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Creating resilient communities with medium-range hazard warning systems

Bapon (SHM) Fakhruddin [a,*], Peter Gluckman [b], Anne Bardsley [b], Georgina Griffiths [c], Andrew McElroy [d]

[a] Tonkin + Taylor, New Zealand
[b] Koi Tū: The Centre for Informed Futures, University of Auckland, New Zealand
[c] MetService, New Zealand
[d] United Nations Office for Disaster Risk Reduction, Fiji

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ABSTRACT

Resilience to natural hazards requires integrated risk management – from hazard identification and risk register, hazard warnings and risk communication, to preparation for and response when an event occurs. Medium-range hazard warnings play a vital role in strategic and tactical planning for resilience to natural hazards. Research advancements have rapidly improved observation, modelling and analysis of natural hazard forecasting for disaster risk reduction. However, many of these advances have not been tailored to benefit communities at risk as geophysical and hydrometeorological hazards continue to claim thousands of lives and cause irreparable damage to homes, businesses and critical infrastructure. This paper discusses the opportunities to use medium-range ensemble forecasting to support decision making to increase the resilience of communities and the ways to embed holistic early warning systems in risk-informed sustainable development. It provides a set of recommendations for medium range forecasting applications for people-centred early warnings and disaster preparedness.

1. Background

With the current trajectory of global climate change, countries face a continual increase in the frequency and intensity of extreme weather [52]. This has gradually led to a greater emphasis on climate and disaster risk assessment, and identification of adaptation, mitigation and disaster risk reduction options. Early warnings are crucial in disaster risk reduction, as they empower communities to prepare for natural hazards [58] and, if effective, can prevent loss of life, protect property and livelihoods, and reduce the economic impacts of disasters [72]. The United Nations Global Assessment Report [79] revealed that investing USD 6 billion in appropriate disaster risk management strategies can generate benefits of USD 360 billion. Similarly, it has been demonstrated that one dollar invested in disaster preparedness and reducing vulnerability of people can prevent six dollars' worth of disaster-related economic losses [22,26].

A risk register plays a critical role in disaster risk reduction by identifying and documenting risks, their likelihood and impact on the system of interest (e.g., a community, country or region, a business or sector). Risk is typically placed in a register in the form of matrix consisting of risk scores (using hazard, exposure and vulnerability assessment) [38,48]. A risk register outlines proactive actions to mitigate the risks with assigned responsibilities, thus ensuring good risk governance [40]. Ideally, risk registers highlight and assist in systemic risk and cascading and compounding effects [7,11,16,54] and are linked to ensure an effective people-centred early warning systems. Outlining risks in a public risk register enables effective risk communication, which is key for any early warning system [58,59]. Particularly, dissemination/notification and community capacity (connection and response) are two interconnected fundamental elements within an early warning system to better understand local context, culture and sensitivity [23].

With the recent enhancement of numerical weather forecasts and meeting the demand of increase lead time, there is a shift from single deterministic weather model outputs to probabilistic weather forecast information, generated from ensemble-based prediction systems. The concept of using an *ensemble* (group) of weather models to obtain a *range* of possible future weather outcomes partially side-steps the issue of initialisation error and weather model error and allows predictions across longer time periods. Ensembles are now commonly used operationally to predict weather outcomes over the 7-to-30-day validity period and potential inputs for the hazard modelling such as flood, droughts, cyclones, etc. [10,42]. The evaluation and improvement of forecasting and warning system been changed time to meeting lifesaving needs, meeting people's demands, leveraging

* Correponding author.
E-mail address: bfakhruddin@tonkintaylor.co.nz (B.(S.H.M.) Fakhruddin).

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Fig. 1. Evaluation of ensemble-based forecasting systems since 2000 (Source: Authors).

resources and economic benefits of sectors. Fig. 1 presents a brief summary of evaluation of ensemble-based forecasting systems over the last two decades.

The initiatives of the subseasonal-to-seasonal (S2S) timeframe focus on period-averaged forecasts, usually weekly, at lead times of weeks to months [29]. The S2S timeframe is considered difficult to forecast, since it is largely beyond the influence of initial weather conditions but not long enough for significant variation in slowly evolving earth climate system components (such as the ocean, soil moisture and sea ice) to add predictive skill relative to persistence [66]. However, there is growing demand for medium-range forecasts (7–30-day validity period) from a number of sectors (e.g. agriculture) [24].

There are numerous opportunities provided by ensemble-based predictions to enhance medium range forecasts. For instance, "Anticipation Hub", a platform hosted by German Red Cross along with International Federation of Red Cross and Red Crescent Societies (IFRC) to facilitate exchange of knowledge, "learning, guidance, and advocacy around anticipatory action both virtually and in-person", uses forecasts or warnings to carry out early actions and finance anticipatory actions (Anticipation [5]). Forecast-based Financing (FbF), a programme developed under the Anticipation Hub, predicts disasters to prevent their impacts using detailed forecast information and risk analysis. As of 2020, FbF projects are implemented across Africa, America and Asia-Pacific ([37]; Anticipation [5]). The World Meteorological Organization (WMO) initiatives on multi-hazard impact-based early warning system and Climate Risk and Early Warning System (CREWS) are applied in many countries to achieve the global target G (early warning system) in the Sendai Framework for Disaster Risk Reduction and enhancing lead-time forecasts [14,23].

2. Political challenges for effective end-to-end early warning systems

Risk registers can highlight rare but forecastable events that experts can describe in terms of likelihood and impact. What cannot be identified with any certainty is when the events will occur. Because some events are extremely rare, but their impacts are high, the challenge is how to communicate to governments, organisations and communities of interest to invest in resilience preparation and risk mitigation, including in early warning systems.

The issues that lead the public sector to not prepare for risks associated with hazards are generally not technical; rather they largely relate to risk perceptions and cognitive biases of the decision makers [31]. Communicating risk and actions to the policy and political community is never a simple technological discussion, it is a complex matter of dealing with cognitive biases and political realities [76].

A major bias affecting most people, including politicians and policy makers, is myopia or short-termism: a focus on immediate needs at the expense of longer-term planning – and for the politicians, the length of an election cycle is critical [31,34]. Prevention of disasters that may occur in the future gets no political credit if an event does not occur during the politicians' mandate. There is always an opportunity to procrastinate preparing for major events until they happen, by which time it is too late. There is also a tendency to forget lessons of the past disasters [9].

Policy makers must first recognise potential risks in order to establish a system that scans for change in identified risk parameters and alerts to a potential event. In a traditional, idealised view of early warning system, the warning system acts as a "searchlight" on society - it finds a problem, alerts the government and the problem gets addressed. The reality of this is more precarious and the stability of society can often balance on the accuracy of early warning systems, leaving little room beyond survival in the face of a major event or disaster. Lessons from historical events are motivation for governments to improve early warning systems; governments need to know what lies ahead to help maintain civil and political stability.

An imbalance exists between the user expectations and what forecasters, or national meteorological services, can provide to the community. As global climate changes, we need to use technology to enable various scale forecasting models to predict weather as accurately as possible and bring them to operational use. Science can provide informed services up to a certain limit, but user expectations always demand more. When expectations are not met, users are less willing to use the information and take action. It is necessary to find a balance between the user expectations and the services that forecasters can provide. Managing expectations and explaining fully the limitations of forecasts would enable users to understand why they may not be able to receive all the information they want, and why information may be uncertain. As climate change intensifies future droughts and floods, the importance of this community-based anticipatory approach will grow.

3. Medium-range ensemble forecasting applications

Ensemble-based prediction is now commonly used at most national weather services [10]. An ensemble of models is run with varying amounts of error associated with weather conditions at initialisation for an extended period of time, which gives a probabilistic range of possible future weather states. This gives decision makers viable statistical information over extended validity periods (7–30 days in most cases).

Common uses of ensemble forecasting include tropical cyclone track outcomes. For example, 15% of ensemble members may track a tropical cyclone formed in the south-west Pacific towards northern New Zealand, while 85% of ensemble members show that it will stay in the tropics. This split in outcomes is useful information to decision makers, as percentiles can be worked out to assess risk; this would not be possible if just a single weather model was used. Another common application of medium-range ensemble forecasting are precipitation probabilities. Forecast ranges and probabilities of precipitation totals over an extended duration can be useful information for hydro-storage lake level managers who want to know how full their lake may be and manage lake levels accordingly. Generally, the ensemble mean (50th percentile) output is the most commonly used statistic from an ensemble forecast; however, knowing a range of probabilities allows decision makers to assess what the width of the possible forecast outcome is (Fig. 2).

Medium-range forecasts are inherently uncertain due to the chaos in the atmospheric system; moreover, forecasting skill varies geographically, temporally, and by climate parameter [66]. A medium-range to long-range forecast is useful to a recipient only if the weather variables it predicts are relevant and the forecast is timely for the recipient to make an action. Useful forecasts are those that meet recipients' needs in terms of such attributes as timing, lead time, and currency; climate parameters; spatial and temporal resolution; and accuracy. Because the usefulness of forecasts is dependent on both their accuracy and their relationship to recipients' informational needs and coping strategies, the utility of forecasts can be increased by systematic efforts to bring scientific outputs and users' needs together.

3.1. Weather, water and climate service framework

A framework for weather, water and climate services is a policy and institutional mechanism to strengthen the capacity and streamline the systems for weather, water and climate services for enhanced decision making. The WMO [70] developed guidelines for strategic plan and framework for weather, water and climate service to enhance national meteorological and hydrological services' capacity [12,69–74]. Several countries already adopted a national strategic plan and framework for weather, water and climate services. The potential increase in occurrence and intensity of extreme weather events as a result of climate change, coupled with increasing population in vulnerable areas, reinforces the need for seamless integration of weather, water and climate information systems (Fig. 3).

3.2. Day-to-day forecasting: adopting ensemble forecasting for dealing with uncertainty

Errors in weather forecasting can be attributed to two causes: inaccurate initial conditions and deficiencies in the weather model [8]. Analysis error —having an incorrect or incomplete representation of the atmospheric state at initialisation —is one source of uncertainty. Given the infinitesimal scale on which the world and atmosphere operate, it is a practical impossibility to devise a perfect representation of the weather system state.

Model error also has a strong impact on the evolution of forecast skill [15,53]. When many different types of forecast models are used to generate an ensemble forecast, the approach is termed *multi-model ensemble forecasting*. This method can improve forecasts when compared to a *single model-based ensemble forecasting*. Forecasts are only as good as the language and method used in communicating to affected communities. Ensemble forecasting is a good approach to gather a range of forecast weather outcomes and to produce probabilistic information from which agencies can assess risk and inform decision making. It is a good way to deal with both initialisation error and model error uncertainty for the medium-range (1-to-14-day horizon in particular). However, because ensemble forecast information is significantly different from the usual 'deterministic' weather

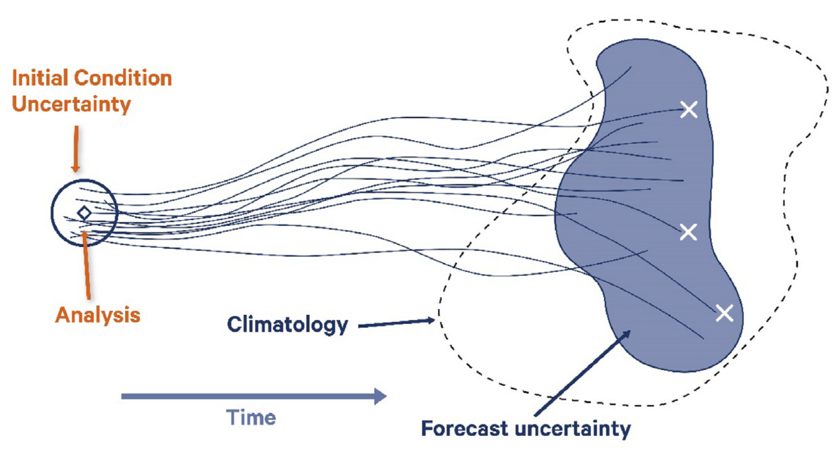

Fig. 2. Ensemble forecasting concepts (Source: MetService, 2021). This diagram shows initial condition uncertainty at analysis time, with multiple models producing differing forecast solutions through time (depicted as the forecast uncertainty). The forecast outcomes from individual ensemble members can differ considerably (selected model outcomes are depicted by white crosses), but we do not know which outcome is more reliable [33].

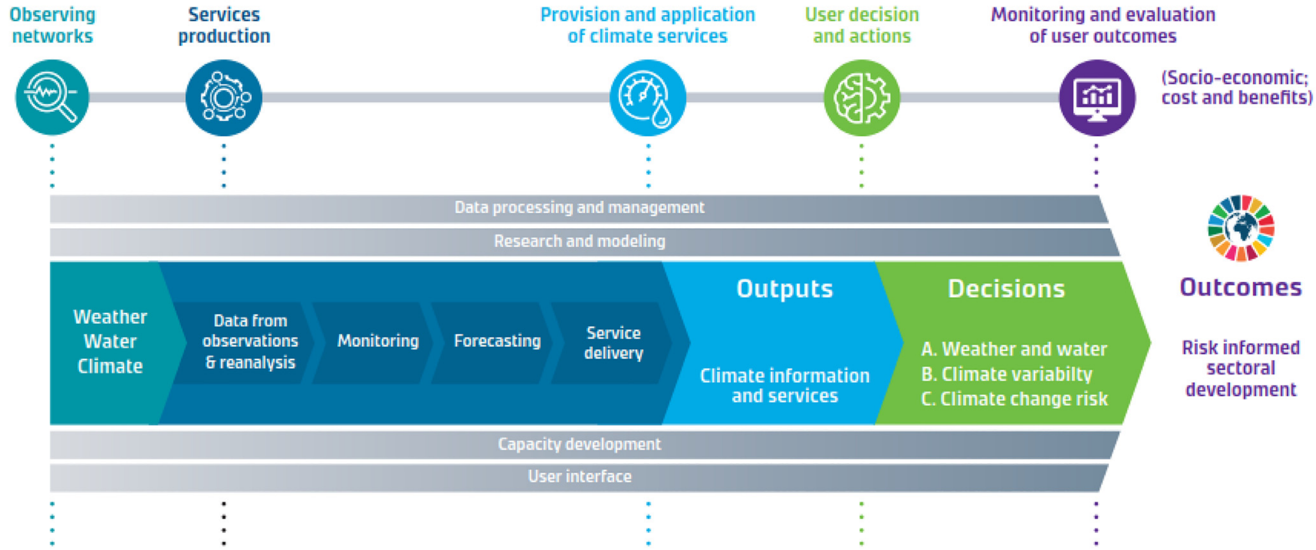

Fig. 3. Value chain of risk-informed sectoral development of weather, water and climate services (Based on [71])

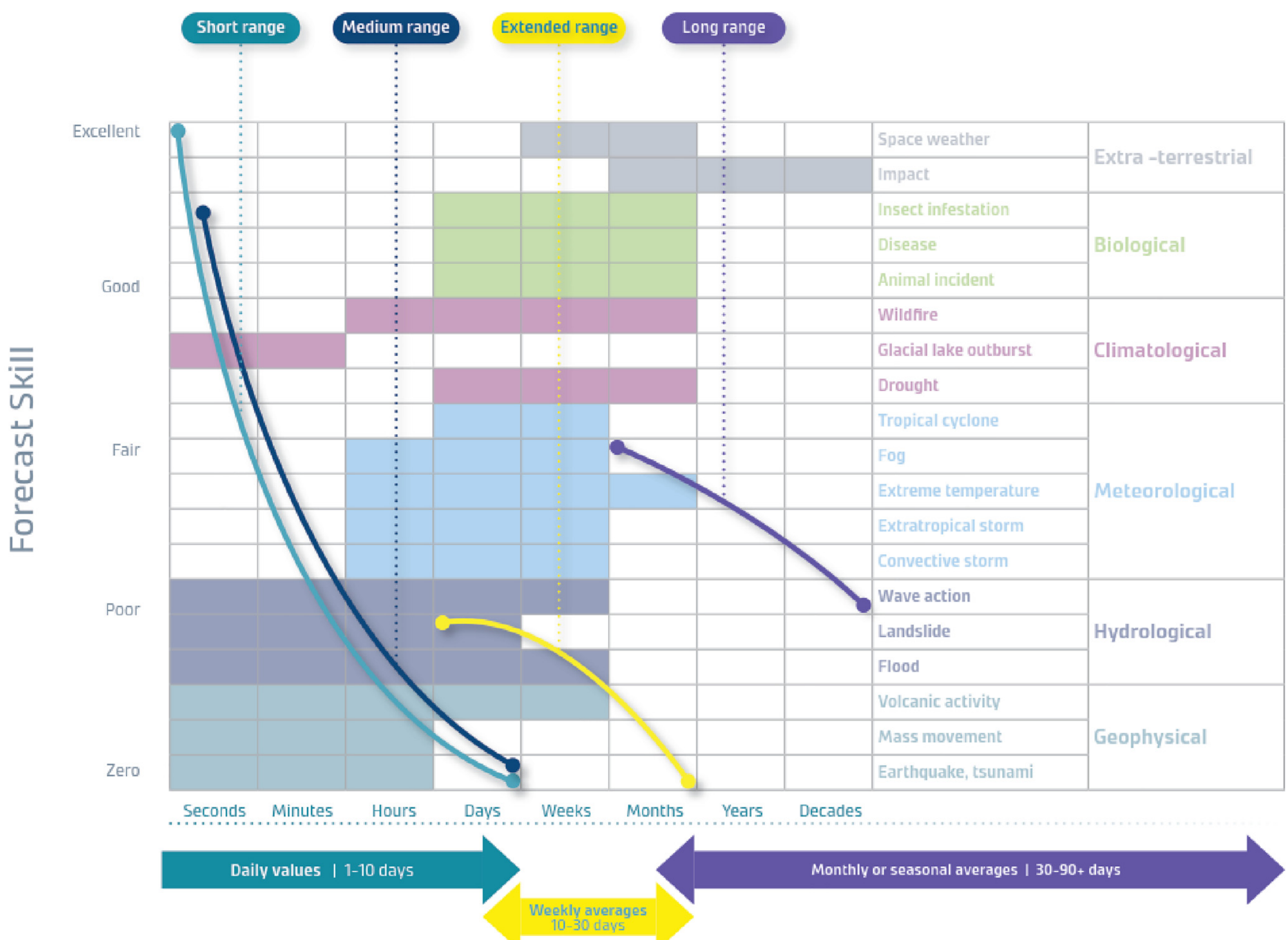

Fig. 4. Forecasts skills and integrations (Source: [78]).

predictions seen on TV news, careful presentation of weather outcome versus predicted chance of occurrence is essential. To enhance community resilience and disaster preparedness, there is a need to involve communities at risk, facilitate public education and awareness of risk and potential impacts, and disseminate warnings in a timely manner [70].

3.3. Integration of short-, medium- and long-term and subseasonal forecasting applications for disaster response

Many national hydrological and meteorological services are moving towards a multi-hazard impact-based forecast and warning services that translate hydrometeorological hazards into sector and location specific impacts and responses [71]. Effective impact-based forecasting requires collaboration with other decision makers including disaster and emergency managers, stakeholders and communities [74]. Each day of additional warning provides emergency managers the time to inform communities at risk to prepare for extreme weather and climate related shocks (Fig. 4).

Short-term models, like those readily available on smart phones, use current weather observations to make predictions. For forecasting further into the future, the weather at time of initialisation becomes less relevant. Long-term seasonal outlooks predict how different the climate will be compared to normal over the next three months (i.e., will it be hotter or colder). This high-level perspective on how regional climate is expected to vary is based on the slowly changing planetary patterns which drive the weather over a number of months, such as intermittent oceanic warming patterns like El Niño and the extent of sea ice coverage in the Arctic Ocean [69].

Subseasonal forecasting lies between short-term forecasts (up to 10 days) and seasonal forecast (one month to several months) [69]. Making such forecasts is difficult because the initial information that drives the short-term models is no longer as useful, and the long-term climate drivers associated with seasonal forecasts have not yet become apparent [69]. Subseasonal forecasting has been ignored in the past, due to how difficult it can be. It is improving slowly but steadily, largely due to advanced technology to produce better computer models and new insights about the atmospheric and oceanic patterns that drive weather over the long term [68].

Many weather patterns, some of which are not predictable, influence the weather on the subseasonal scale. Some weather patterns, such as the Madden-Julian Oscillation (MJO),[1] have been researched to improve hazard predictions [69], but more advancements in modelling the MJO events are still needed. Another weather pattern which needs to be understood to improve subseasonal forecasting is a “sudden stratospheric warming” above the Arctic or Antarctic. It happens every couple of years in the northern hemisphere and less often in the southern hemisphere and can affect the weather worldwide.[2] Periods in which these events occur is called “forecasts of opportunity” as during this time subseasonal forecasts become more skilful. An analysis conducted by Giuseppe et al. [30] revealed that the skills provided by the ensemble prediction systems extend beyond 10 days when compared to the deterministic models.

Ensemble forecasts can be used to generate flood thresholds as floods are the most frequent disaster event that occurs across the world [18]. Thresholds that reflect the flood event frequencies of the real-time ensemble forecasts across all forecast lead times is crucial for accurate forecasts [77]. According to the study on “Ensemble reforecasts to generate flood thresholds for improved global flood forecasting” (by [77]), reanalysis-based thresholds were found effective for the first one to four days of the 30 days forecast range.

[1] The MJO is an eastward moving tropical disturbance of clouds, rainfall, winds, and pressure that traverses the planet every 30 to 60 days on average.

[2] For instance, a northern stratosphere warming often causes storms in the United States. A large southern stratosphere warming set up the weather events which led to the tinder-dry conditions in Australia and caused major bushfires in late 2019 and early 2020 [45].

3.4. Improving forecast of high-impact weather events

High-impact weather events pose threats to human life, property and the economy, and inflict significant societal hazards. It is, therefore, crucial to have skilful forecasts of the risks with sufficient lead time to make appropriate precautions. As climate change causes global temperatures to rise and more extreme weather events to occur, researchers need to continue improving forecasting and modelling to be as accurate and as far in advance as possible [27]. Effective forecasting of high-impact events often requires perspectives and tools that are different from routine forecasts. A number of factors make advance forecasts of high-impact weather events challenging, including insufficient resolution to simulate hazard scenarios dynamically in a forecast model; model biases in representing storms which often become increasingly pronounced in extreme scenarios; and even difficulty in defining and verifying the high-impact event. New technologies (e.g., machine learning and artificial intelligence) and international collaboration may accelerate these efforts.

3.5. Risk register for proper risk assessment

Risk register can inform the authorities on the most significant risks that could occur in future that might have huge impact on the nation or community. It serves as a guide to identify the areas that need actions in a nation or community [13,67]. Risk registers facilitate a logical and efficient approach towards the risk management. The National Risk Register developed by the Government of United Kingdom presents an assessment of the likelihood and potential impacts of risks related to environmental, human and animal health, major accidents, societal, malicious attacks, and risks occurring overseas that might affect the United Kingdom [32]. For instance, fatalities, damage to property and infrastructure, and disruption to essential services were some of the identified risks posed by earthquakes, and regulations, seismic hazard studies, models and forecasts, seismic risk mapping, and research projects on the United Kingdom earthquake activity were a few mitigation measures to the earthquake risk [32].

The reality is complex and system-based thinking is crucial [6]. An early warning system factoring in compounding and cascading hazards and a seamless integration of short-range, medium-range and long-range weather and climate forecasts could enhance the decision-making process. With a change in our mindset using advanced seasonal warnings, we can produce more useful, usable information to help industries, sectors and communities to better understand foreseeable risks, scenario analysis and adaptation options.

3.6. Dealing with uncertainty

Risk communication is an essential component in reducing disaster risk, especially for medium-range hazard warning systems [19,23,80]. Effective communication through hazard forecasting is critical for communities to understand risks and take appropriate actions. As we face a complex environment where risk is more systemic, national, and local governments need to have ability to successfully communicate hazard risk and actions through a coordinated all-of-society approach (Fig. 5).

3.7. Impact-based forecasting

Impact-based forecasting allows practitioners to interpret the hazard warning and requires strong partnerships between hydrometeorological services at national level and sectors functioning in disaster risk reduction and management [72]. It results in people taking early actions such as evacuating vulnerable communities, individuals, and their livestock, “pre deployment of flood barriers”, and closing roads and bridges [73]. Aspects of the Sendai Framework for Disaster Risk Reduction, the Sustainable Development Agenda, and the aims of the Risk informed Early Action Partnership and the Anticipation Hub could be achieved by impact-based forecasting [5,72].

Fig. 5. User needs and application for forecasts (Source: [23])

When developing and implementing an early warning system, we need to consider that a more widespread application of early warning systems equates to a more widely experienced uncertainty. Even when there is warning information available, especially for sector and strategy decision making, it does not immediately translate into successful application, as there is a time horizon to turn strategic decisions into actions.

Impact-based forecasting utilises either deterministic forecast data or ensembled forecast data for generating results. It is proven that ensemble-based forecasting data produce more consistent and successive forecasts than other systems [56], hence, it should be used for determining the impact-based forecasts.

3.8. Socio-psychological aspects of the end users

Ensemble forecasting allows users to have reliable forecasting of the range of most likely future scenarios. It provides estimates of the atmosphere and assists in generating future climate projections [10]. Schroeter et al. [56] reported that "thresholds on probabilistic forecasts derived from EPS can be set to alert forecasters and other users to the likelihood of a hazard occurring, which can substantially increase the lead time of useful forecasts for end users".

Besides, a wide range of psycho-social benefits could be gained with the assistance of ensemble-based forecasting. For example, the value to weather forecast to road transport carried out by NZIER [50] revealed that direct costs such as loss of life and life quality, vehicle damage, medical expenses, legal and court costs, and loss of productivity could be minimised with the availability of accurate forecasts. The 1–10 days flood forecasting system has proven enormous benefits to the community in Bangladesh [24,35]. The European flood alert system (EFAS) is widely used for planning and operational uses. Additionally, forecasts may reduce or avoid some intangible costs such as trauma, mental illness, bereavement, loss of trust in authorities, and loss of jobs (societal disruptions) [50].

3.9. Benefits of ensemble-based warning system for climate-sensitive countries

Small Island Developing States (SIDS) and the Asia region are one of the world's most disaster-prone in terms of the recurrence and severity of natural hazards, with high exposure to floods, landslides, tsunamis, cyclones, forest fires, earthquakes, droughts, and volcanic eruptions [21]. Countries in these regions have limited to no infrastructure for early warning systems and are inadequately prepared and extremely affected by these disasters [28]. Pacific Island Countries (PICs) are far behind the implementation and applications of medium range ensemble forecasting system. Currently, all Pacific Island countries are providing basic level of climate services that include climate outlooks, summary of statistics, ENSO updates, and climate change information [28]. "Explore the use of ensemble techniques in tropical cyclone forecasting and probable forecasts" is one of the key priorities of Pacific Islands Meteorological Strategy 2012–2021 [60]. The ensemble-based forecast warning systems could benefit PICs and SIDS in preparing for adverse weather conditions, prepare to response to hazards and minimize the risks and enable faster responses.

3.10. Resilience through medium range forecasting

The ensemble forecast models presents the practitioners and users with most likely scenarios of the weather and supports them in being prepared to face the disasters and assists in reducing losses and faster recovery [49]. For instance, New Zealand is susceptible to natural and climate hazards such as earthquakes, volcanic eruption, tsunami, floods, cyclones, coastal erosion, sea level rise and extreme weather events. New Zealand's National Disaster Resilience Strategy focuses on creation of resilient communities by managing risks, effective response to recovery from emergencies, and enabling empowering and supporting community resilience. Strategies were developed across social, cultural, economic, built environment, governance, and natural sectors. One of the priorities is to improve the availability and accessibility of multi-hazard early warning systems in New Zealand [47]. As of 2021, the country is underutilising the medium-range forecast services, however, with the adequate infrastructure facilities these forecast services could be enhanced [49].

4. Conclusion

Issuance of reliable forecasts and warnings in a form that is readily understood and creating awareness on how to prepare against such hazards before they become a disaster is necessary for any warning system [72]. With the advances in science and multi-model ensembles, warning skills have increased and have the potential to reduce disaster risk and sectoral decision making as across fields such as water resource, agriculture, dairy, livestock, energy, epidemics and ecology. Weather never stops, it is ever-evolving, and is never quite the same twice. It affects almost every aspect of society in some capacity, from daily life to the economy. However, it is not the ordinary weather conditions, but the intense or rare weather events, that produce the greatest societal impacts.

Weather forecast services are traditionally based on conventional synoptic methods, enhanced by the use of numerical weather prediction. However, there is a growing demand for predictions of weather and climate conditions that go beyond the usual weather forecast window (days 1–7), with interest in medium-range outlooks extending from weeks to months. This drives an emerging shift from single deterministic model weather forecast outputs, to probabilistic forecasts generated from ensemble prediction systems, covering the medium-range window (7–30 days).

Disclaimer

The article does not reflect the official views of the UN.

Declaration of Competing Interest

None.

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