Original Research

Normalized Difference Vegetative Index-related Assessment for Climate Change Impact on Indigenous Communities from High Resolution IKONOS Satellite Imagery in West Papua

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Abstract

High-resolution satellite imagery permits acquisition of critical data to observe climate-change and environmental impact on conflict-impacted indigenous communities with co-existing socio-economic factors, often within unstable regimes. Conflict may prevent direct access in remote regions to validate civilian conflict actor evidence. In such cases use of remote sensing tools, techniques, and data are extremely important. Software-based imagery assessment can quantify radiometrically calibrated or Normalized Difference Vegetation Index (NDVI) and provide temporal changes with rapid detection over large search areas. In this work we evaluate recent trends in equatorial alpine glacier ablation to address the probability of indigenous water scarcity, as pure glacial water reserves are depleted near the Grasberg gold and copper mine in the Carstenz region, Western part of Papua Island, North of Oceania.

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Keywords

Normalized difference vegetation index; temporal change; indigenous communities' climate change impact

1. Introduction

The global security landscape is changing rapidly, influenced by geopolitical and ideological shifts, with increasing survival pressures on indigenous ethnic actors on the fringes of society. Understanding the driving factors and dynamics behind vulnerable communities may help solve disagreements and prevent armed conflict. Today satellite imagery provides us with the unprecedented ability to monitor a wide range of man-made and natural land cover activities in high resolution from space-based platforms. Our recent engineering market survey for Airbus of upstream and downstream satellite-based imaging requirements from 90 key military and civilian stakeholders highlighted the moderate but growing dependence on high resolution optical and Synthetic Aperture Radar (SAR) [1] for both man-made and natural humanitarian disasters. We also presented the importance of space exploitation to the UK Government [2].

This ability allows various state and non-state actors, often Non-Governmental Organisations (NGOs), to monitor isolated regions with climate significance, or are at risk of climate security destabilisation [3]. This work looks at mining activities in a poorly documented region [4], and follows previous government-indigenous communities conflict studies including: Southern Sudan, and Zimbabwe [5, 6]. As one of the first researchers to gain access to high resolution satellite imagery awards from the GeoEye Foundation after 2003 for indigenous community studies, we developed a customer-driven 'image change' method, used by NGOs and humanitarian media-relations to meet user needs.

Very few maps or similar data are available in such areas due to their inherent inaccessibility. Due to ongoing conflict near Grasberg, West Papua between government forces, mining staff, and indigenous tribes seeking re-independence from directly imposed Indonesian rule, ground measurement and glacial monitoring is dangerous, as evidenced by the deaths of Papuans, including Kelly Kwalik who was killed close to the Tembagapura mine complex the day before our Papuan imagery press release [8], as well as tourists and journalists [7]. Tembagapura is the biggest and highest copper mine in the world, whose rim is 4270 metres above sea level, and the region of our study. Kwalik's death heightened existing tensions in the region. Prior to his death, he advocated passive resistance to tribal homeland occupation by Indonesian military forces. The accelerated rate of mine and infrastructure development and consequent environmental destruction adds to rising tension. Such volatile situations make satellite imaging the safest route to obtaining data for analysis of civilian actor resource access, tropical glaciers, and mine workings for regional issues impacting remote indigenous communities. Satellite imaging has led the market, but there is increasing use of Unmanned Aerial Vehicle platforms in isolated areas, due to operational flexibility, with reduced costs when compared with satellite imagery [9]. Because of the area's remoteness and persistent cloud cover, available aerial photography of the Irian Jaya glaciers is limited. Before 1975, the only vertical aerial photographs of the Puncak Jaya glaciers were obtained in 1942 during an aerial survey using a USAF trimetrogon military camera. More recently medium altitude (up to 11.5 km) vertical

aerial photographs of the region were obtained from several combined Indonesian and Australian military mapping operations (1976 – 1981), producing a few useful images, due to the high number of partly cloudy and overcast days per year [10]. However, at the turn of the millennium, with legislation permitting development of high resolution civilian satellite imaging systems in the West, combined with declassification of existing military satellite data that high-resolution now provides the detail required to look for changes in small equatorial glaciers. Even with the launch of Landsat 7 (1999), at the time of our imagery demand, Landsat 7 provided insufficient resolution for our requirements (15m panchromatic band 8 spatial resolution).

However, developments in SAR will largely supersede optical based camera system use by the mid-2020s [11] significantly increasing opportunities for high resolution satellite imaging. Recorded tropical mountain glacier retreat can supplement the instrument record of tropical tropospheric climate change monitoring because they have receded drastically since the late 1800s. Tropical glaciers exist in three regions: the Andes, the East African highlands, and Western New Guinea [12]. As glaciers have almost universally receded, this fact strongly suggests this is a global wide phenomenon, quantified in a comprehensive study of global glaciers [13]. Global observation favours atmospheric warming as the primary driver [14] because atmospheric moisture changes are more localised; evidence supporting this hypothesis comes from ice-core measurements conducted by Thompson [15] from glaciers on Kilimanjaro due to atmospheric warming. The frequency of present-day ground-truthing observations has increased vastly due to the international tourist trade, and rapid access to imaging through social media, generating large amounts of potential ground data collection in accessed regions. Anecdotal evidence of glacial retreat is also provided by a long history of mountaineers and climbers to the region [16].

In Papua, analysis of climate forcing of the 20th Century glacier recession, however, has been hindered by a lack of field studies on the glaciers. This is due to recent conflict restricted access, as well as physical inaccessibility- mountainous terrain, extreme persistent cloud conditions, high altitude etc. In fact our *Pleaid* 2015 data acquisition was rescheduled, even after maximising the probability of clear skies, due to cloud conditions.

1.1 Indigenous Community Study Region

Indigenous Amungme and Komoro West Papuan tribes live in close proximity to the Grasberg gold and copper mine complex (2.6 Million hectares), which impacts its delicate alpine ecosystems and glaciers. Grasberg is an important factor in the Indonesian economy. The mine and surrounding glacier region were first prospected and mapped by Dutch geologists in the 1930s, after colonial reigns of the Spanish, and British. First explored by the Portuguese (1526), it was in 1623 that Dutchman Jan Carstenz, became the first to record a snow-capped peak on the far horizon. 300 years later a British expedition penetrated the interior and confirmed a great mountain towering over the New Guinea jungles, with a people documented thoroughly in the work of Heinrich Harrer [16]. This ecological area has compromised several unique ecosystems co-located due to the mountainous region, composed of: alpine meadow, wetland and mangrove forest.

The Tembagapura mine (figure 1) is seen with tropical glaciers right, sensitive markers of immediate climate change, over the period June 2000 to June 2015 (figure 2a June 2000, figure 2b June 2015).

Figure 1 Topographical Map and Tembagapura mine.

Figure 2 a: Grasberg Gold and Copper mine, Carstenz Glacier overview June 2000 ©Ikonos imagery. b: Grasberg Gold and Copper mine, Carstenz Glacier overview June 2015 ©Pleides composite image.

In 1936 Dutch geologist Jean Jacques Dozy retrieved confirmed rich gold and copper deposits. The Grasberg gold and copper mine is operated by Rio Tinto and the Indonesian Government. In 1967 the Indonesian Government gave Freeport the right to excavate mineral wealth situated in the heartland of the Amungme, without their permission or consultation. It is estimated there is about 15B US\$ worth of gold to be excavated besides copper. In 1970 Freeport began construction of a 120 km long highway between Amamapare on the coast and the Carstenz highland plateau, to serve a new city, Tembagapura, '*copper city*.' Grasberg has been a source of great wealth for shareholders, but for local communities has impacted pure water availability. The Brisbane Catholic Justice and Peace Commission [17] described the conflict as a '*slow-motion genocide*', warning its indigenous population is at risk of becoming '*an anthropological museum exhibit of a bygone culture*.' Freeport's operation began 4270 metres above sea level, and upon completion expect to leave a 450 metre deep crater. A comprehensive report [18], stated concerns over Rio Tinto's failure

to address basic human rights, and shortcomings in environmental protection in this delicate environment, including: copper wastage, pollution, legal breaches, engineering inadequacies, habitat destruction, river tailing toxicity, and food chain contamination.

Some tribes were forcefully relocated, leaving thousands of indigenous removed from traditional farming and food gathering territories. Moving tribes to tropical lowlands brought them into contact with malarial mosquitoes for the first time, which increased mortality rates. This is compounded by the CV-19 risk, with desperate local tribesmen and illegal Indonesian gold miners potentially bringing CV-19 with them [19]. Influx of Indonesian artisanal miners is an added existential threat to Amungme and Komoro with Indonesian authorities encouraging non-indigenous settlement, with the Amungme estimated to be a minority by the year 2020 [7]. Tribes from across the region have exploited and expanded artisanal mining, causing disruption to local communities. Environment damage caused by mining has impaired the ability of local tribes, traditional owners of the gold mine site and rivers, to access clean water and food, and maintain their cultural practices. Contamination of waste in local water systems resulted in deoxygenation, killing plants and fish, and threatening concentration in the food chain. Thousands of tons of waste rock is transferred by lorry into nearby valleys where high tropical rainfall (often obscuring imaging) and erosion leads to fine materials moving downstream, releasing heavy metals into the river networks. Satellite detail allows monitoring of individual trucks (7 m × 14.6 m, width × length figure 3).

Figure 3 Imagery distinguishes crawler machinery from ore trucks © GeoEye Foundation.

1.2 Western New Guinea Alpine Glaciers

The tropical Carstenz glacier in the Papua Province (formerly Irian Jaya) is melting; 80% of the collective glacier area was reported lost between 1942 and 2000 (figure 4).

Figure 4 Meren Glacier system (after Prentice and T Kiev).

The West Meren Glacier has receded some 2.6 kilometres since first surveyed in 1936, before melting away completely sometime during the recent period 1997 – 1999 alongside the shrinking East Northwall Firn (figure 5). In Papua New Guinea, three ice domes in the Central Cordillera Range disappeared in the 1960s. Whilst, in temperate New Zealand, some 127 glaciers surveyed in the Southern Alps retreated by 38% and lost 25% of their total area since the mid-1850s; however, many of these glaciers have advanced further in recent decades, [13]. According to Thompson *et al.* (2002) [15], this is likely due to global atmospheric warming as the primary driver, because changes in *atmospheric moisture* are generally much more localised; hence the growth of some glaciers in localised regions where precipitation has increased [9]. The years 2011 - 2015 have been the warmest 5 year period on record, with many extreme weather events influenced by recent climate change. It is not surprising then that the present observed speed of glacier retreat world-wide has been correspondingly increased in the contemporary Anthropocene period. Increased rates of glacial retreat, twice the rate of a decade ago, are reported, although the contribution of man-made human warming cannot be attributed accurately. Additionally, records are almost non-existent in this region, and there is no long-term baseline of high resolution of satellite imagery to clarify the overall historic picture. However, in the past few years, researchers have noted rapid rises in meltwater and alarming glacial retreat from Greenland, to West Antarctica, and to the Himalayas [20].

Figure 5 Image Data processing Methodology Work Plan.

Seasonal climate variations on the Puncak Jaya massif are small. Monthly mean temperatures vary below 0.5°C during the year, and there appears to be no observable seasonal variation in precipitation, radiation, or cloud cover. Consequently, the net mass-balance of glaciers remains seasonally uniform, and glacier ablation occurs throughout the year below the equilibrium line, with snow accumulation occurring above the equilibrium line. Thus, the snowline elevation on equatorial glaciers should remain near the equilibrium line altitude except for short periods after heavy snow. Mass-balance measurements show an overall reduction over recent decades. The ice extent on the Puncak Jaya massif is small, but the area is one of only a few present-day, ice-covered equatorial regions. The rapid and continuous retreat of glaciers throughout the 20th Century however, indicates that the mass budget has been consistently negative. This suggests we are in the middle of a warming period of climatic change, of which glaciers are a sensitive indicator. Using a numerical model of glaciers and their dynamics [21], Molg estimated the mass budget change needed to give the observed retreat between 1850 - 1972 of over 2 km for Carstensz, and some 3 km for the Meren glaciers respectively. He showed a steady rise of the equilibrium-line elevation at a rate of 80m per century allowing the model to match the observed retreat, with the most likely explanation for the mass-balance change due regional air temperature warming of 0.6°C per century, in agreement with work by Thompson *etc. al.* [14, 15].

2. Methodology

2.1 The Grasberg Mine Complex at Tambang Terbuka

The GeoEye Foundation, a not-for-profit organisation with an imagery archive of 300 Million km² of map accurate imaging, provided us with imagery over the coordinates of the mine area (Latitude: -3.98°; Longitude: 137.10° (June 2000, June 2002) and imagery of some infrastructural developments within the tropical rain forest South of the mine (Latitude: -4.47°; Longitude: 136.83°

(June 2000, June 2008). The mine complex itself, stands at approximately 12.6 Million m² with the bored out circular core of the mine (Tambang Terbuka) standing at 1.85 Million m² (see figure 1).

2.2 Imagery Acquisition

The general methodology here uses high resolution satellite imagery to look for changes in acquired images to observe and quantify them. Original research was based on Dr Chris Lavers' *GeoEye Foundation* imagery award for civilian actor conflict research impact (now DigitalGlobe) composed of high resolution *Ikonos* satellite data (one of a select handful of UK recipients) between 2000 - 2002 [22], supplemented by further higher resolution (50 cm imagery) from the *Pleades* satellite in 2015 from an internal Plymouth University research grant. The grant was to specifically monitor decadal glacial changes impacting conflicted indigenous communities in this region, with access to lesser detailed Landsat imagery (with lower resolution by comparison with Ikonos and Pleades imagery).

2.3 Image Data Processing

IKONOS imagery from the GeoEye Foundation archive was provided geometrically rectified for chosen comparative dates, following closely a methodology developed previously for land clearance assessment in Zimbabwe [6, 23]. The necessary methodology, shown in figure 5, takes the Digital Number (DN) values recorded by the satellite's imaging sensor, in the chosen satellite bands, and converts these DN values to at sensor spectral radiance [24]. The at sensor spectral radiance is then converted to at sensor apparent reflectance. A further atmospheric correction permits calculation of actual at earth reflectance. The spectral radiance L_λ observed at the sensor aperture can be calculated from the digital number DN_λ values and using the band calibration coefficients $CalCoef_\lambda$ and the bandwidth $Bandwidth_\lambda$ values for the satellite bands with the product metadata, by the equation:

$$L_\lambda = \frac{10^4 \times DN_\lambda}{CalCoef_\lambda \times Bandwidth_\lambda} \quad (1)$$

where at-aperture radiance is equivalent to the exoatmospheric radiance.

From this planetary reflectance ρ may be obtained, defined by the equation:

$$\rho = \frac{\pi L_\lambda d^2}{E_{sun\lambda} \cos \theta_s} \quad (2)$$

where d is the day-dependent Earth-Sun distance in astronomical units, $E_{sun\lambda}$ is the mean solar exoatmospheric spectral irradiance at an Earth-Sun distance of 1 astronomical unit, and θ_s is the solar zenith angle.

However, this is an exoatmospheric correction and does not correct for atmospheric effects. So this correction may be followed by removal of atmospheric effects due to both scattering and absorption (otherwise known as the atmospheric correction), with the Second Simulation of a Satellite Signal in the Solar Spectrum- Vector (6SV) method [23-25], to provide the reflectance of pixels at the Earth's surface. The 6S Vector code enables accurate simulations of satellite observations, accounting for elevated targets, with use of anisotropic and lambertian surfaces, and

the calculation of gaseous absorption. The vector code is based on the method of successive orders of scatterings approximations.

2.4 Multispectral Land Use and Land Cover Change Detection Analysis

Landsat 7 is a multispectral satellite providing both visible and Near Infra-Red (NIR), used partly in this analysis, as well as Short Wave Infra-Red and thermal imagery, which together are used routinely to characterise urban areas, monitor land cover and land use, or manage change such as forced land clearance [6]. IKONOS 2 is also a multispectral satellite with one metre panchromatic resolution, and four 4 m bands (blue 0.42 - 0.52 microns, green 0.52 - 0.60 microns, red 0.63 - 0.69 microns, and NIR 0.76 - 0.90 microns respectively). A combination of both the IKONOS panchromatic with various 4m band combinations can provide imagery spectra *similar* to Landsat Thematic Mapper products. This methodology can also be used to quantify *visible* glacial extent, which is driven by climate change. To locate large change areas quickly for human rights and media-related analysis of conflict-related factors a pre-detection non-radiometric Matlab process was used providing output similar to the Normalized Difference Vegetative Index (NDVI) for numerous published work, and our press releases since 2009 [5, 6]. Landsat NDVI derived-products provide several indices related to leaf area, biomass or physiological function [26]. Our Ikonos 2 image outputs are similar to Landsat NDVI. For our NGO workers, and media users, often no atmospheric correction is used, and most do not use radiometric calibration. United Nations Institute for Training and Research (UNITAR <https://www.unitar.org/maps/latest-maps>), the globe's largest humanitarian satellite imagery disaster provider, does not provide NDVI images but almost exclusively annotated before/after image products. We used Ikonos NDVI-related outputs which do not require IKONOS radiometric calibration [27], based on existing Landsat methodology [28]. Comparative analysis of IKONOS, SPOT, and Enhanced Thematic Mapper Plus (ETM+) data shows slight spectral band sensitivity differences [29] thus radiometrically calibrated IKONOS NDVI is not identical to Landsat NDVI, due to these selected spectral band differences, nor radiometrically calibrated, and with IKONOS and Pleiades-1A there are fewer potential band comparisons available, see table 1.

Table 1 Satellite Spectral Band Comparison.

Spectral Bands	Landsat 7 Enhanced Thematic Mapper Plus (ETM+) Spectral range (µm)	Ikonos 2 Spectral range (µm)	Pleiades-1A Spectral range (µm)
Blue	Band 1 0.45 - 0.52 (30 m)	0.45 - 0.53 (3.2 m)	0.43 - 0.55 (2 m)
Green	Band 2 0.52 - 0.60 (30 m)	0.52 - 0.61 (3.2 m)	0.49 - 0.61 (2 m)
Red	Band 3 0.63 - 0.69 (30 m)	0.64 - 0.72 (3.2 m)	0.60 - 0.72 (2 m)
NIR	Band 4 0.77 - 0.90 (30 m)	0.76 - 0.86 (3.2 m)	0.75 - 0.95 (2 m)
NIR	Band 5 1.55 - 1.75 (30 m)	N/A	N/A
Thermal	Band 6 10.4 - 12.5 (60 m)	N/A	N/A
MIR	Band 7 2.08 - 2.35 (30 m)	N/A	N/A
PAN	Band 8 0.52 - 0.90 (15 m)	0.45 - 0.90 (0.82 m at nadir)	0.48 - 0.83 (50 cm colour sharpened)

Human rights workers, NGOs, and press representatives, are not interested in radiometric assessment, they only want to see a specific area, with key features, e.g. burned villages, newly built structures, etc., and as such use of non-radiometric assessment is legitimate, determined by user needs, and accuracy. However, in NDVI-related work, as an impact assessment factor for scientific studies of land use and land cover impacting indigenous communities, does require radiometric calibration. Images should be geometrically corrected and co-registered, for images taken on the same date, and those taken on different dates. Any useful climate perspective will require data covering several decades. Calibration provides at surface reflectance to correctly calculate vegetation products.

For large area assessment in the analysis we used Matlab software (version 2013b released September 6th, 2013, The Math Works Inc. Natick, MA USA) chosen for its wide range of digital image processing approaches. Matlab is a numerical computing environment to plot functions and data, as well as implementation of algorithms. Matlab allows wide area assessment of land cover to be achieved quickly and provides for a variety of image based signal processing approaches. In our method we designed a Matlab program to co-register before and after imagery in single or multiple bands, ensuring co-registered ortho-rectification pixel to pixel on chosen scenes. In the Matlab workspace these elements undergo matrix manipulations. The simplest analysis uses IKONOS NDVI such that after at earth reflectance calculation and atmospheric correction:

$$NDVI = \frac{(\rho_{NIR} - \rho_{Red})}{(\rho_{NIR} + \rho_{Red})} \quad (3)$$

following the method for calculation of Landsat NDVI, and is more commonly applied to vegetative land cover. NDVI has a Normalized index between modular values of 0 and 1, but is not necessarily radiometrically calibrated and is one of several possible Normalized indices used for vegetation, soil and other common surfaces [30].

As stated previously media outlets, NGOs, and collaborating human rights workers do not require NDVI, they want photographic evidence, and in some cases, driven by user requirements, images may not be at earth reflectance, nor atmosphere corrected. Market assessments might address this issue by advocating for a 'scientific and standardised radiometric approach' but our media users and workers find false colour NDVI confusing. Human rights NGOs often work with aerial or ground-based visible single band black/white imagery, and historically military aerial surveillance operations used single image comparison. It might be easier to persuade adoption of a standard black and white NDVI corrected image output to meet the expectation of their output requirement, but contain *more* detail if it is a dual-band NDVI plot. Radiometric NDVI was analysed for at aperture apparent reflectance values with IKONOS red and Near Infra-Red bands, co-registered with the NDVI workflow diagram (figure 5) and equations discussed, to yield at sensor apparent reflectance changes. Ice and agricultural changes are quite different, from the low value of the featureless ice/snow East Northwall Firn (figure 6a), consistent with workers elsewhere (<https://eos.com/ndvi/>), contrasting with the higher vegetation NIR reflection influence in our template Zimbabwe case study (figure 6b), where we also see the clearance replaced with new horticulture and roads (figure 6b). NDVI values are in the range between -1 and 1, with most of our data in the NDVI range 0 - 0.5. An appropriate atmospheric correction method (6SV) (figure 5) corrected at-aperture spectral radiance to provide Normalized NDVI for pixels at Earth's surface for our IKONOS 2 multispectral data, red

and NIR bands for at earth NDVI assessment. Normalization changes the contrast magnitude but retains any features observed previously. The Zimbabwe corrected at Earth NDVI also shows linear man-made change features (figure 6b).

Figure 6 a: left, East Wall Firn Glacier NDVI, and b: right, at Earth radiometrically calibrated Zimbabwe land clearance NDVI examples [4, 18].

3. Results and Discussion

3.1 Satellite Imagery of Nearby Tropical Glaciers

Local alpine glaciers, amongst the closest to the Equator: (Latitude: -3.9°S , Longitude: 137.1°E), are considered sensitive climate change markers, exhibiting documented retreat since the mid-19th Century. GeoEye Foundation imagery (June 2000, and June 2002) with NASA earth observatory imagery from June 2005 allowed accurate determination of glacial ice and snow over a 5-year period. The East Northwall Firn (figure 7) and Carstenz glaciers (figure 8), remnants of previously larger glaciers are shown, having changed mostly in snow cover, rather than ice cover, over the period (2000 - 2002).

Figure 7 East Northwall Firn 7a top June 2000, 7b middle June 2002 © GeoEye Foundation, 7c bottom June 2015 ©Pleides. 1:10000 (Latitude: -3.98° , Longitude: 137.10°).

Figure 8 left: 1:7500 Carstenz glacier June 2000 © GeoEye Foundation, right: June 2015 ©Pleides.

The overall area of the snowfields shows a significant reduction between 2000 and 2002, particularly for the East Northwall Firn and Carstenz, -35% and -56% respectively, determined from plotting area polygons using ARCGIS 10 software, followed by an increase of about 25% and 80%

respectively between the June 2002 and June 2005. Nevertheless, the overall trend for these and the other respective regions over the study period June 2000 – June 2002 is down (-18% and -21% decrease for East Northwall Firn and Carstenz respectively). The overall area of glacial ice shows a small change in ice cover between June 2000 and June 2002, more noticeable in the smallest ice/snowfield regions less able to withstand immediate temperature induced changes due to their mass limitation on heat capacity. The smaller ice fields show a small decrease in area, whilst the large areas show a slight uncorrelated increase, possibly due to increased precipitation. East Northwall Firn increased by 4.6% while Carstenz increased by 9%. Snow cover may be misleading in considering glacial extent, investigated in an earlier Papuan study [31]. It isn't possible to distinguish snow from ice cover in the Landsat imagery, or confirm the presence of some of the smaller regions from previous years June 2002 IKONOS imagery. It is likely that these smaller regions have melted (by June 2005), as did the larger Meren glacier between 1970 – 1990 [31]. Data must be acquired over a much longer period to look at long term climate-related reductions of tropical glacial cover.

A visual comparison of the North Wall Firn area shows that the total area of snow and ice cover present in June 2000 is reduced when compared with the June 2015 image. Visual comparison may be conducted in individual bands (but discriminates poorly with difference algorithm), but is better quantified with NDVI (dual bands). Looking at our data from Ikonos, Pleiades, and Landsat, the June 2000 East North Wall Firn extent was 1454500 m² (snow), almost entirely covering 1470228 m² (ice) in June 2000, reduced to 956800 m² (snow), *partially* covering a slightly increased area of ice (1537000 m²) in June 2002, most likely due to local increase in precipitation in accordance with the hypothesis proposed by Thompson [14], with Landsat (1195500 m²) snow covering ice in June 2005, and finally in 2015, 517,824 m² of snow (totally covering any ice, which may be present underneath as it is not visible on imagery). This provides an overall reduction of 64.4% in total snow/ice cover, when comparing 2015 cover with that observed in June 2000. Although there are many issues with trying to use high resolution data from such short time period, and without immediate ground-truthing, this data provides some variability in the end date prediction for the snow/ice cover of the East North Wall Firn, by the Fall of 2023, unless local precipitation patterns increase and tropospheric air temperature falls globally so the equilibrium line also falls.

Carstenz Glacier results Co-registered images on relevant dates show temporal changes over the period, of importance in determining ice melt and/or snow precipitation. Analysis used 1m panchromatic data, with evidence indicating changes in snow cover rather than changes in the ice field extent. Fixed boundaries at the ice edge are present in both images, with overall reduction in surface snow cover in this June 2000 - June 2002 data comparison (figure 9).

Figure 9 Carstenz glacier surface a) top left June 2000 and b) top June 2002. The discrimination of snow field change is clear, © GeoEye Foundation.

3.2 Satellite Imagery of Developments South of the Mine Complex

Development of land and river systems South of the mine (Latitude -4.47° , Longitude 136.83°) led to rapid man-made deforestation between 20th December 2000, and 11th October 2008 figure 10a (June 2000), and figure 10b (June 2008) respectively. Land cleared on the right of the river (figure 10b) along the coastal-highland highway is about 6010 m^2 , with bridges and man-made lakes created: 305, 246, 85 and 58 m^2 respectively. New square building plots, displacing recent pristine forest, are visible at about $14.6 \times 14.6 \text{ m}$ dimensions. Some buildings have been partially removed during this period. This land clearance, sadly, is not an isolated incident, but a common problem, documented in recent ESA satellite projects. ERS-1-SAR data has been used to monitor rain forest “Conversion” and land use planning. ESA’s TRULI project results, (an acronym for Tropical Rainforest and Use of Land Investigation project PP2-D11, commenced 1993), located on Borneo, 450 km upstream of the Mahakam River, set a benchmark for monitoring Indonesian tropical rain forest removal [32]. The West Papuan rainforest is also heavily impacted by illegal logging, which dramatically increased in volume due to an order of $22,653,000 \text{ m}^3$ of Merbau wood for the 2008 Beijing Summer Olympics. The scope of the logging violates Indonesian forest law and threatens the biodiversity of the rainforest, and the subsistence of indigenous farming cultures that exist, and additionally increases the likelihood of flooding during heavy rains.

Figure 10 a: June Figure. b: June 2008. © GeoEye Foundation. Highway between Amamapare on the coast and the Carstensz highland plateau.

One issue indigenous people often face is government forced land eviction, as we observed in our Zimbabwe land clearance study [4]. A second conflict-related agricultural Zimbabwe study identified roads beside minefields, lost minefield perimeter vegetation, or mixed agricultural area regeneration from remotely sensed data [33]. In another conflict-related agricultural study by Witmer (2009), he showed sudden reflectance change was associated with crops and re-vegetation associated with abandoned agricultural land on imagery separated by a minimum of 3 years [34, 35]. Witmer also examined Bosnia Herzegovina's conflict with Landsat imagery, with specific vegetation detection algorithms [36]. These approaches used in these Zimbabwe Case Studies, may be applicable in other conflicted areas. Algorithms combined with artificial Intelligence and Machine learning may provide sufficient automation and digital filtering, for space-based monitoring to provide near-real time data to international forces, NGOs, medical personnel, and human rights observers remotely located [37].

4. Summary

We provide the first high resolution visible spectra satellite imagery analysis of the Grasberg region, over a 12 years period in the brief annual June 'acquisition window' for cloud free imagery. However, until researchers are permitted back into this conflicted region, scientists, NGOs, and mountaineering tourists are at risk of attack, delaying ground-work validation of our satellite-based 'biometric' equatorial glacier ablation assessment. Further work will provide a qualitative and quantitative assessment of equatorial glacier NDVI. 'Real-time' global monitoring of such glaciers, on at least an annual basis for remaining endangered glaciers, is vital in the light of the 5th Report of the Intergovernmental Panel on Climate Change. It is important for the sake of the local populations to follow up on such high resolution satellite imagery Case Studies to look at mining and environmental issues affecting Papuan tribal communities with another set of high resolution images to address the question of whether these glaciers have at last completely ablated or not. Tropical glaciers should certainly be considered as '*canaries in the cage*', sensitive markers responding in near real-time to rapid temperature change trends and as such provide a window to look at consequent environmental impact. Societal change is likely to reflect some of the local environmental changes, such as water scarcity and deforestation, which affect the Papuan Amungme tribe.

We have used these latest technological developments to look at several regions of global concern, and quantify issues where possible. We have focused here on glacial and industrial and artisanal mining impact on the West Papuan Amungme, likely to be compounded when the glacial supply is finally exhausted post-2023.

Comparison of '*before and after*' high resolution satellite imagery provides visual evidence of changing land cover in inaccessible regions. Comparison of before and after IKONOS satellite imagery can provide evidence to corroborate altered land use: building removal, addition, and agricultural changes. Manual assessment formerly used to assess Porta Farm, Zimbabwe was time consuming [6]. We now use Matlab software to obtain large area change assessment with suitable algorithms, which provide rapid change assessment, with false colour contrast delineating manmade boundaries, e.g. fields, from natural ones, such as lake edges with various digital filters [6]. A high pass filter can also define built edges in high reflectance imagery. Suitable Matlab spectral and temporal comparisons provide radiometrically calibrated and non-radiometrically calibrated NDVI products to quantify and visualise a range of human rights-related issues.

High resolution satellite imagery provides detailed evidence supporting claims by all parties in disputed territories, isolated mining areas, indigenous tribal lands, and mines under study. We document West Papuan glacial change 2000 - 2015, consistent with established long-term retreat in glacier cover since the 1850s [15]. Matlab methods with false colour representation shows promise for glacial assessment NDVI estimation, and other change detection topics. Tropical alpine glaciers close to the Equator are considered sensitive climate change markers. Ongoing monitoring of the remaining equatorial glaciers is needed because of their important climatic implications. GeoEye Foundation and Pleiades satellite imagery (June 2000 and June 2015) allowed accurate determination of relative changes glacial ice and snow cover. The once extensive Carstenz glacier has almost completely disappeared, with dramatic ice melt between 2002 and 2015; whilst the extensive East North Wall Firn above the Meren Glacier has retreated into much smaller dispersed fragments.

By 2023 the probability of pure water scarcity will increase, with expected loss of the remnant East Northwall Firn, and Carstenz glaciers, in addition to mining tailing contamination of available indigenous water supplies.

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Author Contributions

Dr Mazower and Dr Grig provided background humanitarian research, and liaison with Papuan ground contacts. Dr Mason provided help with writing of Matlab image co-registration. Dr Lavers helped write the Matlab image co-registration software, processing of imagery, and conducted the image analysis.

Competing Interests

The authors have declared that no competing interests exist.

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