WV-2 data pre-processing

WV-2 satellite imagery corrections for internal sensor geometry, optical distortions, scan distortions, line-rate variations and band registration were already performed by the data provider []. In case of the radiometric correction, WV-2 products were delivered as radiometrically corrected digital numbers (DN) ($q_{\text{Pixel,Band}}$) [2]. The calibration information in a metadata file (.XML) of the WV-2 imagery was used to calibrate WV-2 by applying the WV-2 calibration utility (ENVI 5). We followed three steps in processing the image. Step 1 involves conversion from radiometrically-corrected digital counts (16-bit products) into spectral radiance (μWcm^{-1}sr^{-1}nm^{-1}) using the following equation:

$$L_{\lambda_{\text{Pixel, Band}}} = \frac{K_{\text{Band}} \cdot q_{\text{Pixel, Band}}}{\Delta\lambda_{\text{Band}}} \tag{S1}$$

where $L_{\lambda\text{Pixel, Band}}$ is the TOA radiance or spectral radiance (μWcm^{-1}sr^{-1}nm^{-1}) of the pixel at the given band, K_{Band} is the absolute radiometric calibration factor (μWcm^{-1}sr^{-1}count^{-1}) for the band, $q_{\text{Pixel, Band}}$ is the DN of the pixel at the band and $\Delta\lambda_{\text{ Band}}$ is the effective bandwidth of the band (nm). In the second step, spectral radiance was converted to TOA reflectance by using the equation [2]:

$$\rho_{\lambda_{\text{Pixel, Band}}} = \frac{L_{\lambda_{\text{Pixel, Band}}} . d_{ES}^2 . \pi}{Esun_{\lambda_{\text{Band}}} . \cos(\theta_s)} \tag{S2}$$

where $L_{\lambda\text{Pixel, Band}}$ is TOA band-averaged spectral radiance, d_{ES} is the Earth-Sun distance in astronomical units (AU) during the image acquisition, $Esun_{\lambda\text{ Band}}$ is the band-averaged solar spectral irradiance (Wm$^{-2}\mu$m^{-1}) normal to the surface being illuminated, and θ_s is the solar zenith angle (in degrees) during the image acquisition. The sun-earth distance is calculated based on the Julian Day of the image acquisition and the zenith angle can be obtained from the image's metadata.

In the final step, TOA reflectance was converted to at-surface reflectance by using the physics-based ATmospheric and Topographic CORrection version 3 package (ATCOR-3) algorithm [3]. The ATCOR-3 (**Supplementary Figure S3**) algorithm, which is available as a module within ERDAS Imagine 2014 (written by Hexagon Geospatial) and Geomatica 2014 (written by PCI Geomatics) image analysis software, utilizes sensor orientation data and the MODTRAN-4 (MODerate spectral resolution atmospheric TRANsmittance) radiative transfer model [4]. Here, ATCOR-3 was used for atmospheric correction of the WV-2 imageries. We used a DEM of the SO region constructed by the synergistic merging of ground-based GPS measurements, Cartosat-1 based photogrammetric DEM, and RAMP based point elevation dataset [5]. Model parameters used for ATCOR-3 processing of the WV-2 image are summarized in **Supplementary Table S2**. Based upon MODTRAN-4 code [4], ATCOR-3 has an option to treat the atmosphere thickness over the scene as homogeneous, and is capable of handling horizontally varying optical depths and contains a statistical haze removal algorithm. This feature was applied because external (*in situ*) atmospheric data were not available. Ortho-rectified and geo-referenced WV-2 imageries were used, as the ATCOR-3 calculates the topographic correction depending on an accurate fit between the DEM and the imagery.

Mathematical expressions:

NDBI Threshold definition:
The threshold technique can be expressed as;

$$T = T\,[\text{x, y}, p(x, y), f(x, y)], \tag{S3}$$

where T is the threshold (Tmax or Tmin) value; x, y are the coordinates of the threshold value point; $P(x, y)$ is the probability distribution of the pixel located in the x^{th} column and y^{th} row of the NDBI image and $f(x,$

y) is the value of the pixel located in the *x*th column and *y*th row of the NDBI image. The threshold image *g(x, y)* can be defined as:

$$g(x, y) = 1, \text{ if } f(x, y) > T$$
$$= 1, \text{ if } f(x, y) \leq T \quad \text{(S4)}$$

Based on this procedure, we defined the upper limit (Tmax) and lower limit (Tmin) of the threshold T to define the threshold range (Tmin-Tmax). The threshold range (Tmin-Tmax) was empirically defined by repeat observation or manually scrutinizing the most obvious blue ice patches on the NDBI images confirmed by ground truth data. Pixels having a NDBI value ranging between Tmin-Tmax were coded as 1 (target vegetated pixels); pixels with a NDBI value outside the Tmin-Tmax range were coded as 0 (non-target class pixels). After classifying the image based on each customized NDBI, the semi-automatically extracted blue ice patches were vectorized to calculate the area.

Mathematically, RMSE is expressed as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Ar_i - Am_i)^2} \quad \text{(S5)}$$

where Am_i is the i^{th} original blue ice area measured using the semi-automatic extraction method, Ar_i is the corresponding value on the reference surface (reference blue ice map), and n is the number of tiles, corresponding to the sample size of the dataset.

The bias represents the error in total blue ice area extraction performed using various pixel-based methods. In general, total bias represents the total misclassified blue ice area. Bias for each extracted tile is defined as:

$$\text{Bias} = A_{\text{reference}} - A_{\text{measured}} \quad \text{(S6)}$$

where, $A_{\text{reference}}$ is the area of blue ice obtained from manually digitized ground reference data, A_{measured} is the area of blue ice calculated from semi-automatic extraction method. A positive (negative) bias value indicates an average amount of underestimation (overestimation) in the blue ice area. Bias values were expressed in percentage.

For any semi-automatic extraction method, total misclassified area (m^2) can be calculated by summation of all absolute bias values (independent of positive or negative sign) for 12 tiles, as follows:

$$\text{Total misclassified area } (m^2) = \sum_{1}^{12} |\text{Bias}| \quad \text{(S7)}$$

where, |Bias| is the absolute values of bias (m^2) for all the 12 tiles for a particular semi-automatic extraction method under consideration. The total misclassified area, overestimated area, and underestimated area can also be expressed in terms of percentage, as follows:

$$\text{Total misclassified area } (\%) = \frac{\sum_{1}^{12} |\text{Bias}|}{\sum_{1}^{36} A_{\text{reference}}} \times 100 \quad \text{(S8)}$$

$$\text{Total underestimated area } (\%) = \frac{\sum \text{Positive Bias}}{\sum_{1}^{12} A_{\text{reference}}} \times 100 \quad \text{(S9)}$$

$$\text{Total overestimated area } (\%) = \frac{\sum |\text{Negative Bias}|}{\sum_{1}^{12} A_{\text{reference}}} \times 100 \quad \text{(S10)}$$

where, $\sum_{1}^{12} A_{\text{reference}}$ is the summation of areas obtained from ground reference data for 12 tiles, $\sum$ Positive Bias is the summation of all positive bias values (out of 12 tiles) produced by semi-automatic extraction method, and $\sum$ |Negative Bias| is the summation of absolute (positive) values of all the negative biases produced by semi-automatic extraction method.

Additional discussion points:

5.11. Performance of blue ice mapping methods in terms of computational processing time

The mean processing time needed to map BIRs from one tile (mean area 201,831 m^2) of the study region using the 16 mapping methods varied from 2 to 30 min (excluding pre-processing and pansharpening) using an HP Z840 computer [RAM: 512 MB, Processor: Intel® Xeon® CPU E5-2650 v3 @ 2.30 GHz, OS: Windows 10]. The total time required for digitizing one tile was around 4 days (8 hours per day) including quality assessments and post-digitization corrections. In terms of computation resources and processing, the customized NDBI approach produced results using minimal time (average c. 5 min) compared to the other three approaches (TD, 10 to 14 min; SP, 13 to 20 min; PSC, 25 to 30 min) (**Supplementary Table S5)**. For an operational blue ice mapping application for the entire Antarctic continent, processing performance should be enhanced using high performance supercomputing and parallel processing.

5.12. Seasonal effects

Performance of blue ice mapping methods can be affected by both surface melting and snowfall, with melting accelerating as summer progresses [6]. The reduced BIR extent derived in the present study compared to previous MODIS/Landsat based estimates can be attributed to seasonal snow cover changes. Scambos et al. [7] determined that seasonal winter snow cover reduces BIR area estimates significantly prior to December and after about February 10th, depending on the year. In the current study, the choice of WV-2 imagery acquired on 5th February 2012 was intended to minimize the uncertainty due to snow cover. We emphasize that mid-summer maximum BIR extent in future studies should be based on images acquired at the appropriate time of season.

5.13. Errors associated with temporal differences between image acquisition and ground survey data

In this study, ground-truthing was conducted during several austral summer periods (December to March) between 2011 and 2015, and the WV-2 image was acquired on 5th February 2012. Therefore, there are both inter- and intra-seasonal timing differences between the mapping using WV-2 and the ground surveys. These clearly have potential to introduce some error into the analyses. We recognize that this is a likely minor but unquantifiable source of error. For future studies to account for temporal changes in blue ice extent over the short summer season, we suggest that multiple WV-2 images should be acquired between December and March to give certainty of any temporal changes in blue ice extent. Combining more detailed ground-truthing data, real-time VHR data acquisition and the use of high-performance feature extraction methods will underpin the provision of accurate information on blue ice extent and spatiotemporal changes therein in future.

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