Emergencies do not stop at night: Advanced analysis of displacement based on satellite-derived nighttime light observations

M. Enenkel
R. M. Shrestha
E. Stokes
M. Román
Z. Wang
M. T. M. Espinosa
I. Hajzmanova
J. Ginnetti
P. Vinck

Around 68.5 million people are currently forcibly displaced. The implementation and monitoring of international agreements, which are linked to the 2030 agenda (e.g., the Sendai Framework), require a standard set of metrics for internal displacement. Since nationally owned, validated, and credible data are difficult to obtain, new approaches are needed. This article aims to support the monitoring of displacement via satellite-derived observations of nighttime lights (NTL) from NASA's Black Marble product suite along with an short message service (SMS)-based emergency survey after Cyclone Idai had made landfall in Beira, Mozambique, in March 2019. Under certain conditions, the spatial extent of power outages can serve as a proxy for disaster impacts and a potential driver for displacement. Hence, information about anomalies in NTL has the potential to support humanitarian decision-making via estimations of people affected or the coordination of rapid response teams. Despite initial issues related to cloud cover, we find that around 90% of Beira's power grid had been affected. In collaboration with the Internal Displacement Monitoring Center, we use these findings to establish a framework that links NTL observations with existing humanitarian decision-making workflows to complement ground-based survey data and other satellite-derived information, such as flood or damage maps.

Introduction

According to the latest Global Report on Internal Displacement of the Internal Displacement Monitoring Center (IDMC) [1], more than 28 million new displacements associated with disasters (61%) and social conflict/violence (39%) were recorded in 2018 across 148 countries and territories. At least 41.3 million people are estimated to be living in internal displacement as of the end of 2018—the highest number ever recorded. Another 25.4 million people are currently considered refugees, and 3.1 million are seeking asylum [2].

There are various research-based tools to support humanitarian needs assessments, risk analysis, investment planning, and progress monitoring. However, national and local authorities often lack the technical and financial support to apply them. Other major gaps that decision-makers are still facing, primarily in remote areas, are rapid estimations of the magnitude of a disaster impact as well as the progress of reconstruction and recovery over time, which can be approximated, e.g., via information about the restoration of electricity grids.

Satellite-derived information has shown its added-value for various applications related to development aid or humanitarian decision-support, but has played a relatively minor role in the monitoring of internal displacement.

Activities have concentrated on the estimation of population numbers via building heights from synthetic aperture radar (SAR) [3], the detection of infrastructure

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damage [4] as a proxy for potential population movements in hard-to-reach areas, and the identification of informal settlements or slums [5]. While the use of daytime Earth observation in disaster situations is more established, satellite-based nighttime light (NTL) observations, and their use in the humanitarian domain, specifically to understand the impacts of disasters on population displacement, are new fields of research.

Previous empirical work has established connections between NTL observations and processes linked to human activities. These processes include poverty estimation in Africa [6] or socioeconomic activity in China's cities [7], developments related to urban built-up expansion [8], the timing of energy use [9], or carbon emissions [10]. In the disasters realm, NTL has also been used to track the impacts to and recovery of the electrical grid, and was shown to closely track utility data on recovery in Puerto Rico after Hurricane Maria [11]. Initial explorations with NTL have indicated that temporal light patterns may have value for monitoring short-term population changes, for example, in the case of conflict after the Syrian civil war [12, 13] or in the case of an economic downturn that causes population losses [13]. However, the potential added value of NTL to inform humanitarian decision-support in the area of displacement monitoring remains unknown and, thus, untapped. Empirical assessments on how well and under what conditions NTL can help to monitor displacement are a priority for future research.

This article concentrates on research-based operational applications, aiming to provide insights into how NTL could be integrated into a humanitarian decision-making processes on displacement. Based on the use case of a tropical cyclone named "Idai" that made landfall in Mozambique in March 2019, we present a novel strategic framework to consider the Black Marble dataset as an additional source of information for displacement monitoring, which can be adapted to different scenarios, user requirements, and workflows. Information derived from the Black Marble dataset along with contextual information may help to quantify the long-term impacts of different natural or man-made displacement drivers and the recovery of affected communities (including possible returns, local integrations or resettlements). This article is the first attempt to identify where Black Marble data could fit into the humanitarian decision-making process.

Region of interest

Mozambique is located on the east coast of southern Africa on the Indian Ocean. The coastline measures 2,515 km. About 62% of the total surface (roughly 490,000 of 800,000 km^2) classifies as agricultural land, and 69% of the total population (roughly 20.4 of 29.6 million people) live in rural environments [14]. Although the island of Madagascar often acts as a natural barrier against tropical cyclones,

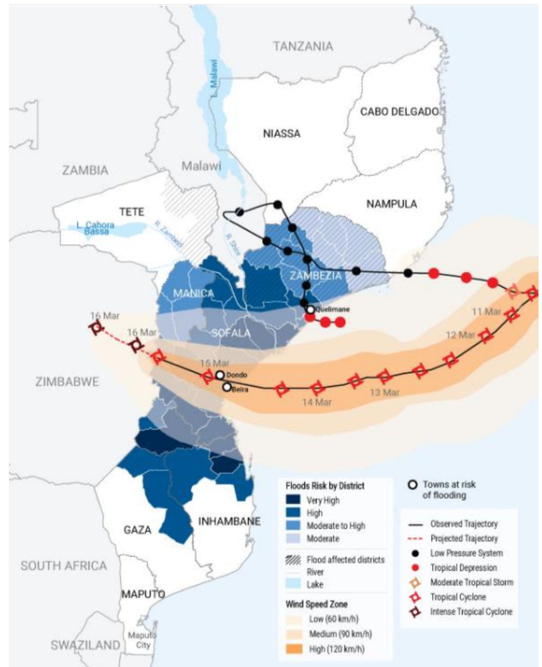

Figure 1

Forecasted trajectory of cyclone Idai.

Mozambique has been hit by severe cyclones in the past—most notably by Cyclone Dineo (February 2017), two years before Cyclone Idai (March 2019) [15]. These and other vulnerabilities are reflected by the Global Facility for Disaster Reduction and Recovery's risk estimates, which rank river/urban/coastal flood and cyclone risk, but also extreme heat and wildfire, as "high."[1]

Due to a tropical depression, the central and northern region of Mozambique was affected by heavy rains since March 4, 2019. Among the 32,222 people affected, at least 4,242 had been sheltered in transit centers, and seven casualties had been recorded [16]. On March 10, the National Institute of Meteorology issued a warning that the tropical depression had formed to a moderate tropical storm, which would later be called Idai. The number of people affected by floods doubled to 62,975, and at least 10,512 sought shelter in 15 transit shelters. In addition, more than 83,000 ha of farmland had been inundated [17]. One day later (March 11), the government of Mozambique decided to call for an emergency meeting of the Coordinating Council of Disaster Management, following the forecasted trajectory of Cyclone Idai (see **Figure 1**) and a projected landfall on March 15.

A budget of US$ 18 million was estimated to cover both food and non-food items for potentially affected people [18].

[1][Online]. Available: http://thinkhazard.org/en/ report/170- mozambique

During the night of March 14 to 15, Cyclone Idai made landfall near the city of Beira in central Mozambique. Based on the projections of people living in the cyclone's path, the UN and humanitarian partners appealed for US$ 40 million to fund vital emergency response operations to 400,000 people [19]. By early April, nearly 200,000 houses had been totally destroyed, damaged, or inundated, with more than 700,000 ha of Cropland flooded [20]. The IDMC estimated that cyclone Idai led to about 478,000 new displacements [21]. On April 29, the number had risen to 1.85 million people in need and more than 11,000 children under the age of 5 severely malnourished, whereas several remote locations remained cut off due to damaged roads [22].

Data and methods

The following section concentrates on a description of the two main data sources for this study: a short message service (SMS)-based survey that estimated displaced people/damages and satellite-derived NTL observations from Black Marble, including an explanation of the methods behind the spatial and temporal NTL analysis used in this article.

Data

Mobile phone data have already shown their added-value for displacement in various disaster situations, such as the assessment of population displacement after the 2015 Nepal earthquake [23]. In the case of Mozambique, an SMS-based survey conducted by Geopoll (www.geopoll.com) was carried out shortly after the cyclone had made landfall on March 21, 2019.

It reached around 700 households, representing over 4,700 individuals, and covered topics related to perceived cyclone strength, destruction level of infrastructure and power grids, road conditions, etc. The Geopoll was anonymized through non-perturbative statistical control methods, which resulted in reduced detail in the data without distorting the structure. However, respondents provided information about their age and gender. Particularly, the disaggregation by gender is crucial for disaster risk management because girls and women tend to be disproportionately highly affected by extreme climate events [24, 25].

The Geopoll assessments were accessed via the Humanitarian Data Exchange Online Portal.[2] The variables "home state" (level of destruction), "cyclone strength," and "electricity" were disaggregated by age group, gender, and province and visualized via software named Tableau. The Geopoll covers (name and location of province in brackets): Beira (Sofala, North), Chimoio (Manica, Central), Massinga (Inhambane, South-east), Maxixe (Inhambane, South-east), and Quelimane (Zambezia, North), and an "NA" (not applicable) category. It does not facilitate any kind of time-series analysis because the Geopoll was designed as a one-time rapid assessment, a snapshot of conditions on the ground directly after cyclone Idai had made landfall.

The second source of information is the Black Marble standard 500 m product (VPN46) [13]. Since 2012, NASA's global nighttime lights product is derived from the Day/Night Band detectors on board the Suomi National Polar-orbiting Partnership Visible Infrared Imaging Radiometer Suite (VIIRS). Black Marble is available in near-real time, with a latency of 3–5 hours between data acquisition and the completion of the processing chain, making it useful for disaster monitoring and emergency response.[3]

Black Marble is a science quality, daily, and global dataset that has been corrected for various artifacts that alter estimates of NTL, such as terrain, snow, vegetation, lunar, and atmospheric effects. Atmospheric corrections are based on a vector radiative transfer model of the atmosphere–land surface system [26] to limit the impact of aerosols, water vapor, and ozone on NTL radiances. Impacts of moonlight, aerosols, and surface albedo are controlled by inverting the bidirectional reflectance distribution function (BRDF). Seasonal variations in vegetation are carried out via a canopy radiative transfer method [13]. We choose Black Marble over other VIIRS-NTL datasets both because of its daily production, which is more useful for monitoring disaster-related displacement, and because it corrects for these non-anthropogenic factors that would significantly alter the light signal over time.

Population estimates were downloaded from NASA's Socioeconomic Data and Applications Center (SEDAC), hosted at Columbia University's Center for International Earth Science Information Network (CIESIN). Version 4 of the dataset is available via the SEDAC online population estimation service[4] and uses 2015 as the baseline.

Methods

The initial impact assessment on the power infrastructure due to the cyclone was established by comparing pre- and post-cyclone Black Marble time-series data. The pre-cyclone period consisted of a typical cloud-free nightlight observation. The most recent clear-sky observation after the cyclone had passed was used to characterize the post-cyclone period. These two periods (March 9–24) were used to create a map identifying the location and severity of power outages. Demographic estimates were calculated by intersecting the hot spot map with gridded population estimates from NASA's SEDAC.

Finally, the combination of both sources of information was discussed with the IDMC along with the results of the Geopoll. These discussions led to the schematic flowchart

[2][Online]. Available: https://data.humdata.org/dataset/mozambique-cyclone-idai-data

[3][Online]. Available: https://blackmarble.gsfc.nasa.gov/

[4][Online]. Available: https://sedac.ciesin.columbia. edu/mapping/popest/pes-v3/

that links the results presented in this study to operational humanitarian workflows. The flowchart aims to identify potential pathways that could be used to integrate the Black Marble dataset into the existing assessment process. The flowchart is centered on one key issue, which is the lack of information about the origin of internally displaced people after natural or man-made emergencies and the temporal patterns underlying the return to their homes. This "pulse" of migration is where assessments derived from Black Marble data will likely have the largest impact on decision-support.

Results

The results of this study concentrate on three interrelated topics.

1) The socioeconomic impact assessment after Cyclone Idai had made landfall on the coast of Mozambique based on the results of the Geopoll.
2) The manifestation of these impacts on the power grid (power outages), represented by time series before and after the cyclone made landfall during the night of March 15, 2019, and a corresponding hot spot map to illustrate the spatial extent of power outages as a proxy for disaster impacts and potential driver for displacement; advanced time-series analysis is limited due to the lack of frequently updated socioeconomic data in Mozambique at high (sub-national) scale.
3) Links between both sources of information in an operational data-driven humanitarian workflow.

The results of the Geopoll survey are summarized in **Figure 2**, whereas the locations of the surveys are illustrated in **Figure 3**. The SMS-based survey is a simple way to conduct rapid damage assessments, but is likely biased by disproportionately higher penetration of mobile technologies among younger people between ages 18 and 24. However, the overall mobile phone penetration rate in Mozambique was nearly 50% already in 2017 [27], resulting in a potentially representative sample in urban areas. The Geopoll survey shows that cyclone strength and infrastructure damage were perceived as the highest/strongest in Beira, Chimoio, and the "NA class," whereas impacts on the power grid seem to have been the strongest in Beira (low counts = few reports on functioning power grids). Overall, more men than women replied to the Geopoll survey. The youngest class of respondents showed the best balance of male and female responders. The Geopoll's strength is that it allows a quick and easy assessment of disaster impacts. However, it provides only a restricted snapshot in time, whose added-value for displacement monitoring is limited.

Figure 4 outlines the temporal evolution of satellite-derived assessments for Cyclone Idai from March 20 to April 4, 2019 to provide the big picture of satellite-based retrievals for the event. The NASA Black Marble time-series observations (see **Figure 5**) are derived from averaging daily radiance of about 20 pixels (randomly selected) within the "power outage" area, i.e., area that went dark when compared with the before (normal) image. We find a significant drop in NTL intensity after Cyclone Idai had made landfall mid-March 2019 (DOY 75). However, there are strong fluctuations/variations in the daily observations caused by variations in the view angle of the VIIRS sensor and cloud cover. The quality assessments for each day of the time series are also included to indicate the retrieval quality of the observation [28]. This delayed the retrieval of the first clear observation until March 21 (DOY 80). At the time of writing, the time series also indicate that the city has not fully recovered from the cyclone's impact and the power restoration process is still ongoing.

Figure 6 represents the impact of Cyclone Idai on Beira's power grid spatially. We estimate that 90% of the power grid was affected. We find that, in line with the cyclone's trajectory, the Eastern parts of Beira were hit a lot harder than the city's West. This is represented by power outage numbers exceeding 80% in the East and less than 30% in the West. Based on Black Marble NTL estimations applied to the latest population estimates from 2015, the total number of people affected in the Beira area alone is around 79,000, whereas the age group of 15–64 years represents the largest fraction with roughly 46,000 people, followed by roughly 32,000 in the age group 0–14. While these numbers are far lower than the official census data, which listed more than 530,000 inhabitants in 2017 [29], the pattern of the power outage is complementary to the damage maps that had been published by the European Commission's Copernicus Emergency Management Service (see **Figure 7**).

Based on the use case of a tropical cyclone, we propose a possible framework to integrate Black Marble data into existing humanitarian decision-making workflows (see **Figure 8**). It starts with the early warning (cyclone trajectory) and available information on population distribution, vulnerability, etc. Once the cyclone makes landfall, it is possible to cross-validate "traditional" satellite-derived damage maps, for instance, inundation maps from radar satellites, and novel information sources, such as georeferenced tweets, with the Black Marble dataset. Ideally, Geopolls or comparable assessments are available before and after the impact of a cyclone to strengthen the cross-validation component. In the case of Cyclone Idai, only an ex-post survey was available.

The Black Marble time series can answer questions regarding the degree of damage in the region because time series can be derived before and after the impact of the cyclone. In parallel, the spatial maps can help to identify geographic hot spots that could require humanitarian assistance. However, both approaches require an in-depth

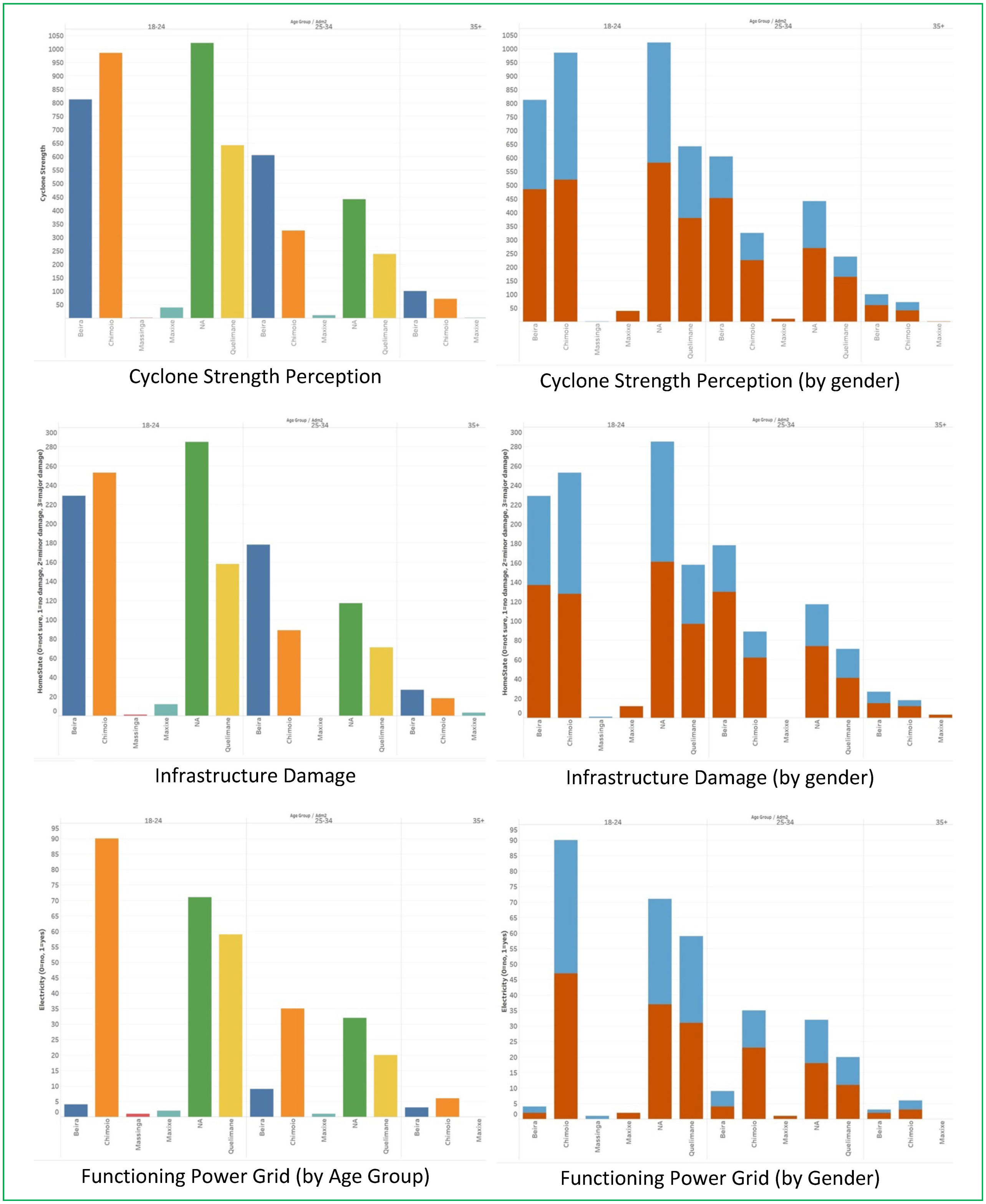

Figure 2

Geopoll results for cyclone strength perception (top), impact on infrastructure/housing (middle), and impact on power grid (bottom) illustrated via sum of Geopoll respondents (y-axis), disaggregated by age group (both columns) and gender (right column, blue = female, red = male).

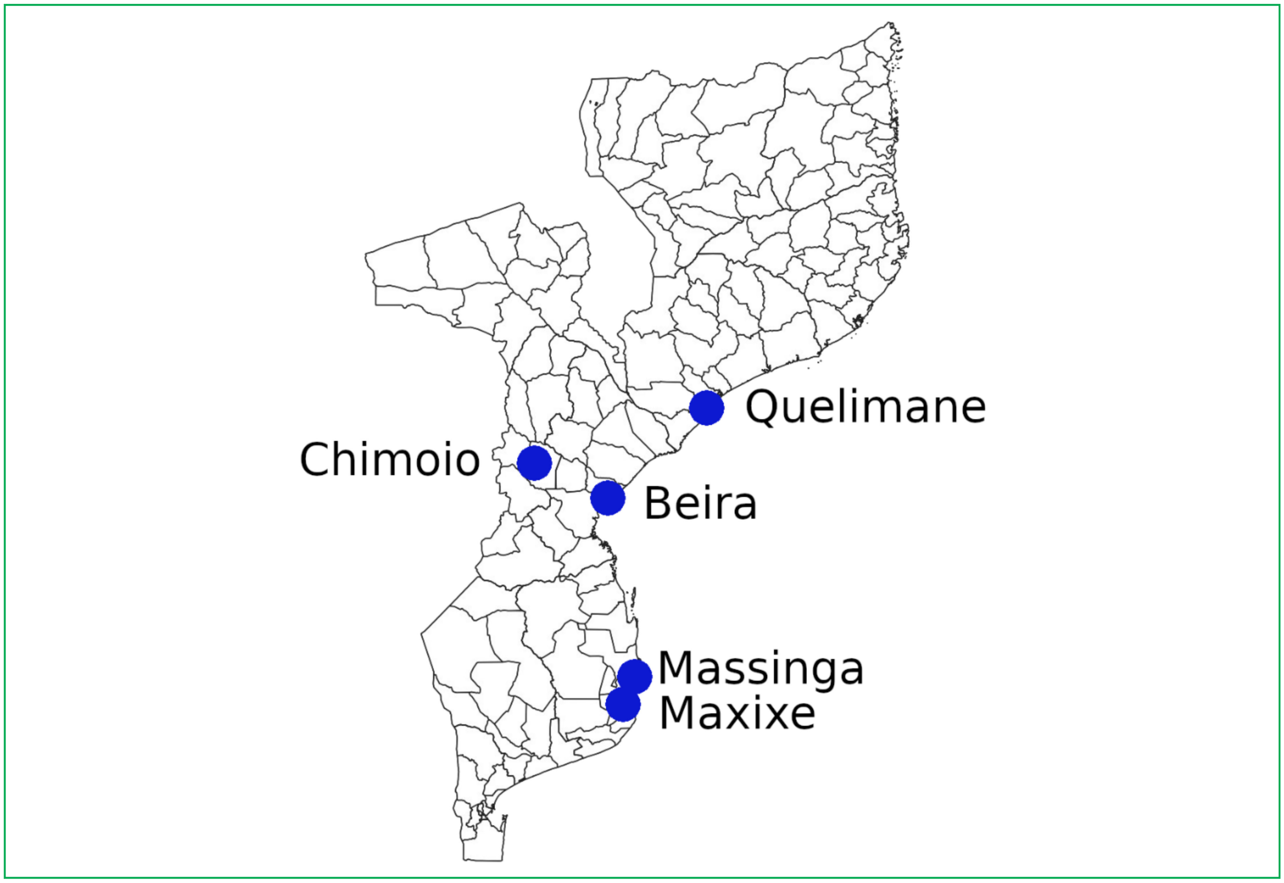

Figure 3

Location of Geopoll surveys.

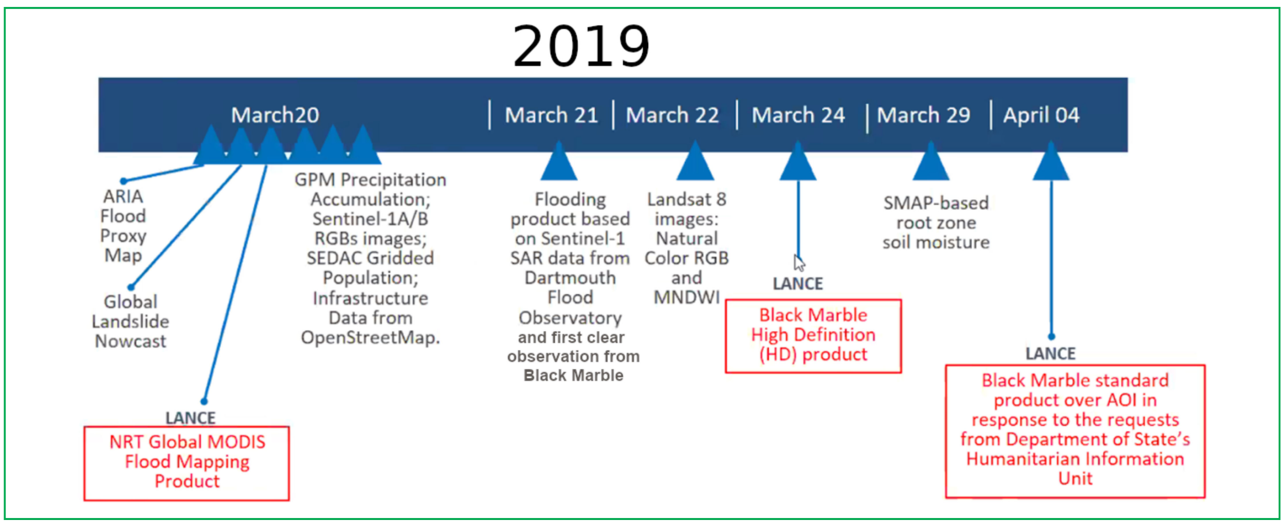

Figure 4

Temporal evolution of satellite-derived assessments for Cyclone Idai from mid-March to April 4, 2019; LANCE = NASA's Land, Atmosphere Near real-time Capability for EOS (Earth Observation System).

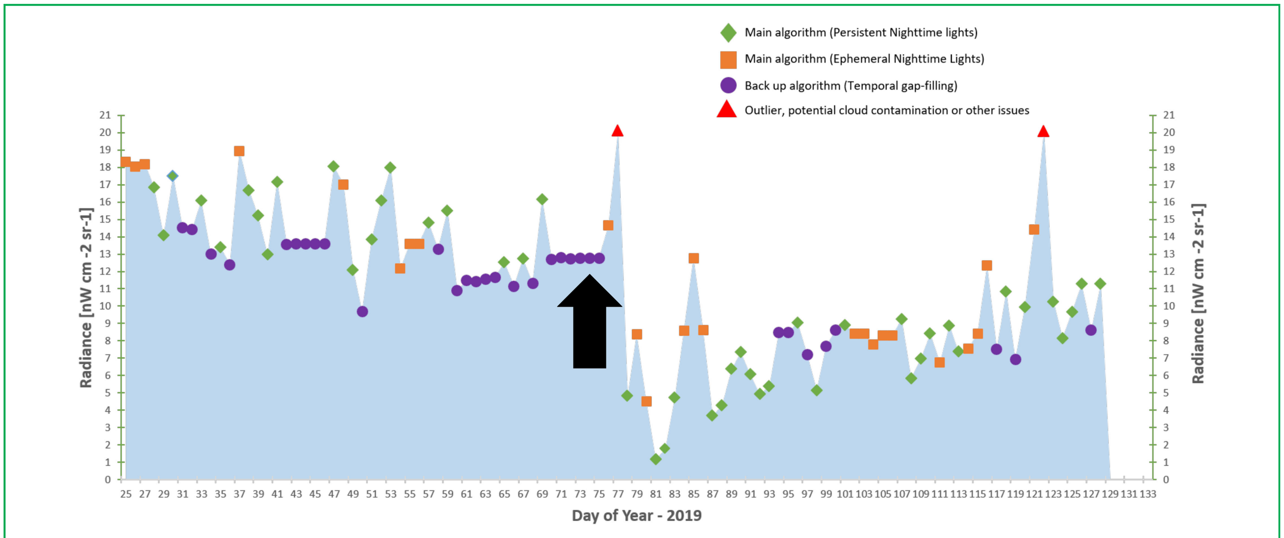

Figure 5

NASA Black Marble time series observations with quality assessment for Beira; Cyclone Idai made landfall on Day of Year (DOY) 75 (15/16 March), illustrated by the black arrow.

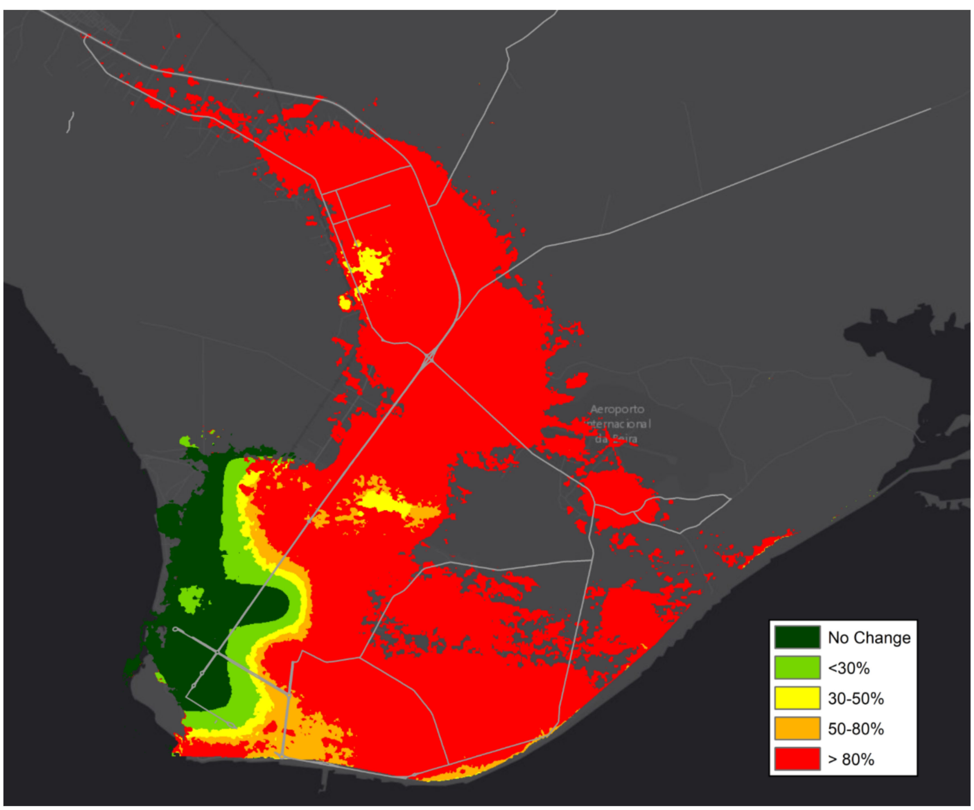

Figure 6

NASA Black Marble power outage estimations for Beira, ranging from dark green (no change) to >80% (red). Gray areas are permanently dark at night. The illustration shows changes in NTL between 9 and 24 March 2019.

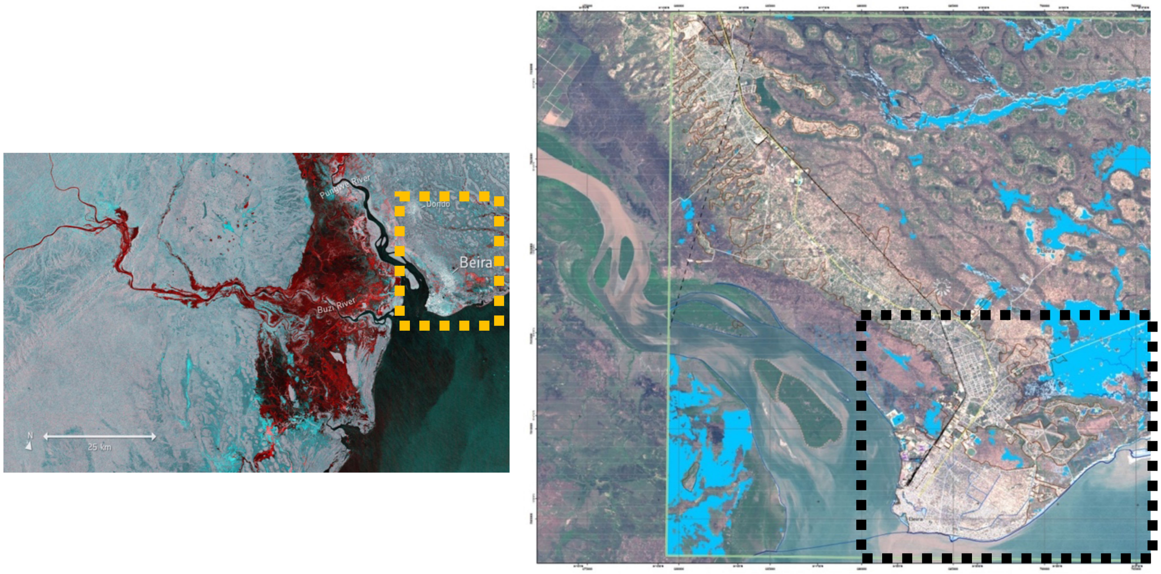

Figure 7

ESA flood extent map for Beira, Mozambique (Beira city area highlighted as a yellow rectangle) derived from Sentinel-1 on March 20, 2019 [34] (left) and Copernicus Emergency Management Service (EMS) activation EMSR348 for Cyclone Idai, published on April 8, 2019 [31]. The black rectangle represents the footprint of the analysis in Figure 6 (covering larger parts of Beira in the East).

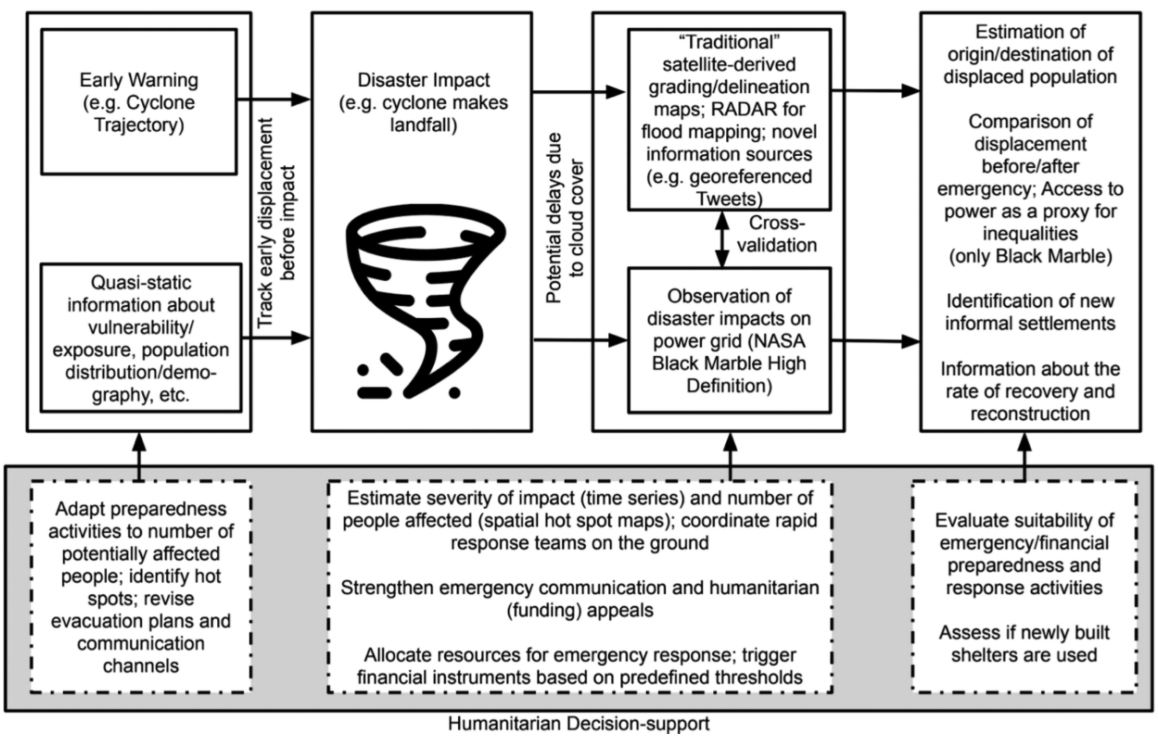

Figure 8

Schematic framework to integrate information derived from Black Marble data into humanitarian decision-support workflows.

understanding of the suitability of NTL anomalies as a proxy for disaster impacts in the region of interest, particularly in areas in which switching off the lights might serve as a coping mechanism (e.g., in social conflict zones) and not a proxy for displacement. If these relationships are well understood, the Black Marble data can strengthen displacement monitoring via different mechanisms. On one hand, Black Marble data can help to estimate both the origin and destination of displaced people. Regarding the latter, the identification of informal settlements and their level of electrification is one major source of information. On the other hand, the Black Marble time series can serve as a temporal reference in addition to change detection maps that usually only compare two snapshots in time—one before and one after the impact. In contrast, Black Marble time series allow us to understand the fluctuation of NTL over longer periods, putting individual extreme events that affect the power grid into perspective.

Conclusion

Satellite-derived information is gradually becoming more powerful regarding the direct monitoring of human behavior. This article aims to identify the added-value of NASA's Black Marble dataset in the context of monitoring internal displacement caused by tropical cyclones. Our use case concentrates on the impact of a tropical cyclone named Idai on the city of Beira in Mozambique in March 2019. The Black Marble time series allow an estimation of disaster impact severity by using the functional efficiency of the power grid as a proxy for people affected. We find that roughly 90% of Beira's power grid was affected by Cyclone Idai, but absolute numbers are questionable due to strong underestimations of the SEDAC/CIESIN dataset compared to the latest official census data from 2017. Future studies will have to investigate NTL anomalies in several potentially affected cities simultaneously, which was not possible for this study due to NASA's focus on the official publication of the Black Marble High Definition dataset and related time constraints.

In addition, the existence of a light source could mean that one family member remained, while the rest of the family got displaced, and the number of people affected does not necessarily correspond to the number of displaced people. However, many assessments of internal displacement only record the destination of the population affected. In this regard, the Black Marble dataset could support estimates regarding their origin, to support needs assessments and provide an understanding of the time of recovery, reconstruction of areas affected, as well as the construction of resettlement areas after the impact of a disaster. Complementary to the time series, the spatial representation of the disaster hot spots, characterized by regions whose power grid has been most severely hit, can help to reinforce decision-support in the area of resource allocation and the coordination of rapid assessment teams on the ground and provide information about areas that require long-term assistance after the emergency phase of a disaster.

If combined with other sources of information, such as satellite-derived flood maps or impact estimations based on social media analytics, the Black Marble dataset can help to improve our understanding of human behavior in the context of disaster risk management from a previously unknown perspective. In the case of an early warning for a tropical cyclone, this might mean relatively straightforward reactions, such as preventive evacuations to safer spots further inland. In the context of social conflict, the non-existence of NTL might not necessarily represent power outages. Switching off the lights might be a coping mechanism that the Black Marble cannot directly explain. However, once these coping mechanisms are clear for particular regions of interest, the Black Marble dataset can again contribute to the development of advanced disaster preparedness and response mechanisms. Such applications will require clear thresholds and an in-depth understanding of existing humanitarian decision-making workflows.

Cloud cover remains an issue, particularly in the context of tropical cyclones, which are naturally associated with low pressure systems. The Black Marble retrieval algorithm produces cloud-free nighttime radiances that have been corrected for atmospheric, terrain, lunar BRDF, thermal, and stray light effects [13]. While the nighttime radiances captured at different view zenith angle and accuracy of cloud mask of the VIIRS sensor might result in some uncertainty in the quality of the observation, a mandatory quality assurance (QA) flag is provided as a separate science data set layer to establish the pixel-specific estimates of retrieval performance of the Black Marble product [28].

Radar sensors, typically used to monitor flood extent, work largely independent from cloud cover. Nevertheless, following an activation of the International Charter Space and Major Disasters by United Nation's Operational Satellite Applications Program UNITAR/UNOSAT on behalf of the International Federation of Red Cross and Red Crescent Societies (IFRC), the first inundation maps for Beira were published on March 26, 2019 [30]. The publication of the first damage/inundation maps for Beira, generated via the Copernicus EMS and based on imagery from Sentinel-1/COSMOSkyMed, took less than 48 hours [31]. The Black Marble dataset was among the first to record the impact of Cyclone Idai with a latency of around 5 days, although heavy cloud cover had impeded reliable measurements of changes in the NTL signal. A comparable latency was recorded for the flood maps derived from NASA's near-real-time global flood mapping services,[5] which is based on the Moderate

[5][Online]. Available: https://floodmap.modaps.eosdis. nasa.gov/

Resolution Imaging Spectroradiometer (MODIS). NTL observations might have the potential to provide valuable information regarding displacement after severe emergencies that other satellite-derived sensors, such as SAR, missed. Particularly in urban areas similar to Beira, which are characterized by vulnerable above-ground power infrastructure, this could mean an added-value for the geographic planning processes of early responders.

In the face of increasing frequency and intensity of hydrometeorological extreme events, such as tropical cyclones or flood events, in large parts of the world; rapid urbanization, particularly in African coastal cities; and rising numbers of internally displaced people, it is becoming more and more important to understand the factors that influence where, when, and which disaster relief and recovery efforts are needed. It is estimated that climate extreme events will force tens of millions of people into poverty, whereas the projected costs for cities could increase up to $314 billion by 2010, an increase of $64 billion from today [32]. In this regard, the Black Marble dataset cannot only help to identify the severity and hot spots of disaster impacts. In combination with assessments on the ground, the Black Marble dataset might shed light on crucial questions aiming to understand if urban areas are simply expanding or "growing into poverty." While measuring the spatial expansion of cities or refugee camps via high-resolution optical satellite data [33] is a well-established approach, the estimation of poverty levels based on electrification, estimated by the Black Marble dataset, could add valuable information to existing humanitarian decision-support systems.

Future applications of the official Black Marble dataset could range from the calibration of financial instruments (e.g., parametric insurance) to an improved understanding of the root causes for displacement (extreme climate vs. social conflict) and the development of new machine learning methods to forecast the actual impact of tropical cyclones, not just their trajectory. What these applications have in common is that they require statistical analyses applied to historical, spatially explicit disaster impact estimates. It would also be possible to decouple migration movements completely from external shocks, such as tropical cyclones, which might allow the use of the Black Marble dataset to anticipate large population movements caused by social conflict or drought—factors that do not affect the functionality of the power grid at all. Finally, the most vital prerequisite for all kinds of new applications or operational services is to build trust among data/service provider and end-users, to foster the willingness of aid organizations to build up internal technical capacities as well as the understanding of data providers with regard to humanitarian decision-making workflows.

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Markus Enenkel *Harvard Humanitarian Initiative Cambridge, MA 02138 USA (menenkel@hsph.harvard.edu)*. Dr. Enenkel is a Senior Research Fellow at Harvard Humanitarian Initiative. He completed his postdoctoral studies at the International Research Institute for Climate and Society, Columbia University (Earth Institute). He received a Bachelor of Science degree in natural resource management from the University of Natural Resources and Life Sciences, Vienna, Austria, a Master of Science degree in natural resource management and ecological engineering from the University of Natural Resources and Life Sciences and Lincoln University, Lincoln, New Zealand, in 2010, and a Ph.D. degree in geodesy and geoinformation from Vienna University, Vienna, Austria, in 2015. His research interests include the added-value of remote sensing for humanitarian decision-support and related financial instruments. In addition to applications of the Black Marble dataset, his publications cover disaster risk management and remote sensing applications in the area of climate services, tropical storms, drought, and food insecurity. He is a Reviewer and Guest Editor for different scientific journals, and a winner of the global space app challenge and the Neptune water award.

Ranjay M. Shrestha *NASA Goddard Space Flight Center/Science Systems and Applications, Inc., Greenbelt, MD 20771 USA (ranjay.m.shrestha@nasa.gov)*. Dr. Shrestha is a Scientific Programmer/Analyst for Science Systems and Applications, Inc., working at the NASA Goddard Space Flight Center. He received an undergraduate degree in computer science and geography information science from the University of Idaho in 2008, and a master's degree in geographic and cartographic sciences and a doctorate degree in earth systems and geoinformation sciences from George Mason University in 2011 and 2017, respectively. During his doctorate, he was a Research Assistant at the Center for Spatial Information Science and Systems (CSISS), George Mason University, focusing on using satellite-based images and products to understand the risk and impact of natural disasters toward agriculture and food security. He is currently part of a scientific team of the NASA Black Marble nighttime light product suite that enables, through tracking power failures over time, monitoring the impact and recovery effort during major disasters and better understanding the state of basic service provision in local communities and how vulnerable populations with poor access to resources are being affected.

Eleonor Stokes *NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA (eleanor.stokes@nasa.gov)*. Dr. Stokes is a Research Scientist and Science PI of the Black Marble Product at NASA Goddard Space Flight Center. She received a Bachelor of Science degree in math and studio art from Dartmouth College, Hanover, NH, USA, in 2004, a Master of Science degree in mechanical engineering from the Massachusetts Institute of Technology, Cambridge, MA, USA, in 2008, and a Ph.D. degree in environmental science from the Yale University School of Forestry and Environmental Studies, New Haven, CT, USA, in 2018. She is a remote sensing and urban land Scientist interested in the planetary impacts of urbanization. Eleanor has seven peer-reviewed publications using Black Marble data and was a NASA Jenkins Fellow when the product was first being developed.

Miguel O. Román *Universities Space Research Association (USRA), Columbia, MD 21046 USA (mroman@usra.edu)*. Dr. Román is the Founding Director of the Earth from Space Institute (EfSI), an independent program of USRA dedicated to supporting the development of long-term strategies for reducing disaster risk and promoting community resilience, using the unique vantage point of space. He received a B.Sc. degree in electrical engineering from the University of Puerto Rico, Mayagüez Campus, Mayaguez, Puerto Rico, in 2004, an M.Eng. degree in systems engineering from Cornell University, Ithaca, NY, USA, in 2005, and a Ph.D. degree in remote sensing from Boston University, Boston, MA, USA, in 2009. Before joining USRA, he served for ten years as a Civil Servant Scientist at NASA's Goddard Space Flight Center, where he pioneered the iconic Black Marble—a suite of satellite products that provide daily global views of Earth at night, with an emphasis on tracking the signatures of recovery across vulnerable communities affected by major disasters. He has also led international activities under the Committee on Earth Observation Satellites (CEOS) and the Group on Earth Observations (GEO). President Barack Obama named him a recipient of the Presidential Early Career Award for Scientists and Engineers (PECASE), the highest honor bestowed by the U.S. government on researchers beginning their independent careers.

Zhuosen Wang *University of Maryland College Park, College Park, MD 20742 USA (zhuosen.wang@nasa.gov).* Dr. Wang has been an Assistant Research Scientist at the Earth System Science Interdisciplinary Center (ESSIC), University of Maryland College Park and NASA Goddard Space Flight Center, Greenbelt, MD, USA. He received a B.S. degree in geography from Beijing Normal University, Beijing, China, 2003, and a Ph.D. degree in geography from Boston University, Boston, MA, USA, in 2011. His areas of interest include monitoring energy services in human settlements using Suomi-NPP VIIRS nighttime light products, modeling and evaluation of the anisotropic characteristics and albedo of the land surface, monitoring the vegetation phenology and climate change, and canopy structure estimation using optical remote sensing and Lidar. He has authored more than 50 publications. He co-leads the CEOS Land Product Validation (LPV) Subgroup Surface Radiation/Albedo Product Validation focus area and serves as Chair of the IEEE Geoscience & Remote Sensing Society (GRSS) Washington, D. C./Northern Virginia Chapter.

Maria Teresa Miranda Espinosa *Internal Displacement Monitoring Center, 1202 Geneva, Switzerland (maria.espinosa@idmc.ch)*. Ms. Espinosa is a Monitoring Expert with IDMC and focuses on monitoring and research of displacement in Europe, Central Asia, Latin America, and the Caribbean. She has a background in environmental engineering at the University Catolic of Bolivia, Cochabamba, Bolivia, and received a master's degree in environmental sciences as well as a certification in geographical information systems (GIS) from the University of Geneva. She joined IDMC in 2016, bringing experience in information management, humanitarian needs, and the analysis of Earth Observations datasets for humanitarian applications in different international NGOs. In 2019, she published an article in the *International Journal on Digital Earth* about the discoverability and accessibility to data and information products linked to essential climate variables, in collaboration with the EnviroSpace Lab University of Geneva, the Institute of Environmental Sciences of the same university, and the GRID-Geneva.

Ivana Hajzmanova *Internal Displacement Monitoring Center, 1202 Geneva, Switzerland (ivana.hajzmanova@idmc.ch)*. Ms. Hajzmanova is a Monitoring Expert at IDMC and focuses on monitoring and research on displacement in MENA and eastern and central Africa. She received a master's degree in human rights and humanitarian action from Sciences Po, Paris, France, and spent one semester studying international law and history of violence at the Graduate Institute of International and Development Studies, Geneva, Switzerland. She joined IDMC in 2016, bringing experience in humanitarian needs and conflict analysis. She has a background in humanitarian and human rights law and previously worked on humanitarian needs analysis and assessment and human rights advocacy with national and international NGOs.

Justin Ginnetti *Internal Displacement Monitoring Center, 1202 Geneva, Switzerland (justin.ginnetti@idmc.ch)*. Mr. Ginnetti is IDMC's Head of Data and Analysis. He received a bachelor's and master's degrees in English literature from the University of Pennsylvania, Philadelphia, PA, USA, and a master's degree in law and diplomacy from the Fletcher School at Tufts University, where he studied climate change-induced displacement and forced migration of agro-pastoralists in the Horn of Africa. He joined IDMC in 2012 after having served as a Policy Officer at the UN's Office of Disaster Risk Reduction (UNISDR), where he worked on the Global Assessment Report. He served as a chapter Scientist and contributing author of the IPCC's Special Report on Extreme Events and Disasters (SREX) and the WMO's guidance on assessing droughts. At IDMC, He and his team are responsible for all of the figures in the Global Report on Internal Displacement and IDMC's efforts to estimate future displacement risk, assess displacement associated with slow-onset hazards, detect incidents of internal displacement, and fill critical data gaps.

Patrick Vinck *Harvard Humanitarian Initiative, Harvard University, Boston, MA 02138 USA (pvinck@hsph.harvard.edu).* Dr. Vinck is the Research Director of the Harvard Humanitarian Initiative. He received a Ph.D. degree in international development from Tulane University in 2006. His research focuses on resilience, peacebuilding, and social cohesion in contexts of mass violence, conflicts, and natural disasters. This research has led him to examine the role of technology and ethics of data in the field. He holds Assistant Professor appointments at the Harvard T. H. Chan School of Public Health and Harvard Medical School and is a Lead Investigator at the Brigham and Women's Hospital. He is the co-founder and Director of KoBoToolbox, a digital data collection platform, and the Data-Pop Alliance, a Big Data partnership with MIT and ODI.