The Impact of COVID-19 Pandemic on Socioeconomic Activity Exchanges in the Himalayan Region: A Satellite Nighttime Light Perspective

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***Abstract*— As a key region of natural and socioeconomic systems, the Himalayan region has an important impact on socioeconomic development, geopolitical situation, and climate change worldwide. However, as a result of the coronavirus disease 2019 (COVID-19) pandemic, trade channels among countries have been forced to close in the Himalayan region, which has a great impact on socioeconomic development. In this letter, satellite remote sensing nighttime light (NTL) images were used to evaluate the impact of the COVID-19 pandemic on socioeconomic activity exchanges in the Himalayan region from perspectives of NTLs of trade ports and channel nodes and interactive NTLs (INLs). Results show that the total NTLs (TNTs) at trade ports showed a downward trend in fluctuation during the pandemic because of the pandemic blockade policy. Most of node TNTs on the channels are still growing during the pandemic, mostly because of the recovery and development of economies in countries. The INL model indicates that the pandemic has partly prevented socioeconomic activity exchanges between countries, particularly between China and other countries, but there has been a stronger interaction between domestic subunits. This letter provides new insight into the assessment of the socioeconomic development in the Himalayan region based on the NTL data.**

***Index Terms*— Coronavirus disease 2019 (Covid-19) pandemic, nighttime light (NTL), socioeconomic activity exchanges, the Himalayan region, trade channel.**

I. Introduction

THE coronavirus disease 2019 (COVID-19) pandemic has continued to spread throughout the world since the end of 2019. By the end of November 2022, more than 600 million have been confirmed cases and about 6.6 million deaths worldwide. In the absence of specific drugs, many countries had to take non-drug interventions, such as city closures, home orders, and social alienation, to control the pandemic [1]. Although isolation, blockade, and other measures have effectively curbed the spread of the virus, they have had a significant impact on people's daily lives and socioeconomic activity exchanges [2]. Therefore, the socioeconomic system and the natural environmental system have been impacted unprecedentedly [3].

As a key region of the "world roof," the "third pole," and the "Asian water tower," the Himalayan region has the highest altitude in the world, which has an important impact on socioeconomic development, geopolitical situation, climate change, and the ecological environment worldwide [4]. For example, the Himalayan region's rich natural resources contribute to global climate regulation, biodiversity protection, and sustainable ecosystem development [5]. With its unique physical-geographical environment and human-social processes, the Himalayan region has played an important role in the communication and development of China, India, Nepal, and Bhutan [6]. However, owing to the impact of the COVID-19 pandemic, the forced closure of trade channels between countries in the Himalayan region has hindered border trade and cross-border labor cooperation and has severely damaged religious pilgrimage and tourism. These effects further exacerbated the regional geopolitical instability. From the trade statistics for China's border ports, under the impact of the COVID-19 pandemic, Gyirong Port's total volume of import and export in 2019 (before the pandemic) was 3752 million Yuan, whereas in 2020 and 2021 (during the pandemic), it decreased by 79.5% and 79.2%–769.31 and 779.86 million Yuan [7], respectively. Our field investigations also revealed that many international trade ports were closed or semi-closed during the pandemic. In general, owing to the impact of the pandemic, the exchange of socioeconomic activities between countries or regions in the Himalayan region has been restricted, thereby increasing vulnerability and fragmentation of the human-socioeconomic environment.

Timely and effective monitoring and evaluation of the COVID-19 pandemic's impact on socioeconomic activity exchanges can provide scientific guidance for pandemic prevention and control, production resumption, and economic and

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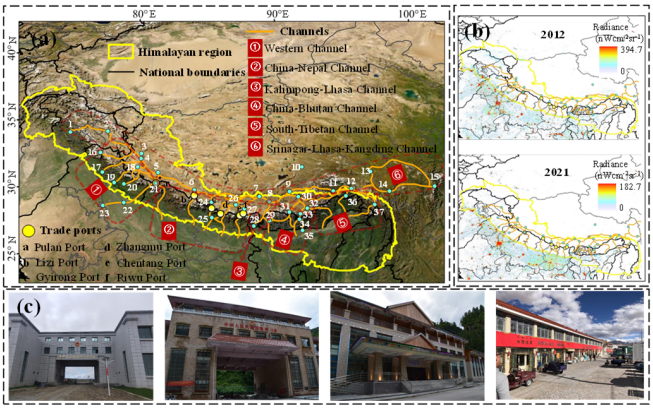

Fig. 1. Overview of the study area. (a) Spatial distributions of the study area, including six mainly traditional trade channels, six trade ports, and 37 channel nodes. (b) Spatiotemporal distributions of NTLs. (c) Field survey pictures of trade ports (The pictures were taken in July–August 2021). Note: 37 channel nodes are as follows: Srinagar, Leh, Gar, Kunsha, Mount Kailash, Zhongba, Shigatse, Gyangzê, Lhasa, Naqu, Linzhi, Bomê, Changdu, Markam, Kangding, Keylong, Shimla, Zanda, Dehradun, Srinagar, Purang, Moradabad, New Delhi, Gyirong, Kathmandu, Tingri, Dinggyê, Kalimpong, Thimphu, Shannan, Lacan, Lhünzê, Cona, Dawang, Odalguri, Medog, and Zayü.

cultural exchanges and cooperation. Statistics are traditionally used to assess the pandemic's socioeconomic impact from various angles; however, they have a slow update, lack spatial details, have inconsistent statistical caliber, and present human error [8]. Satellite remote sensing nighttime light (NTL) images can capture the light information on the Earth's surface at night, which can directly present the scope and intensity of human activities and further reflect the level of socioeconomic development on a large scale with long time series [9], [10]. Thus, data from NTL monitoring have been widely used to assess the impact of the COVID-19 pandemic [1], [11], [12]. For example, the NTL data were usually used to assess the recovery of the city's socioeconomic development affected by the pandemic [13]. Beyer et al. [14] also explored NTL intensity to determine the economic impact of the pandemic in India.

This letter aims to determine the impact of the COVID-19 pandemic on the socioeconomic activity exchanges in the Himalayan region from a satellite NTL perspective. The first step was to evaluate spatiotemporal variations of NTLs for trade ports and channel nodes in the Himalayan region before and during the pandemic. Then, an interactive NTL (INL) index was developed to analyze the light interaction with different countries and subunits within a country.

II. Study Area and Data Sources

A. Study Area

The Himalayan region refers to the vast mountainous area between the southern and northern Himalayas, including China's Tibet and Xinjiang border area, India's northwest border area, Nepal, and Bhutan (Fig. 1). The Himalayan region serves as a transition zone between the Qinghai Tibet Plateau and the South Asian subcontinent, including hub connecting Central and South Asia. A series of traditional trade channels and ports has been formed along the mountains, fractures, valleys, and mountain passes (Fig. 1), which have become the carriers of commercial, cultural, social, and economic exchanges with different countries or regions. The Himalayan region's trade channels should be developed to maintain socioeconomic stability and prosperity. Recently, the Himalayan region has grown in population due to the northward movement of the Indian population and the construction of channels and ports of entry has led to economic development in the region. However, most trade channels were forced to close because of the COVID-19 pandemic. Thus, a timely and effective understanding of spatiotemporal changes in socioeconomic activity exchanges brought about by the pandemic will be an essential prerequisite and basis for promoting the sustainable development of social-economic-political-environmental health and safety in the Himalayan region.

B. Data Sources

The traditional trade channels, trade ports, and channel nodes are derived from multiple sources of data interpreted together (Fig. 1). Specifically, a visual interpretation technique was used to extract fault valleys in the Himalayan region using digital elevation model data, water systems, traffic, and Google Earth images. Then, historical literature data, archeological sites, county chronicles of border counties, and other data were employed to determine the main channels, ports, and nodes. Finally, a field study was conducted to verify the accuracy of the data [6]. Notably, trade ports serve as exchange points for people and goods between countries or regions. A channel node is typically a city, county, or town distributed on trade channels, each of which is a social or economic cluster in the Himalayan region.

Black Marble NTL data were collected from the National Aeronautics and Space Administration, NASA (https://blackmarble.gsfc.nasa.gov/#product). When compared to traditional NTL data, Black Marble data removed cloud pollution and corrected deviations caused by variables, such as atmosphere, terrain, vegetation, snow, moonlight, and stray light [15]. The product used in our letter is the full-angle snow removal layer of the annual corrected NTL data (VNP46A4), with a spatial resolution of about 500 m. The quality layer was used to mask the data's poor quality pixel (value is 01) and fill value (value is 255) reference.

III. Methods

A. Statistical Analysis of NTLs

We statistically analyzed spatiotemporal changes of total NTL (TNT) in mainly trade ports and channel notes from 2012 to 2021 to evaluate the impact of the COVID-19 pandemic on the socioeconomic activity exchanges in the Himalayan region. Then, a total of typical six trade ports and 37 channel nodes were selected as the research objects (Fig. 1), considering their role as gathering places for the region's most important socioeconomic activities. As no clear administrative boundaries for points of trade ports and channel nodes exist, we extracted and compared TNT changes within 5- and 10-km buffer zones, respectively.

B. Developing the INL Index

There are often difficulties in obtaining socioeconomic activity exchanges between subunits in the Himalayan region,

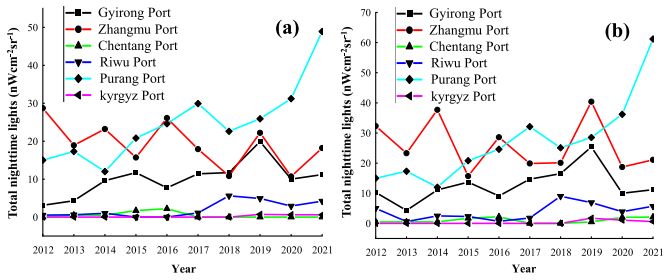

Fig. 2. TNT changes in different trade ports from 2012 to 2021. (a) 5-m buffer zone analysis. (b) 10-m buffer zone analysis.

such as information flow and commuter flow. Thus, taking NTL brightness as the standard measure for regional socioeconomic development, we proposed the "INL index" model in this letter. The INL model measures the attractiveness between subunit centers and visualizes and analyzes them in a directed network. Specifically, according to the radiation model proposed by Simini et al. [16], the internal unit center (P) in one region would interact with the external unit center (Q). Therefore, Q's attraction to P (AF_{pq}) was calculated as follows:

$$\mathrm{AF}_{pq} = \frac{\mathrm{TNL}_p^2 \times \mathrm{TNL}_q}{(\mathrm{TNL}_p + \mathrm{NTNL}_{pq}) \times (\mathrm{TNL}_p + \mathrm{TNL}_q + \mathrm{NTNL}_{pq})} \tag{1}$$

where AF_{pq} is the attraction of P to Q in one region. TNL_p and TNL_q are TNT of units P and Q, respectively, which are used to represent the unit's socioeconomic development. NTNL_{pq} is the development level of surrounding units. In this letter, the distance between the light center of gravity of every two units (P, Q) in an area was taken as the radius, and the light center of gravity of P was taken as the center to make a circle. Then, NTNL_{pq} can be obtained by accumulating the TNL of all surrounding units. In the same way, we could also make a circle by taking the light center of Q. Except for units P and Q, all units in the coverage area are considered the surrounding units. NTNL_{qp} was calculated by accumulating the TNL of all surrounding units. Owing to the size difference between NTNL_{pq} and NTNL_{qp}, AF_{pq} and AF_{qp} have a directional characteristic [17].

IV. Results and Discussion

A. Spatiotemporal Variations of NTLs in the Himalayan Region

As shown in Fig. 2, the TNT has changed statistically in different trade ports from 2012 to 2021. We found a similar trend in TNT variation for the 5- and 10-m buffer, indicating that our calculation is more reasonable. In the next step, the 5-m buffer TNT was selected as the standard for statistical analysis. As important ports for international trade in southern Tibet of China, a significant increase in TNT in Purang and Gyirong ports occurred before the pandemic, and a fluctuating pattern of TNT was found in Zhangmu port from 2012 to 2019 [Fig. 2(a)]. This case illustrates smooth exchanges of socioeconomic activities before the pandemic

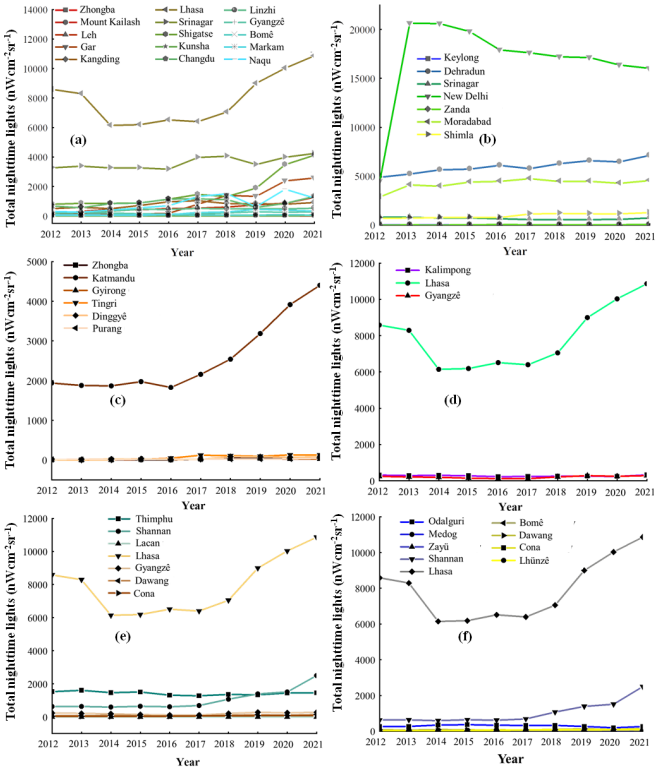

Fig. 3. TNT changes in different nodes with trade channels from 2012 to 2021. (a) Srinagar-Lhasa-Kangding Channel. (b) Western Channel. (c) China-Nepal Channel. (d) Kalimpong-Lhasa Channel. (e) China-Bhutan Channel. (f) South-Tibetan Channel.

in the Himalayan region. Additionally, it shows that national policies have a tremendous effect on the region, and some trade channels open and close at unknown times. A downward trend of fluctuation has been observed in the TNT at Zhangmu and Gyirong ports from 2019 to 2021 as a result of the pandemic blockade policy. Notably, Purang port's TNT is on the rise (2012–2021) possibly because of the Chinese Government's increased construction and expansion of the port. Considering that these ports are currently closed to traffic, the level of light brightness in Riwu, Chentang, and Lizi is low. Apart from small-scale exchanges between people, these ports have not achieved full freedom of trade.

Moreover, we separately counted the TNT changes in different nodes with trade channels. There are more changes in the TNT within nodes to reflect socioeconomic development. All node TNTs on the Srinagar-Lhasa-Kangding channel [Fig. 3(a)] showed a fluctuating growth trend from 2012 to 2019. As a result of the national blockade policy, TNTs in Naqu, Bomê, and Markam declined from 2020 to 2021. Other node TNTs also show an upward trend possibly because tourism in Tibet continues to thrive during the pandemic. Although people are concerned about the COVID-19 pandemic, Tibet continues to receive millions of domestic tourists during the holiday season [7]. Fig. 3(b) shows an upward trend in most node TNTs from 2012 to 2019 along the Western channel. Except for New Delhi, all other node TNTs showed an upward trend from 2020 to 2021. A loose pandemic prevention policy in India Uttar Pradesh

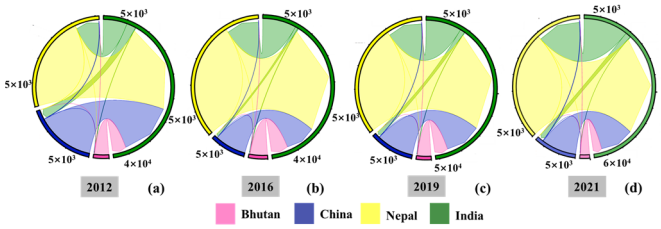

Fig. 4. INLs in the Himalayan region at the national level. Note: the thickness of the lines represents the intensity of the NTL flow, and the arrows of the lines represent the direction of the NTL flow. (a) 2012. (b) 2016. (c) 2019. (d) 2021.

may result in reverse migration and the recovery and development of industry and agriculture, which may lead to the rise of TNTs [14], [18]. TNTs for all nodes on the China–Nepal channel except Tingri showed an upward trend from 2020 to 2021 [Fig. 3(c)], possibly attributed to Nepal's relatively loose pandemic prevention policies. During the pandemic, of all nodes on the Kalimpong–Lhasa channel still showed an upward trend [Fig. 3(d)]. Transnational tourism has been affected by the pandemic, but domestic tourism remains unaffected because these nodes are popular tourist destinations. There is a general upward trend in the node on the China–Bhutan and South–Tibetan channels [Fig. 3(e)–(f)], which may be attributed to Tibet's tourism industry driving their socioeconomic development.

In general, the COVID-19 pandemic blockade policy partly prevented countries from trading or exchanging personnel, as evidenced by the decline in TNTs at some trade ports. However, most of the node TNTs on the channels are still growing, which are mostly because of the continuous opening and prosperity of Tibet's tourism industry and the recovery and development of economies of South Asian countries. However, notably, NTL does not distinguish between the socioeconomic development of sectors on different channels and ports in the Himalayan region, which will need to be explored in future studies.

B. Regional Interactive Analysis of NTLs in the Himalayan Region

The INL model was employed to evaluate the intensity of socioeconomic interconnectivity at the national and domestic subunit levels in the Himalayan region. As shown in Fig. 4, owing to the pandemic prevention and control policies in China and Bhutan, the import and export intensity of these countries declined significantly during the pandemic. In other words, these two countries have a weaker spatial interaction (e.g., socioeconomic activity exchanges) with other countries. This finding is consistent with the results of some trade ports' TNT decline (Fig. 2). However, the increasing spatial interaction between India and Nepal is a trend that has been observed for years. Given India's long-term role as Nepal's top trade partner and donor [19], loose pandemic prevention policies have not slowed down the trend of increased spatial interactions between the two countries.

The pandemic has affected socioeconomic activity exchanges between countries to some extent, particularly between China and other countries. However, a stronger interaction between domestic subunits has been established

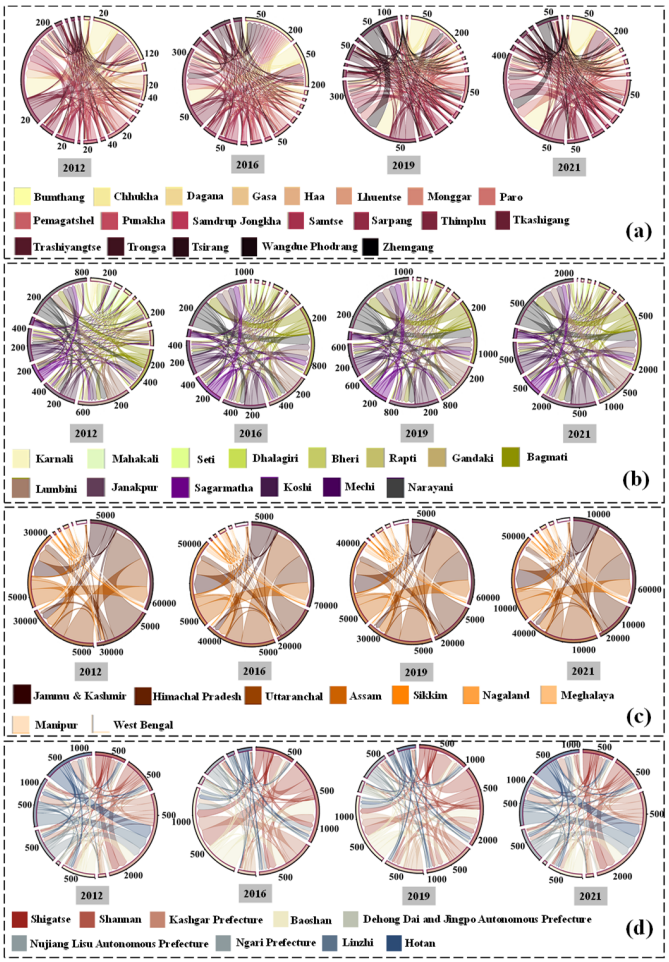

Fig. 5. INLs within different countries at the domestic subunit level. Note (a) Bhutan (county), (b) Nepal (district), (c) India (state), and (d) China (prefecture-level city). Here, the Himalayan region mainly involves Tibet and Xinjiang in China.

in the Himalayan region. As shown in Fig. 5(a), Bhutan's INLs of internal subunits rose from 514 to 527 during the pandemic. The INLs of subunits in Nepal increased from 3132 in 2019 to 4944 in 2021 [Fig. 5(b)]. India's INLs for internal subunits have had the most significant upward trend, from 86 797 in 2019 to 100 371 in 2021 [Fig. 5(c)]. In China, INLs of internal subunits grew from 3634 in 2019 to 4085 in 2021 [Fig. 5(d)]. The above changes may also be attributed to the relatively loose pandemic blockade policies in India and Nepal [18], the sustainable prosperity and development of tourism in Tibet of China.

However, though NTL can reveal socioeconomic interactions between countries and subunits within countries in 2020 and 2021, it is not possible to distinguish whether these socioeconomic interactions phenomena are entirely caused by COVID-19. This limitation will be one of the key issues we focus on in the future.

V. Conclusion

Based on NTL data, this letter examined the impact of the COVID-19 pandemic on socioeconomic activity exchanges in the Himalayan region. The results show that the pandemic blockade policy has caused a downward trend of fluctuation in the TNTs at trade ports during the pandemic. There is

still a growth in the node TNTs on the channels, which is mostly caused by the recovery and development of economies in the Himalayan region. Furthermore, the INL model suggests that the pandemic has partly affected socioeconomic activity exchanges between countries, particularly between China and other countries, but there is a stronger interaction between domestic subunits.

Despite the terrain, climate, and geopolitics also playing a role in socioeconomic development in the Himalayan region, NTL data can directly reveal NTL differences before and during the COVID-19 pandemic to a certain extent. Our understanding of socioeconomic activity exchanges within a country or region can be improved by using this intuitive approach. Although INL can represent socioeconomic activity flows within the Himalayan region, the results need to be verified across countries as these are also affected by various factors, such as international politics or border barriers.

REFERENCES

[1] G. Xu, T. Xiu, X. Li, X. Liang, and L. Jiao, "Lockdown induced night-time light dynamics during the COVID-19 epidemic in global megacities," *Int. J. Appl. Earth Observ. Geoinf.*, vol. 102, Oct. 2021, Art. no. 102421.

[2] N. S. Diffenbaugh et al., "The COVID-19 lockdowns: A window into the Earth system," *Nature Rev. Earth Environ.*, vol. 1, no. 9, pp. 470–481, 2020.

[3] J. Verschuur, E. E. Koks, and J. W. Hall, "Observed impacts of the COVID-19 pandemic on global trade," *Nature Human Behaviour*, vol. 5, no. 3, pp. 305–307, Feb. 2021.

[4] A. Bhattacharya et al., "High mountain Asian glacier response to climate revealed by multi-temporal satellite observations since the 1960s," *Nature Commun.*, vol. 12, no. 1, p. 4133, Jul. 2021.

[5] S. Nautiyal, "Interaction of biodiversity and economic welfare—A case study from the Himalayas of India," *J. Environ. Informat.*, vol. 6, no. 2, pp. 111–119, Dec. 2005.

[6] S. Wu, J. Yan, Y. Zhang, T. Peng, and K. Su, "Evolutionary process and development implications of traditional trade routes in the Himalayan region," *J. Geographical Sci.*, vol. 32, no. 9, pp. 1847–1865, Sep. 2022.

[7] (2022). *Tibet Travel Advisory*. [Online]. Available: https://www.yowangdu.com/tibet-travel/tibet-travel-advisory.html

[8] K. Shi et al., "Evaluating the ability of NPP-VIIRS nighttime light data to estimate the gross domestic product and the electric power consumption of China at multiple scales: A comparison with DMSP-OLS data," *Remote Sens.*, vol. 6, no. 2, pp. 1705–1724, Feb. 2014.

[9] K. Shi, Z. Chen, Y. Cui, J. Wu, and B. Yu, "NPP-VIIRS nighttime light data have different correlated relationships with fossil fuel combustion carbon emissions from different sectors," *IEEE Geosci. Remote Sens. Lett.*, vol. 18, no. 12, pp. 2062–2066, Dec. 2021.

[10] K. Shi, C. Huang, B. Yu, B. Yin, Y. Huang, and J. Wu, "Evaluation of NPP-VIIRS night-time light composite data for extracting built-up urban areas," *Remote Sens. Lett.*, vol. 5, no. 4, pp. 358–366, Apr. 2014.

[11] M. Alahmadi, S. Mansour, N. Dasgupta, A. Abulibdeh, P. M. Atkinson, and D. J. Martin, "Using daily nighttime lights to monitor spatiotemporal patterns of human lifestyle under COVID-19: The case of Saudi Arabia," *Remote Sens.*, vol. 13, no. 22, p. 4633, Nov. 2021.

[12] T. Ghosh, C. D. Elvidge, F.-C. Hsu, M. Zhizhin, and M. Bazilian, "The dimming of lights in India during the COVID-19 pandemic," *Remote Sens.*, vol. 12, no. 20, p. 3289, Oct. 2020.

[13] R. Yin et al., "Night-time light imagery reveals China's city activity during the COVID-19 pandemic period in early 2020," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 14, pp. 5111–5122, 2021.

[14] R. C. M. Beyer, S. Franco-Bedoya, and V. Galdo, "Examining the economic impact of COVID-19 in India through daily electricity consumption and nighttime light intensity," *World Develop.*, vol. 140, Apr. 2021, Art. no. 105287.

[15] Z. Wang, R. M. Shrestha, M. O. Román, and V. L. Kalb, "NASA's black marble multiangle nighttime lights temporal composites," *IEEE Geosci. Remote Sens. Lett.*, vol. 19, pp. 1–5, 2022.

[16] F. Simini, M. C. González, A. Maritan, and A.-L. Barabási, "A universal model for mobility and migration patterns," *Nature*, vol. 484, no. 7392, pp. 96–100, Apr. 2012.

[17] Y. Tu, Z. Chen, C. Wang, B. Yu, and B. Liu, "Quantitative analysis of urban polycentric interaction using nighttime light data: A case study of Shanghai, China," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 15, pp. 1114–1122, 2022.

[18] M. M. Islam, A. Jannat, D. A. Al Rafi, and K. Aruga, "Potential economic impacts of the COVID-19 pandemic on South Asian economies: A review," *World*, vol. 1, no. 3, pp. 283–299, Dec. 2020.

[19] D. Tripathi, "Influence of borders on bilateral ties in South Asia: A study of contemporary India–Nepal relations," *Int. Stud.*, vol. 56, nos. 2–3, pp. 186–200, Apr. 2019.