Evaluation of Remotely Sensed Nighttime Light as Complementary Data Source for Economic Indicators of Pacific Island Economies

Homer Pagkalinawan, Madhavi Pundit, Jaqueson Galimberti, and Priscille Villanueva
Economics Research and Regional Cooperation Department, Asian Development Bank

Abstract

Nighttime light (NTL) has increasingly been used in economics research for evaluating its potential as a proxy for measuring economic activity. Existing literature on the correlation of NTL with economic indicators focuses on big economies, with little work that includes Pacific Island Economies (PIEs). This study assesses the potential of remotely sensed NTL as a complementary data source of economic data in small and large PIEs. Various sources of NTL are investigated and the harmonized NTL series that combines the pioneer Defense Meteorological Satellite Program (DMSP) and newer Visible Infrared Imaging Radiometer Suite (VIIRS) is used in this study which covers 30 years from 1992 to 2021. Correlation analysis between natural log transformed sum of lights (SoL) from NTL and GDP level in terms of US dollars yields moderate to strong results for 9 out of 14 PIEs. Concentrating on areas with higher human activity such as residential and commercial buildings and built-up areas resulted in minimal improvement. However, using pixel-level values and selecting positively correlated grids generated better results. All 14 economies produced moderate to strong correlation between natural log transformed sum of lights and GDP level. Removed grids only account for about 30%, maximum, of the total number of grids providing a substantial number of remaining samples. This finding suggests that NTL can provide granular information on economic activity in the Pacific. The dataset being timely, frequent, and publicly available when compared to conventional datasets can be useful in different applications in the region.

Introduction

Nighttime light (NTL) images are satellite products based on observations of evening time illuminations on the Earth's surface. The United States Air Force first produced images by the pioneer Defense Meteorological Satellite Program (DMSP) in the 1970s and were originally intended to detect clouds at night to complement daytime weather information (Elvidge, et al 2022). As lights emanating from cities started showing up from the cloud images as a by-product of the program's original design, DMSP gave way to a new type of imagery that can be used in monitoring human activities, such as urbanization, socioeconomic activities, conflicts and disasters, and environmental changes including fisheries, energy, gas flares, and light pollution (Zhao et al, 2019).

With no long-term archives of NTL images, the earliest available images are from 1992. NTL images has become a widely used dataset in different research applications including in economics where its potential as a proxy for measuring economic activity is evaluated. Existing literature on the correlation of NTL with economic indicators either cover global scale or limited to large economies such as United States, People's Republic of China, India, and Indonesia (Sutton, Elvidge and Gosh, 2007; Ghosh, et al, 2010; Chen and Nordhaus, 2011; Henderson, Storeygard, and Weil, 2012; Yu, Shi, Huang, Cheng and Wu, 2015; Hartojo, Ikhsan, Dartanto, and Sumarto, 2022). Given the smaller land area and economic size of Pacific Islands Economies (PIEs), they are typically excluded in NTL studies on economic monitoring, except for the two biggest economies of Papua New Guinea and Fiji. Recently, World Bank (2023) published a working paper highlighting their applications on NTL in their different projects in the Pacific. They concluded that NTL has potential as complementary data source to official statistics particularly in monitoring gas industries, supporting poverty mapping exercises, and generating detailed electrification statistics.

This study is designed to further address the research gaps on NTL applications in the PIEs. With the goal of assessing the potential of remotely sensed NTL as a complementary data source of economic conditions, this research aims to complement the recent findings of World Bank (2023). In evaluating NTL's capability for monitoring economic development, this research used harmonized data from Li, Zhou, Zhao M. and Zhao, X. (2020) that combined NTL from both DMSP and VIIRS. To enhance characterization of NTL trends and its potential, additional datasets that show concentration of human presence and activities, such as building footprint and land cover, were also incorporated. Pixel-based analysis of NTL was also used to identify specific locations that are highly correlated with a country's overall economic activity.

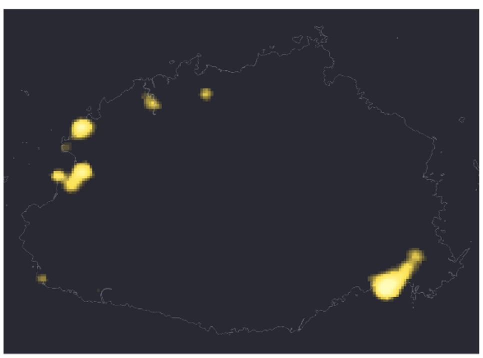
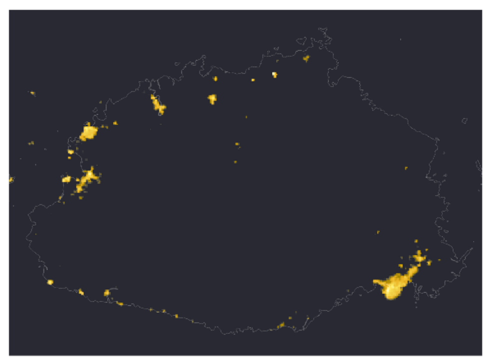
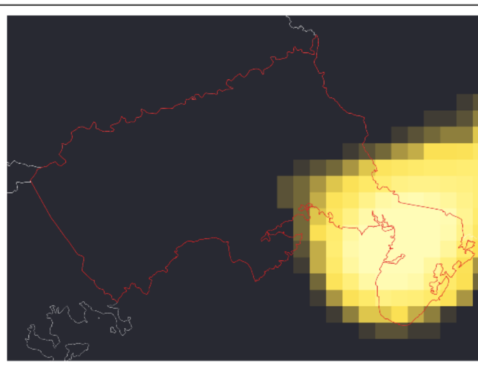
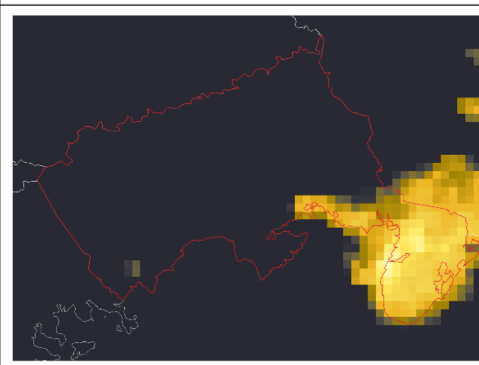
Data and Methodology

The following datasets have been compiled for this study:

Nighttime Light

Nighttime light images have two available data sources – the earlier Defense Meteorological Satellite Program (DMSP) and the more recent Visible Infrared Imaging Radiometer Suite (VIIRS). The US National Oceanographic and Atmospheric Administration (NOAA) acquires the data while several channels provide the corresponding products including NOAA and National Aeronautics and Space Administration (NASA). DMSP covers 30 arc-second grid resolution (converted to 1km x 1km grids along the equator) at an annual frequency from 1992 to 2013 while SNVIIRS has a finer resolution of 15 arc-second grid resolution (projected to 500m x 500m grids along the equator) with availability starting in 2012 at daily, monthly, and annual frequencies. Figure 1 shows a comparison between DMSP and VIIRS images that cover the Viti Levu Island in Fiji and its capital, Suva.

Figure 1. DMSP and VIIRS Nighttime Light Image for 2012

	Defense Meteorological Satellite Program	Visible Infrared Imaging Radiometer Suite
Frequency	Annual	Daily, Monthly, Annual
Resolution	1km	500m
Availability	1992 – 2013	2012 – present
Location: Viti Levu Island		
Location: Suva (boundary in red)		

Source: NOAA and Earth Observation Group

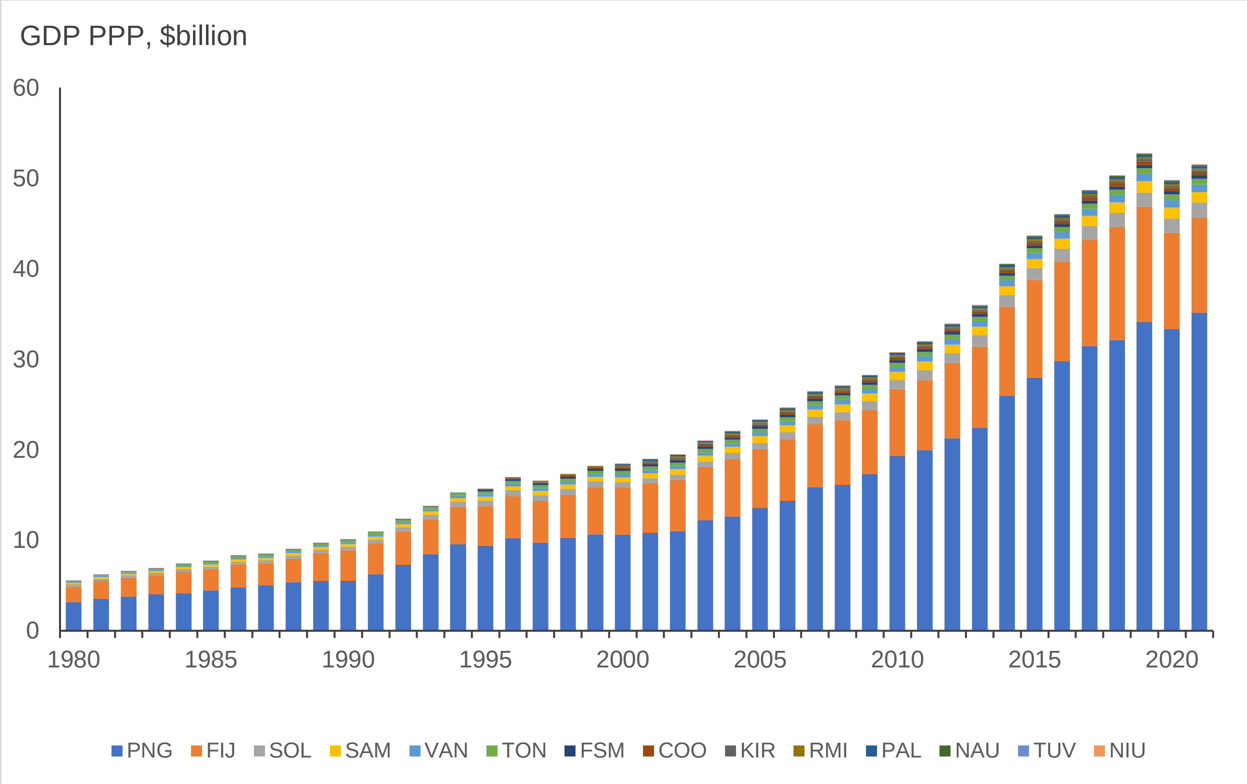
Li, Zhou, et al (2020) integrated both sources to produce a longer time series of NTL from 1992 - 2018, originally, and subsequently extended to 2021. The harmonized NTL data was based on calibrating DMSP images from 1992 to 2013 and taking its range of values to adjust VIIRS for subsequent years, albeit losing the latter's higher resolution. The process of harmonizing DMSP and VIIRS has three steps: (1) composition of monthly VIIRS data to annual equivalent, (2) conversion of annual VIIRS value to DMSP equivalent, and (3) evaluation of the resulting DMSP-like equivalent of VIIRS data across time in a global scale. Although the use of DMSP and VIIRS images were separately explored initially, the integrated and consistent dataset by Li, et al (2020) that covers 30 years was evaluated as more fit for this research's purpose, which is to monitor economic trends.

Gibson, Olivia, and Boe-Gibson (2020) discussed two well-referenced studies that used NTL, specifically DMSP, for monitoring economic activities. Henderson, et al (2012) concluded that NTL can contribute to analyzing growth at sub- and supranational levels where detailed income data are not available. Chen and Nordhaus (2011), however, mentioned that NTL data can add value as proxy to countries with insufficient statistical systems only. Following these two ideas, the capability and usability of harmonized NTL datasets for monitoring economic activities in the PIEs will be evaluated.

Gross Domestic Product

Gross domestic product (GDP) measures the value of goods and services produced by an economy in a given period. It is a commonly used indicator to track the size and growth of an economy. GDP is monitored periodically, e.g., annually, and quarterly, with its growth signifying economic development and increased business activities. The Asian Development Bank (ADB) maintains and publishes the Asian Development Outlook (ADO) database which monitors the GDP of its 47 developing member countries including the 14 (PIEs. ADO database contains both GDP based on purchasing power parity (PPP) and the corresponding growth rate. For PIEs, the earliest available data is 1980 (Figure 2).

Figure 2. GDP PPP for PIEs



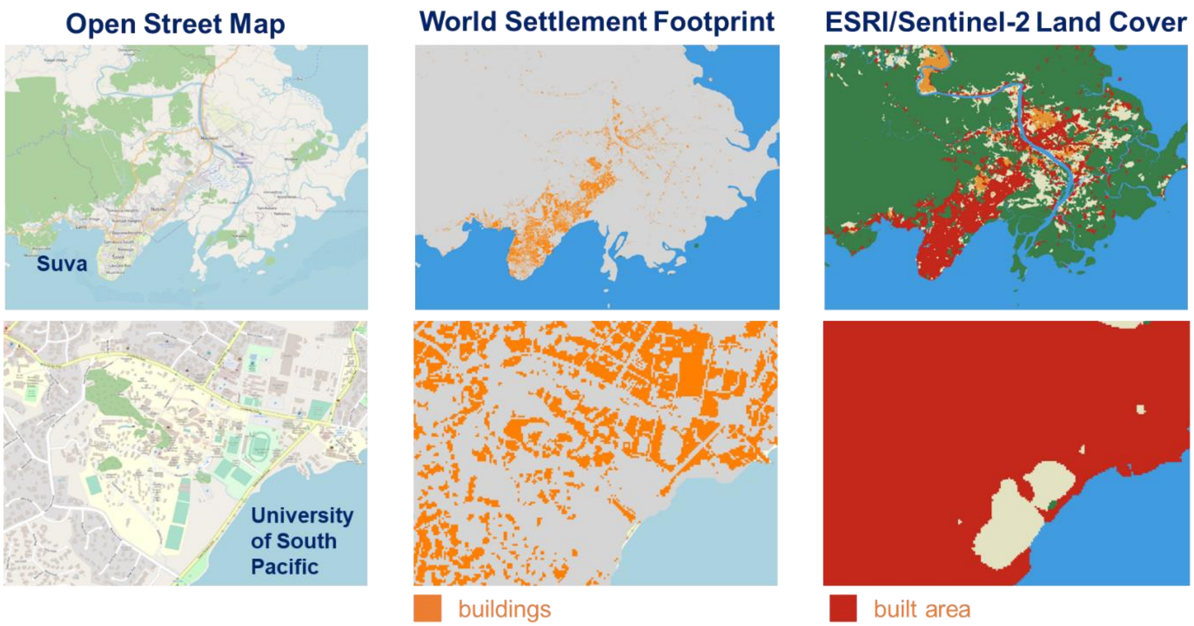
Source: ADO Database

Concentration of Human Activities: World Settlement Footprint and ESRI/Sentinel-2 Land Cover Data

The World Settlement Footprint (WSF), developed by the European Space Agency (ESA) and the German Aerospace Center (DLR) is a unique and comprehensive dataset on location of building footprints. Available for 2015 and 2019 with global coverage, it was originally made publicly accessible to better understand urbanization. Separately, ESA and Environmental Systems Research Institute (ESRI), to produce an annual series of land cover maps. This land cover series starting in 2017 features nine classifications including vegetation types, bare surface, water, cropland, and built area.

Built areas comprised of buildings and infrastructure are centers of human and economic activities. These activities done in light-producing infrastructure contribute to production and movement of goods and services. Geospatial techniques can filter NTL from the identified building footprints and built areas (Figure 3). Using data from WSF and ESA, and ESA and ESRI, respectively, NTL attributed to the location of buildings and built-up areas can be selected and its correlation with an economy's GDP can be estimated.

Figure 3. Comparison of Open Street Map ©, Word Settlement Footprint, and ESRI/Sentinel-2 Land Cover ©

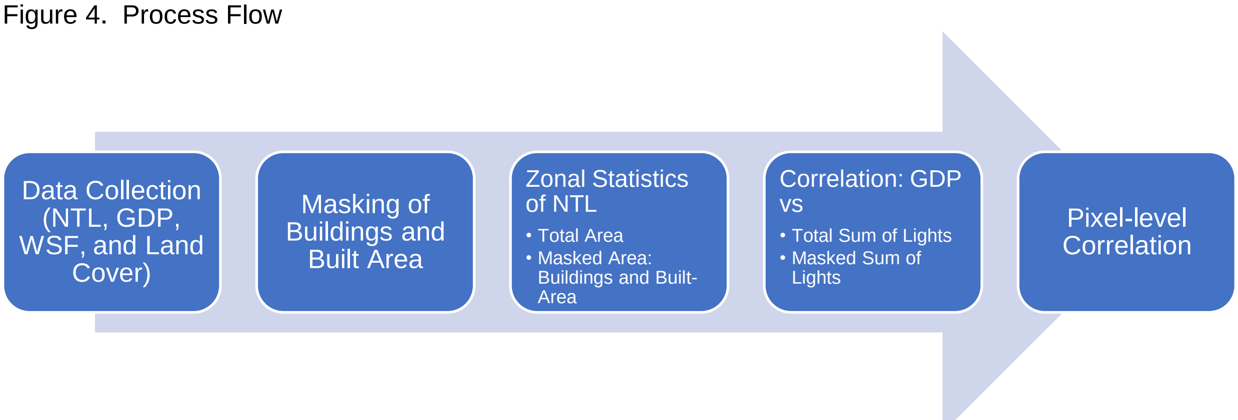


Source: Open Street Map ©, ESA and DLR, and ESRI

Geospatial Processing

The following steps were taken for data processing and analysis:

Figure 4. Process Flow

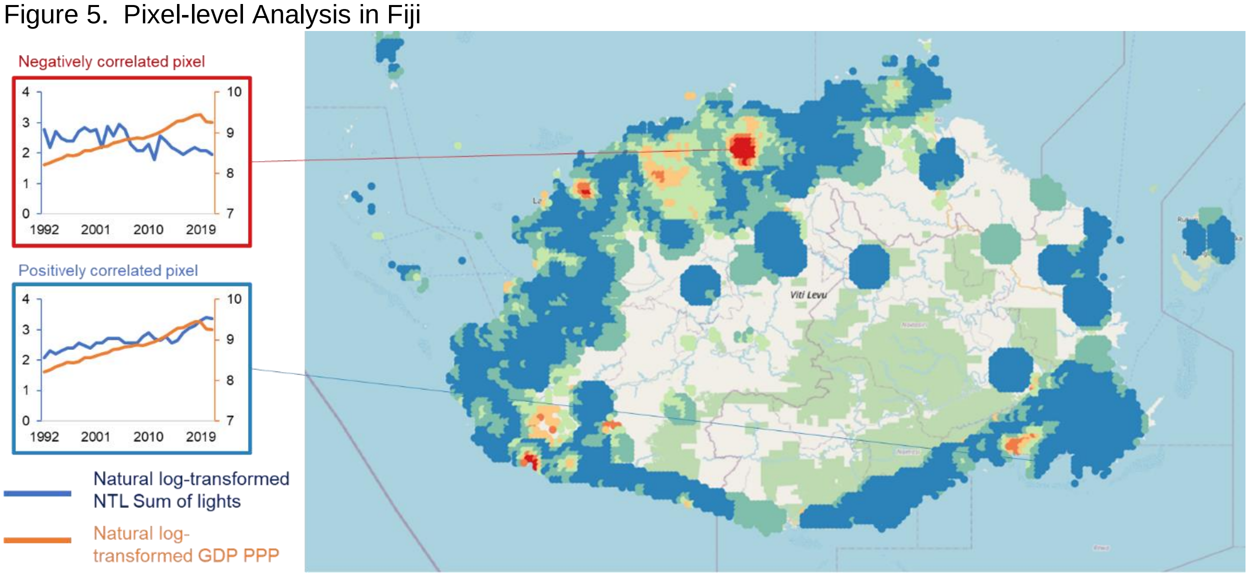


Evaluating the potential of NTL as a complementary indicator of economic activity in PIEs entails the following steps: collection of data, masking areas of interests, i.e., buildings and built area, deriving area-level summary from zonal statistics and correlation analysis (Figure 4). Masking is a geospatial technique wherein an area is limited to a selected overlaying mask. For example, in Figure 3, instead of the whole administrative area of Fiji (shown on the left figure), an area of analysis will be masked or limited to those locations identified as buildings (orange area in the middle figure) or built area (red zones in the right figure). Zonal statistics allow conversion of pixel-level values of NTL to tabulated statistics based on administrative boundaries. Different methods of aggregation are applicable – sum, mean, minimum, maximum, count, standard deviation, median, range, variety, and variance. NTL was aggregated as the sum representing the total value of NTL for each administrative boundary (total sum of lights) and masked area (masked sum of lights).

Various iterations representing the harmonized NTL datasets were explored – digital number (DN), natural log transformed DN, year-on-year difference, and year-on-year growth rate. Digital number is a representation of observed NTL using numeric numbers ranging from zero (0) to 63, following the 8-bit format. Natural log transformation of DN was selected based on its property to reduce skewness and highlight the relationship between variables. Likewise, GDP levels were transformed using natural logarithm.

Following the methodology of Galimberti (2020), pixel-level analysis was explored and assessed as an option in characterizing correlation between NTL and GDP. Pixel-level analysis requires converting pixels of NTL to points representing centroids of these pixels. This allows selection of pixels and areas that will be used for further analysis. Individual pixels are classified based on their level of correlation with their corresponding economy's GDP (Figure 5). Bluish to greenish areas are made up of pixels that are positively correlated while orange to red areas are composed of negatively correlated pixels. Also shown in Figure 5 are samples of both positively and negatively correlated pixels, with their corresponding graphs showing natural logarithmic transformed NTL and GDP values.

Figure 5. Pixel-level Analysis in Fiji



Source: Open Street Map © and Author's Calculation

Results and Discussions

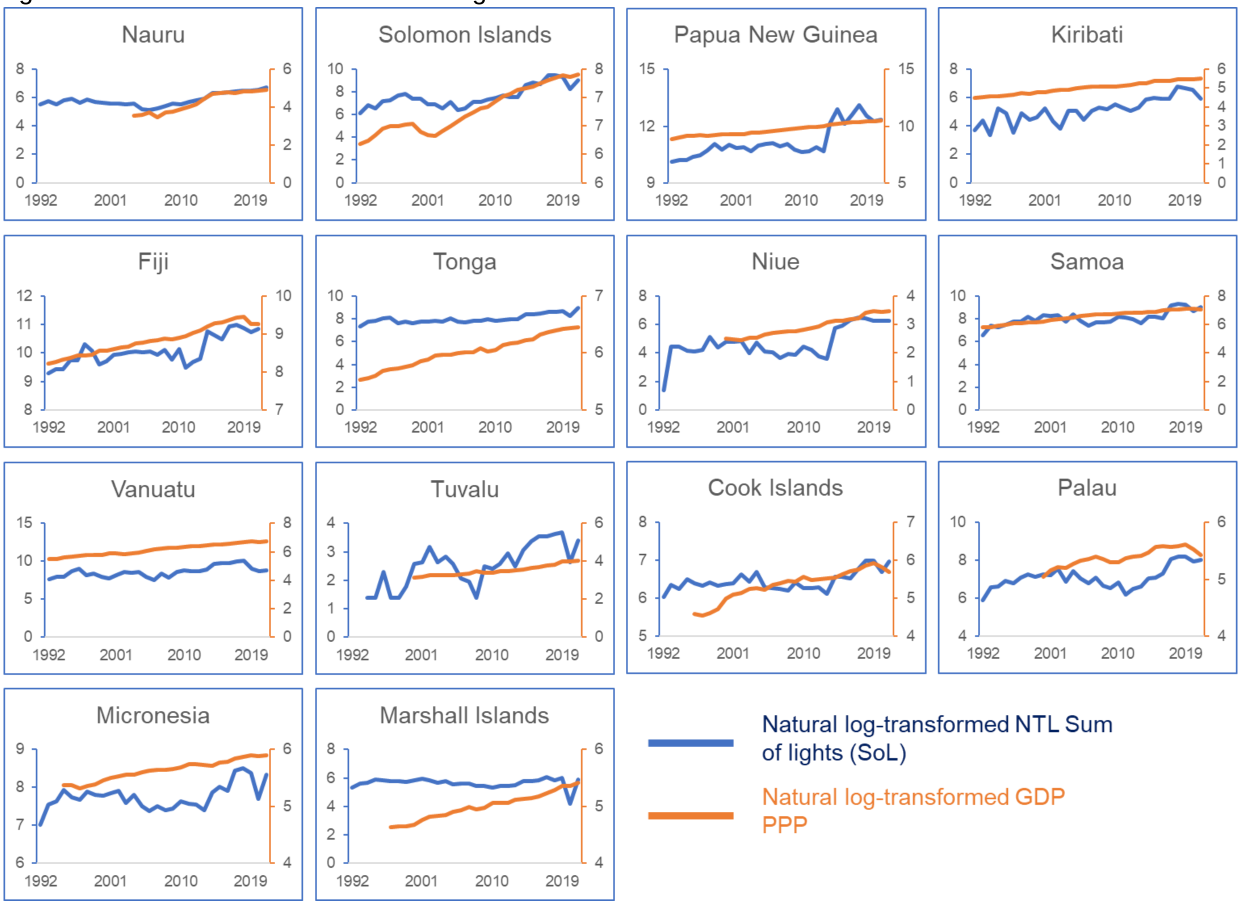
Correlation between natural log transformed NTL and GDP yielded moderate (at least 0.5) to strong (at least 0.7) levels for 10 out of 14 PIEs (Table 1 and Figure 6). Comparison of sum of lights (SoL) and GDP levels during the same year resulted in a slightly higher correlation level compared to a one-year lag, i.e., comparing sum of lights of the previous year with GDP levels of the current year. Significance test using p-value was run and yielded statistically significant correlation except for Kiribati. Given that PIEs' economic statistics are not regularly updated, and sub-national information are not readily available, the results are aligned with both Henderson, et al (2012), which is more optimistic on the reliability of NTL, and Chen and Nordhaus (2011), which emphasized benefits only for those economies lacking available data. This will also complement the recent World Bank (2023) working paper which analyzed microeconomic applications of NTL. Once historical sub-national economic data are available, NTL's capability at this detailed level of information can be further evaluated.

Table 1. Pearson's Correlation between natural log transformed NTL vs GDP PPP

	NTL vs GDP PPP, natural log transformed	
PIEs	Correlation (Same year for GDP and NTL)	Correlation (1-Year lag for NTL)
Nauru	0.9702***	0.9484***
Solomon Islands	0.8517***	0.7997***
Papua New Guinea	0.8463***	0.8204***
Kiribati	0.8334	0.8263
Fiji	0.8053***	0.7685***
Tonga	0.8033***	0.7927***
Niue	0.7224***	0.6804***
Samoa	0.6688***	0.6504***
Vanuatu	0.6557***	0.6819***
Tuvalu	0.5610***	0.6044***
Cook Islands	0.4614***	0.3775***
Palau	0.3960***	0.2956***
Micronesia	0.3377***	0.3032***
Marshall Islands	-0.2097***	-0.3118***

Note: Significance was tested using t-test, ***p < 0.001, **p < 0.05, *p <0.1
Source: Author's Calculation

Figure 6. Correlation between natural log transformed NTL vs GDP PPP



Source: Author's Calculation

NTL in areas of human activities such as building from WSF and built-up area from ESRI/Sentinel-2 only improved correlation with GDP in 5 PIEs (Table 2). Nauru, Solomon Islands, and Papua New Guinea, which already yielded strong correlations using total sum of lights, yielded slightly different values when using masked sum of lights from built areas. On the other hand, Kiribati, Fiji, Tonga, and Niue even resulted lower correlation values when using masked sum of lights from built area. The group of Samoa, Vanuatu, and Tuvalu generated the highest increase in correlation using masked sum of lights from built area. Vanuatu improved the most, signifying how much NTL are produced from non-built areas in the island nation, specifically lava-spewing volcanoes.

No significant improvement in the previously weak correlation for Cook Islands, Palau, Micronesia, and Marshall Islands. Micronesia's correlation slightly improved when using masked sum of lights from buildings while the rest even resulted to more negative correlation.

Table 2. Correlation between natural log transformed NTL vs GDP PPP

	NTL vs GDP PPP, natural log transformed		
PIEs	Sum of Lights - All Areas	Sum of Lights - WSF Buildings Only	Sum of Lights - Built-up Areas Only
Nauru	**0.9702**	0.9602	0.9635
Solomon Islands	**0.8517**	0.7746	0.8510
Papua New Guinea	0.8463	0.8268	**0.8586**
Kiribati	**0.8334**	0.4062	0.4686

Fiji	**0.8053**	0.7400	0.7653
Tonga	**0.8033**	0.0892	0.5153
Niue	**0.7224**	0.3883	0.5555
Samoa	0.6688	0.7301	**0.7608**
Vanuatu	0.6557	0.4455	**0.8431**
Tuvalu	0.5610	0.5691	**0.5950**
Cook Islands	**0.4614**	-0.0063	0.0384
Palau	**0.3960**	-0.6687	-0.3799
Micronesia	0.3377	**0.4957**	-0.2996
Marshall Islands	-0.2097	-0.3880	-0.4359

Source: Author's Calculation

Pixel-level analysis resulted in drastic improvements of correlation between NTL and GDP of all PIEs, each one with at least 0.5 correlation coefficient when using pixels that are at least 0.25 correlated to GDP (Table 3). Marshall Islands, which has the sole negative correlation coefficient when using total SoL, gained the highest increase that reach 0.75996 correlation when using pixels that are at least 0.70 correlated with GDP (Figure 7). This further supports the research's earlier finding that NTL can serve as a complementary indicator of economic activity. Limiting which areas, represented by pixels, to include in correlation can also show which ones are highly productive and contributes to the overall growth of a country's economy. Conversely, pixels that have weak or negative correlation can signify areas that need intervention or support to grow alongside other progressive areas in a country.

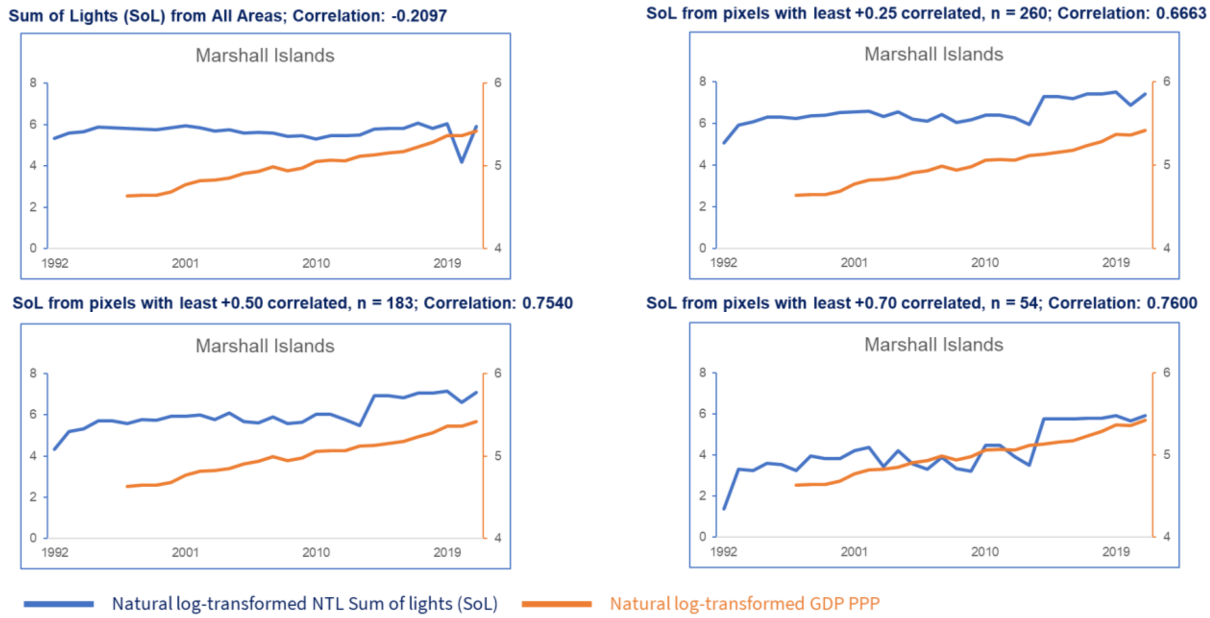
Due to difference in the smallest processing units, i.e., polygons (representing administrative boundary) in sum of light against points in pixel-level analysis, slight decrease in correlation coefficients can be observed for Nauru, Kiribati, and Niue.

Table 3. Comparison of Correlation from Pixel-level Analysis

	NTL vs GDP PPP, natural log transformed			
PIE	Sum of Lights - All Areas	Sum of Lights - Pixels at least + 0.25 correlated	Sum of Lights - Pixels at least + 0.5 correlated	Sum of Lights - Pixels at least + 0.7 correlated
Nauru	0.97018	0.96291	0.96291	0.96291
Vanuatu	0.6557	0.74645	0.92265	0.9356
Papua New Guinea	0.84632	0.89939	0.91244	0.93138
Fiji	0.80531	0.85585	0.88532	0.91743
Solomon Islands	0.85171	0.86211	0.86289	0.88572
Samoa	0.66879	0.74218	0.80612	0.85981
Kiribati	0.83344	0.8002	0.80727	0.85511
Tonga	0.80329	0.81981	0.81736	0.84361
Palau	0.39601	0.51721	0.53246	0.80517
Micronesia	0.33772	0.60448	0.69751	0.78026
Niue	0.72236	0.71374	0.72258	0.77587
Marshall Islands	-0.20969	0.66631	0.75398	0.75996
Cook Islands	0.46144	0.57175	0.62028	0.67251
Tuvalu	0.56104	0.56123	0.56123	---

Source: Author's Calculation

Figure 7. Pixel-level Analysis in Marshall Islands



Source: Author's Calculation

Limiting the pixels based on correlation threshold did not remove a substantial amount of samples, with the largest share removed at 32% or 291 out of total 902 for Micronesia (Table 4). Seven PIEs only took out 10% of pixels including Nauru and Tuvalu whose all pixels met the correlation threshold.

Table 4. No. of Grids and %Share per Correlation Threshold

	No. of Grids				% Share		
	Total	At least 0.25 correlation	At least 0.5 correlation	At least 0.7 correlation	At least 0.25 correlation	At least 0.5 correlation	At least 0.7 correlation
Nauru	27	27	27	27	100%	100%	100%
Tuvalu	4	4	4	2	100%	100%	50%
Niue	94	92	71	60	98%	76%	64%
Tonga	692	656	580	306	95%	84%	44%
Solomon Islands	1,182	1,113	1,015	590	94%	86%	50%
Vanuatu	1,481	1,375	728	469	93%	49%	32%
Papua New Guinea	34,408	31,669	26,671	15,575	92%	78%	45%
Kiribati	85	75	56	29	88%	66%	34%
Cook Islands	148	127	55	12	86%	37%	8%

Fiji	8,697	7,122	4,909	2,133	82%	56%	25%
Palau	674	549	371	69	81%	55%	10%
Samoa	1,617	1,315	731	274	81%	45%	17%
Marshall Islands	353	260	183	54	74%	52%	15%
Micronesia	902	611	297	56	68%	33%	6%

Conclusion

Pacific Islands economies have been generally excluded in NTL research, prior to one recent work that focuses on the region and highlights micro-level application of NTL. In this study, NTL, and its potential as an indicator of economic activity in these countries were evaluated. Various sources and representations of NTL have been explored and the natural long transformed digital number values of harmonized DMSP-VIIRS images was determined to be the most applicable for the research. Integrating DMSP's longer availability and VIIRS higher resolution, the harmonized dataset was able to produce a 30-year annual NTL series. Total sum of lights from the corresponding administrative boundaries showed moderate to strong correlation with GDP to 9 out of 14 PIEs. Limiting the area of interest to buildings and built-area improved correlation minimally. Pixel-level correlation improved results among all PIEs, each one yielding moderate to strong correlation. The number of excluded grids only reached up to around 30% maximum and only seven PIEs need to remove 10% or less.

With significant correlation established between NTL and GDP, taking advantage of this publicly available dataset can be a focus of research in the subregion. Aside from GDP, NTL's relationship with other macroeconomic indicators can be evaluated if macroeconomic data is available. Creation of econometric models that will approximate these indicators based on NTL can also be explored. This will address the commonly encountered problem of data unavailability or lacking frequency. Once a robust model is established, NTL can approximate these values as frequent as daily or monthly variation. VIIRS, through NASA's Black Marble Suite, offers daily NTL images which can be used for studies that require high data availability e.g., GDP nowcasting, electrification, population monitoring, and pandemic impact assessment.

Like other remote sensing data, NTL is not designed to replace conventional datasets. Rather, different applications of NTL are studied to complement traditional datasets and methods. However, with minimal advances in improving conventional methods of acquiring economic data and old-age problem of data sharing, innovations such as NTL can be further explored and relied on. As better technologies that could provide better spatial granularity and temporal frequency of NTL become available, more research in the Pacific region can be anchored to this publicly and frequently available dataset.

References

- Chand, T., Badarinath, K, Elvidge, C., Tuttle, B. 2009. *Spatial characterization of electrical power consumption patterns over India using temporal DMSP-OLS night-time satellite data. International Journal of Remote Sensing*. https://doi.org/10.1080/01431160802345685
- Chen, X., and Nordhaus, W. 2011. *Using luminosity data as a proxy for economic statistics*. Proceedings of the National Academy of Sciences of the United States of America. https://doi:10.1073/pnas.1017031108
- Elvidge, C. Baugh, K., Ghosh, T., Zhizhin, M., Hsu, F., Sparks, T., Bazilian, M., Sutton, P., Houngbedji, K. and Goldblatt, R. 2022. *Fifty years of nightly global low-light imaging satellite observations. Frontiers in Remote Sensing*. https://doi:10.3389/frsen.2022.919937
- Galimberti, J. 2020. Forecasting GDP growth from outer space. Oxford Bulletin of Economics and Statistics. https://doi:10.1111/obes.12361
- Ghosh, T., Powell, R., Elvidge, C., Baugh, K., Sutton, P., and Anderson, S. 2010. *Shedding light on the global distribution of economic activity*. Open Geography. https://doi.org/10.2174/1874923201003010147
- Gibson, J., Olivia, S., and Boe-Gibson, G. 2020. *Night lights in economics: sources and uses*. Journal of Economic Surveys. https://doi.org/10.1111/joes.12387
- Hartojo, N., Ikhsan, M., Dartanto, T., and Sumarto, S. 2022. *A Growing Light in the Lagging Region in Indonesia: The Impact of Village Fund on Rural Economic Growth*. Economies. https://doi.org/10.3390/economies10090217
- Henderson, J., Storeygard, A., and Weil, D. 2012. *Measuring Economic Growth from Outer Spac*e. American Economic Review. https://doi.org/10.1257/aer.102.2.994
- Li, X., Zhou, Y., Zhao M., and Zhao, X. 2020. *A harmonized global nighttime light dataset 1992-2018*. Scientific Data. https://doi:10.1038/s41597-020-0510-y
- Sutton, P., Elvidge, C., and Ghosh, T. 2007. *Estimation of Gross Domestic Product at Sub-National Scales using Nighttime Satellite Imagery*. International Journal of Ecological Economics and Statistics.
- Yu, B., Shi, K., Huang, C., Chen, Z., and Wu. J. 2015. *Poverty evaluation using NPP-VIIRS nighttime light composite data at the country level in China*. IEEE Journal of Selected Topics in Applied Earth Observation and Remote Sensing. doi.org/ 10.1109/JSTARS.2015.2399416
- Zhao, M., Zhou, Y., Li, Xuecao., Cao, W., He, W., Yu. B., Li, Xi, Elvidge, C., Cheng, W., and Zhou, C. 2019. *Applications of satellite sensing of nighttime light observations: advances, challenges, and perspectives*. Remote Sensing. https://doi.org/10.3390/rs11171971
- World Bank. 2023. *Pacific islands pacific observatory, monitoring economic activity by nighttime light data: nighttime lights - application for the Pacific*. http://hdl.handle.net/10986/39810