Exercise 3 - Solution

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Question 1

Landsat Sensors

Landsat 5 carries the Multispectral Scanner (MSS) and the Thematic Mapper (TM) sensors. TM measures the outcoming top-of-the-atmosphere (TOA) radiation in bands ranging from visible to thermal infrared. More information can be found here. The thermal infrared band (band 6) can be exploited to better characterize the temperature of the Earth surface as well as the cloud tops.

Spectral Observations

Based on its spectral properties, an object will absorb, reflect and/or transmit a specific 'set' of electromagnetic waves. The interest of having space-borne sensors observing the incoming radiance at multiple spectral bands is to enable a better discrimination of atmospheric and Earth surface features. Visible bands measure the solar irradiance reflected by the Earth surface features, and are therefore only useful during daytime. The thermal infrared bands record the radiation emitted by objects at temperatures typically encountered at the Earth surface, which can be related to their temperature.

IR Atmospheric Window

The electromagnetic waves emitted at the Earth surface travel through the atmosphere before being sensed by space-borne sensors. Absorption and re-emission of electromagnetic waves occurring along this path can dampen/modulate the signal measured by satellite instruments. At short infrared bands, most of the Earth surface emitted IR radiation is absorbed and/or re-emitted by gaseous particles such CO2, H2O and O3 as well as clouds. In order to exploit IR wavelengths to characterize the Earth surface temperature, it is necessary to sense the incoming radiation (from clear-sky) with spectral bands around 12 μm (TM band 6). This region of the electromagnetic spectrum is called the 'IR atmospheric window' and is characterized by a low absorption (attenuation) of IR radiation in the atmosphere. Therefore the signal emitted by the Earth surface arrives almost unattenuated at the space-borne sensors and can be used to estimate the Earth surface temperature.

Question 2

Here we describe some common normalized difference indices (NDIs). Since some Earth surfaces have similar spectral signatures, multiple NDI(s) or spectral bands are often required for an accurate landscape identification. A more comprehensive list of NDIs can be found here. Note that all NDIs have values between -1 and +1.

NDSI = Normalised Difference Snow Index

NDSI makes use of the green and SWIR bands. NDSI is used to distinguish snow from clouds and other Earth surface features. While clouds are rather reflective at both green and SWIR wavelengths, the snow accumulated on the ground has a much lower reflectance in the SWIR band. Hence clouds have a small NDSI and snow has a larger NDSI. A shortcoming of the NDSI is that it can often not properly discriminate cold water from snow.

Typical cloud/snow thresholds are:
low confidence: NDSI ≥ 0.4
medium confidence: NDSI ≥ 0.5
high confidence: NDSI ≥ 0.6

Landsat 4-7 NDSI = (B02:G – B05:SWIR) / (B02:G + B05:SWIR)
Landsat 8 NDSI = (B03:G – B06:SWIR) / (B03:G + B06:SWIR)
Sentinel2 NDSI = (B03:G – B11:SWIR) / (B03:G + B11:SWIR)

NDVI = Normalised Difference Vegetation Index

NDVI is a numerical indicator that is associated with vegetation content. High NDVI values correspond to areas that reflect more in the near-infrared spectrum. Higher reflectance in the near-infrared corresponds to denser and healthier vegetation. The chlorophyll pigment in a healthy plant absorbs visible red light, while the cell structure of a plant reflects near-infrared light. Areas with high photosyntheic activity and hence high vegetation cover will have small reflectance in the red band and large reflectance in the near-infrared. This leads to a high NDVI.

A shortcoming of the NDVI is a 'saturation' at the end of the growing season (further increases in plant health or abundance lead to only small changes in NDVI) which leads to a decrease in sensitivity.

Landsat 4-7 NDVI = (B04:NIR - B03:R)/(B04:NIR + B03:R)
Landsat 8 NDVI = (B05:NIR - B04:R)/(B05:NIR + B04:R)
Sentinel 2 NDVI = (B08:NIR - B04:R)/(B08:NIR + B04:R)

NDMI = Normalised Difference Moisture Index

The NDMI detects moisture levels in vegetation using a combination of near-infrared (NIR) and short-wave infrared (SWIR) spectral bands. It is used to detect water stress in crops.

The SWIR is sensitive to the vegetation water content and the mesophyll structure of leaves. The NIR detects the bright reflectance off the leaf internal structure and leaf dry matter content. Short wave infrared response (SWIR) is highly associated with changes in vegetation water content and the spongy mesophyll structure in the vegetation canopies. Dry conditions are indicated by a NDMI approaching -1, whereas waterlogged conditions are indicated by values approaching +1.

A shortcoming of the NDMI is that damages to the plant canopy and mesophyll structure can be caused by factors other than water shortages. Therefore a low NDMI may not always indicate a low water availability.

Landsat 4-7 NDMI = (B04:NIR - B05:SWIR)/(B04:NIR + B05:SWIR)
Landsat 8 NDMI =(B05:NIR - B06:SWIR)/(B05:NIR + B06:SWIR)
Sentinel 2 NDMI = (B08:NIR - B11:SWIR)/(B08:NIR + B11:SWIR)

NDWI = Normalised Difference Water Index

The Normalized Difference Water Index (NDWI) is used to highlight open water features in a satellite image. It uses the difference between visible green wavelengths and near infrared (NIR). Water has a high reflectance in the visible green and a low reflectance of NIR. Soil has a similar reflectance in the green and NIR bands. Therefore water bodies have a positive NDWI and soil and vegetation have a low or negative NDWI.

Typical ranges used to distinguish features using the NDWI are
0.2 – 1 : Water surface
0.0 – 0.2 : Flooding, humidity
-0.3 – 0.0 : Moderate drought, non-aqueous surfaces
-1 – -0.3 : Drought, non-aqueous surfaces

A shortcoming of the NDWI is that it sometimes detects built structures., which can lead to overestimation of water body sizes.

Landsat 4-7 NDWI = (B02:G - B04:NIR)/(B02:G + B04:NIR)
Landsat 8 NDWI =(B03:G - B05:NIR)/(B03:G + B05:NIR)
Sentinel 2 NDWI = (B03:G - B08:NIR)/(B03:G + B08:NIR)

Question 3

To estimate the area covered by snow/ice, one should use bands or combinations of bands which allow the differentiation of snow/ice from other surface and atmospheric features. We can use the spectral properties of snow and ice to choose bands which may be good for this. For example, while snow tends to reflect waves in the visible part of the electromagnetic spectrum, it has a greater absorption at IR wavelengths. Hence, indices based on those wavelengths can be used as a first step to separate snow/ice from other elements. Then, one can use the index value and set a threshold on this value to define the range of value associated to snow/ice.

Index-based Detection

An index-based solution, e.g. the NDSI, can isolate snow and ice surfaces very well. However, to additionally remove water bodies, either a second index (NDWI) or another band (e.g. green band) may be used.

Detection Using the Thermal Band

The thermal band alone is insufficient, as it does not differentiate cold clouds from ice or snow. Additionally, in summer the glaciers are covered by debris, which allows the surface temperature to rise above 0°C. As we are looking at summer images, the glacier and snow surfaces are nonetheless significantly colder than their surroundings and can be separated. However, to remove clouds, information from another band or index is necessary.

Question 4

The glacier retreated significantly between 1995 and 2018. The monitoring of the glacier area can be influenced by the presence of snow cover and clouds. For this reason, the images analyzed were selected at the end of the summer, during cloud-free days and with the absence of snow cover at the ground. To investigate the slow retreat of glaciers, it is sufficient to acquire an image in late summer without clouds and snow once a year. As a consequence, the revisit times of Landsat are appropriate.

Question 5

The glacier area can be estimated using a raster or vector based approach. For the raster approach, first crop the available images to the area of interest, then calculate the NDSI with the raster calculator. For the years 1994 and 2005, the NDSI is computed using the band 2 and band 5 from Landsat 5. For the year 2018, the NDSI is computed using the band 3 and band 6 from Landsat 8. The snow and ice cover is obtained by imposing the condition of NDSI >0.6 and NDSI ≤ 1 in the raster calculator. The lower threshold value might change a bit depending on the user and the identified best NDSI threshold value. This results in a binary image, where snow/ice pixels have the value 1.

By computing the histogram of this image (zonal histogram), the number of snow pixels is obtained. Using the number of snow pixels (value = 1) and non-snow pixels (value = 0) and knowing the total area of the AOI polygon, one can first compute the proportions of snow pixels and non-snow pixels in the AOI polygon and then the corresponding glacier area.

Another option is to vectorize the binary layer and compute the total area of the polygons representing the snow/ice surfaces. The glacier extent area estimates can vary based on the selected thresholds and methods. Indicatively, these are some meaningful values:

- 1994: 1.91 km^2
- 2005: 1.49 km^2 (-22% compared to 1994)
- 2018: 0.64 km^2 (-67% compared to 1994)

Question 6

The NDSI is the most appropriate index to visually discriminate clouds from the rest of the image. The Sentinel2 NDSI formula is:

NDSI = (Band 3 (green) – Band 11 (SWIR)) / (Band 3 (green) + Band 11 (SWIR))

While the clouds are rather reflective at both green and SWIR wavelengths, the snow does reflect the green band but it has a low reflectance in the SWIR band. This makes the NDSI an effective index to visually separate clouds from snow. Regarding NDWI and NDVI, which use respectively green/NIR and NIR/red band couples, they appear less effective in identifying clouds. Indeed, such band combinations lead to lower differences of reflectance between snow and clouds (at NIR wavelength the reflectance difference between snow and cloud is not very significant).

Question 7

Appropriate Range

The lower and upper bound NDSI values of the range corresponding to clouds are respectively about 0 and 0.5 (with some variability around those depending on location).

Limitations of Segmentation Method

Such a segmentation based on the identification of 2 threshold values has several limitations:

- Pixels with NDSI index values that fall within this range do not necessarily correspond to clouds. Indeed some other features might have similar index value but do not correspond to clouds.
- Segmentation based on visual aspect is 'subjective' and varies depending on the practitioner.
- Depending on the atmospheric conditions, the atmosphere can impact the propagation of electromagnetic waves differently. Hence, such interval might need to be re-evaluated if images are acquired under different atmospheric conditions.
- Depending on the type of clouds, the NDSI value is not the same.

Question 8

Composite Image Advantages

While the normalized difference indices condense the information of 2 different bands into 1 single continuous indicator, the image composite preserves all the information from the 3 initial bands in the final image by placing each band into a specific channel of the RGB image. This gives a higher granularity of the information and hence more possibilities to represent different features of the image through different color combinations.

Differences in the Composite Images

Based on the composite images, the following differences can be observed between the two Sentinel-2 acquisitions:

- On the 19th January 2023 acquisition, almost no clouds are observed over Switzerland. Some cloud layers (appearing in white in this composite image) can be observed over France (West and North-West of Switzerland) and over Austria (East of Switzerland). Those cloud layers are probably rather thin as some of the ground surface can be observed through the cloud layers, especially over France. This acquisition probably follows a recent snow event as snow is present over the whole Swiss territory, also in the plains.

- On the 8th February acquisition, the meteorological situation is very different. A rather thick cloud layer can be observed over the Plateau and Jura regions of Switzerland. Snow is still covering the Swiss mountains, but no snow cover is left in the visible plains and valleys bottom (e.g. the Rhone valley in Wallis).

Question 9

- **Clouds** appear bright white because they tend to reflect the red as well as the SWIR 1 and SWIR 2 bands. This leads to rather high reflective values in all 3 RGB channels of the image composite.

- **Snow** appears in bright red because it is highly reflective to the red band but it absorbs both SWIR bands. This leads to rather high reflective values in the the R channel of the image composite, but low reflective values in the G and B channels.

- **Water bodies** appear dark because none of the red nor SWIR bands are reflected. This leads to rather low reflective values in all 3 RGB channels of the image composite.