is to “promote standardization of meteorological and climatologic observations and to ensure the uniform publication of observation and statistics”. WMO defines as climatic normal the arithmetic average of a climate parameter or element such as temperature or precipitation (rain, snow, hail etc) over a prescribed thirty-years interval. The thirty years interval was settled due to an international agreement, based on the recommendations of the International Meteorological Conference in Warsaw in 1933. The climate record used to construct a climatic normal should be continuous and homogeneous (no changes in instruments, location or observation procedures).

Hydrometeors (Precipitation) are very important climatic elements as they include all the water reaching the earth's surface by falling either in liquid or in solid state. The most significant forms are rain, snow, and hail. Rain, snow and hail have a wide range of variability over the surface of the earth, therefore longer series of observations are required to establish mean and extreme values (maximum, minimum, mean maximum, mean minimum, absolute maximum, and absolute
minimum). In daily weather analysis—observations rain and snow are expressed in millimeters and in climate analysis (climate atlases) with isopleths of the same value (millimeters per year/month).

A thirty years interval is sufficiently long to filter most of the short-term interannual fluctuations and anomalies of the observations, thus to describe changes in temperature and precipitation patterns based on mesoscale atmospheric circulation variability, but sufficiently short in order to be used to reflect longer term climatic trends such as climatic oscillations like the North Atlantic Oscillation or the El Nino southern Oscillation which require a hundred-years climatic intervals.

1.5 Climate Change

A change in Climate Normals is a certain way to detect climate change and then to evaluate the anthropogenic climate change impact. For the understanding of the climate system and climate change, continuous long-term systematic monitoring is needed on the national, regional and global scale.

2. SNOW PARAMETERS AS A CLIMATE INDICATOR

2.1 Introduction

Snow parameters such as extent, depth, and snow water equivalent play an important role to the global and local energy budget in areas with permanent or seasonal snow cover. Global and regional snow properties are considered to be important fingerprints of climate change because snow is:

- considered to be one of the most important renewable known resources –
- highly contributing in the preservation of the water needed in agricultural areas
- a critical factor in the generation of hydroelectric power. Annual snow variability may cause either negative or positive feedback to the local energy budget:
In colder weather conditions more snow forms on the surface and this raises the surface albedo which causes less solar radiation to be absorbed. Less absorption of solar radiation causes even cooler conditions and lowest snow melting rate.

In warmer weather conditions snow starts to melt uncovering the bare surfaces lying underneath having significantly lower albedo which causes more absorption of the solar radiation in the surface and this causes even warmer weather conditions and higher snow melting rate.

The depth and extent of the snow covered areas on Earth have been used as tools for measuring climate variability and change since the early 1970s when satellite-derived measurements of large-scale mapping of snow, became reliable. The Third Assessment Report of Working Group I of the Intergovernmental Panel on Climate Change (IPCC-2001) states: “Satellite data show that there are very likely2 to have been decreases of about 10% in the extent of snow cover since the late 1960s, and ground-based observations show that there is very likely1 to have been a reduction of about two weeks in the annual duration of lake and river ice cover in the mid- and high latitudes of the Northern Hemisphere, over the 20th century”. This corresponds nicely with the atmospheric warming that has occurred across the hemisphere, and intuition leads to the conclusion that snow cover reduction is a response to global warming”.

2.2 Snow cover extend as a climate indicator

The Cryosphere is a vital component of the climate system affecting more than any other land surface texture the global energy balance with its high albedo and low conductivity. Snow and ice reflect up to 80-90 percent of the incoming solar radiation whereas 10-25 percent is reflected by ice-snow free surfaces - such as bare soil or vegetation. A warming trend results in decreased snow cover. Decreasing snow cover is leads to a decrease in the reflected energy, then increase in the

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2 In this Summary for Policymakers and in the Technical Summary, the following words have been used where appropriate to indicate judgmental estimates of confidence: virtually certain (greater than 99% chance that a result is true); very likely (90-99% chance); likely (66-90% chance); medium likelihood (33-66% chance); unlikely (10-33% chance); very unlikely (1-10% chance); exceptionally unlikely (less than 1% chance). The reader is referred to individual chapters for more details.
absorption of the solar radiation, adding heat to the atmospheric system, therefore causes even more ice-snow cover melting. This is a classic positive temperature-albedo feedback mechanism, which is a key component in climate modeling and prediction.

For the past decade, monitoring the parameters of the cryosphere has been used as a climate trend indicator. Parameters such as inter annual melting and ice coverage variability (minimum – maximum) in the Poles have been promoted to be primary climate change indices. Alpine ice and snow cover data-sets are also contributing to the performance of Global Atmospheric Models running on a Synoptic scale and using

Moving from the Synoptic, to Mesoscale and Local scale atmospheric forecasting, the variability of the annual snow cover extent, proves to be rather important as it improves the forecasting performance of the respective models by offering more accurately the initial seasonal conditions for running them. This also helps to identify heavy-snow-producing weather patterns affecting local scale weather and climate.

The change in the temperature observed, either on global or national scale, using both satellite and in situ data for the past decades is not affiliated with a linear change in precipitation patterns (Hydrometeors), thus a more detailed study of mountain snow cover is required, moderating the transfer of energy at the land surfaces, affecting inter seasonal and inter annual water budgets in the surrounding hydrological basins. Mountain Snow Cover Extent data sets are quite important, as they can be used to:

- initialize and improve parameterization of mesoscale and local scale numerical weather prediction models
- update and improve local hydrological analysis and forecasting models
- depict climatic changes related with the presence and strength of Weather Patterns.
- depict climate changes related with increasing local temperatures

In large geographical areas, the daily snow cover extent is calculated using NOAA satellite datasets, while for monitoring smaller areas, Landsat data-set is preferred due to the smaller pixel size. In the retreating of the Cryosphere the last two decades a retreat of annual snow cover on the order of 1 to 3 percent per decade is also pointed out by the use of visible and passive microwave satellite data. This retreat rate (snow melting rate) is observed to be more intense during spring and
summer (where for Mid Latitude Mediterranean climates, frequency and snow precipitability of the weather systems is almost negligible) and is highly associated to the increase of local surface temperatures.

3. Climate of Greece and Hellenic Weather Station Network

3.1 Climate of Greece

The climate in Greece is typical of the Mediterranean climate: mild and rainy winters, relatively warm and dry summers, with generally, extended periods of sunshine throughout most of the year. A great variety of climate subtypes, always within the Mediterranean climate frame, are encountered in several regions of Greece. This is due to the influence of topography (great mountain chains along the central part and other mountainous bodies) and the air masses coming from the moisture sources of the central Mediterranean Sea. Thus the weather in Greece varies from the dry climate of Attica (Athens’ greater area) and East Greece in general, to the wet climate of Northern and Western Greece. In climatologic terms, the area of interest for this study is designated based on Alpine Mediterranean climate. In this climate, winters are harsh with abundant snowfalls and summers are cool with frequent thunderstorms.

3.2 Greek weather station network and snow observations

The meteorological observation system in Greece is being operated by the Hellenic Weather Service under the auspices of the World Meteorological Organization. To the present though, the network lacks completely of snow observation reports due to the fact that there are no stations in high mountains like Olympus. Another important milestone for snow studies is the lack of climatologic research related to the types of weather systems producing snow in the winter season. The use of satellite data for snow cover mapping, in Greece, is a solution to produce high-quality measurements for the snow extend and therefore contribute to climate and climate change study in the country.
4. Snow Cover Climatology for Olympus Area -Time Equivalent Snow Cover Index (T.E.S.C.I.).

4.1 Snowfall in Olympus area

Snowfall is a common occurrence during the winter in the greater area of Olympus mountain range (figure 1).

Figure 1: Olympus mountain range
Seasonal snowfall and snow cover is not considered to be a regular climate parameter in Greece and it is not measured due to the absence of the weather stations in the mountain areas. Annually snow cover can be used to compare the relatively high severity of the winter seasons as well as to define the climatic trends using long term snow cover statistics. The snow cover is affected by both the total snowfall the specific area experiences and the duration of cold temperatures. Higher snowfall and/or colder temperatures should result in prolonged periods of snow cover. Conversely, less snowfall and/or relatively warmer winter temperatures should result in shorter durations of snow cover. Finally, since global warming and climate change is one of the main issues of our century; snow cover climatology is able to help meteorologists to detect any weather conditions change.

4.2 Proxy Information regarding snow in Olympus area

Testimonies from permanent inhabitants and regular visitors of Olympus mountain area assures that in the winter of the 70s or 80s, the area that was cover by snow during winter season, was occasionally preserved in Olympus Mountain range until the beginning of the new snow season which usually starts in November. For the past decade though, no such observation has been made and to make things worse the last two years snow coverage was so limited that resulted to a drinkable water shortage during the summer season in the mountain lodges, located to a 2000 meters altitude. Noteworthy to point out here, that in such altitude, the only source of drinkable water is the melting snow itself.

4.3. Snow cover parameters

The data to be needed in order to extract a useful, snow cover related, index is:

a. Dates of earliest and latest occurrences of various amounts of snow cover.

In order to record exact days of snow occurrence daily observations are needed. The lack of local snow observing network and of daily satellite data makes the detection of snow occurrence difficult.
b. Maximum snow cover

Snow cover is common during the winter in the greater Olympus mountain area. In some winters snow cover can be almost continuous from mid-December through mid-March. Occasionally snow in Olympus area has been created by shallow and short lived weather systems passing over during the month of July. Early snow has been observed in late autumn. The detection of maximum snow coverage with good accuracy is feasible with less frequent satellite data (fluctuations due to late spring snow melting rate or due to late spring snowfall have to be studded)

c. Snow free area.

d. Time period which indicates complete melting of snow cover (  

e. Average maximum snow cover per 5-year and 10-year periods

f. Yearly comparison of snow cover

4.4 Calculation of - normalized – T.E.S.C.I.

A simple, to be calculated, Time Equivalent Snow Cover Index (T.E.S.C.I.) is proposed to compare the relative severity of winters.

\[
\text{T.E.S.C.I.} = \text{Maximum Snow cover area} \times \text{number of days from the maximum snow cover until complete snow melting.}
\]

To increase the use of the Index it can be normalized using the days of the year, therefore becoming:

\[
\text{Normalized T.E.S.C.I.} = \frac{\text{T.E.S.C.I.}}{\text{days of the year}}
\]

The simple but important concept concealed in this index is the fact that 4 basic but with no past-data parameters, have been substituted with the known Time parameter, in order to give
accurate and efficient data to calculate the Time Equivalent Snow Cover Index (T.E.S.C.I.). Consequently, the relative estimation of the quantity and quality of the snow is derived from the time needed for it to melt.

This way, the lack of the snow depth and density data, followed by the calculation of the snow water equivalent, and the effect of the sun exposure and the temperature on melting process, can be overcome.

The index assigns 1 square Km of snow cover to have the value of one. Subsequently a snow cover of 25 Km² will be assigned with a value of 25. For a period of 100 days until complete snow cover SC=2500 Km² Days.

The proposed indicator will be evolved as a time series of the melting rate of snow for spring and summer in mountain areas of Greece. The absence of any snow data set in Greece elevates the importance of the satellite derived T.E.S.C.I. to detect temperature and sun exposure changing trends for the same period but only with long data sets. Temperature also affects the altitude of the snowline in mountainous areas, hence the total size of the area above the snowline (snow cover). As temperature increases, the area above the snowline decreases. This in sequence affects the proportion of total precipitation that falls and can be stored as snow in addition to the amount of runoff in spring and summer. The production of maps depicting the Time Equivalent Snow Cover Index trends is a useful tool to recognize patterns of local climate change trends.

To work under climatic normal prerequisites and to create a T.E.S.C.I. time series based on maximum snow cover area and snow melting period, the availability of existing satellite data archives, present satellite data and future satellite data will be examined in the next chapter. Furthermore a suitable methodology for the estimation of maximum snow cover and of complete snow melting period will be discussed.
5. Review of the adequacy of available data archives for the creation of T.E.S.C.I

5.1 Maximum snow coverage time series for the calculation of T.E.S.C.I.

5.1.1 Generalities

Satellite sensors can be either of optical or microwave type. For snow cover, the most accurate estimates are provided by methods based on optical sensors especially under cloud free conditions (Soldberg et al, 1997). Microwave sensors on the other hand can see through cloud but have the disadvantages of not being sensitive at the wavebands where snow reflects and of a relatively low spatial resolution. The selection of the appropriate sensor depends strongly on the objective of the study and should aim at an optimal combination of a sufficiently high spatial and temporal resolution. For climate studies the length of the satellite record is also of primary significance. Finally, for snow detection purposes it is essential that the spectral coverage and the spectral resolution of the sensor include the visible and the near infrared spectral bands, where the reflectance properties of snow shows maximum value.

It should be stressed that ideally a satellite focusing on applications such as snow mapping should take into account the physical properties of snow. For example in the case of Landsat, by analyzing the snow reflectance curve obtained with the TM4 and TM5 bands (image 1), it is possible to infer the change in the snow curve, (from almost maximum value to zero. In fact, by comparing the pixels’ values between the 0.90 μm to 1.55 μm spectrum wavelength it is possible to discriminate snow among other surface materials.

![Image 1](image1.png)
5.1.2 Optical Sensors

1. Landsat TM (Thematic Mapper) – *NASA, USGS* -

1982–present, 80 m resolution, multispectral, platforms: Landsat 4,5

2. Landsat ETM+ (Enhanced Thematic Mapper) – *NASA, USGS* -

1999–present – lifetime expired –, 15-60 m resolution, multispectral, platform: Landsat 7

3. SPOT 1,2,3,4 – *CNES* -

1986-2006, multispectral in: 0.5-0.59, 0.61-0.68, 0.79-0.89, panchromatic: 0.51-0.73, resolution: 20 m in multispectral, 10 m in panchromatic

4. SPOT 5 – *CNES* -

2003–present – lifetime expired –, multispectral in: 0.43-0.47, 0.50-0.59, 0.61-0.68, 0.78-0.89, short-wave IR: 1.58-1.75, resolution: 2.5-20 m

5. IKONOS - *Space Imaging* -

1999–present – lifetime extended –, multispectral and panchromatic, resolution: 4 m in the multispectral

6. MODIS (Moderate Resolution Imaging Spectroradiometer) – *NASA* -

2002–present, multispectral, resolution: 250-1000 m, platforms: Terra and Aqua
7. ASTER (Advanced Spaceborne Thermal Emission Reflection Radiometer) – NASA
2000-present – lifetime expired -, multispectral, resolution: 15-90 m, platform: Terra

8. CHRIS (Proba Compact High Resolution Imaging Spectrometer) – ESA -
2000-present, multispectral, 19 spectral bands, spectral range 0.41-1.05, resolution: 20 m at nadir

9. Envisat MERIS – ESA -
2002-present – lifetime expired -, multispectral: RGB and NIR bands, resolution: 250 m

5.1.3 Microwave Sensors - Synthetic Aperture Radar

ERS 1,2 – ESA -
1991-present – lifetime expired -, waveband: C-band, 5.3 GHz, VV polarization, bandwidth: 0.06-15.5 MHz, resolution: 26 m across track, 6-20 m along track

Envisat ASAR – ESA –
1,2 – ESA - 2002-present – lifetime expired -, waveband: C-band, 5 polarization modes (VV, HH, VV/HH, HV/HH, VH/VV), radiometric resolution: 1.5-3.5 dB, resolution: 30x30 m, 150 x 150 m, 1000x1000 m

5.1.4 Cost
1. Landsat TM - 25 x 25 km scene: 425$, 25% off if more than 25 scenes

2. Landsat ETM - 475$ per scene with SCL, 200$ per scene without SLC

3. SPOT 1,2,3,4 - 60 x 60 km scene: 1200$-1900$

4. SPOT 5 - 60 x 60 km scene: 1200$-3375$

5. IKONOS - 1 x 1 km scene: 34$-39$

6. MODIS - free but only RGB product available, limited availability of acquisition dates

7. ASTER - 60 x 60 km scene: 91$ 3-D image product also available at 91$

8. CHRIS Proba - 26 x 26 km scene: 50 Euro

9. Envisat MERIS - 50 Euro

<table>
<thead>
<tr>
<th>Criteria of Satellite Selection Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Availability in the past</td>
</tr>
<tr>
<td>Resolution / Pixel Size</td>
</tr>
</tbody>
</table>

3 The Landsat Archive Data will be freely distributed via FTP servers effecting 30th of September 2008 according the official site of the satellite data’s management [http://landsat.usgs.gov/products_data_at_no_charge.php](http://landsat.usgs.gov/products_data_at_no_charge.php)

4 SLC-off operation

In May 2003 the Scan Line Corrector (SLC), a tool that compensates for the forward motion of the ETM+ Landsat 7, failed. The failure causes a zig-zag pattern on the dataset which duplicates part of the data. The width of the duplicated area increases toward the scene edge. The maximum width of the duplicated data and also of the data gaps along the edge of the image is approximately 390-450 m. As a result an estimated 22% of any given scene is lost. However, the middle of the scene that is approximately 22 km wide, is of equally high radiometric and geometric quality as the image data collected before the SLC failure. The presence of duplicated data in the SLC-off images mostly affects the Level 1 Reformatted (L0Rp) and the Level 1 Radiometrically Corrected (L1R) ETM+ data. For the L1G, L1Gt and L1t products a variety of methods is made available by the U.S Geological Survey to apply to the correction of the data in the duplicated zones.
The Landsat and SPOT satellites being those with the longest record (mid-80s to present) are the most appropriate to use in a climate study. In the following part we focus our attention on Landsat as the cost of the SPOT dataset renders its purchase prohibitive and the Infrared Band Coverage of the latter is obviously limited. In a later stage of the project the snow cover estimates, obtained from the Landsat data, can be validated against the respective estimates from the optical sensors that are operational since 2000 and possibly against estimates from the SAR microwave sensors.

5.2. Landsat properties\(^5\)

For each TM band below we quote: the band’s wavelength range in microns, the corresponding minimum and maximum satellite radiances \(L_{min}, L_{max}\) in Watts/m\(^2\)/\(\mu m/sr\), and the exo-atmospheric solar Irradiance \(S_0\) in Watts/m\(^2\)/\(\mu m\).

**Spectral bands**

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength Range ((\mu m))</th>
<th>(L_{min})</th>
<th>(L_{max})</th>
<th>(S_0)</th>
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<tbody>
<tr>
<td>TM1</td>
<td>0.45-0.52</td>
<td>-1.50</td>
<td>152.1</td>
<td>1957</td>
</tr>
<tr>
<td>TM2</td>
<td>0.53-0.61</td>
<td>-2.80</td>
<td>296.8</td>
<td>1829</td>
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<tr>
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<td>TM4</td>
<td>0.78-0.90</td>
<td>+1.50</td>
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<td>TM7</td>
<td>2.10-2.35</td>
<td>-0.15</td>
<td>14.38</td>
<td>74.52</td>
</tr>
</tbody>
</table>
6. Evaluation of remote sensing techniques, for seasonal – annual snow cover area mapping

6.1 Snow Cover Retrieval and Interpretation

6.1.1 Sources of Inaccuracies

In order to calculate a climate index (T.E.S.C.I) depending on the snow cover extend, certain inaccuracies should be taken into consideration before any image processing. The snow cloud discrimination, the grain size reflectance absorption, the seasonal effect and the topography variety are the most important of them.

6.1.2 Snow-Cloud Discrimination

6.1.2.1 The need for a method to differentiate between snow and cloud

With the exception of a narrow window in the mid-IR part of the spectrum, snow and cloud have very similar spectral properties. So, the distinction between the two can be achieved by processing the satellite retrievals in the wavelength bands where the spectral signatures of the two media differ. The need for a method to differentiate between snow and cloud is particularly evident over mountainous terrain where the probability of cloud coverage\(^6\) is high during all seasons (such as Olympus mountainous area).

6.1.2.2 Specific Properties to be taken into consideration during discrimination.

Clouds consist of water droplets and to a lesser extent of ice crystals. The cloud’s reflectance is therefore determined by the absorption properties of water and ice and by their relative amounts

\(^6\) The area can be partly (20% - 80%) or fully (>80%) covered by clouds thus depriving the optical sensors from acquainting the useful data in the captured images.
in the cloud. Also, by the size distributions of water droplets and ice crystals relative to the 
distribution of snow grains, and by the optical depth of the cloud. Similarly, the snow pack’s 
reflectance is determined by the absorption characteristics of the snow grains and their size 
distribution. In the visible wavelengths ice and water are highly transparent, so their reflectivity is 
low. It follows that snow is brighter than cloud in Landsat bands TM1 and TM2 because the 
snowpack is less transparent than cloud. In using the TM1 band however, a fact to consider is that it 
saturates over snow surfaces especially in spring, except in shadowed areas. So, if a pixel is located 
in a shadowed area and does not saturate the sensor at TM1, one of the criteria that can be applied 
for it to be labeled as snow rather than cloud covered, is that its R(TM1) ie. the reflectance in band 
TM1, is above a threshold of 0.16 with a range from 0.15 to 0.2.

In the near-IR wavelengths ice and water are both moderately absorptive and the absorption 
increases with wavelength. However, ice is more absorptive than water in the region between 1.55-
1.75µ. Despite the general similarities in the absorption characteristics of ice and water in the near-
IR, clouds are much more reflective in Landsat band TM5 than snow. There are two reasons that 
cause clouds to be more reflective: First, cloud droplets and ice crystals are smaller that snow 
grains. As such they are likely to absorb less radiation than the larger grains.

The difference is greatest at wavelengths where the medium is modestly absorptive ie. near 
TM5. Second, since ice and snow grains are slightly more absorptive than water in the band 1.55-
1.7µ, the snow pack will have a lower reflectance in TM5 than clouds, that are mostly composed 
of water droplets even at temperatures below 0C. The difference in the size of scatterers between 
clouds and snow, however, is more important in determining the reflectance than the difference in 
composition. Following the above it was found that the intersection of two criteria involving band 
TM5 can give a reliable classification of a pixel as snow covered.

First, R(TM5) must be less than a threshold of 0.2-0.25. Second, the 

\[ \frac{[R(TM2)-R(TM5)]}{[R(TM2)+R(TM5)]} \] – Normalized Difference Snow Index – N.D.S.I. - must be greater

than 0.4. The first criterion excludes pixels whose reflectance in band TM5 is too high. The second 
criterion rejects pixels whose reflectance in TM5 is too great when compared to their reflectance in 
TM2 ie. cloud covered pixels.

The aforementioned threshold values can be used as a first guess ; they will need to be fine-
tuned to the specific properties of the atmosphere over the site in question. Inspection of several 
satellite images at different times can also be used to specify the threshold values as a function of 
regional conditions. A point to be considered in the application of the above to the Landsat images
is that although generally speaking clouds will appear white and snow black in the TM5 band, there will be considerable variation in the snow’s `blackness’ depending on the snow age. The reason is that the reflectance of the snow is higher when it is fresh and decreases as it ages. Another point to consider is that although in the visible wavelengths (ie. TM2) snow is generally brighter than clouds because clouds are optically thinner and a lot of the incident light is transmitted through them, thick clouds can be as bright as snow. Noteworthy to be pointed out that further use of thresholds in various band-ratios allow the researcher to distinguish the water bodies from the snow covered area.

6.2 Effect of Snow Grain size\(^7\) and of absorbing impurities on reflectance estimate

6.2.1 What is the effect

Snow nature along with repeated snowfall events create a variety of different texture patterns that snow surface -top layer- may have. Going even further, snow physical properties keep changing due to the continuous metamorphosis taking place. According to these the spectral attitude of snow varies respectfully.

Grain size, liquid water and impurities are important factors influencing the visible, near- and mid-infrared reflectance of snow (0.4–3.0 µm). Increasing grain size generally decreases the near and mid-infrared reflectance (0.7–3.0 µm) (Nolin, Dozier, & Mertes, 1993) and strongest sensitivity occurs between 1.0 and 1.3 µm (Dozier, 1989). When liquid water fills the pore volume, between the snow grains, the effective grain size increases, leading to further reduced reflectance. Organic and inorganic impurities accumulating on the snow surface and within the snow cover may be considerable in forests, and the impurities strongly affect the visible reflectance (0.4–0.7 µm) of snow (Warren &Wiscombe, 1980).

This effect is enhanced when the impurities are inside the snow grains because refraction focuses the light on the absorbers. The amount of absorbing contaminants, usually dust and soot, near the surface of the snowpack increases with age therefore the effect of impurities is among the factors that contribute to the observed decrease in the snowpack reflectance with age.

\(^7\) Snow grain = the snow’s molecule - used to describe the smallest measurable part of fallen snow already fallen on the earth’s surface
The snow albedo, defined as the integrated reflectance between 0.4 and 3.0 µm, may therefore vary from 35% to 90% (Hartmann, 1994, p. 88).

6.2.2 Wavelength Sensitivity, Solar Anisotropy

In the near-IR wavelengths ice is moderately absorptive so snow reflectance is sensitive to grain size (Wiscombe and Warren, 1980) and drops with grain size. The sensitivity is greatest at wavelengths from 1.0 to 1.3 µm, a band that is not covered by the TM range. Also, the reflectance anisotropy deals with the geometric manner in which surfaces reflect radiance. Snow and trees have different anisotropic reflectance characteristics. Snow is a forward scattering reflector (Steffen, 1987), whereas trees are backward scattering reflectors (Deering, Eck, & Banerjee, 1999; Hapke, Dimucci, Nelson, & Smythe, 1996). The snow anisotropy increases with decreasing solar elevation angle but also with growing snow grains. Similarly to impurities, the observed decrease with age of the snowpack reflectance is associated to the effect of grain size; the overall tendency is for snow grain to become larger as the winter season progresses. Estimates of the grain size and the contamination amount of the snowpack can be made on the basis of the respective effect of each on the reflectance of the snowpack in bands TM1, TM2, TM4, TM5. To this purpose two indices can be calculated:

a. \[\frac{R(TM1)-R(TM2)}{R(TM1)+R(TM2)}\]

This one may serve as a contamination index, with higher values corresponding to cleaner snow. Its application however is limited to scenes where TM1 is not saturated since saturation over snow-covered scenes is frequent in TM1.

b. \[\frac{R(TM2)-R(TM4)}{R(TM2)+R(TM4)}\]

A grain size index, with higher values corresponding to larger grain sizes.

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8 Saturation or chroma is a measure of how much white is mixed with the colour. A highly saturated colour has little white whereas an unsaturated colour has a lot of white mixed in.
6.3 Seasonal Effect on Reflectance estimate

As the winter season progresses toward its end the ratio of wet to dry snow rises in the snowpack. Spring snow is often characterized by water ponds that occur when melting snow overlies an impermeable stratus of snow or when rain falls on fine-grained snow. The liquid water content of spring snow however does not exceed 6%, an amount that does not affect the radiative properties of the snowpack except in a few narrow wavelength regions (Hyvsrinen and Lammasniemi, 1987). In the near-IR wavelengths decrease in the reflectance of the snowpack is observed as snow melts, but this does not result from the different optical properties of water and ice, but from the micro-structural changes caused by the increasing amount of water. In wet, unsaturated snow there is clustering of grains in two to four-grain clusters that behave optically as large single grains, thus reducing the reflectance (Colbeck, 1986).

In radiative transfer models the range of grain radii used varies from 50 to 1000, with the 1000 radii representing spring snow. Grain clusters in coarse spring snow can be as large as 5 mm in radius. The seasonal effect of contaminating impurities has been discussed earlier. As for melt water the net effect of the rise in the level of contaminants within the snowpack with time is to reduce the reflectance in the visible wavelengths. Therefore spring snow will reflect less in the visible TM bands than fresh winter snow. Finally, a seasonal effect to consider when interpreting Landsat images is the rise in the level of image saturation from winter to spring. As a general rule for regions in the mid-latitude zone, the TM1 band usually saturates over snow during all months, except in the shadows. TM2 and TM3 will not usually saturate in December or January but will occasionally saturate in February and will frequently saturate in spring. TM4 will only occasionally saturate after new snow in spring, while bands TM5 and TM7 should never saturate over snow. The latter may saturate however, over clouds of bright soil. According to the rationale above, according to the season respective filters have to be created prior to any index calculation.

6.4 Effect of Topography on Reflectance estimate

Over alpine terrain topography causes changes in the reflectance at all wavelengths, visible and near-IR. The changes are associated with the effect of topography on the illumination angle and the shadowing that it causes from local horizons (Dozier et al, 1981a; Olyphant, 1984). Considering the above, the total irradiance in alpine regions consists of three components, the direct irradiance
from the sun, the diffuse irradiance from the sky, where a portion of it is obscured by terrain and, the irradiance (direct and diffuse) on nearby terrain, that is reflected toward the point of interest. Therefore, the total radiance at a point has considerable anisotropy associated with the geometric effects of the terrain. A digital elevation model will be needed to generate estimates of the slope and aspect of each pixel and to correct the reflectance estimates accordingly. Another point to consider is the need to adapt the snow retrieval algorithm to forest or non-forest alpine terrain. Although snow covered areas in Greek mountains tend to be situated well above the tree line a correction of the reflectance for low vegetation may be considered at a later stage. Algorithms for this purpose have been developed over boreal regions, with an estimated accuracy of 85% for forested areas with full snow coverage.

7. Settling the TESCI methodology into presence and future.

7.1 Use of the Snow Cover extent in various geophysical products.

When it comes to data output, the use of the snow cover area estimation can be used to facilitate the calculation of other indices, or improve the accuracy of certain products. According the monitoring -time needed for each product three categories can be identified:

*Short - Term*
- *Calculation of the Snow Water Equivalent (S.W.E.)*
- *High Flooding Possibility Detection during the snow melting season(in areas with dynamic streams)*

*Mid – Term*
- *Droughts detection, due to annual decrease of the SWE in addition to weather and hydrological data.*

*Long – Term*
- *Contribution in the desertification trend monitoring, cause of severe or excessive drought period in an area.*
Blending the Data Archive Created with this of the global snow cover mapping (based on NASA’s EOS Aqua and Terra Spacecraft (AMSR-E and MODIS) ) a comparison can be conducted on order to extract important differences between the global and the local climate change trend.

7.2 TESCI compatibility with the forthcoming satellite Data

The upcoming Sentinel satellite family from ESA, incorporates characteristics that enable the respective researcher to calculate the Time Equivalent Snow Cover Index (T.E.S.C.I.) with updated data - other than the Landsat archive -, therefore increasing the accuracy, the lifetime and the use of the index itself.

The 5 member family consists of:

- **Sentinel 1 – SAR Imaging**
  
  All weather, daylight applications, interferometry

- **Sentinel 2 – Superspectral imaging**
  
  Continuity of Landsat. SPOT & Vegetation-type data

- **Sentinel 3 – Ocean monitoring**
  
  Wide – swath ocean color and surface temperature sensors, altimeter

- **Sentinel 4 – Geostationary Atmospheric**
  
  Atmospheric Composition monitoring. Trans – boundary pollution

- **Sentinel 5 – Low orbit atmospheric**
  
  Atmospheric Composition monitoring

The Sentinel 2 satellite, acquaints multi spectral images with high resemblance with the Landsat imagery, therefore, allows the implementation of similar image analysis.

The big advantages provided in addition to the main users’ requirements that new satellite family intents to grand are:
- Continuity of data for user services
- Data availability – no data gaps
- Long term commitment to data provision
- Data quality e.g. resolution, radiometry compatible with existing
- User driven mission
- Respond directly and demonstrably to user requirements
- Traceability between user, mission and system requirements
- Conflict-free satellite operation for reliable access to data and exploitation of archive

According to ESA, Sentinel-2 mission aims to satisfy its user requirements in terms of data availability, coverage & revisit, timeliness and the quality of its data products.

8. Case study example

Sample Result of the first implementation of the methodology in a Greek mountainous area.

In order to calculate the Snow Cover Area using the Landsat Thematic Mapper data, Greek mountainous Area was used as a study area and the snow mapping algorithm\(^9\) was performed. The presence of many sources of inaccuracy, made the testing implementation even more realistic. During the winter is rather difficult to have a cloud free image in a mountainous area, thus making even harder to distinguish the snow and the clouds as both have similar reflection attributes. To make it even more challenging, shadows at hand with the clouds, there for had to be taken into consideration during processing. The topography, itself makes the whole image processing a testing procedure, though as the outcome demonstrates, having the elevation data, helps overcome this problem.

\(^9\) Chapter 5
It would be worthy to point out that the accuracy of the image analysis is updated continuously, embracing the newest techniques and technologies, such as Object Oriented Image Analysis, Weather Radars’ Data etc, in the algorithm’s development and evaluation.

On the pictures bellow you can see the Red marked area on the western part of Greece, on the Pindos mountain range before and after the image processing.

The snow was calculated to be less than 1.8 % of the study area (6644p / 370032p of the image – meaning that the snow cover area was 5,97 km²) and it was fully melt within 5 months. The T.E.S.C.I. calculation is $5.97 \times 150 = 895.5$.

According to this, having a series of this index calculated, will promote the trend of the snow coverage towards the time, and therefore enhance the tendency of local - and in extension global - climate status, for there is a great connection between them

"Snow cover exerts a greater influence on the Earth's energy exchange than any other land surface characteristic"\(^{10}\).

- Richard Armstrong, NSIDC Senior Scientist

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\(^{10}\) [http://nsidc.org/noaa/search/indicators/snowcover_index.html](http://nsidc.org/noaa/search/indicators/snowcover_index.html) / 05-10-2008
Image 2. Initial Data

Image 3. Result - Highlighted Blue is the Snow

Image 4. Result - Zoom In
To final step of the procedure is to collect the snow cover area data for a certain period of time and calculate T.E.S.C.I. for each year of this period. As an example using random number generator, the following results were produced (for demonstration purposes only).

<table>
<thead>
<tr>
<th>Snow Covered Area (sq.km.)</th>
<th>Days to complete Melting</th>
<th>T.E.S.C.I.</th>
<th>Normalized T.E.S.C.I.</th>
</tr>
</thead>
<tbody>
<tr>
<td>65,75935104</td>
<td>306</td>
<td>20122,36</td>
<td>55,12975731</td>
</tr>
<tr>
<td>96,66025847</td>
<td>26</td>
<td>2513,167</td>
<td>6,885388275</td>
</tr>
<tr>
<td>10,28500347</td>
<td>145</td>
<td>1491,326</td>
<td>4,085823297</td>
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<td>4758,418</td>
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<td>352</td>
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<td>0,678146078</td>
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<td>18,4517471</td>
</tr>
<tr>
<td>61,52321534</td>
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<td>17,02423219</td>
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<tr>
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<td>214</td>
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<tr>
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<td>12187,85</td>
<td>33,39137592</td>
</tr>
<tr>
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<td>196</td>
<td>11011</td>
<td>30,1671289</td>
</tr>
<tr>
<td>97,48033164</td>
<td>109</td>
<td>10625,36</td>
<td>29,11056479</td>
</tr>
<tr>
<td>50,23544888</td>
<td>285</td>
<td>14317,1</td>
<td>39,22493954</td>
</tr>
</tbody>
</table>
42,85256895  154  6599,296  18,08026197
8,7792848  236  2071,911  5,676469076
71,18047701  70  4982,633  13,65105039
28,96147763  339  9817,941  26,89846826

This is the histogram occurred from the random data generated. The result is expected to be far more homogenous than this diagram, though it gives the sense of the kind of the result that will be produced.
9. CONCLUSIONS AND RECOMMENDATIONS

The methodology to study climate and climate change varies significantly from a methodology that approaches a natural hazard itself. In the second case the event describes the need on Earth observation data and the final EO product or service is very complicated in determination and process and consists of remote sensing, in situ and other data, modeling data, geodetic positioning data, navigation data and telecomm efficiency. Another important difference is that in climate and climate change, we study widespread areas while in real time needs a much smaller area is to be analyzed.

Two important considerations/recommendations can be formulated: First, the continuity of standardized climate monitoring products has to be ensured. Secondly, it is important that the end-products be taken already into account at Instrument Design level. This approach will ensure the highest users return.

In studying the climate however, we pay attention to:

- Parameters resulting from weather systems like temperature, rain, snow, winds in a given time sequence second
- Frequency of specific natural events (number of Hurricanes in the US or Severe Thunderstorms in Athens per year).

This differentiation to the approach needed between the near real time needs and the tactical & continuous needs such as climate and climate change differentiates also the philosophy of studying climate. In general three very important prerequisites should apply:

1. Agreement and documentation on international level on the climate indexes used to describe a parameter (including metadata and standardization of the definitions).
2. Long time series of data used for the estimation of the climatic indexes
3. Compatibility of future raw data with existing and archived data in order to produce the same climate indexes with better precision.

Discussing the three prerequisites for the present situation in EUROPE’s Earth Observation Programmes (ESA and, EU) it is obvious that the 1st prerequisite does not apply. We discuss and decide on satellite missions for the cryosphere and land cover but we are not moving forward into agreements for methodologies, procedures and quality assurance in the production for specific parameters used for climate indexes. This extra work and cost stays usually as a burden within ESA member states because they have different needs in real time needs (different kind and frequency of natural disasters).

However climate and climate change is not a local but European and Global issue in which ESA, EU and member states should be focused also in the parameters describing climate taking into account in their programmatic planning the question: Is a proposed satellite sensor useful in providing continuously (for climate this means at least monthly) specific parameter used to produce a specific climate index. Is this index documented and agreed in international level (prerequisites 1 and 3).
Parameters describing climate and climate change have to follow international standards regarding time frame of reference (30 years series with 10 years intervals and at least monthly values). This implies that long term satellite image archives should be used in order to provide answers for the first prerequisite. This extra work is needed to assure that planning and programmatic for future sensors is also based on the knowledge relevant to the parameters produced from the future satellite data in order to study climate and climate change where we do not need only 2, 5 or 10 years or satellite data but 30. The time frame for an Earth Observation Satellite is maximum 10 years but the minimum timeframe to study climate is 30 years. A general recommendation is that ESA should provide end users and research community with archived data and coordination resources in order to develop studies for climate- climate change parameter oriented standards and methodologies.

In this study we discussed climate and climate change standards for the study of snow cover as climate index. A variety of sensors were evaluated along with data availability and costs, in order to find the most suitable one (or more) for this application. Having in mind what the climate monitoring dictates, a 20 - 30 year archive of the data is needed, and therefore our options were significantly narrowed. Having in mind also the area of the future implementation of the pilot program, high image resolution is desired, and while snow is the main item of the analysis, IR bands is proved to be necessary. Landsat is what we think will provide us with the best and more efficient data on order to start creating the first Greek Snow Cover Maps Library. It goes without saying that this is nothing but the first step of our approach, as sensors like SAR or Hyperion can considerably improve this product and move it to the next level.

In the first experiment parameters such as: snow-cloud discrimination, grain size, seasonal effect and local topography were taking in to account but many other may be added in the long process of the survey. The subsequent table sums up the steps of the snow mapping process.

<table>
<thead>
<tr>
<th>Snow-Cloud Discrimination</th>
<th>[\frac{[R(TM2) - R(TM5)]}{[R(TM2) + R(TM5)]} ] – Normalized Difference Snow Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect of Snow Grain size(^{11}) and of absorbing impurities on reflectance estimate</td>
<td>a. [\frac{[R(TM1) - R(TM2)]}{[R(TM1) + R(TM2)]}] (\rightarrow) contamination index</td>
</tr>
<tr>
<td></td>
<td>B. [\frac{[R(TM2) - R(TM4)]}{[R(TM2) + R(TM4)]}] (\rightarrow) grain size index</td>
</tr>
<tr>
<td>Seasonal Effect on Reflectance estimate</td>
<td>Filters to prevent saturation of the image</td>
</tr>
<tr>
<td>Effect of Topography on Reflectance</td>
<td>Digital Elevation Model</td>
</tr>
</tbody>
</table>

\(^{11}\) Snow grain = the snow’s molecule - used to describe the smallest measurable part of fallen snow already fallen on the earth’s surface
Under the given circumstances, methodology’s simplicity is one of its major advantages. The main reason being, that as technology grows faster, new hardware equipment, and software suites, become available, thus new modifications may take place in our technique. The simplicity of this work increases the flexibility of the approach as a whole.

The lack of time series of data archives with remote sensing products suitable for climate monitoring is one of the biggest problems that must be solved for ESA to face future challenges in climate change. Despite the varying levels of information available for controlling and monitoring climatological parameters such as snow cover or sea surface temperatures the use of ESA archives is vital to enhance and validate present climate change research efforts. A general limitation for this kind of studies is the lack of sufficient data to build a detailed digital elevation model for data analysis. Another fact to be considered in the design level of future space instruments is the lack of bands in specific IR wavelength (between Landsat TM4 and TM5).

The free access and utilization of the ESA archives from its member states for the extraction of climate change monitoring parameters should follow the standardization principles of WMO for climate normal: continuous and homogeneous. This strategy is going to overcome the lack of harmonization and interoperability of climatologic information produced from satellite data between public administrations of the member states.
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