The Best of Both Worlds: A Decision-Making Framework for Combining Traditional and Contemporary Forecast Systems

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ABSTRACT

In most countries, national meteorological services either generate or have access to seasonal climate forecasts. However, in a number of regions, the uptake of these forecasts by local communities can be limited, with the locals instead relying on traditional knowledge to make their climate forecasts. Both approaches to seasonal climate forecasting have benefits, and the incorporation of traditional forecast methods into contemporary forecast systems can lead to forecasts that are locally relevant and better trusted by the users. This in turn could significantly improve the communication and application of climate information, especially to remote communities. A number of different methodologies have been proposed for combining these forecasts. Through considering the benefits and limitations of each approach, practical recommendations are provided on selecting a method, in the form of a decision framework, that takes into consideration both user and provider needs. The framework comprises four main decision points: 1) consideration of the level of involvement of traditional-knowledge experts or the community that is required, 2) existing levels of traditional knowledge of climate forecasting and its level of cultural sensitivity, 3) the availability of long-term data—both traditional-knowledge and contemporary-forecast components, and 4) the level of resourcing available. No one method is suitable for everyone and every situation; however, the decision framework helps to select the most appropriate method for a given situation.

1. Introduction

In many regions of the world, local communities are able to make forecasts about seasonal and extreme weather events, such as tropical cyclones, floods, and drought, by observing the environment around them (e.g., Lefale 2010; Orlove et al. 2010; Garay-Barayazarra and Puri 2011; Masinde 2015). History has shown great adaptive value in the use of traditionally based science (e.g., King et al. 2008; Lefale 2010; Hilhorst et al. 2015; Johnston 2015). However, the value of traditional forecast methods is being eroded by two main challenges. The first is the rapid loss of knowledge due, in

part, to rapid urbanization and emphasis on Western science (Brahy 2006; Berkes 2012). Modern education systems and the growing interest in the cash economy and Western goods can leave tradition-based knowledge as a thing of the past. In some communities, there may be less than a handful of elders left who still hold this wealth of knowledge.

The second challenge to the value of traditional forecast methods is the apparent changing reliability and loss of the traditional indicators. There are growing concerns among many indigenous communities that changes in the climate over time have reduced the effectiveness of some biological indicators for weather and climate forecasting (King et al. 2008; Ziervogel and Opere 2010; Mogotsi et al. 2011). In addition, changes in land-use practices may also influence the availability of species commonly used as traditional indicators (Brahy 2006; Gyampoh and Asante 2011; Zuma-Netshiukhwi et al. 2013; Masinde 2015). Despite these challenges,

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traditional forecast methods remain highly valuable to remote communities where outside communication is limited and traditional ways are more relevant. Indeed, even when weather service forecasts are available, some communities will only use traditional ways to forecast [e.g., Altiplano region, Peru (Gilles and Valdivia 2009); northeast Brazil (Andrade and Gosling 2011); Greater Horn of Africa (Tadesse et al. 2015); and Zimbabwe (Dube et al. 2016)].

Most countries' national meteorological services (NMSs) either generate seasonal climate forecasts (SCFs) or have access to forecasts generated for their country by other agencies. These numerical forecasts often take the form of probabilistic outputs of percentage chance of above or below normal rainfall or temperature and are often available at a subnational level. Despite contemporary seasonal forecasts now being available in most countries, uptake by local communities is often limited (e.g., Lemos and Dilling 2007; Gilles and Valdivia 2009; Ziervogel and Opere 2010; Marshall et al. 2011; Masinde 2015; Tadesse et al. 2015; Dube et al. 2016). There are a number of reasons for this, including the forecast's output covering too large a region to be relevant to local communities, incomplete understanding or trust of the SCFs, and limited access to the forecasts because they are not disseminated via appropriate media or at an appropriate time (Lemos and Dilling 2007; Gilles and Valdivia 2009; Ziervogel and Opere 2010; Zuma-Netshiukhwi et al. 2013; Masinde 2015; Jiri et al. 2016; Dube et al. 2016).

Evidence is now appearing that the acknowledgment and incorporation of traditional forecast methods into contemporary SCF systems could significantly improve the communication of climate and weather information, especially to local communities in remote areas (Pennesi 2007; Lefale 2010; Orlove et al. 2010; Andrade and Gosling 2011; Sanni et al. 2012; Zuma-Netshiukhwi et al. 2013; Plotz et al. 2014; Tadesse et al. 2015). In addition, incorporation of traditional knowledge (TK) provides an opportunity to enhance both the spatial and temporal resolution of the forecast information available (Riedlinger and Berkes 2001; Masinde 2015). If forecasts are going to be useful, they must be skillful, timely, and relevant to potential users (Valdivia et al. 2000; Jiri et al. 2016). Forecast information must therefore address current needs and be trusted by the users and expressed in their language (Blench 1999; Stern and Easterling 1999; Valdivia et al. 2000; Kolawole et al. 2014).

Although forecasts based on both contemporary and traditional approaches appear to offer a number of key benefits, the development of seasonal forecasts that take into account both contemporary and traditional approaches can be problematic as there are significant differences between the two systems (Table 1). As a consequence, a number of different methodologies have been proposed and tested for combining this information. This paper is a review of the various methods proposed and tested in the literature. In particular, the benefits and limitations of each approach are considered, with practical recommendations provided (in the form of a decision-making framework) on which methods would be more appropriate in various contexts. Case studies are provided throughout to further illustrate the approaches.

Traditional-, indigenous-, or local-knowledge forecasts are based upon observations, know-how, skills, and practices that are developed, sustained, and passed between generations, often forming part of a community's cultural or spiritual identity (World Intellectual Property Organization 2010; Armatas et al. 2016). While there is no consensus for the appropriate term for such knowledge, the term "traditional knowledge" is used in this paper, covering both indigenous and nonindigenous peoples and recognizing that the knowledge can evolve over time. While the authors acknowledge all domains of TK, this paper focuses solely on weather- and climate-related TK and its combination with contemporary SCFs.

2. Approaches to combining TK and contemporary seasonal forecasts

Although numerous authors have argued that there is a need to incorporate both contemporary and traditional knowledge in environmental decision-making (e.g., Valdivia et al. 2010; Zuma-Netshiukhwi et al. 2013; Sanni et al. 2012; Armatas et al. 2016; Jiri et al. 2016), there are others who claim that this either is not possible or is inappropriate because of potentially significant differences between the two perspectives (e.g., Agrawal 2002; Table 1), including that TK is embedded with particular communities and is culturally and contextually bound. Sillitoe (2002) refutes these latter claims by arguing that the different knowledge systems can have similar essential elements and content, that the methods used to investigate reality have aspects in common, and that contemporary science is "no less culturally located than other knowledge traditions" (Sillitoe 2002, p. 10). In addition, by embracing the strengths and weaknesses of the different knowledge systems, there is an opportunity to improve overall understanding of the problem and, in the case of seasonal climate forecasting, potentially produce products that are based on collaborative relationships that are better suited and understood by local users, thereby increasing

TABLE 1. Comparison of TK and contemporary seasonal forecasting methods.

	TK methods	Contemporary seasonal forecast methods
Context	Often embedded with cultural context, e.g., can include behavioral message/morale. Part of a holistic world view built upon generations of experience.	Numerical simplification of real-world processes generated using models and empirical meteorological data.
Spatial scale	Generally localized knowledge, e.g., relevant to a particular village. Full extent of spatial applicability often unknown.	Generally broad, e.g., El Niño–Southern Oscillation forecasts for large spatial scales. Seasonal forecasts by NMSs often apply only down to province level, occasionally to a small number of villages for which meteorological observations exist.
Temporal scale	Forecasts generated when indicator/sign (biophysical or spiritual) is seen—timing can vary.	Forecasts generally coincide with calendar months.
Forecast generation	Ability of individuals to understand the forecast process varies, e.g., ability to generate a forecast may be restricted according to position in community (e.g., rain prophet) or may be part of the community's general knowledge.	Larger meteorological centers may be able to generate their own forecasts, or they may be reliant on forecasts from distant centers.
Communication	Knowledge typically communicated through nonwritten methods, such as stories. Rarely documented.	Computer-generated forecasts. Forecasts generated by external agencies generally communicated via the Internet. Regional phone discussions on forecast generation and verification may occur (e.g., Seasonal Climate Outlook for Pacific Island Countries; http://cosppac.bom.gov.au/products-and-services/seasonal-climate-outlooks-in-pacific-island-countries/).
Verification	Informal verification. Continued use dependent on cultural constraints and/or continued usefulness.	Formal mathematical verification, e.g., skill scores.

overall climate resilience (Riedlinger and Berkes 2001; Roncoli et al. 2002; Pennesi 2007; Chand et al. 2014). An example of the advantage of combining the two sources of information is that SCFs often forecast the likelihood of above or below "normal" rainfall, whereas TK forecasts can provide additional useful information, such as expected onset and cessation dates (e.g., appendixes B and C).

Methods proposed to date for combining information from traditional seasonal forecasts with those from contemporary SCF systems can be classified into two broad categories, labeled here as consensus and science integration. The consensus approach includes meetings of experts, usually representatives from the indigenous group that holds the TK and representatives from the NMS. Together, they discuss their respective forecasts for the coming period (e.g., season) and form an agreed (consensus) forecast. In the second approach, the TK forecast is formally (mathematically) combined with a statistical or dynamical weather or climate model. This may involve field monitoring of TK weather- or climate-related environmental indicators. How these approaches work in practice, including their benefits and limitations, are discussed in the following sections.

a. The consensus forecast approach

Consensus forecasts are based on an "agreed" final forecast built upon consideration of both a TK forecast and a forecast from an NMS (for example). As such, the method of arriving at a consensus forecast can take a variety of forms. These range from a more formal or structured methodology, where an individual or group of TK forecast experts (e.g., elders) and representatives from the meteorological service regularly meet to discuss and decide on an agreed forecast for the coming period (e.g., season), to the less structured and harder to quantify form based on an individual's internal methods of combining the two knowledge systems (e.g., NMS products received via print or other media and TK forecast either self-generated or from local experts; Dube et al. 2016). The more structured consensus approach to SCFs has been practiced in the African environment for a number of years (e.g., Ziervogel and Opere 2010; Guthiga and Newsham 2011; Mahoo et al. 2013, 2015; appendixes A and B). An alternative form of this approach is through the use of local committees who adapt information provided by NMSs and TK experts before providing an agreed forecast that is disseminated by local radio and/or liaison officers, such as agricultural extension officers (e.g., Ziervogel and Opere 2010; Thoto and Hounkponou 2012; Kolawole et al. 2014). Local social networks may facilitate discussions around the NMS and TK forecasts that lead to a shared understanding of expected seasonal climate outcomes.

There are both benefits and limitations of the consensus approach to combining seasonal forecasts that are described below.

1) BENEFITS OF THE CONSENSUS APPROACH

An advantage of using a consensus approach to forecasting is that the method is flexible enough to respect cultural sensitivities associated with the TK. As the finer details of how the TK forecast is made do not need to be revealed to all parties, this approach makes it possible for the community to retain their TK and to maintain the status and role of tribe members, such as elders or rainmakers (who may be the traditional custodians of the TK).

For this approach to work well in practice, it is important to have good community engagement. This method can be seen as a participatory approach where elders and communities are more likely to feel empowered by the recognition of their knowledge and their involvement in the process (i.e., recognized as the experts). In addition, involvement of local experts in the forecast process can increase the trust in the process and increase the likelihood of the combined forecast being used by the community.

Another advantage, which has contributed to the predominance of consensus forecasts over science integration forecasts, is the immediacy of the available forecasts. Unlike the science integration method, where many seasons or years of historical forecasts (both TK and NMS) are required to build and verify a model, consensus forecasts can be developed and issued as soon as the respective forecasts for that season are available and can be verified at the end of each season.

2) LIMITATIONS OF THE CONSENSUS APPROACH

A potential disadvantage of consensus forecasting is that there may be unknown or hidden aspects to the forecasts. For example, the NMS may not be made aware of how the TK forecast is generated, including what is observed by the TK experts and how these signs should be interpreted. On the other hand, the TK experts may not fully understand the processes behind the NMS forecast. This means that neither group would be able to generate a combined forecast without the other group as the full set of rules on how a forecast is generated is unknown. This leaves this approach vulnerable to the loss of key experts, particularly those associated with the TK forecast. In many regions of the globe, there are concerns over the rapid loss of TK, including in the Bolivian Altiplano region (Valdivia et al. 2010), which has the potential to impact the future effectiveness of the consensus forecast approach. As the TK is retained by the TK experts, it is not always possible to test how far spatially the forecast could be applied, thus restricting the combined forecasts to the region associated with the knowledge holders.

Another disadvantage to consensus forecasting is that the seasonal forecasts may not be entirely repeatable. For example, in the case of two groups of experts (e.g., a TK one and one from an NMS), the final agreed outcome may be influenced by the membership of the groups and personalities involved. There is even the potential for the TK forecast to vary depending on an individual's interpretation of specific "environmental indicators" (e.g., plant, animal, atmospheric, or astronomical) on that occasion or depending on which TK experts are consulted. The ability to obtain a consistent forecast may also be influenced by how much of the forecasting process is "hidden." See appendixes A and B for examples of the consensus forecast approach in use in Africa.

Given the often highly localized nature of TK and participatory nature of consensus forecasting, this approach can require significant resources to ensure forecasts can be regularly produced. For example, transport and accommodation may be required for the TK experts and/or meteorologists to meet face to face to discuss their respective forecasts. If forecasts are required for multiple localities, then a significant amount of time and resources may be needed to produce each season's forecast. Insufficient ongoing funding has the potential to halt otherwise successful consensus forecasting projects (L. Chang'a 2016, personal communication).

This approach has the potential for the SCF system to fail should one or the other of the partners (TK holders or NMS) no longer be involved or be unavailable during the forecast discussion period, be it as the result of a disagreement or the loss of TK experts. However, trials so far have found the consensus approach to be a useful way of respecting both forecasting techniques and increasing community resilience to climate variability and extremes (e.g., appendixes A and B).

b. The science integration forecast approach

Science integration forecasts are based upon validating the accuracy of TK forecasts in order to convert predictions into a format appropriate for use in a statistical analysis. This process typically requires the collection of elders' forecast "models" using a specially designed questionnaire or survey (e.g., Andrade and Gosling 2011; Chambers et al. 2017) that extracts the information required to create a formal model and/or formula. For this reason, science integration forecasts usually take a more formal or structured approach compared with the consensus approach. One approach to science integration forecasts involves a group of elders or prophets who hold traditional weather knowledge and a few statisticians, scientists from the meteorological service, or local universities, who help to convert their

knowledge into a statistical model for analysis. In contrast to the consensus approach, there are generally fewer meetings to discuss and decide on the formula for integration; typically, one or two meetings are sufficient to gather the information required to produce a model. As with the consensus approach, the science integration approach requires agreement between elders and the statistician to build and validate the initial SCFs, but once agreement is achieved and the model is fitted, it is possible to quantify future TK predictions without needing the TK experts' input.

Science integration is also possible with minimal or no community involvement if it is known how TK indicators predict the coming season and long-term datasets are available. For example, the fruiting of certain plant species like mangoes in the Pacific indicates the arrival of the rainy season (e.g., Chand et al. 2014). Long-term historical mango fruiting records, where available, could be combined with prevailing climate data records from meteorological stations to build probability models. This process has not yet, to our knowledge, been extensively applied, perhaps because of difficulties in obtaining and maintaining long-term standardized biological and climate records.

The approach adopted to combine TK and NMS forecasts is likely to vary according to the method used to generate the NMS forecast (e.g., statistical or dynamic modeling) and according to the organization's/developer's preferences. Some suggested approaches include the use of regression or general linear models (GLMs), probability thresholds, heuristic models, artificial neural networks, and Bayesian analysis (e.g., Mackinson 2001; Waiswa et al. 2007; Andrade and Gosling 2011; Masinde 2015; Mwagha and Masinde 2015).

Science integration approaches that involve the community and statisticians in forecasting have been practiced in rural Africa (e.g., Waiswa et al. 2007; appendix C), where using knowledge of the TK indicator and long-term historical records to integrate systems remains unreported in the literature.

The benefits and limitations of the science integration approach are described below.

1) BENEFITS OF THE SCIENCE INTEGRATION APPROACH

In science integration forecasting, there are fewer unknown or hidden aspects to the forecasts. This means that NMSs can generate a combined seasonal forecast without ongoing assistance from traditional experts. Traveling regularly over large distances to meet with experts can be costly and challenging in the rural areas of developing countries. This approach, therefore, can be more cost effective than consensus forecasts, especially when forecasts are required for regions distant from the NMSs or if the forecasts need to be generated for multiple regions.

Another benefit of this approach is that it is less vulnerable to the ongoing loss of TK, including failing intergenerational transfer of TK. For this approach to continue to work, the NMSs must know the full set of rules on how a TK forecast is generated. The process of TK forecasting therefore needs to be preserved (recorded) for future analysis and generations.

Science integration forecasting increases the ability to obtain a consistent forecast because less of the forecasting process is hidden, and the forecast outcome is less dependent on particular individuals (e.g., elders), so this approach is more resilient to the loss of TK experts. See appendix C for an example of the science integration forecast methods used in Africa. As the TK forecast methodology is known by the NMSs, it is possible to test how widely the forecast can be applied, thus enabling the expansion of forecasts from the original knowledge holders to more regions. The ability to expand the range of TK forecasts with lower costs means that the likelihood of combined forecast continuity is greater using this approach.

2) LIMITATIONS OF THE SCIENCE INTEGRATION APPROACH

The disadvantage of using a science integration approach to forecasting is that the method is less flexible with regards to respecting cultural sensitivities associated with the TK. As the full methodology for making the TK forecast is revealed, this approach makes it impossible for the community to retain full control of their TK and to maintain the status and role of tribe members (where these are dependent on specialist forecast knowledge), thus leaving the method potentially vulnerable to cultural backlash. Nonetheless, there needs to be a sensitivity and respect shown during the initial community consultations, and getting this right becomes crucial to the success of the approach. One approach to overcome these concerns may be to only use public (or low sensitivity) TK, as determined by the TK holders and their communities, when building forecast models.

Other challenges for the science integration approach is that a large amount of ongoing data are needed (both TK and NMS) to build and verify a model. Science integration requires many seasons or years of historical forecasts (both TK and NMS) to build and verify a model, whereas the consensus forecasts can be developed and issued as soon as the respective forecasts for that season are available and can be verified at the end of each season. This means that producing forecasts using

the science integration approach is often more technical than consensus forecasts and can therefore take much longer to develop. If historical data on the environmental indicators needed for the TK forecast are not available (e.g., flowering records for mangoes—used in the Pacific as an indicator of the rainy season), then an ongoing monitoring program may need to be instituted (Chand et al. 2014). Such monitoring programs may require significant additional resources (e.g., money and people) to set up and maintain TK data collection, storage, and analysis over several years (e.g., rainfall monitoring network in Vanuatu; Plotz et al. 2013), which has limited the application of this approach in the past (e.g., Andrade and Gosling 2011).

3. A decision-making framework for selecting a combined seasonal climate forecast approach

Although practical examples of two main approaches (consensus and science integration) are provided within this paper, people or organizations attempting to combine TK and contemporary meteorological forecasts will be faced with a myriad of context-related decisions that will affect what approach is possible or best suited to their situation.

Here, we develop a decision framework that incorporates scenarios, or decision trigger points, to help with deciding on the approach best suited to the user's context. The framework can also accommodate fusion between the two approaches (i.e., does not have to be static between one approach or the other forever). As you accumulate more data and gain the trust of the community/TK experts, it is possible to change from a consensus approach toward a science integration approach (via consultation and codesign).

The main decision points (DPs) within the decision framework encompass the following questions, which are discussed in greater detail below and illustrated in Figs. 1 and 2:

DP1: Is existing TK climate forecasting knowledge widely known?
DP2: What level of TK expert/community involvement is required?
DP3: Are there long-term data available on the environmental indicators used as part of the TK forecast or on the accuracy of past TK forecasts and on the contemporary forecast components?
DP4: What level of resourcing is available?

a. DP 1: Level of existing TK forecasting knowledge

Before TK and contemporary SCFs can be combined, there needs to be an understanding of the need for such forecasts, including the current level of reliance on TK forecasts. The level of use of TK forecasts and community interest in provision of combined forecasts is best gauged through surveys within the communities (e.g., Waiswa et al. 2007; Chang'a et al. 2010; Acharya 2011; Chambers et al. 2017). If TK of seasonal forecasting has largely been lost, then there is little opportunity to develop a combined forecast, regardless of the method proposed, and it may only be possible to consider combined seasonal forecasts for a small number of locations where this knowledge exists.

When collecting information on TK used for seasonal climate forecasting, it is important to note the level of cultural sensitivity associated with it. If the TK forecast method is hidden (i.e., is considered to be culturally sensitive and only available to select individuals), then it should remain hidden to maintain community trust and status of the TK experts. In this situation, it may only be possible to combine forecasts through use of the consensus approach. If the TK forecasts are made using information that is widely known, that is, it is deemed to have a lower cultural sensitivity, then other options for forecast combinations are possible, including one of the science integration methods.

b. DP 2: Level of community involvement

One of the first aspects to consider when developing SCFs that incorporate both TK and contemporary components is who needs to be involved in the process and when, how, and for how long they will be involved. There are many different models for this, and the most appropriate model for an individual situation is likely to depend on a number of factors, in particular, the desired level of community/expert involvement and availability of existing TK on seasonal climate forecasting.

Community/TK expert involvement in the process can occur in a number of ways and at a variety of times, depending on the method used to combine the TK and contemporary forecasts. In the first instance, a TK expert may provide information on either the TK forecast and/or on the method in which it is done. If the information on how the forecast is made remains hidden (highly sensitive), that is, is only known by select members of the community and not available to the other individuals involved in making the combined forecast, then the only real option is to use consensus forecasting, subject to community willingness to be involved. In this case, forecast discussions can result in either the NMS and TK experts jointly generating a combined forecast through collective discussions (e.g., Ziervogel and Opere 2010; appendix A) or the NMS using the results of these discussions to incorporate only

complementary TK into a combined SCF (e.g., Mahoo et al. 2015; appendix B).

Even when the TK forecast information is widely known and has low cultural sensitivity, it may still be beneficial to involve community members in the combined seasonal forecast process, particularly as this may increase the likelihood of developing products that better suit the needs of the community and lead to the increased uptake potential of the final product. In this case, community members may be involved initially in the consultation process to determine the communities' needs and which TK forecasting information to include in the final product. Representatives from the community may then be involved in the development of the combined forecast, either as part of a consensus forecast process or as part of the team developing the science integration model (e.g., Ziervogel and Opere 2010; Andrade and Gosling 2011; Mahoo et al. 2015). Members of the community may also be involved in validating the combined SCF, refining it, and communicating this seasonal forecast to other community members.

When using the science integration approach to combining TK and contemporary SCFs, it may be necessary to collect long-term data on the TK indicators in order to build and validate the forecast models. Community members can perform a vital function in this process by providing local networks for regular monitoring of the TK indicators (Plotz et al. 2013). This role has parallels with volunteer rainfall observer networks, the data from which are used to develop and verify contemporary SCFs (Tall et al. 2014; Tait and Macara 2016). Through verification of the same TK indicator at a number of locations, it may be possible to expand the value of the combined forecast from a very local area, covering only the village from which the knowledge originated, to a wider area, including those that may not have been originally surveyed for traditional seasonal forecasting knowledge.

c. DP 3: Availability of long-term data

For many of the science integration methods, long-term data are required in order to build and verify the models. These data may already exist or may need to be collected. The types of data typically required include climate data and observations on the objects used as part of the TK forecast (e.g., flowering records of indicator plants). It may also be necessary to obtain information on the accuracy of past TK forecasts and on the contemporary SCF components. Long-term historical data related to indicators within TK forecasts are often hard to come by, and a monitoring network

may need to be set up and run for several seasons/years before sufficient data are available to develop a combined forecast under the science integration approach (e.g., Plotz et al. 2013). There will also be issues around ensuring the continuity and consistency (homogeneity) of the data. This difficulty in obtaining historical datasets or setting up data-gathering monitoring networks, including the resource requirements needed to do so, can hinder the practical application of the science integration approach, and thus, few studies have been able to implement it in its entirety (e.g., Andrade and Gosling 2011).

In contrast, the consensus approach is not as reliant on the availability of long-term data for implementation. However, while this approach can be used almost immediately, it still requires results from a number of years of combined forecasts before it can be formally verified.

d. DP4: Impact of resource levels

Both the consensus and science integration approaches can require significant resources, albeit of differing types. In the case of consensus forecasting, the greatest resource requirements tend to be associated with bringing together the two expert groups, TK and contemporary forecasters, and are therefore ongoing over the life of the project. Costs, both financial and time related, increase with the number of forecasts that need to be made (i.e., the number per year and number of locations forecasts are to be made for). Typical financial costs would include travel and accommodation costs but may also extend to payments to the local TK experts for their forecasts. Therefore, when setting up a consensus forecasting approach, it is important to consider if there will be sufficient funding to bring together the TK experts and NMS staff on a regular basis and, possibly, for multiple forecast locations.

Resource-intensive components of the science integration approach tend to occur early in the project, such as bringing together the relevant experts to develop the combined SCF model, including statisticians/modelers. Significant additional resources may be required to set up a monitoring network for the TK indicators, which may also involve having people in place to perform the monitoring, development of the monitoring forms and software to store the resulting data, people to oversee the process, travel costs associated with training the monitors, and payments to network members who make the observations, as is often the case for rainfall networks. Resources will also be required for quality assurance and control of datasets. The following are key resource-based questions to consider with the science integration approach:
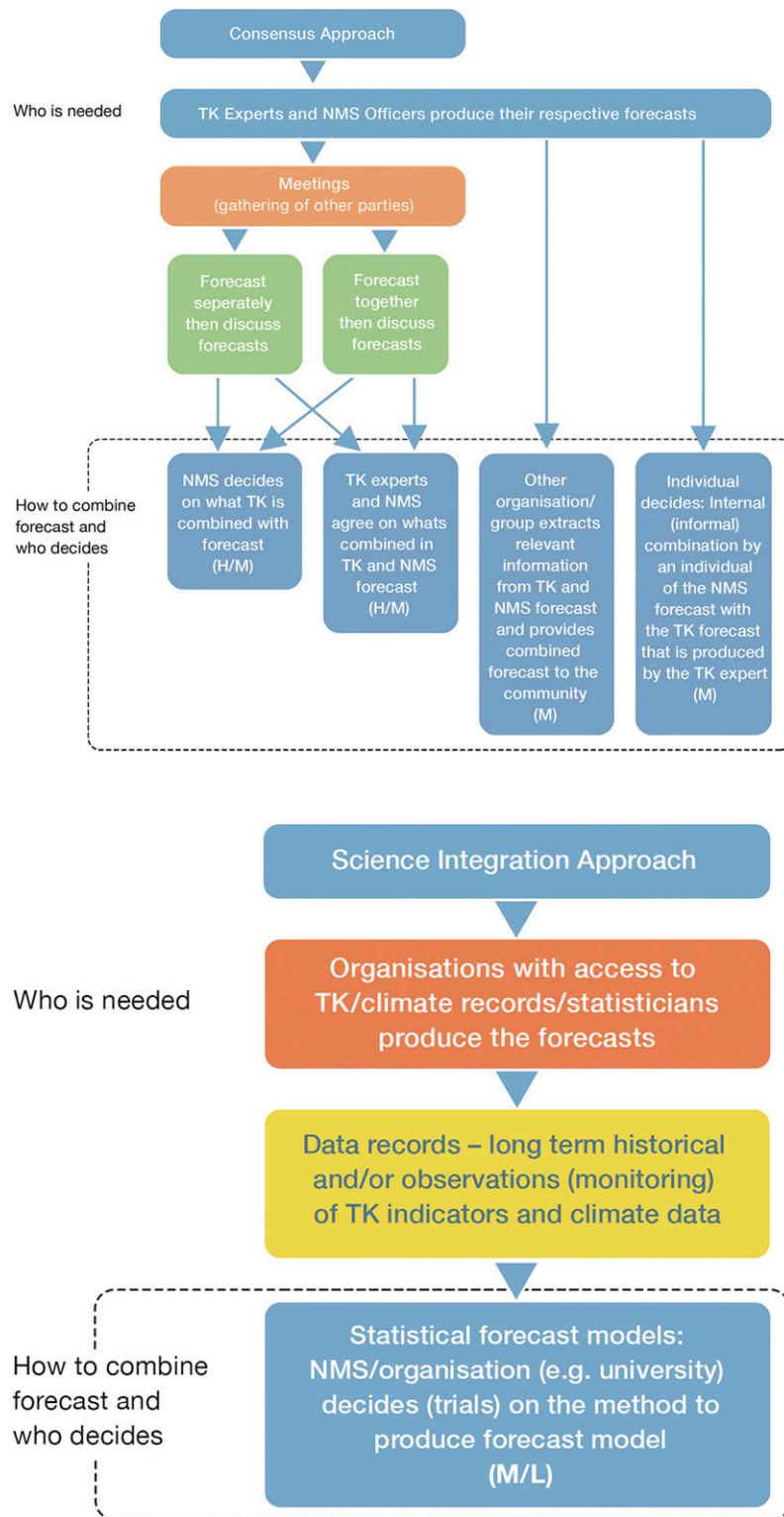
FIG. 1. Basic components of the two main approaches for combining seasonal climate forecasts illustrating typical levels of cultural sensitivity and resource level, expert involvement, and long-term data requirements: (top) the consensus approach and (bottom) the science integration approach. The cultural sensitivity of the information typically used in the forecasts is represented by H, M, and L. Here, H indicates a high
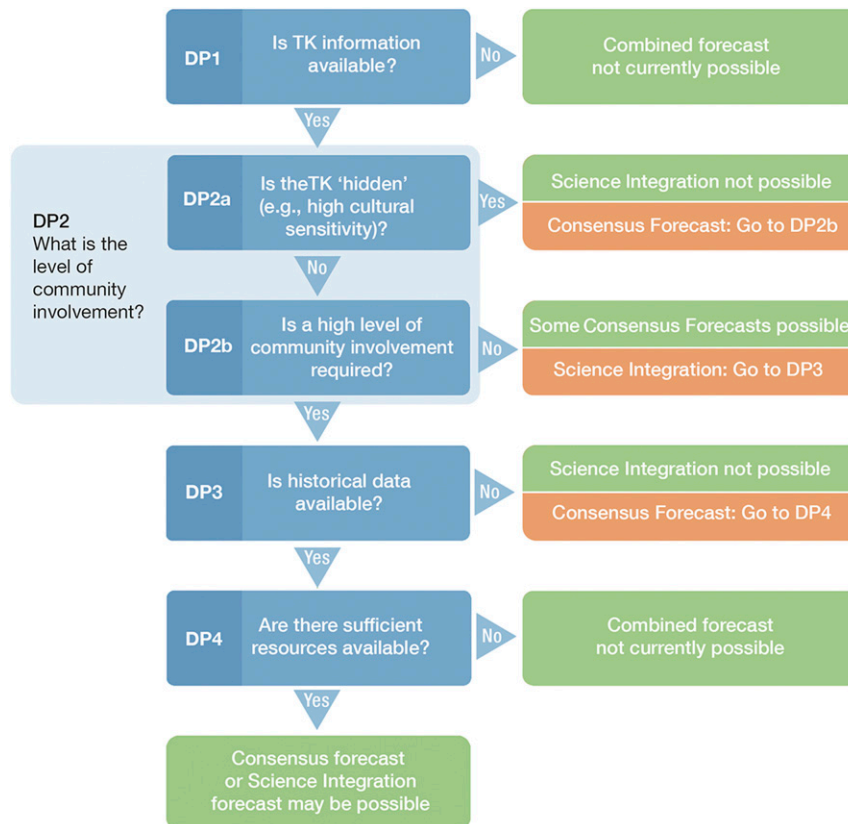
FIG. 2. Simplified decision framework diagram for selecting an approach for combining seasonal climate forecasts. DP indicates the key decision points; see text for greater detail. When a decision is reached, this is indicated by a green box; when a decision is pending, the box is orange. *Consensus forecast methods that may be possible include those where the individual internally combines forecasts from the NMS and TK expert and, depending on resources available, methods where another organization/group combines the forecasts (see Fig. 1, top).

- Are the relevant experts available for analysis and to develop a model incorporating both TK and contemporary forecasts?
- Is there sufficient money and people (both community members and organizational staff) available to facilitate the development of a monitoring network, including data collection and storage, for the TK indicators?

Under both approaches to combining SCFs, projects have failed or been unable to continue because of a lack of sufficient resources. For example, when attempting the science integration approach, Andrade and Gosling (2011) faced resource issues that reduced the power of their interpretations and therefore were unable to integrate the forecasts, having only two years of data available.

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level of sensitivity, where the TK experts would be expected to have a high level of involvement in the combined forecast process as the TK forecast process typically remains hidden; M represents a medium level of sensitivity, where TK experts may or may not be involved in the final forecast decision and some or all of the TK methodology may remain hidden; L represents a low level of cultural sensitivity, and it is not essential to include TK experts in the final forecast decision, and/or the TK methodology is not hidden (e.g., TK is public knowledge). Key to the box colors: orange: resource need is high; green: TK expert involvement essential; yellow: long-term data are required.

Consideration of the key decision points discussed above can assist in selecting the most appropriate forecast combination approach for a given situation. This is summarized below and in Figs. 1 and 2. Here, we suggest the approach that may best match the situation; however, the alternative approach(es) may be possible by adapting the methods.

- High level of TK expert/community involvement is required—consider the consensus approach, though science integration approach can be adapted to incorporate this
- TK seasonal forecasting knowledge is hidden or culturally sensitive—consider the consensus approach
- TK seasonal forecast knowledge is known and has low cultural sensitivity; long-term data needed to build the combined forecast model are available—consider the science integration approach
- The development of combined forecasts is required "immediately"—consider the consensus approach unless long-term data needed to build the science integration models are readily available
- Forecasts are required for many locations; TK forecast knowledge is known and of low cultural sensitivity—consider the science integration approach
- No long-term data are available—consider consensus approach

e. Additional points to consider when selecting an approach for combining TK and contemporary seasonal forecasts

Once an approach is selected, there are a number of other aspects that need to be considered. First, there is the need for ongoing community support for the development and use of the combined forecasts (Jiri et al. 2016). This includes demonstrating that the incorporation of TK into NMS forecasts will provide clear community benefits (Ziervogel and Opere 2010). Forecasts need to meet the needs of the people using the forecasts, so a clear understanding is required of who is the forecast audience. For example, Ingram et al. (2002) highlighted that forecast accuracy for farmers in West Africa must be balanced with timeliness. For these farmers, a less accurate forecast with sufficient lead time would be more valuable than a highly accurate forecast that arrives after farmers have made irrevocable decisions. Without adequate need, benefits demonstrated, and community buy-in, the final product is unlikely to have significant uptake (e.g., Gilles and Valdivia 2009; Valdivia et al. 2010; Ziervogel and Opere 2010). Second, the entire process needs to be respectful and to acknowledge the intellectual property of all knowledge holders (Schnarch 2004; Brahy 2006; Zaman and Wee

2014). Relationships between the parties involved in the development of the forecasts, including with the TK experts and community, need to be built on trust, even in the case of the science integration approach. It takes time to build relationships of trust, particularly when TK is involved, and this should not be underestimated.

Third, sufficient communication tools and processes need to be in place to ensure that the forecast is in the correct format, presented at the correct time, and able to be understood by the recipients. This includes careful consideration of the content and timing of the forecast and who will communicate the forecast, via what media, and in what language (Gilles and Valdivia 2009; Valdivia et al. 2010; Ziervogel and Opere 2010; Mahoo et al. 2013). Andrade and Gosling (2011) recognized language barriers to communication and recommend the use of familiar terms to aid understanding.

Finally, as discussed earlier, there is the need to consider ongoing resources for the project, including for the research to operations transition and ensuring that the forecast process is sustainable into the future.

Ideally, TK experts and/or members of the community for whom the forecast is being developed should be involved in most, if not all, aspects of the forecast development and implementation. This should occur regardless of whether it is necessary to include them to be able to develop the model (i.e., TK is widely known). Keeping the TK experts informed and involved in the process will help to ensure ongoing community support of the process, as it increases trust and understanding, which ensures the end product is relevant, thus increasing the likelihood of the final products being used.

4. Conclusions

By combining the information available from both contemporary- and traditional-knowledge seasonal forecasts, there is an opportunity to increase forecast reliability and usefulness, leading to improved community resilience to climate variability and change. This is especially important with respect to disaster risk reduction. A number of different methodologies have been proposed for combining these forecasts, broadly categorized by the consensus or science integration approaches. These approaches, and the methodologies within them, differ according to resource requirements, the level of involvement of TK experts, historical data requirements, and the cultural sensitivity of the TK used. There is no one method that is suitable for everyone and every situation, and it is important to consider the context of the situation before selecting an approach. Therefore, a decision-making framework that respects the needs of both the provider and the user (community), such as that

developed here, is needed to help select the most appropriate approach for a given situation.

Regardless of the approach taken to combine contemporary and TK seasonal forecasts, there are a number of considerations that apply. Relationships between all parties, including the contemporary forecast experts, the TK experts, and the community, need to be built on respect and trust. Respect for all stakeholders is integral to a long and successful engagement. As such, it is highly recommended that the TK experts and/or community members for whom the forecast is developed are involved in as many aspects of the forecast development and implementation as possible. In addition, resource requirements are a major consideration regardless of the methodology selected, and plans and procedures should be put in place to ensure this is sustainable into the future.

We believe this paper provides a valuable reference for those wishing to develop SCFs based on both scientific and traditional forecast methods, that is, aiming to have the best of both worlds.

APPENDIX A

Consensus Forecasting in Kenya

Since September 2008, the Intergovernmental Authority on Development Climate Prediction and Applications Centre (ICPAC) has brought meteorologists and Nganyi indigenous knowledge forecasters together to produce a consensus forecast for the local area (Ogallo and Ouma 2015).

The Nganyi clan in East Africa is well known for their specialized rainfall forecasting capabilities. This knowledge is specific to local conditions and is dynamic and nurtured by ongoing observations of biophysical and mystical indicators, commonly used to predict the amount and timing of rainfall, including the behavior of certain animals (e.g., frogs croaking, movement of ants) and observations of stars and wind and cloud patterns (Ziervogel and Opere 2010). The specific details within the Nganyi forecast knowledge is shrouded in secrecy and held within the clan as generations pass down their skill and knowledge in interpreting local climate indicators (Guthiga and Newsham 2011). The Nganyi are valued for their seasonal forecasts as they are made at the village level and are better understood by community members than SCFs produced by the meteorological department that are broader in scale and use more technical terminology (Newsham et al. 2011). The community view themselves as the custodians of the sacred ''knowledge,'' and this has made them reluctant to share their information openly for fear of betraying their community.

The Kenya Meteorological Department (KMD) downscales regional climate outlooks produced by the ICPAC to produce regular seasonal forecasts, which are broadcast on local radio to assist farmers in making crop decisions (Ziervogel and Opere 2010; Newsham et al. 2011).

The method of arriving at a consensus starts with a presentation of both the meteorological and indigenous forecasts for the region. Eleven groups from within the Nganyi clan meet once a year to agree on a common regional forecast, which is followed by a facilitated group discussion with representatives from the KMD. All participants are involved in a discussion that explores overlaps between the Nganyi and KMD forecasts (Newsham et al. 2011). Any forecast disagreements are thoroughly considered, and reasons for differences explored. Agreement is then reached on a combined forecast (Ziervogel and Opere 2010; Fig. A1).

These annual meetings also explore the accuracy of the previous season's consensus forecast, including other aspects such as whether people received forecasts on time and any significant climate-related impacts experienced in the region during the season. Evaluations of community feedback (by Great Lakes University of Kisumu; Guthiga and Newsham 2011) concurred that the combined forecasts were accurate (Ziervogel and Opere 2010).

This participatory-action-oriented approach facilitated an ongoing collaboration between the Nganyi community and the KMD (Guthiga and Newsham 2011) and included an agreement by the KMD to address the concerns that the Nganyi had for sharing their knowledge. Importantly, the Nganyi elders were given time to forecast and share with the KMD.

FIG. A1. Members of the Nganyi rainmakers meet staff from the Kenyan Meteorological Service to develop a consensus seasonal forecast [photograph credit: T. Omondi, from Ziervogel and Opere (2010)].

Key outcomes from the project have been an increased uptake in climate information by the community when planning their activities and a substantial increase in trust and information exchange between the KMD and holders of indigenous knowledge. Indeed, the consensus meetings resulted in the Nganyi seeing more value in the KMD forecasts as the variation from their knowledge was deemed as small, while KMD become less skeptical about the practices of the Nganyi (Guthiga and Newsham 2011).

APPENDIX B

Consensus Forecasts in Northern Tanzania

a. Background

Local farmers in regional Tanzania have favored TK, based on observations of their local environment, over seasonal forecasts from the Tanzanian Meteorological Authority (TMA; Kadi et al. 2011; Mahoo et al. 2015). However, it has been recognized that decision-making by farmers would benefit most from seasonal forecasts that are adequately downscaled, reliable, and timely (Mahoo et al. 2015). To this end, several stakeholders in the Lushoto District of northern Tanzania attempted to systematically integrate TK and TMA forecasts (Mahoo et al. 2013, 2015). The objectives and processes to achieve this are described below.

1) IDENTIFY AND DOCUMENT EXISTING TK WEATHER FORECASTING PRACTICES

Stakeholders from the TMA, Soikone University of Agriculture (SUA), and the Lushoto District agricultural

sector collected data on traditional weather and climate information from seven villages—Boheloi, Gare, Kwang'wenda, Masange, Mbuzii, Milungui, and Yamba. Household surveys were provided to randomly selected respondents from each village to gain more information of TK forecasting techniques. The agricultural extension officers worked with elders from three of the villages to identify key local informants to participate in interviews and focus group discussions.

2) ESTABLISH TK WEATHER FORECASTING ZONES AND TEAMS

The seven villages were grouped into three TK forecasting teams, according to their geographical position within the ward (i.e., upper, middle, and lower zones). Each team consisted of seven people whose selection was based on gender and specific TK expertise (i.e., key informants selected by elders), such as plants, insects, animals, wind, moon, and stars. The teams were trained by TMA stakeholders to regularly record their TK weather observations, and a schedule was agreed upon to meet every two weeks to produce a TK forecast.

3) OPERATIONALIZE THE INTEGRATION AND DISSEMINATION OF TK AND TMA FORECASTS

Twenty-one people from the three TK forecasting teams (i.e., upper, middle, and lower zones) were brought together with eight members from the TMA, SUA, and agricultural sector to form the Lushoto District Weather Forecasting Team (LDWFT). The LDWFT meet on a fortnightly basis to discuss, compare, and combine TK with TMA forecasts. TK forecasts that matched the TMA forecast predictions were combined to form a joint TK–TMA forecast and disseminated to all relevant stakeholders in the district (Table B1).

b. Key outcomes

Researchers from the SUA analyzed rainfall data from the TMA and compared it to TK forecast information obtained from the randomly surveyed households (i.e., 77 households). Both TK and TMA forecast approaches matched for the March, April, and May 2012 period; that is, both predicted "normal" seasonal rainfall (Mahoo et al. 2013). Notably, the TK forecasts were more reliable in the long rainy season (from March to May) compared to the short rainy season (from October to December). Over 90% of respondents were aware of combined TK–TMA forecasts, with 83% of farmers reporting that they used it. Previously, 56% of respondents believed that TK forecasts were reliable compared with 28% for TMA forecasts (Mahoo et al. 2015). Radio was found to be the most suitable media to disseminate forecasts (Mahoo et al. 2015).

TABLE B1. Example of a combined TK and meteorological seasonal forecast with performance review, between the TMA and community elders from Same, Tanzania (Ziervogel and Opere 2010).

Season	TK indicators and forecast	TMA forecast	Combined forecast	Combined forecast performance
March–May 2010	Frogs making a lot of noise and ants moving and spreading across roads signify rainy season is about to start (season onset). TK indicators predict rains during this season will decrease, especially in May.	Seasonal rainfall will be normal. Main indicators are sea surface temperatures of the Indian and Pacific Oceans and wind strength.	TK and TMA forecasts indicate normal rains, with an expected decrease as the season progresses.	Reported as "very good." Almost all predicted events occurred.

Farmers expressed great interest in the combined TK–TMA forecasts and recommendations included upscaling forecasts to other districts (M. Hendry 2015, personal communication; Mahoo et al. 2015). Planned expansion of the service is yet to occur as funding has ceased. However, the original three TK forecasting teams continue to meet and make forecasts for their local district (H. Mahoo 2015, personal communication).

APPENDIX C

Statistical Rainfall Prediction Using Traditional Knowledge and Meteorological Forecasts in Uganda: Science Integration Approach

This case study is based upon information found in Waiswa et al. (2007). Knowing when to expect seasonal rains is extremely important to Ugandan farmers. However, the Ugandan Meteorological Service (UMS) forecasts the amount of rainfall expected, not its timing. Rainfall in Uganda is bimodal, with two rainy and two dry seasons. As these seasonal rains arrive sporadically, farmers use TK to forecast when the rains will come. This involves monitoring the behavior of physical and biological indicators such as the wind, clouds, birds, and insects. There was no model to predict both the timing and amount of seasonal rainfall. Research was undertaken to develop a statistical model that combined the UMS and TK forecasts. This was achieved as follows.

a. Collect TK indicators and meteorological data

1) FARMERS' TK INDICATORS

In eastern (Tororo), Lake Victoria basins (Jinja), central, and western (Masindi) Uganda, 230 farmers were asked about their climate-related TK in local language by local research assistants over three days in 2003. The area collaborator, a local agricultural expert, selected participants to survey with a preference toward the elderly.

2) METEOROLOGICAL DATA

The areas selected to survey farmers were chosen because they had operational weather stations with long-term historical data. Because of civil wars in Uganda, no continuous data existed between 1960 and 2000, and few records were available in electronic format. The daily weather data included precipitation, temperature, and wind recorded on paper forms that were sent to the UMS headquarters in Kampala, Uganda, and archived.

b. Validate the TK rainfall onset forecast

Data from the TK surveys were used to derive hypotheses relating to how farmers use local indicators to predict the onset of the seasonal rains. Any uncertainties about the collected data were followed up with revisits to farmers in the survey areas.

Validation of the TK rainfall indicators was based on comparing its predictive capacity against the climate data from synoptic weather stations in the four regions. A regression model indicated a strong relationship between the onset of the first rains and temperature, seen as an objective measure of the surrounding environment. This model could be used to predict the onset of the first rains up to two months ahead.

c. Develop a statistical model combining TK and UMS forecasts

Model development was achieved by linear regression of validated TK temperature and wind indicators with rainfall onset dates formatted in pentads (defined as having 25 mm or more rain in five days), using at least 10 years of recent continuous meteorological data. Specific criteria included the use of data from 1989 to 2003, to reflect recent climate conditions, and high correlation values ($P < 0.05$).

Smoothed daily maximum temperatures for each station were converted to 5-day averages. Significant correlations between temperature values during the dry period, from November to February, and the rainfall

onset date were then used to build a predictive (linear regression) model for each site.

This study showed that combining the two forecasts systems added value because the majority of farmers were better at predicting the onset of the first rains using TK, whereas meteorologists were better at predicting the second rains.

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