Unprecedented Climate Change in India and a Three-Pronged Method for Reliable Weather and Climate Prediction

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India, one of the most disaster-prone countries in the world, has suffered severe economic losses as well as life losses as per the World Focus report. More than 80% of its land and more than 50 million of its people are affected by weather disasters. Disaster mitigation necessitates reliable future predictions, which need focused climate change research. From the climate change perspective, the summer monsoon, the main lifeline of India, is predicted to change very adversely. The duration of the rainy season is going to shrink, and pre-monsoon drying can also occur. These future changes can impact the increase of vector-borne diseases, such as malaria, dengue, and others. In another recent study, 29 world experts from various institutions found that the largest exposure to disasters, such as tropical cyclones (TCs), river floods, droughts, and heat waves, is over India. For improved and skillful prediction, we suggest a three-stage cumulative method, namely, K is for observational analysis, U is for knowledge and understanding, and M is for modeling and prediction. In this brief note, we report our perspective of imminent weather disasters to India, namely, monsoons and TCs, and how the weather and climate forecasting can be improved, leading to better climate change adaptation.

Keywords: KUM method, extreme weather, human suffering, tropical cyclone, monsoon, Indian summer monsoon (ISM)

INTRODUCTION

The Indian economy still significantly depends on agriculture, which, in turn, depends on the summer monsoon rains occurring from June to September. In the present scenario of climate change, it is essential to know how the Indian summer monsoon rainfall is going to change in the future. In a recent detailed study with regional climate model projections, Ashfaq et al. (2020) suggest that an important adverse signal of future climate change over the Indian monsoon region in the RCP8.5 scenario (Krishnan et al., 2020; Jyoteeshkumar Reddy et al., 2021) can occur. The sinking of the Indian monsoon rainy season onset is projected to delay by five to eight pentads and a shrinking of the monsoon rainy season. India can experience pre-monsoon drying as well.

1World focus-special issue July 2014, editorial (peer-reviewed, refereed research journal).
In a recent innovative study, 29 world experts (Lange et al., 2020) from different institutions and different countries, reached some important conclusions. These inferences deserve urgent attention and action plans by policymakers. They considered six categories of extreme climate impact events, namely, river floods, cyclones, crop failures, wildfires, heat waves, and droughts. These authors (Lange et al., 2020) quantified the pure effect of climate change on the exposure of the global population to the events mentioned. One important conclusion, which is of grave concern to India, is that the largest increase in exposure is projected here. Thus, to avoid huge damages due to these disasters, such as deaths and loss of property, urgent and more reliable predictions are needed. We, however, must clarify that there has been tremendous improvement in numerical prediction of tropical cyclones (TCs) in the last few decades in India [e.g., Pattanaik and Mohapatra, 2021; Saranya Ganesh et al., 2021; Sarkar et al., 2021, and all other papers in January 2021 of Mausam, a special issue on the state of the art on TC prediction in the North Indian Ocean (NIO)], but what we claim is that applying theory can enhance the skills from the current day model outputs substantially more as discussed in the following section. To provide an analogy, in a recent study, Rao et al. (2021) attempted to connect observations, theory, and a prediction plan for heat waves. This prediction method can be applied to a numerical weather prediction model to predict deadly heat waves; thus, Rao et al. (2021) used a K, U, and M approach for the prediction of deadly heat waves over India.

From the context of the three-pronged K, U, and M method (hereafter, KUM), there are sufficient observational studies, or K, and also some attempts have been made using highly sophisticated, state-of-the-art (atmosphere and ocean) coupled models for predictions, M. What is most lacking, however, are theoretical studies (U) aiming to find out the causes for disastrous TCs or the highly complex regional monsoons.

According to a recent 2021 overview of current research results by the Geophysical Fluid Dynamics Laboratory of Global Warming and Hurricanes, the severity and frequency of TCs are increasing globally. A recent study (Balaguru et al., 2015) also suggests an increase of TCs globally even over the NIO. Essentially, the increase in the strong TCs has far-reaching implications for society because these include the most harmful aspects, namely, storm surges and heavy rains with intense wind speeds. Indeed, TC rainfall rates will possibly increase in the future due to various anthropogenic effects and accompanying increases in atmospheric moisture. Rapid intensification of TCs poses forecast challenges and increased risks for coastal communities (Emanuel, 2017). Recent modeling studies (Emanuel, 2020) show an increase of 10–15% for precipitation rates averaged within about 100 km of the cyclone for a 2°C global warming scenario. As per IPCC AR5, higher levels of coastal flooding due to TCs are expected to occur, all else assumed to be constant due to rising sea levels. In this situation, together with the rise in sea level, the impact due to the strong TCs deteriorates the conditions of the increasing coastal population across India and the neighborhood. As the NIO is one of the typical regions with a population of 1.353 billion (2018), about 18% of the global population by 2020, it is highly susceptible to strong TCs causing adverse living conditions, and the implication is that stronger TCs will be worse.

According to reports from a respected BBC newspaper3-4, and a potential report5 from the Indian Meteorological Department, Amphan is a very severe cyclone that transited the west coast of India in 2020 and also caused a lot of damage. The super cyclonic storm Amphan is the costliest case in the recorded history of TCs with damage of US$15.78 billion and also total fatalities of 269. Similarly, in the year 2019, a loss of US$11 billion occurred due to TCs. In the year 2020, there was a record-breaking occurrence of eight TCs over the NIO: five cyclones and three major cyclones compared to the climatology of 4.9, 1.5, and 0.7. We note a drastic increase in category 3 and beyond hurricanes occurring in the NIO and also a significant increase in the Northern and Southern hemispheres (Figure 1). Also, there is a substantial increase in accumulated cyclone energy (ACE) in the last two decades in the NIO and Northern and Southern hemispheres (Figure 2). In 2019, record-breaking ACE of 85 × 10^4 knots^2 occurred in the NIO, nearly twice the previous record (Singh et al., 2021; Wang et al., 2021, BAMS). The decrease in the projected number of TCs found in some studies (Sugi et al., 2017) is overcompensated by the huge increase in intensity similar to that found over the NIO in 2019 and 2020. Furthermore, as if to worsen the situation in a colloquial sense, Wang and Murakami (2020) show that the general atmospheric and ocean parameters, which show a high global correlation with the number of TCs, nevertheless show only a very low correlation with TCs of the NIO. Thus, urgent research should be carried out to understand the causes of the occurrence of TCs over the NIO. Even globally, in the last 39 years (1980–2018), weather disasters caused about 23,000 fatalities and US$100 billion in damages worldwide. Each year, weather events displace huge populations, drive people into poverty, and dampen economic growth globally (Kousky, 2014; Munich, 2020; Hoegh-Guldberg et al., in press). The underlying causes show a marked signal of anthropogenic roots and global warming (e.g., Sobel et al., 2016; Im et al., 2017).

Henceforth, we focus on the TCs as well as summer monsoons, which are the two most relevant weather and climate phenomena for the Indian region.

### A THREE-STAGE METHOD TO STUDY AND PLAN RELIABLE PREDICTION

Because India is rigorously prone to natural disasters as well as impacts due to anticipated changes in the summer monsoon in the future, there is indeed a serious question as to how to study the causal mechanisms of these disasters and plan to mitigate them. In this context, the late Gill (1985), an accomplished geosciences expert, suggested almost 35 years ago the KUM method, namely, knowledge, understanding, and modeling, a three-pronged approach. The first step (K) is to improve

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3[https://www.bbc.com/news/world-asia-india-52749935](https://www.bbc.com/news/world-asia-india-52749935)

4[https://en.wikipedia.org/wiki/2020_North_Indian_Ocean_cyclone_season](https://en.wikipedia.org/wiki/2020_North_Indian_Ocean_cyclone_season)

5[https://mausam.imd.gov.in/Forecast/marquee_data/indian111.pdf](https://mausam.imd.gov.in/Forecast/marquee_data/indian111.pdf)
observational knowledge of calamity-causing weather events and next a theoretical understanding to find out the cause of a specific effect, probably utilizing linear analytical mathematical solutions (U). Finally, the third one (M), using the presently available highly complex coupled (atmosphere and ocean) models giving numerical solutions to non-linear equations, pioneered by Phillips (1956), predicting future occurrences. The order of KUM seems to be important. Although relatively substantial observational results are available in the Indian context for meteorological and oceanographic events, very few theoretical studies have been made delineating the causal mechanisms. Thus, this aspect should be given priority. In a recent comment, Emanuel (2020) also stressed the need for theoretical studies. Finally, only after acquiring the observational, knowledge, and cause-and-effect relationships in theoretical studies, only then, should one embark on numerical or climate modeling to successfully predict the future.

In this context, it is illuminating to recall the comments of Phillips (1970), one of the founding fathers of theoretical meteorology and numerical weather prediction: “in making a numerical forecast, one takes a set of numbers...regardless of...synoptic structures...by another set of numbers, representing the forecast. The computation of a set of numbers depicting the formation of a front, is of course, not a theory of fronts (unless one is content to point to the equation of motion as theory!!!!!!)” Thus, one should be very careful using numerical models to develop a theory of TCs, and in the Indian context, monsoon depressions (MDs) are crucial for monsoon
Today, many students and scientists worldwide spend most of their valuable time dealing with huge data sets and running numerical models to simulate rather than to develop a theory. Tellingly, Emanuel (2020), mentions that presently there is “computing too much and thinking too little.” Indeed, there is an urgent need for curiosity-driven theoretical research even in the Indian context. One interesting example to stress the importance of theory is, today, that the best numerical weather prediction is in mid and high latitudes in winter. This is because the basic theory behind the mechanism of winter weather changes, the baroclinic instability, was discovered more than 70 years ago by Charney (1947), and models and observations evolved accordingly. Thus, it is important to realize, without the correct understanding of the causal mechanisms through theory, one will never be able to predict correctly and completely the required weather or climate or its changes with just the brute force of computers available today!!!

**TCS OVER THE NIO**

Regarding the theory of the generation mechanisms of TCs, there are two well-known hypotheses, namely, (a) the conditional instability of the second kind (CISK) and (b) wind-induced surface heat exchange (WISHE) (please refer to Tomassini, 2020 for a comprehensive discussion of these two processes). A detailed discussion of these two is beyond the scope of the
present short article. However, the authors quickly discuss these
two mechanisms in the context of TCs over NIO.

In the case of TCs, the pre-synoptic disturbances get their
energy by the complex interaction of two different horizontal
scales, namely, cumulus convection of about 1 km and synoptic
systems of about 500 km. How this interaction happens is a topic
of debate, though, and most of the research in the published
literature is about TCs in tropical ocean basins other than the
NIO region.

Briefly, we discuss the basic characteristics of CISK and quasi-
equilibrium (or WISHE). In the process of CISK, the buoyant
convection can occur only when low-level stability is weakened
(see Figure 2; Ooyama, 1969), and in the other, moist convection
is governed by the vertically integrated measure of instability.
As noted by Tomassini (2020), meteorological conditions vary
greatly from one region to the other in the tropics and also
in the same region from one season to another (see Ashok
et al., 2000; Rao et al., 2000; Raymond et al., 2015). Raymond
mentions two tropical places, Sahel and the Western Pacific,
where conditions are very different. Now, how do the conditions
vary, during (i) pre-monsoon, (ii) MDs, and (iii) post-monsoon
TCs? Similar to Bony et al. (2017), we suggest that more detailed
observations of both satellite measurements and data developed
in field programs should be used to understand the convection
and circulation coupling of TCs over NIO. For example, the
INCOMPASS IOP field program, which collects data from
strategically installed ground-based instruments in India, is one
such program (Fletcher et al., 2018).

Another, synoptic disturbance of importance is a MD. Despite
several observational and theoretical studies by many
authors (for example, Sikka, 1977; Mishra and Salvekar, 1979;
Aravequia et al., 1995; Boos et al., 2017) trying to understand
the basic mechanism of origin, some fundamental questions
remain unanswered. Similar to TCs, the lack of understanding
of how convection and MD circulation couple hinders the
prediction. For both TCs and MDs, we suggest analyzing time
vertical sections of potential temperature, equivalent potential
temperature, and saturated equivalent potential temperature
such that one can get an idea of the relative importance of CISK
or the quasi-equilibrium hypothesis discussed briefly above.

Another method for elucidating the study is to examine the
system’s energetics, i.e., TCs or MDs. Lorenz (1960) mentions,
“one enlightening method of studying the behaviour of the
atmosphere, or a portion of it, consists of examining the
behaviour of the energy involved.” Earlier Mishra and Rao (2001)
used limited area energetics to infer the mechanism of generation
of Northeast Brazil’s upper tropospheric vortices. Also, Rao and
Rajamani (1972) examined the energetics of MDs. These methods
of energy analysis, for example, can be used to isolate or single out
the basic mechanism of generation of TCs or MDs, using more
recent well-covered data, such as the INCOMPASS IOP program
(Turner et al., 2019). Later, targeted numerical model studies
should be used to not only verify the process/processes identified
in energetic and diagnostic studies, but to design dynamics-
based indices related to TC formation that are relatively easier
to predict. For example, a CISK parameter may be easier to
predict with a longer lead as compared with the TC rainfall.

These methods are again akin to the KUM approach. Such
carefully verified and designed indices, when operationalized,
will substantially help in extending the lead prediction time.
Probabilistic dynamical-statistical downscaling tools can also be
developed to relate local rainfall with these indices. This will
also potentially enhance the lead time of the TC-related deluge.
Similarly, a better understanding of model ability in capturing the
conversions between different forms of energy.

**MONSOONS**

Again, several aspects of monsoons, particularly, the Indian
Monsoon are still not completely clear and hinder the
mechanisms of prediction. In a recent exhaustive study, Geen
et al. (2020), discussed several aspects, primarily from a
theoretical standpoint even though this study was developed
based on the concept of a global monsoon, Figure 2 of Geen
et al. (2020) shows only a very low correlation in interannual
variations of rainfall, the main meteorological element that must
be predicted. However, the different regions of monsoons with
different geographical boundaries raise serious objections about
the global monsoon concept.

Several studies exist in the literature regarding the observed
aspects of the Indian summer monsoon (the K part of the three-
pronged method), and modern numerical models are employed
to improve prediction skills (Sahai et al., 2016; Rao et al., 2019;
Mohanty et al., 2020). From an almost zero skill, we have reached
a stage at which the skills for predicting the area-averaged Indian
summer monsoon are found to be statistically significant. This is
great progress. Having said that, there is a great scope for further
improvement. Although the broad regionally averaged skills are
statistically significant, they are modest. Further, improving the
skills such that they are locally useful is the obvious goal but
still a long way ahead. Although the prediction skill improved
through better methods of, for example, data assimilation and
parametrization schemes, to improve the predictions further, we
need to diagnose the improved representation (e.g., Halder et al.,
2016; Saha et al., 2019; Hazra et al., 2020), better replication of
physical processes and scale interactions.

Notwithstanding all these technical improvements, the
large-scale physical causal mechanisms are not clear yet.
This can only be done with the studies aiming to understand
the cause-and-effect relation or the U in the three-pronged
method. As mentioned earlier, with more observational studies
aiming to identify the correct interaction mechanism over
NIO between convection and large-scale monsoon circulation
(either CISK or WHISE), then this mechanism can be included
in the numerical models. Also, controlled experiments using
simple models, such as the one by Rao et al. (2000), can
be used to identify relative roles of mountains and thermal
contrast in generating the Indian summer monsoon. In
the state-of-the-art coupled models, because of extremely
complex non-linear interactions among various physical
mechanisms, it is almost impossible to isolate the cause of a
specific effect.
Again, the diagnostic study based on energetics, such as the generation of available potential energy (PE) by latent heat and the baroclinic conversions, for example, may reveal relative roles of some physical processes, such as convection in the Indian monsoon. In a recent companion study (Rao et al., under review), comparing the South American and Indian monsoons, we found that, in the Indian monsoon, the baroclinic conversions $P$ (mean available PE) to $P'$ (eddy PE) to kinetic energy (KE) is non-existent, and the KE of monsoon is mainly furnished by the generation of perturbation PE by latent heating (rainfall) and subsequent conversion to KE. In contrast, over the South American monsoon, both the baroclinic conversions and generation terms are equally important. This is probably because the Himalayas extend from East to West across the cardinal northern border of the country, which does not allow mid-latitude baroclinic waves to penetrate at lower levels while the Andes mountains in South America extend along North to South, permit these waves to penetrate even as low latitude as Manaus, where even austral summer cold waves (FRAIAGENS) are noted. Furthermore, studies are necessary to verify how energetics vary between wet and dry monsoons in these two regions.

In a review article by Geen et al. (2020), the authors discuss attempts to understand fundamental dynamics (U in our three-pronged method). Geen et al. (2020) mention a very similar KUM approach for monsoons (their section 3). Such efforts are urgently needed from the context of the Indian monsoon. They even discuss the south Asian monsoon (their section 3.1.2). Although they tried to reconcile between global and regional monsoon features, the differences are more striking as we mentioned earlier, regarding the Indian and South American monsoons. In the case of the East Asian monsoon, at least one author (Molnar et al., 2010) mentions, “‘monsoon’ is somewhat of a misnomer.”

Although there are some uncertainties in the methods used by Lange et al. (2020), the importance of their conclusion is unambiguous. They mention that “anthropogenic” climate change has already substantially increased the exposure to extreme global climatic impacts, and anthropogenic warming is projected to exacerbate the pattern of climate change that we are already noticing nowadays. Thus, it is urgent to restrain the increase in global average temperature well below 2°C, which would significantly reduce the risks and impacts of climate change$^6$ (Benitez, 2009; Dash et al., 2013). All this, therefore, underscores the urgency for climate action expressed in the Paris agreement of 2015. Even in a climate change context, using the KUM approach will help in a better diagnosis of the changes in regional implications for large-scale instabilities to diabatic processes. These can help in design model-based indices that can inform the stakeholders working on climate change mitigation and adaptation.

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**RECOMMENDATIONS**

We are in an era in which observational data availability in the tropics has improved significantly and is going to be further improved. In this context, it is recommended that the forecasters and researchers of Indian weather and climate use this excellent opportunity to build theoretical knowledge unique to the regional weather and climate. The knowledge gained should be translated to identify tangible, large-scale dynamical process indices. Such indices will be very useful to extend the lead prediction skills of important weather and climate phenomenon, such as TCs, MDs, etc. Similarly, (i) evaluating the model capacity in predicting and calibration of association between hindcast perturbation PE, latent heating, and subsequent conversion to KE, and (ii) comparing the observations will potentially provide us with indices that can be directly used to predict subseasonal monsoonal rainfall with longer leads. The above recommendations are just examples. In summary, identifying the key dynamics behind important weather and climate processes at discernible time scales and designing useful dynamical indices that can be used to extend the lead forecast envelope will be the way forward.

**DATA AVAILABILITY STATEMENT**

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: [http://tropical.atmos.colostate.edu](http://tropical.atmos.colostate.edu).

**AUTHOR CONTRIBUTIONS**

VB conceived the idea. VB wrote the manuscript with inputs from KA and using the results from DG analysis. KA comprehensively revised the article. All authors contributed to the article and approved the submitted version.

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