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1. Introduction

As a once-in-100-years pandemic, COVID-19 is changing and reshaping the world. COVID-19 poses grand challenges to human society and drives us to invent new analytical tools to examine the spatiotemporal patterns of the complex system for theories, methodologies, and applications of interdisciplinary research (Yang et al. 2020). The U.S. (US) National Science Foundation (NSF) funded the Spatiotemporal Innovation Center (STC) to conduct a spatiotemporal rapid response to address this global health crisis. Engaging various communities, a diverse team was formed to provide a comprehensive non-medical rapid response to the global COVID-19 pandemic for answering many physically and socially challenging questions. The international team formed by experts and participants from almost every US state and worldwide every time zone including the Geo-Computation Center for Social Sciences at Wuhan University, Tsinghua University, the China Data Institute at Michigan, the University of Queensland in Australia, RMDS Lab at Los Angeles, and many other institutions to achieve the objectives of (1) providing data support for the spatiotemporal study of COVID-19 at local, regional and global levels with information collected and integrated from different sources; (2) facilitating quantitative research on spatial spreading and impacts of COVID-19 with advanced methodology and technology; (3) promoting collaborative research on the spatiotemporal study of COVID-19 on the Spatial Data Lab and Dataverse platforms; and (4) building research capacity for future collaborative projects. In addition to research and development conducted, a series of webinars and a mini virtual workshop were organized to introduce findings and solicit community feedback.

This Special Issue is organized to capture such new developments and findings with a focus on the spatiotemporal analysis of the impact of COVID-19. Research presented in this issue includes studies on theories, methodologies, data and applications, which together help understand the short-term and long-term impacts of COVID-19 on health, demographics, socioeconomics,

environment, politics and other fields over space and time.

The first four papers studied the space-time patterns of the pandemic's impacts in different regions of the world (India/Subramanian et al. this issue, China/Pei et al. this issue, United States/Batta et al. this issue, and 12 secondary cities in 10 developing countries across Africa, Asia and South America/Laituri et al. this issue), examining not only the virus infected cases (Pei et al. this issue) but also the excess death of other diseases (Batta et al. this issue), as well as the pandemic's social, economic and environmental impacts (Laituri et al. this issue). The last four papers explored social media or human mobility data (Shen et al. this issue) in search for their spatiotemporal relationships with COVID-19 transmission (Zhang et al. this issue), non-infectious diseases (Mu et al. this issue), and air quality in an urban metropolis (Li et al. 2022).

At the end of the rapid response project and special issue editing process, we organized a mini workshop with approximately 35 participants to discuss the relevant opportunities and challenges of the pandemic response from a spatiotemporal perspective. This editorial summarizes the findings, challenges, and opportunities from the perspectives of physical and social challenges, data collection, infrastructure operation, computing research, research replication, and community engagement in the COVID-19 rapid response. Social structure and vulnerability as well as convergence science are also practiced as critical components of the COVID-19 rapid response.

2. Physical and social challenges

The scientific findings of the spatiotemporal rapid response project are abundant in addressing many physical and social challenges such as environmental impact, spatiotemporal analytics, health impact of confirmed cases, socio-economic impact, safely reopening campus, and policy efficacy. Specifically,

- (1) The impacts of COVID-19 on environmental factors, such as night-time light, air quality and atmospheric air pollution, are analysed in different

spatiotemporal scales (Liu et al., 2020a). The patterns of these factors are found to have close connections with the pandemic: during the pandemic, both the nighttime light and air pollution reduced over China and recovered after the lockdown orders were lifted (Liu et al. 2020b); most air pollutants are observed to have decrease trend during the lockdown period of California in the US and bounced back after the reopening (Liu et al. 2021a); similar research is also conducted over other countries and the globe such as the United Kingdom, India, Germany, Brazil and South Africa (Liu et al. 2021b; Li et al. 2022). For all the study regions, the pandemic mitigation policies reduced the densities of atmospheric NO₂ over industrial and transportation areas and increased the densities over residential areas. In some region such as India, the atmospheric air pollution even increased to a higher level than pre-pandemic period after economic reopening (Liu et al. 2022). Human activities are dramatically restricted by the spread of the virus and thus the artificial production of air pollution and nighttime light radiances are reduced correspondingly.

- (2) In response to the need for safely reopening schools and campuses amid the COVID-19 pandemic, we utilized a spatiotemporal model that expands upon the base Susceptible, Exposed, Infected, and Recovered (SEIR) model by accounting for multiple variables including testing, masking, symptoms monitoring, and social isolation, among other factors to forecast the potential viral spreading trajectories on-campus settings. The system also recommends policies for decision makers of college campuses and county-level school system reopening. According to evaluations of the model by recorded daily case data from George Mason University and University of North Carolina at Chapel Hill the accuracy of the predicted results is within the range (Lan et al. 2021).
- (3) Social distancing policies have been regarded as effective in containing the rapid spread of COVID-19. We integrate geographical, demographical, and other key factors into a regression-based event study framework, to assess the effectiveness of seven major policies on human mobility and COVID-19 case growth rates, with a spatiotemporal emphasis. The results demonstrate that vaccines, stay-at-home orders, workplace closures, and public information campaigns were most effective in decreasing the

confirmed case growth rate (Li et al. 2021a, 2021b).

- (4) The study finds the spatial distribution of medical resources (hospital beds, ICU beds, and critical care staff) at county level is highly heterogeneous across the U.S. In a spatiotemporal perspective, the visual analytics of established medical resource deficiency index can provide new insights into the U.S. pandemic preparedness and local dynamics relating to medical burdens during the peak period in the COVID-19 pandemic (Sha et al. 2020a).
- (5) Public opinion towards COVID-19 vaccines is analysed spatiotemporally on both national and state scales (Wang et al. 2022). Results show that public engagement towards vaccine-related topics is highly associated with societal public events, such as the first announcement of the Federal Drug Administration (FDA) approving a vaccine. The public sentiment is correlated with the number of newly vaccinated people since the beginning of 2021. The public reception has become more positive as more people get vaccinated. In addition, public opinion is also conducted from different perspectives, including various topics, three brands of vaccines, and different races. It was found that as more people get the vaccine, the public is increasingly satisfied with the administration. After Johnson & Johnson was exposed causing a few cases of blood clots, the public had further discussions about vaccine types and health concerns. As a result, the public sentiment towards Johnson & Johnson also dropped and further led to CDC not recommending it for public use. Racial inequality towards vaccine is also revealed through public opinion analysis. White Americans have a much higher public engagement and a more stable sentiment than minorities, while African Americans have a very unstable sentiment towards vaccines.

Despite the findings derived by this rapid response, many challenges remain, including socioeconomic differences in vaccine distribution, the need for computation environments to improve such that researchers can better collaborate with one another, the inequality in vaccine distribution in some countries (such as India), as well as the fact that the pandemic is fast evolving and how to best handle or live with the global pandemic. It is difficult to come to any definite conclusions or decide how the methodologies will scale over other potential waves. The socioeconomic differences in how

vaccines have been distributed thus far, and plans for future distribution, were a big social justice concern. One prevalent example was the lack of vaccine distribution in India and other developing countries, which has faced drastic inequality in accessing and distributing the COVID-19 vaccine. This raises the question of how this inequality can be addressed to improve the quality of life for (in this example) global citizens as a whole.

Another challenge that can be addressed is the need for improved computation environments, for better large-scale collaborations. It was frequently mentioned that current environments fell short of expectations, and that most group members felt their performances would be improved with faster systems and calculations. The fact remains that the pandemic is not over (New York Times 2022), so this raises the question of how to draw definite conclusions in this early stage? How will current methodologies scale for different waves and variants that emerge?

Specific research opportunities are identified through the research conclusion discussion and the mini workshop as:

- (1) Further improvement of data source and quality assessment;
- (2) The fast-paced research verified the importance of quality of data sources and replicability of research for rapid response to urgent or disastrous events;
- (3) The global scale and increasing availability of global observing and sharing techniques provide global collaboration opportunities;
- (4) The potential to combine different environmental parameters, for example, air pollution and night-time light, to derive more insights that cannot be derived from a single variable;
- (5) The potential to examine and compare the factors behind individual countries' successes in helping, especially, developing countries to fight the pandemic;
- (6) The opportunity to provide science-based health guidelines to the public, such as the benefits of social distancing procedures, mask guidelines, efficiencies of lockdowns, and the spread nature of the virus and social administration of vaccines.

3. Data collection and sustainability

Data service shows the necessity and urgency to develop a well-maintained and well-organized data repository. Our findings, in particular, are focused on the provision of open-access data, effective data

aggregation, and expansion of data to cover more factors. The foundational task that allowed for the research is the establishment and development of a COVID-19 data warehouse (Sha et al. 2020c), open repository (Hu et al. 2020), and portal with virus cases (Sha et al. 2020c), environmental (Liu et al. 0000), and socioeconomic factors for the rapid response (Sha et al. 2020b). It is an effective implementation using open source considering each state in the United States with 1 M+ downloads. Additional research focused on the design and development of the big data collection framework (Sha et al. 2020b), ETL pipelines, data quality control (Sha et al. 2020b), on-demand web crawlers to automate the ingestion of structured and unstructured data from multiple authoritative sources (Lan et al. 2021). This has allowed for gathering daily updated data on the COVID-19 spread, automatically building the historical data covering the global scope, and providing support for research and decision-making. The design, development, and maintenance of a COVID-19 rapid response in a cloud computing environment using web services ensured rapid integration of various functionalities such as a daily updated chronicle of events, live map for global COVID status (PostGIS, GeoServer, leaflet), publication visual analytics of COVID-19 research, as well as dashboards for global COVID cases, medical resource deficiency, campus reopen and many others.

Data collection, distribution and maintenance have their own challenges while helping enable innovations. For example, proper data maintenance and distribution are beneficial in advancing education, cooperation, and predictions for the COVID-19 spread. Recognizing successful solutions in certain countries will help us recover from COVID-19 in other countries. The community discussion also found a requirement to provide tools for other researchers to address resource-intensive challenges. Such sharing will allow for better data as well as faster response to crises like the contemporary COVID-19 pandemic:

- (1) the long-term data maintenance and sources. If most data are sourced from third-party without future maintenance guarantee, it could create a significant issue for projects relying on the data;
- (2) data sharing and privacy, as well as non-public data, for example, local governments have access to more specific data which is not widely available publicly;
- (3) without developed app network for location tracking in the US, we must explore cooperation with private companies; Lastly,
- (4) access to data and data quality is also an important factor with global climate change and the

lack of access to data in rural communities. As the global pandemic showed that cooperation among all countries and communities is needed, and a lack of data in poverty communities should be overcome to prevent potential disasters.

The global scope and impact of these challenges presents an opportunity to expand relevant capabilities and cooperation with institutions across the world.

- (1) Expand data capabilities and cooperation to a global level;
- (2) An automated toolset for updating data with integrated data standardization and an integration framework;
- (3) The security and reliability of the data will allow an increase in the quality of the research as well as for easier access in future studies;
- (4) Close collaboration is needed to address the privacy and proprietary issues of data;
- (5) Development of advanced algorithms (i.e. differential privacy) to ensure the secure access and sharing of sensitive data;
- (6) Expanding big data sources to derived datasets to enrich data for developing countries and rural communities.

4. Cyberinfrastructure

While a good way to address the pandemic challenge, Spatiotemporal studies require an intensive computing infrastructure due to the amount of data, the number of users, and the increasing complexity of principles for convergence sciences. These studies rely on big data analytics, Artificial Intelligence (AI)-based processing, and phenomena simulation that demand significant computing support. The Spatiotemporal Innovation Center built a cross-site centre-wide computing infrastructure in phase 1 to improve computing capability to meet the computing needs. A phase 2 task updated the infrastructure to 600 nodes. The infrastructure consists of three clusters: Message Passing Interface powered High -Performance Cluster (HPC) which provides support to HPC tasks for big data and medium scale simulations, OpenStack Cloud (Superuser et al. 2016) which provides data, information public-oriented services, and Hadoop Distributed File System based Cloud Computing environment (Cloudera Distribution Hadoop – CDH) which allows parallel computing and data backup via distributed storage (Rice et al. 2021). The infrastructure offers opportunities that will benefit the community and boost research in the spatiotemporal domain.

- (1) Hosting COVID-19 applications such as COVID-19 Spatiotemporal Rapid Response Gateway, COVID-19 campus simulation, and COVID-19 Data Scraper (Rice et al. 2021);
- (2) Supporting COVID-19 research such as Air Quality impact during COVID-19, COVID-19 vaccine-related tweets analysis, COVID-19 policy analysis, and COVID-19 related data storage. (Rice et al. 2021);
- (3) The Cloudera Distribution Hadoop cluster will provide parallel computing capabilities to the public since many researchers do not have access to sufficient computing resources for projects that require intensive computation (Rosencrance, Vaughan, and Preslar 2021);
- (4) With third-party integration, this infrastructure will enable strong collaboration within the research community with virtual computing resources shared as cloud resources.

There are majorly three challenges for the operation of such a cluster: project assignment to appropriate clusters, integration with the commercial cloud computing services, and maintenance of secured network environments. Project assignment to appropriate clusters will ensure optimal performance and proper usage of computing resources. Integrating this infrastructure with commercial cloud is necessary for maximizing community-wide collaboration. The current infrastructure is behind the GMU and data centre firewalls, which restrict public access. Public users benefit from the services provided by the infrastructure via a hybrid cloud infrastructure, which grants them access to public services and restricts direct access to the servers (Rani and Ranjan 2014). Currently, guest users may apply to obtain administrator privileges to access the infrastructure through an approval process, but third-party integration will allow researchers to access the infrastructure with regulatory procedures (Rice et al. 2021). Although cybersecurity measures are currently in place, including two-way authentication, OpenStack's security tools (Turjak n.d.), the GMU firewall, and the router-on-a-stick configuration, the infrastructure requires stronger security for addressing both external network attacks and internal transparency for guests who have direct access to the servers (Chow 2015; Zissis and Lekkas 2010). In summary, the computing infrastructure requires further research in the following areas.

- (1) Methodology to assess computational requirements for projects;
- (2) Security tools and operations to ensure the infrastructure's integrity;

- (3) Transparent integration with commercial cloud computing resources.

5. Computing and network research

Computing and network research have played a major role in the COVID-19 research. Since the onset of the pandemic, computing and network applications have been applied towards a variety of different use cases ranging from deep learning for telemedicine applications to network tracing to curb viral transmissions. The field of deep learning alone contains many COVID-19 applications including natural language processing for information retrieval and misinformation detection, computer vision applications for medical image analysis and vision-based robotics, and life science applications for precision diagnostics, protein structure prediction, and drug repurposing (Shorten, Khoshgoftaar, and Furht 2021). With the increased amount of environmental data available since the start of the pandemic, computing and network research have enabled findings such as significant reductions in environmental pollution in countries with severe COVID-19 transmissions (Shakil et al. 2020). Bioinformatics computing research enabled much pandemic research such as tracking with epidemiological models and sharing datasets to boost discovery (Hufsky et al. 2021). Computing and network research continues to be important for researchers in the COVID-19 research with several common pitfalls, potential limitations, and gaps. Many computing and network research methodologies rely on high-quality datasets for optimal results, but the lack of quality public COVID-19 personal-level datasets may result in limitations for researchers. Ethical oversight is necessary for the protection of patient privacy in applications such as contact tracing, and the computing and network research field must adapt to meet the ethical guidelines present (Morley et al. 2020).

Three challenges are identified in the computing and networking COVID-19 research:

- (1) accessibility to high quality and data of privacy concerns: COVID-19 data including patient mobility data and individual mobility data is hard for researchers to access, especially because many datasets containing private patient data including those from the CDC are usually censored to protect patient privacy. Working with censored or partially missing datasets may present a challenge to researchers or impact the quality of the research conducted. This challenge also presents an important discussion in ethical data guidelines, and the establishment of necessary measures including the consent of the parties involved as well as the safe storage and subsequent deletion of data to encourage responsible data usage.
- (2) the optimization of machine learning and deep learning models for higher accuracy and performance: Usage of deep learning methodologies and approaches has been prevalent throughout COVID-19 research, and model optimization is an ongoing challenge faced by researchers who seek to answer specific questions during the pandemic as well as to increase the accuracy and performance of their models. Deep learning has played and will continue to play a significant role in COVID-19 research, with applications ranging from spread forecasting to misinformation detection, but faces limitations including the lack of labelled training data as well as generalized metrics.
- (3) the development of contact tracing tools based on network analysis for real-time notifications and anomaly identification: The lack of contact tracing tools (tools providing the end user with real-time notifications) based on network analysis is a grand challenge that has yet to be tackled by COVID-19 researchers. Once established, such a tool would increase the capabilities of existing technologies responsible for rapidly alerting individuals when they have been in contact with someone infected with COVID-19 and strategies aimed at bringing the pandemic under control.

While the challenges above should be taken into consideration, opportunities in the computing and network research space are prevalent including 1) the increased availability of certain types of data during the pandemic, 2) providing valuable tools and literature collections for future pandemics as well as related research work, and 3) establishing a collection identifying overlooked aspects in the research process.:

- (1) Continue to open the data such as social media Twitter and Facebook and environmental data;
- (2) The prevalence of research conducted on the COVID-19 pandemic allows for valuable tools and literature collections to be established as a resource for future pandemics as well as related research work;
- (3) The lack of readily available research material at the start of the pandemic contributed to its enormous impact on society;
- (4) The high rate of COVID-19 research output by researchers have resulted in overlooked aspects

including overfitting and bias in deep learning models as well as the presence of the modifiable areal unit problem (MAUP) in spatial analysis;

- (5) Overlooked areas in the research process are important to ensure the quality of future research with community impact;
- (6) Spatiotemporal computing is important to support building and evaluating models at multiple scales, enabling visualization, asking additional questions, generating hypotheses.

6. Reproducibility

The reproducibility is vital for COVID research because it provides transparency and clarity in findings. However, the reproducibility problem is a familiar issue in both the scientific community and the general public (Buck 2015; McNutt 2014). A survey conducted by Nature found that more than 70% of researchers have failed to reproduce another scientist's studies, and more than 50% have failed to reproduce their own experiments (Baker 2016). In the COVID-19 pandemic, for example, models for projecting infectious disease spread have always played a vital role in informing public health policy worldwide. Researchers from cross-disciplinary communities have been developing many new models since the beginning of the pandemic. Making the models reproducible can significantly facilitate cross-disciplinary researchers to evaluate models' reliability, develop new models and apply the model to different regions. However, sharing data and source code is necessary, but not sufficient, to make research reproducible. There are several main challenges when reproducing existing research: 1) unavailable dataset, Some data are private or too large to share, making it different for public access; 2) different environment, different operating systems, computing environments, software, and library versions, make it difficult to replicate the process and reproduce results the same as original research; 3) lack of documentation, many COVID-19 studies require a well-documented set of apriori decisions that set the parameters of analysis. While those parameters can affect the results of a study, researchers from different disciplines typically do not have complete knowledge of their actual values. This lack of knowledge widens the range of reasonable specifications a researcher might expect.

The challenges also brought some new opportunities for reproducible and replicable research:

- (1) Establishing an open framework with global standards for reproducibility and replicability. The framework enables capturing various aspects of the research lifecycle, including built environment (i.e.

operation system, tools, and packages), sharing and analysing collected data, results demonstration, and drafting reports or papers;

- (2) Providing an integrated open environment for data, source code sharing and results preview. With the standard, an open platform facilitates researchers to share data and code freely. The platform also provides an environment running the code based on users predefined configurations and previewing the results;
- (3) Developing reproducible research workflow models. Easy-to-use scientific workflows for reproducible, replicable, and expandable data analysis is a promising direction. Python Jupyter Notebook and R Markdown have been widely used to turn the analyses into high-quality documents, reports, and presentations with codes. Emerging interactive workflow tools (i.e. KNIME and Alteryx) facilitate cross-disciplinary researchers to implement the processes of data pre-processing, analysis, modelling, and visualization in a WYSIWYG (what you see is what you get) fashion.

7. Community engagement

Contagious disease spread is a community process which engages various levels from individual, family, neighbourhood, community, to society. To understand and control the spread process, we need to conduct community-based research and there are several components in community engagement for spatiotemporal research of rapid response to COVID-19. These include the engagement of the multi-disciplinary research communities for participation in the collaboration; the engagement of decision makers at all levels for providing research questions and implementing research outcomes; the engagement of industry and other organizations for sharing data, tools, and technology; and the engagement of the public at large for education, training, and workforce development. Research communities have been widely and highly mobilized by the pandemic. There was no lack of will in collaboration, though there is much room for improvement in coordination and communication, especially between computing sciences and biomedical sciences. Spatiotemporal research may play a larger role in bridging multi-disciplinary research communities as it provides a common framework (space-time) for scientific inquiry.

It is more challenging to engage decision makers at all levels, for most of them are preoccupied by urgent COVID-19 response issues in daily operation, thus can hardly spare any time or attention on research initiatives. However, their participation in such rapid response

research is critically important. There is much work to be done in improving communication effectiveness to this community, to entice their input in the entire research lifecycle. Engagement with industry and other organizations for data, tools and technology sharing has been an instrumental component in the success of this research. However, there are many challenges as well as opportunities in this area. First, there is severe inequality in data availability, accessibility, and quality. This makes it extremely hard to conduct comparative studies. Even though there are many new innovative ways to harness data through the Internet of Things, some foundational data are still missing or not available in the public domain for a rapid response to a global pandemic. One opportunity is to engage local volunteers in data collection, while helping them to establish standards and provide training and coordination. Moreover, privacy protection is a critical issue, especially when contact tracing and baseline health conditions are such key factors in COVID-19 response. Even though differential privacy algorithms are proven solutions for desensitizing data, most differential privacy libraries do not consider spatiotemporal properties of the data, thus may not be as statistically reliable when applied to spatiotemporal data. On the other hand, no matter what desensitizing method to use, there is always a tradeoff between privacy protection and accuracy. Considering how widely different privacy is viewed and handled in various parts of the world, the COVID-19 pandemic also provided an opportunity to study the effectiveness and impacts of different approaches, and if possible, quantify the tradeoff between saving lives and protecting privacy using different response measures.

Public engagement will be essential in the comparative study of privacy protection as well as many other issues, such as how to combat misinformation, how to evaluate the effectiveness of public education on health risks, and how to predict public response to policies on pandemic prevention measures.

Some examples of public input in future research topics include:

- (1) the intersection of pandemics with other disasters, the effect of inequality on pandemic vulnerability and impact;
- (2) the new way of life after the pandemic, such as virtual connection, remote participation, e-commerce, etc.; and
- (3) its impact on work-life balance.

8. Summary

A number of experiences are observed as: a) spatiotemporal studies including thinking, computing and applications expand to workforces, and social interactions are critical for addressing the global problem to form a rapid response infrastructure; b) a well-conceived and implemented computing infrastructure leveraging the advantages of high performance computing, cloud computing, GPU computing, and network system is critical to enable solutions for such a multi-faceted

Various aspects	Challenges	Opportunities
Data	Automatic long-term collection, share and use of spatiotemporal data	Expand our capabilities and cooperation with institutions across the world.
	Data sharing and security	Consider the implementation of integrated data standardization, an integration framework, and ensure integration and data integrity from a variety of data sources
	Data availability and quality for countries in the global community and rural areas	Aim to work towards using big data sources to derived datasets to enrich data in developing countries
Infrastructure	Decide the best type of cyberinfrastructure for each project	Host public applications for research groups
	Maintain high standard of security	Provide secured parallel computing services
	Expand existing computing resources with commercial cloud platforms	Strengthen collaboration with other research groups community- and world-wide
Computing & Networking	Access to high quality and private data while considering data ethics	Ensure availability of needed data to combat the global pandemic
	Optimize ML and DL models to get higher accuracy and performance	Provide valuable tools and literatures for future pandemics/ related research works
	Contact tracing tools based on network analysis to notify people in real-time	Establish guidelines for researchers to identify overlooked aspects
Science & Application	socioeconomic differences in vaccine distribution	the opportunity to further improve upon data source and quality assessment
	the need for computation environments	methodologies for rapid response research
	inequality in vaccine distribution	replicable research, the opportunity to expand accessibility of data to countries who currently lack access

(Continued)

(Continued).

Various aspects	Challenges	Opportunities
social structure and its role in spreading and controlling	Lack of theory model to simulate the viral cases spreading in multi-scales	Develop a cross-domain model based on social science and public health knowledge from big data accessing/monitoring availability
	Racial disparities in COVID-19 transmission	Investigate racial characteristics in COVID-19 transmissions and explore its relations to socio-economic, demographic, and environment factors in multiple geographic scales
	Inequalities in access to healthcare and health outcomes for different groups	Prioritize equity across sectors and provide resources to support efforts to advance equity
Cross Disciplines/Converging Science	How to ensure effective communication cross domains?	Standard framework, thinking, methods, and tools
	How to create a collaborative and engaging interdisciplinary environment?	Foster cross domain collaborations, facilitate cross domain discussion, and results sharing
Replicability	Knowledge structure may not be enough	New or emerging science and research fields
	How to make replicable research feasible for a wide range of researchers from different backgrounds?	Enhance recognition and citation by promoting replicability.
	How to facilitate the global research community to replicate the research efforts conducted?	Foster collaboration among researchers across the globe.
	What are the best coding practices and internal standards that we can adapt to make replication easy and reliable?	Adopt live coding practices for open-source collaboration and interactive computing.
Community Engagement	Data inequality	Engage volunteers in data collection, establish standards, provide coordination
	Combat misinformation	Improve education for the public on COVID-19 as a health risk
	Balance privacy protection and pandemic control	Study different privacy protection approaches. Apply differential privacy algorithms on spatiotemporal data

problem; c) engagement and collaboration among various domain scientists is key to initializing and identifying critical research aspects to combat the global pandemic; d) collecting, collocating, and fusing big spatiotemporal data into an analysis-ready fashion for

further studies; e) emerging spatiotemporal computing research including network mobility, supply chain and logistics, anomaly identification, and bottleneck detection provides enabling capabilities to process big data. Such capabilities are important to extract knowledge and identify potential solution to simulate the evolution of the pandemic and potential solutions; f) sharing spirit and capability of producing reproducible results are also critical elements to enable such a global, broadly impactful, and dynamic response.

The COVID-19 pandemic is still evolving even with some effective vaccines developed and administered in the U.S. and many countries. Challenges are grand before we can control the spread and resume a revised global normalcy, when COVID-19 becomes a long-term disease like the flu but with annually updated vaccines that can help control the spreading and severity of symptoms. These challenges, including scientific, quality of data and information, as well as community disparity issues, call for innovations at various aspects.

The innovation opportunities include advancements in almost all spheres which have been impacted. For example, development of evolved or new vaccines to combat new virus variants. Operational and administration strategies should be optimized for more effectiveness in prioritizing vaccination and goods coordination based on the balance of overall spreading of the virus and minimizing socio economic impacts. Adjustment in domain research and especially in convergence or cross disciplines that can address complex challenges like the global pandemic. Specifically, to the spatiotemporal rapid response, we identified the following challenges and innovation opportunities:

The top 3 challenges and innovations from each aspect of the spatiotemporal rapid response:

With the top three challenges and opportunities identified for each major theme, we hope this editorial shed some light for further innovation to enable our fight against the global pandemic as well as prepare us for future pandemics and similar disasters.

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