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From Doing to Thinking in Meteorological Forecasting: Changing Work Practice Paradigms with Knowledge Management

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Abstract

This research aims to improve meteorological decision making through the application of knowledge management to the forecasting process. The aim of the research is not to solve the problems of forecasting but to provide appropriate support to enable forecasters to spend more time reflecting on the meteorological situation. To this end, we are engaged in change of the IT paradigm in this problem domain from the one based on scientific normative models to intelligent support. This change of paradigm allows forecasters not only perform the task but also to consistently share knowledge and learn from their collective experience. The paper also presents a system that allows diverse technologies to be employed in providing decision support for meteorological forecasting.

Keywords: Decision support systems, organizational issues, knowledge management, intelligent decision support, meteorological forecasting.

INTRODUCTION

Meteorology presents a challenging environment for knowledge management (KM). Although atmospheric science offers sophisticated numerical weather prediction (NWP) models, the meteorologists still rely on their experience and knowledge of local conditions to interpret and adapt the results of these models. Organizationally, this reliance on interpretation raises the issue of the consistency of forecasts prepared by different meteorologists. As a public sector organization, the Australian Bureau of Meteorology has limited resources and needs to develop innovative approaches to forecasting for geographically distributed centers. This is being addressed by increasing the emphasis on the role of the meteorologists' knowledge in the preparation of public forecasts by assessing, interpreting, judging, and resolving inconsistency in automatically generated forecasts.

The Bureau has had a long history in using IT to support its primary function of issuing of the forecast products mainly based on a variety of simulation numerical models. However, since the late 1970s, there has been more pervasive use of IT to support meteorologists in all work aspects including distributing IT resources into regional forecast centers and the development of applications that directly support forecast production.

The Bureau collects and records a vast amount of data on an on-going basis. The weather observations are used as inputs to NWP and a wide range of other products based on the analysis of that data. The observations data and the analytical products based on the observations are available to operational meteorologists as aids in preparing their forecasts. The major problem, as well as opportunity, is the management of these massive data holdings. From the organizational point of view, there is a need for meteorologists to use as much of the available material as possible to maximize forecast accuracy. Thus on the one hand, there is too much material for meteorologist to consult while, on the other hand, certain weather conditions require the meteorologist to refer to a very broad range of material to reliably construct the forecast.

In this paper, we present an implementation of a task-based KM system that provides an environment in which the forecaster is able to explore all available data, manipulate it, access guidance material, construct a forecast, and provide a rationale for the forecast. The system intelligently manages the data allowing forecasters to exercise their own judgment. Collaboration is supported in that forecasters are able to reconcile their individual forecasts with others. This is achieved by making the forecast instance available to other forecasters, thus enabling knowledge sharing. With these facilities, we also demonstrate how individual and organizational learning processes are supported. The aim of the research is not to solve the problems of forecasting but to provide appropriate support to enable forecasters to spend more time reflecting on the meteorological situation.

A TASK-BASED APPROACH TO KNOWLEDGE MANAGEMENT IN WEATHER FORECASTING

Meteorology presents a range of fundamental issues that are intrinsic to knowledge management. The forecasting task requires continuous sharing of experiential and tacit knowledge through effective organization of historical data holdings for re-use and learning from experience. A significant characteristic of forecasting is rapid verification, provided by regular observations data, that reflects the forecaster's skill. In such an environment, the emphasis of work practices shifts from "doing" to "thinking," which facilitates knowledge creation.

The work of a forecaster involves dealing with a complex task, multiple sources, and a great variety of information and strict time lines, all overlaid by a legal regime. Judgment and experience are also important in forecast construction to overcome the inadequacy of science at the level of detail required. To this extent, forecasting work can be essentially categorized as knowledge work (Iivari and Linger 2000), lending itself to KM and intelligent decision support.

The approach we have adopted for KM is based on a task-based model for decision support as shown in Figure 1 (Linger and Burstein 1997). The model presents the task at two levels: the *pragmatic* level presumes the performance of the task (doing) while the *conceptual* level represents the understanding of the task by the actors involved in its performance (thinking).

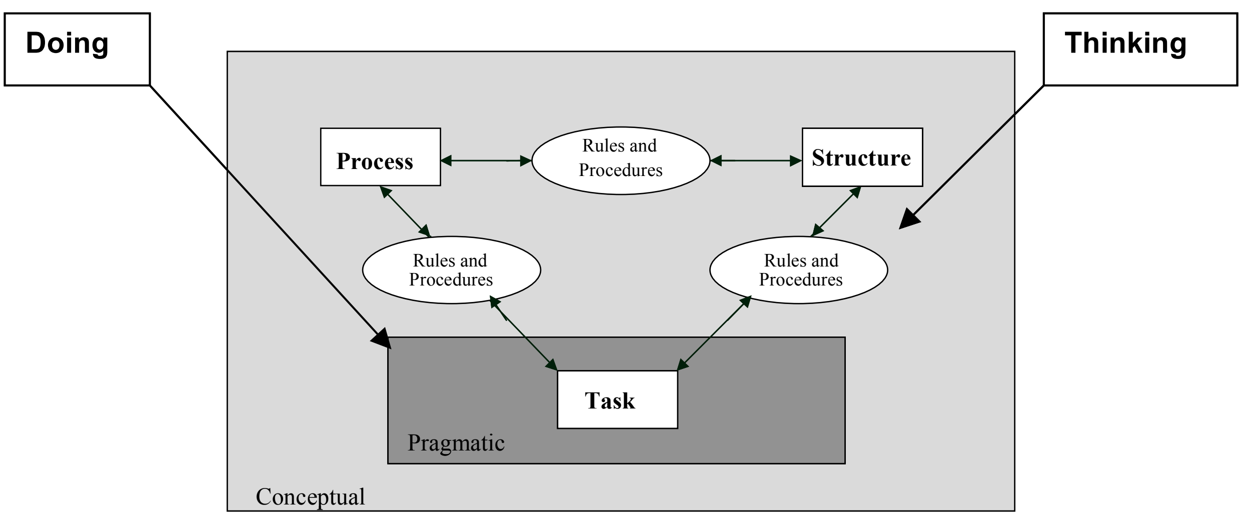

Figure 1. A Framework for Task Based Knowledge Management
(adapted from Linger and Burstein 1997)

From the point of view of knowledge management, we concentrate on the conceptual level as we assume that the actors are knowledge workers who have the expertise to perform the task. The model represents a generalization of the task. Each time a forecast is produced, the *structure* and *process* models are instantiated to reflect the specific weather situation. Each instantiation then becomes a record of the task and cumulatively represents a task-based organizational memory (Ackerman and Mandel 1995). The importance of this interpretation of the framework is that this memory is an essential part of the learning process. In the next section, we describe the forecasting task and justify the suitability of the task-based approach for KM in this area.

THE FORECASTING PROCESS

The forecasting process can be summarized as a sequence of four main processes:

- *Guidance generation process* – includes the post-processing of NWP output and models to formulate predictions.
- *Decision process* – the point at which the forecaster evaluates NWP and other guidance for consistency, uncertainty, and feasibility drawing on his/her own knowledge as well as climatology. The forecaster utilizes decision support tools, taking into account operational and service requirements and levels of detail need to be achieved.
- *Production process* – this is where the forecast is converted from policy to the actual forecast product ready for end users presented in various formats.
- *Delivery process* – the means by which the media and users obtain forecast products.

The production of meteorological forecasts and warnings begins with collection of data that describe the current state of the atmosphere. These data come from a variety of sources including human observers' weather reports and reports from a variety of instruments. This large volume of data must be sorted and arranged into a comprehensible form before it is useful for predicting the weather patterns in map form. A number of times each day, the latest collection of data is processed via parallel manual and computer based paths that result in weather analyses and prognoses.

Applying manual weather analysis, the meteorologists identify important patterns in large volumes of data and integrate different data types. Meteorologists use their experience and knowledge to predict the likely evolutions of those patterns, analyzing a range of displays and plotting data on weather maps. This is termed the forecast policy. While the policy is the responsibility of the senior meteorologist on each shift, it is developed with contributions by all meteorologists on the shift and represents a consensual view.

In parallel with the manual prediction, at least twice each day, collected weather data are processed on a supercomputer to simulate the behavior of the real atmospheric events. Computer-based prognoses make rigorous use of the available data and consistently apply the known physical laws describing atmospheric evolution. Such simulations are repeatable and generate useful insights into the future. On the other hand, they cannot use some types of data, poorly cope with small weather events and conflicting data, and take several hours to compute mathematical models of the atmosphere running

A synthesis of the manual and computer analyses and prognoses forms a reality check on the computer simulations and provides the forecaster with alternative solutions on which to exercise judgment. The forecast policy emerges out of this process and forms the basis for the production of a consistent set of forecasts for particular areas and localities and other weather products. Products are disseminated through the media or via poll (demand) fax services (Weather-by-Fax) and through the Internet. These products are usually generated according to a fixed schedule. This requirement to issue products to a fixed schedule, and to insert additional warnings and special products during an event (i.e., sports competitions), adds substantially to the pressure of the manual forecasting task. One of the most important tasks for each weather forecasting office is to continuously evaluate the performance and to compare their predictions with the manual analysis of the current weather situation to facilitate improvements.

The Bureau's forecasting service is subject to many pressures both externally and internally. The key influences which make a new approach to the forecast process necessary are summarized as follows:

- *Rising user expectations and needs*: Users require more evidence of the quality, consistency, and reliability of the processes and evidence of continuous refinement of products. They expect to be able to access sophisticated applications for meteorological information, including graphical and audio-visual presentation, computerized decision support systems, and real-time alerting.
- *Efficiency requirements*: Increasing user demands require more and better output, leading to steadily increasing workloads. The Bureau is committed to streamlining the forecasting process to achieve the greater efficiency required to cope with these demands.
- *Opportunities arising from technological advances*: The Bureau is involved in an international effort devoted to improving the forecasting infrastructure both in terms of the technology and its content. This allows taking advantage of work already carried out while focusing on areas that will provide more sophisticated and effective tools for meteorological product preparation.

- *Opportunities to make better use of forecasters' scientific skills*: Improved scientific understanding of meteorological phenomena has not always been translated into improved forecasts. This is due to a number of causes, including the heavy workloads of forecasters, inadequate data, and insufficient attention to on-the-job learning.

The Bureau's change strategy is to reconceptualize the forecasting task from the production of forecasting products to the construction of forecasting policy. This strategy is based on an important presumption that forecasting production cannot be automated. For example, the output of numerical models cannot be issued as a forecast without the intervention of a meteorologist, even if the model output is accurate.

To achieve the required organizational outcomes, meteorologists will need to engage in knowledge reuse and sharing activities. This implies that work practice needs to evolve so that conceptual level modeling (thinking) is represented and recorded explicitly while performing the actual pragmatic task (doing) (Linger and Burstein 1997). This requires a paradigm shift to emphasize that the target processes, guidance, and decision processes are privileged over the existing emphasis on forecast production. The Mandala project, discussed below, is concerned with implementing this change strategy (Linger and Burstein 2001).

THE MANDALA PROJECT

The Mandala project is a collaboration between Monash University and the Bureau of Meteorology. It aims to develop integrated support systems for operational forecasters within a task-based KM framework. The Mandala project focuses on forecasters' assessing the weather situation and exercising professional judgment, rather than the actual writing and dissemination of the forecasts. The approach also embeds learning as an explicit component of the forecasting task (Bureau of Meteorology 1999; Linger et al. 2000).

The Mandala project changes the focus of the forecasting task from the production of forecast products to the decision processes that establish the forecast policy with the aim of:

- encouraging more consistent and scientifically sound forecasting practice;
- making better use of the increasingly accurate output from automated systems;
- maximizing the time available to forecasters to consider meteorological decisions;
- minimizing the time spent by forecasters in typing or formatting products;
- expanding the application and visibility of forecast verification information; and
- easily sharing all data, including archive, observations, guidance, policy, and forecast data.

The name of the project borrows from the Buddhist concept of the mandala, which is a term in Jungian psychology for the whole self, implying *well-being*. A mandala is represented as a circular symbol for the "whole universe" that is divided into four quadrants. This indicates a holistic approach that takes into account the constituent parts. The mandala has been adopted for the forecast process as it accommodates the key aspects that characterize the forecasting task. For example the four quadrants enable the meteorologist to construct the forecast (*produce* quadrant), chose and access relevant information (*view* quadrant), aids or guidance for that forecast, manipulate the material as appropriate (*edit* quadrant), and *explain* the reasoning behind the forecast (*explain* quadrant). This cyclic way of moving within the work space encouraged a holistic view while allowing each quadrant to respond with information that is pertinent to its function while also relevant to whatever work is being done in any quadrant. All quadrants are dynamically linked to each other so that all material displayed is consistent between the quadrants.

Applying the Mandala to the Forecasting Task

Applying the Mandala to the forecasting process, it is important to consider three perspectives: the *system function*, the *forecast task* and *KM elements* (see Table 1).

The functions of inspecting manual and computer analyses and prognoses can be described as a *view* task. The synthesis step is a combination of *edit* and *explain*, where *edit* is the process by which the forecaster currently mentally adjusts the various inputs to ensure consistency, or disregards/deletes the inconsistent from consideration. *Explain* documents the decision, making it available to other forecasters. *Produce* prepares the end product for dissemination to users.

Table 1. Three Perspectives of the Mandala

Generic Description of the Forecast Activity	System Function	Forecast Task	KM Elements
Inspect weather data; analyses, prognoses, and guidance	View	Assess	Access/retrieve organization memory
Synthesize guidance to develop a conceptual model of the forecast state of the atmosphere	Edit	Apply Policy	Assess adequacy of conceptual task models
Prepare forecasts and set ready for dissemination	Produce	Forecast	Instantiate task model
Describe policy decisions to others; inspect performance statistics for previous forecasts	Explain	Verify Policy	Contextualize task instance

The meteorologist can potentially gain access to review forecasts prepared by other meteorologists when they are made public. This can be done by selecting the forecast in the *view* quadrant. In this way, the Mandala approach supports the meteorologists as a learning community that has a professional and scientific interest in the quality of the forecasts they produce (Linger and Burstein 2001).

Although the learning function is not explicitly represented in the table, it is embedded in the process and takes a number of forms. First, the process of explaining the reasons for a given forecast and/or policy makes that knowledge public and allows other meteorologists to understand the rationale behind the forecast/policy, thus providing an opportunity to learn from this instance (single loop learning). Second, the forecast product is verified by comparing it to actual weather observations that are made later as part of the normal data collection process. This systematic review of performance through verification provides the means to evaluate the current state of knowledge which, taken to the organizational level, results in a double loop learning.

The Learning Process within the Forecasting Task

There is an imperative, organizationally and scientifically, for meteorologists to learn from their forecasting experience with the aim of improving their practice as well as creating knowledge necessary for implementing more sophisticated models, forecast aids, and guidance material. This creates a need for forecasters to reflect on and review their performance and practice on an ongoing basis (Schön 1991). The aim of such reflection is to improve task performance through knowledge creation, especially the heuristics needed to address deficiencies in scientific knowledge. This reflection is an intrinsic part of the forecasting task and determines the forecasters as a learning community (Arygis and Schön 1978). Moreover, meteorologists are all engaged in a specified task, weather forecasting, and have a professional interest in that work (Wenger 1998).

The emphasis on learning in the Mandala project is expressed at the individual level, in terms of the knowledge and experience of the forecaster; at the community level, in terms of the review processes; and at the organizational level, in terms of improving the forecast process. The most important aspect is that learning occurs at each level (representing individual, community, and organizational learning) and in the organizational and social processes that occur between the levels (Linger and Burstein 1998). In this approach each meteorologist maintains an individual/private knowledge model. This allows them to specialize their task model to reflect their own knowledge, and to use this to both perform the task as well as explore the boundaries of this knowledge. This is the micro level, the *personal* and *private*. The meteorologist then has the opportunity to publicize their view of the task by making their model available to the community. The intention is to provoke discussion and debate, not necessarily to gain acceptance. This is the meso level, the *personal* and *public*. The result of the discussion within the community is the macro level, which is a minimal *consensual* task model. This is the organizational view as it represents the current shared understanding that all meteorologists would be required to apply to the task (Levitt and March 1988). Moreover, it expresses the outputs required by the organization.

Within the Bureau, forecasters are found in all centers, which are usually located in capital cities and major airports. For the whole community to be included in the review process, these discussions need to be virtual and asynchronous. In the Mandala, each forecast instance is conceptualized and thoroughly documented, which lends itself to knowledge sharing and re-use in this distributed environment.

In the Bureau, there is an explicit acknowledgment that the experience and knowledge of the forecaster is required to overcome the limits of science. In the professional environment of the Bureau, meteorologists are encouraged to develop conceptual models of weather phenomena, to exhaustively evaluate these models, and then the organization incorporates the models into the forecast process. In this context, the forecaster is assumed to be autonomous and responsible and is assigned the necessary authority to issue a public forecast. Such work practices are consistent with post-Fordist work (Amin 1994) and can be categorized as knowledge work (Blacker 1995; Iivari and Linger, 2000).

THE MANDALA AS KNOWLEDGE MANAGEMENT

Mandala Architecture

The implementation of the Mandala, as shown in Figure 2, is a specific instance of the task-based KM framework. The Mandala represents the three perspectives shown in Table 1 through an interface that is consistent with the forecaster's work practices.

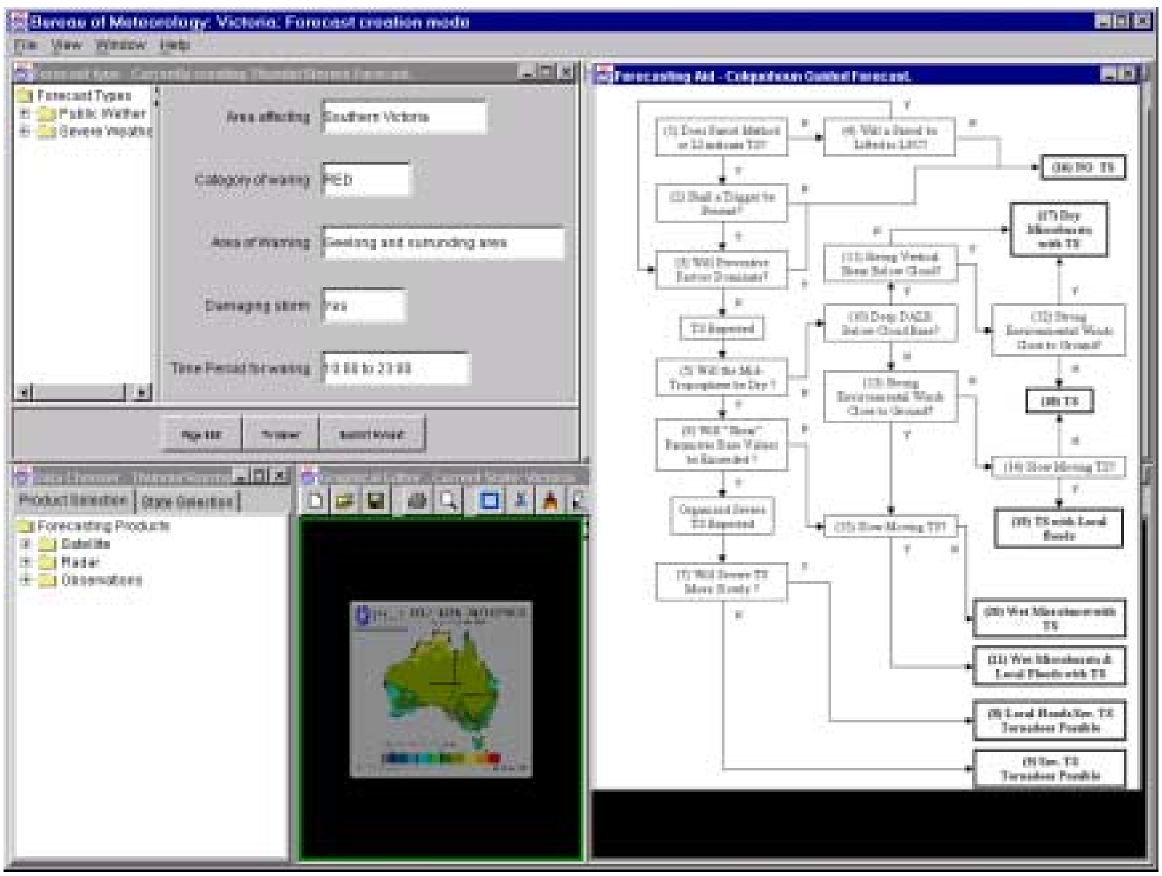

Figure 2. The Mandala Implementation

In terms of the forecasting process, Figure 2 represents the decision and production processes as discussed earlier. The *view* quadrant, labeled *Data Chooser* in the lower left corner, allows the forecaster to select any electronically stored material that the forecaster needs to consult to help them make a decision regarding the forecast. This material ranges from the NWP products to the actual observation data. The selected item is displayed in the *edit* quadrant, labeled (in this instance) *Graphic Editor*. The software that drives this editor is a powerful system that is being developed at the University of Wisconsin (Hibbard et al. 1999). It allows the forecaster to interactively manipulate products that are presented graphically and to visually explore the effects of changing the product according to their weather interpretation. The material representation form and what can be done with it in this quadrant depends on the material itself. The *produce* quadrant is the *Forecast Composition* area. In this instance, the meteorologist enters the necessary data in a form. The composition of the forecast wording is software driven. It is based on the data provided in the quadrant, and is highly structured and constrained. The meteorologists can review the automatically generated forecast prior to its public release. The forecast is selected in the *Data Chooser* and can be modified in the *edit* quadrant.

The *explain* quadrant is shown in this instance as a Forecast Aid-Colquohoun Guided Forecast. The example contains a Thunderstorm Decision Tree, which may be used to assist the forecaster in assessing the potential for thunderstorms, severe thunderstorms, or tornadoes (Colquhoun 1987; Linger et al. 2000). The decision tree consists of 21 nodes representing *true/false* decisions based on prevailing or prognostic conditions. The decision tree guides the meteorologist through the decision process to determine whether sever weather is likely and represents the meteorologist's understanding of the evolving weather pattern. This example shows a guidance product that also provides a rationale for a specific instance of that forecast. The decision tree can be annotated to enhance the ability to conceptualize the forecast.

The Mandala explicitly posits authority for the forecast with the meteorologist. Irrespective of how much of the forecast preparation is automated, the meteorologists must exercise their professional judgment before a forecast is released consistently with the view that forecasting is knowledge work (Davenport et al. 1996). The Mandala can also be used to review forecasts prepared by other meteorologists, when they are made public, by selecting the forecast and its rationale in the *Data Chooser*. In this way the Mandala supports collaborative knowledge work and emphasizes the meteorologist as a member of a learning community.

The quadrants of the Mandala map onto the task-based KM framework, shown in Figure 1. The decision tree above is an example of a conceptual model of the structure underlying thunderstorm forecasts. It is an organizationally sanctioned model that is presented to the forecaster for guidance or as an aid rather than a prescribed procedure. The *produce* quadrant represents a model of the pragmatic task. In this instance the task is mediated by the automated forecast composition application that alleviates the need for the forecaster to actually compose the forecast wording. At this stage, the *rules* and *procedures* in Figure 1 are not incorporated in the Mandala so forecasters are not prescribed in what they do. This suggests that current Bureau procedures are the individual responsibility of forecasters. This raises the issue of forecast consistency and the scientific adequacy of any existing manual procedures. The last element of Figure 1 is the model of the conceptual process. At this stage, each meteorologist constructs the forecasts according to their own way of doing things. The Mandala reflects this flexibility in terms of process but also has the capacity to conform to a specific process if one is defined.

The Mandala interface presents the task-based KM framework as a single surface that incorporates both the pragmatic and conceptual layers. The four quadrants are used in different guises at different stages of the forecast process. The *thinking* aspects involve retrieving any information objects that support reflection on the current situation including conceptual maps such as the Colquohoun decision tree. It can also involve the graphical editor to simulate possible scenarios. The results of this activity are then utilized in the construction of the forecast that can also involve the graphic editor and the modification of the forecast in the edit quadrant. Decision aids are used both to generate candidate forecasts and to record the rationale that underlies the forecast that is published

Computational Implementations of the Mandala Components

The Mandala has been developed as a prototype to demonstrate how work practices in forecasting can be modified so as to more effectively utilize the data resources, reduce the manual load on the forecasters by automating aspects of the task, and provide more support for exploring the meteorological context of the forecast. The research is not intended to directly impact on forecast quality but to indirectly impact by enhancing the ability of forecasters to exercise their meteorological knowledge. The success of the prototype has resulted in a major development project within the Bureau, the forecast streamlining and enhancement program, based on the Mandala concept. In conjunction with this program, future research will focus on a detailed study of work practices to assess the impact of the Mandala on forecast quality, development of a broad range of conceptual models of different aspects of meteorology, and the application of a wide range of intelligent technologies, including data mining, as forecast aids and guidance.

The Mandala currently does not reflect the individual mental models of each forecaster. To address this, we are applying the metadata concept to structure the electronic material held by the Bureau. This structure will reflect both the information needs of the consensual models prescribed by organizational policies as well as the needs of the individual forecasters. The intention is for the Mandala to initially limit the material available through the *Data Chooser* window to the material that has been deemed relevant to the forecast being produced. For example each node of the decision tree shown in Figure 2 would have defined prescribed material that the forecaster needs to consult to make a decision. This material can be extended by the forecaster to reflect their individual work practices and tacit knowledge. The metadata attached to stored items would then reflect both the consensual and individual information requirements in respect to a specific forecast and would be available when that forecast is selected in the *produce* quadrant. We are also exploring whether the metadata concept can be used in the resulting output to document the forecast rationale by highlighting the specific data that influenced the decision.

Accepting that forecasters are not the only knowledge sources for intelligent decision support, it is possible to utilize the rich data holdings within the Bureau as a potential source of knowledge discovery. Currently a project is underway that employs data mining algorithms to establish patterns which could be used in the automatic generation of guidance material. Current work is addressing the problem of fog forecasting (Viademonte et al. 2001). Thirty years of data have been assembled into a data warehouse against which soft computing technologies have been applied resulting in an intelligent decision support system for accurate fog prediction. This approach is being developed as a system that will be available as a guidance component in the Mandala.

CONCLUSIONS

This paper presents a task-based approach to KM, which has been derived through the action research performed in collaboration with the Bureau. This approach represents a paradigm shift in terms of how information technology is used to support the forecasting process. Applying KM in supporting meteorological work practices creates an opportunity to employ a variety of technologies in implementing more sophisticated heuristic models in order to identify, acquire, share, and apply knowledge from different sources as well as forecast aids and guidance material.

The Mandala is a specialization of the task-based KM framework that previously has been applied to areas such as epidemiology (Linger et al. 1999). The Mandala is an artefact of an action research intervention in the Bureau. As such, it targets the specific context and requirements of the forecasting task. It employs technologies that are most appropriate for the functionalities required in this situation. However, the methodological guidance that underlies this intervention, namely the task-based KM framework, can be deployed in most contexts that are focused on a knowledge work task. We used the Australian context in exploration of the specific issues; however, research deals with generic forecasting focusing on the knowledge work aspects of the task. Irrespective of country differences, the objective is to realign the work practices to a more reflective practice.

The experience gained from this intervention provides further evidence to support the contention that the focus of any KM initiative lies in focusing on the actual work practices of knowledge workers and community of practice related to a particular task. This approach is fundamentally bottom-up in contrast to most organizational KM initiatives. The advantage of this approach lies in the ability to implement a KM system that is consistent with work practices but emphasizes the knowledge flows within the community of practice. In the longer term, this approach has the potential to improve the community's work practices as a result of learning and reflective practices.

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