Weather Forecasting: The Next Generation
The Potential Use and Implementation of Ensemble Forecasting

by

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Abstract

This thesis discusses ensemble forecasting, a promising new weather forecasting technique, from various viewpoints relating not only to its meteorological aspects but also to its user and policy aspects. Ensemble forecasting was developed to overcome the limitations of conventional deterministic weather forecasting. However, despite the achievements of ensemble forecasting techniques and efforts to put them into operation, the implementation and utilization of ensemble forecasting seems limited in society. This thesis studies meteorological aspects, potential uses and value, and policy issues to give an overall picture of ensemble forecasting and suggests directions of measures to increase its utilization.

Conventional weather forecasting cannot achieve perfect forecasts due to the chaotic nature of the atmosphere and imperfect analyses of the current atmosphere. The imperfect description of numerical weather prediction models in the forecasting process is another source of the disparity between forecasts and the real atmosphere. Conventional weather forecasting offers only a single scenario, which sometimes fails to predict the actual weather; ensemble forecasting provides probabilistic weather forecasts based on multiple weather scenarios.

This thesis also illustrates potential uses and values of ensemble forecasting. Ensemble forecasting could help disaster management officers prepare for probable hazardous conditions. It is also useful for risk management in business. Using concepts of information values and real options, this thesis demonstrates that ensemble forecasting can be valuable in decision making. Potential uses of ensemble forecasting in agriculture and the wind electricity sectors are also discussed.

Implementation of ensemble forecasting requires huge costs, so collaboration within weather sectors and with non-weather sectors is key. Relationships between public, private, and academic sectors in the weather world are analyzed in this thesis. The public-private relationship seems characterized by dilemmas in both sectors. As for the public-academic relationship, there are different situations in the US and in Japan due to differences in research environment and policies. International collaboration and partnerships between weather sectors and non-weather sectors are also discussed. If all these collaborations among the sectors work well, then ensemble forecasting can give rise to a new generation of weather forecasting.

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This two-year experience is certain to benefit to my life in the future. Again, I would like to give thanks to all the people who supported me, and I hope I will contribute to the society in gratitude for this treasured experience at MIT.

Disclaimer: This thesis represents the personal opinions of the author and does not reflect the opinions of any other person and organization.

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Chapter 1. Introduction

This thesis discusses a weather forecasting technique, ensemble forecasting, from various different viewpoints that concern not only the technique's meteorological aspects but also user and policy aspects. Studies with such overlapping realms have been conducted by the National Research Council (NRC). For example, the NRC issued *Fair Weather: Effective Partnerships in Weather and Climate Services* in 2003 to shed light on partnerships among organizations in the weather world. Following *Fair Weather*, the NRC dealt with uncertainties in weather forecasts from various viewpoints of natural and social sciences, and it suggested ways to achieve better communication regarding uncertainties of forecasting between weather-related organizations and users (NRC 2006). Recently, in the academic sector in the U.S, some meteorology researchers have begun to participate in the Weather and Society* Integrated Studies (WAS* IS) project to explore an interdisciplinary area between social science and meteorology (National Center for Atmospheric Research 2007). Moreover, the American Meteorological Society has implemented a Policy Program to discuss policy issues related to meteorology (American Meteorological Society 2007). In contrast, in Japan, there seem to be few NRC-like reports or research activities to approach weather from various viewpoints other than strictly meteorological. Thus, this thesis is expected to ignite, or at least contribute to, research efforts to explore new areas of weather on both sides of the Pacific.

This thesis covers one promising new weather forecasting technique, ensemble forecasting, from the viewpoints of meteorology (Chapter 2), potential use and value (Chapter 3), and ways to effective collaboration to achieve better weather services (Chapter 4).

Following in the wake of achievements in computational resources, ensemble forecasting was introduced in several forecasting centers around the world. Ensemble forecasting was implemented for monthly or seasonal forecasting in the 1990's (Molteni et al. 1996, Toth and Kalnay 1993); some centers are about to use it for shorter time-range forecasting. For example, Japan Meteorological Agency will implement ensemble forecasting for typhoon track prediction in 2007 (Japan Meteorological Agency 2006). However, some researchers and developers of ensemble forecasting feel that the advancement of the technique is not being fully utilized in society, despite their efforts (Hamill, personal communication, 2007).

Ensemble forecasting requires huge costs in terms of new computers, data storage, and data processing methods, and these costs have slowed its implementation. Without public understanding of the use and value of ensemble forecasting, it is unlikely that it will be implemented effectively. Thus, this thesis discusses its potential use and values both for hazardous weather prediction and for day-to-day business decision making. Demonstration of the value of ensemble forecasting is based on concepts of information values and real options (De Neufville 1990, De Neufville 2006)

Finally, this thesis analyzes the weather realm, including its various stakeholders (e.g.

operational weather forecasting organizations, private weather companies, academia, international, non-weather sectors) and political issues. The NRC report *Fair Weather* covered relationships between the public, private, and academic sectors in meteorology in the U.S. This thesis tries to view these relationships in a different way: by introducing political economy concepts (e.g. Oye (2006)) to the public-private partnerships, by discussing cases in the U.S. as well as in Japan, and by covering partnerships with non-weather sectors.

Discussion from such vantage points might be uncommon in academia (especially in the weather realm); thus, the author hopes this thesis will be regarded as an introduction to ensemble forecasting and its use beyond the weather world, and a review of institution challenges that must be addressed if the true value of ensemble forecasts is to be realized.

Chapter 2. Meteorological Aspects of Ensemble Forecasting

Current weather forecasting systems using computational simulation of the atmosphere stem from the work of Lewis Fry Richardson, a British physicist in the early 1920's. Increased amounts of observation data and advancement in numerical weather prediction (NWP) models have enabled weather forecasting organizations to implement weather forecasting systems. However, the chaotic nature of the atmosphere, first described in the 1960's by Edward Norton Lorenz, Professor in Meteorology at Massachusetts Institute of Technology, prevents perfect weather forecasting. One of the limitations of conventional forecasting is that it provides a single weather scenario, which might sometimes turn out to be inaccurate. An "ensemble forecast," which is a set of multiple simulations by numerical weather prediction models with slightly different initial conditions and which can provide a probability distribution function for each weather element, has been developed to overcome the limitations of forecasting in practice (National Research Council 2006). This chapter discusses the advancement of conventional numerical prediction and ensemble prediction, and current research issues related to ensemble prediction.

2-1. Deterministic Weather Forecasting Systems

2-1-1. Basic Concepts of Deterministic Forecasting Systems

Numerous weather forecasting organizations operate deterministic weather forecasting systems, while ensemble weather forecasting is implemented only by nine national weather forecasting centers[1]. Current deterministic weather forecasting systems consist of the following steps: acquisition of weather information, analysis, numerical weather prediction, post-process, forecasters' judgment, dissemination, and actual use of the forecast by the public (as shown in Figure 2-1).

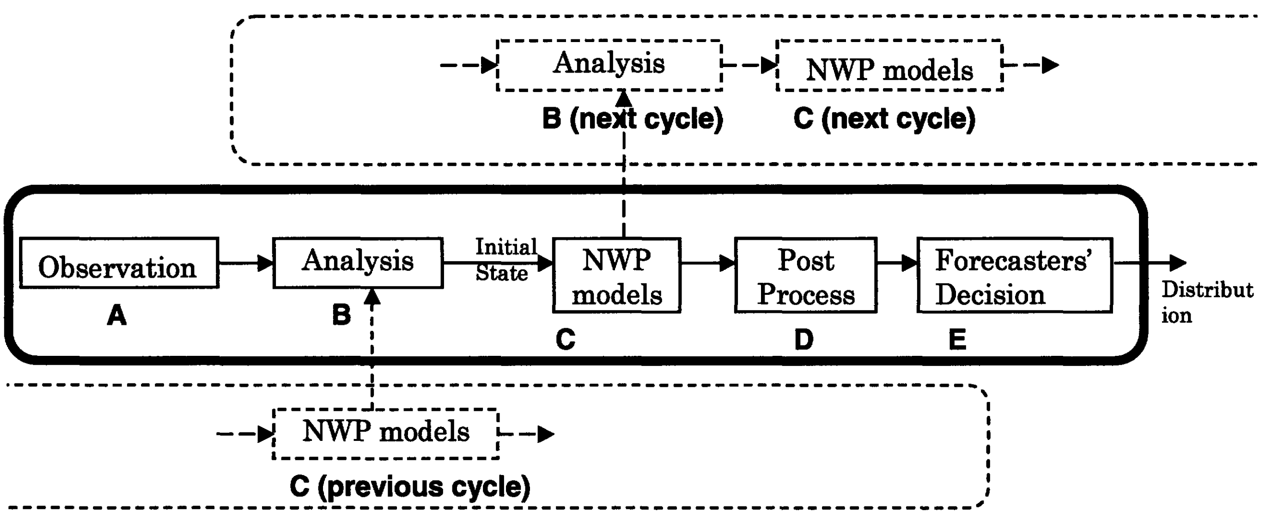


Figure 2-1 Diagram of a (deterministic) weather forecasting system

Because weather forecasting refers to predicting how the present state of the atmosphere will change (Ahrens 2007), present weather conditions should be obtained as the first step of forecasting ("A"

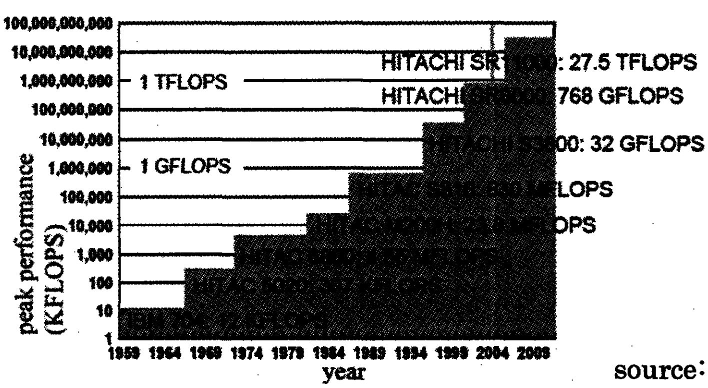
[1] Centers in Australia, China, Canada, Brazil, , Japan, and South Korea, two centers in the US and ECMWF (European Centre for Mid-Range Weather Forecasts)

in Figure 2-1). Observation data by observatory stations, ships and buoys, aircraft, radar, and satellite are collected and reported worldwide. The collected data are processed toward an "analysis" system (B in the figure), which combines the observation data ("A") and a "first guess" data produced by the previous forecasting ("C(previous cycle)"). The "analysis" data provides the "best" guess of the state of the atmosphere, considering the uncertainty of both the observation and the first guess. Numerical weather prediction (NWP) models are run to show the future path of the atmosphere from the "analysis" as the "initial" condition of their computation ("C"). The future states computed by NWP models are processed by the post-NWP process. The "post-process" translates the raw result of NWP models into common elements of weather forecasts such as high/low temperature, amount of snow, humidity and so forth ("D"). Human forecasters create the forecasts considering all the products from each step of the forecasting process ("E"). The forecasts as final products are reported through many types of media to the public. The product through this process is deterministic, based on the "best" guess of the "analysis," and one scenario of future weather simulated by an NWP model in the figure. However, the reality often deviates from the forecast due to the uncertainty that a forecasting system inevitably includes.

2-1-2. History of the current forecasting system

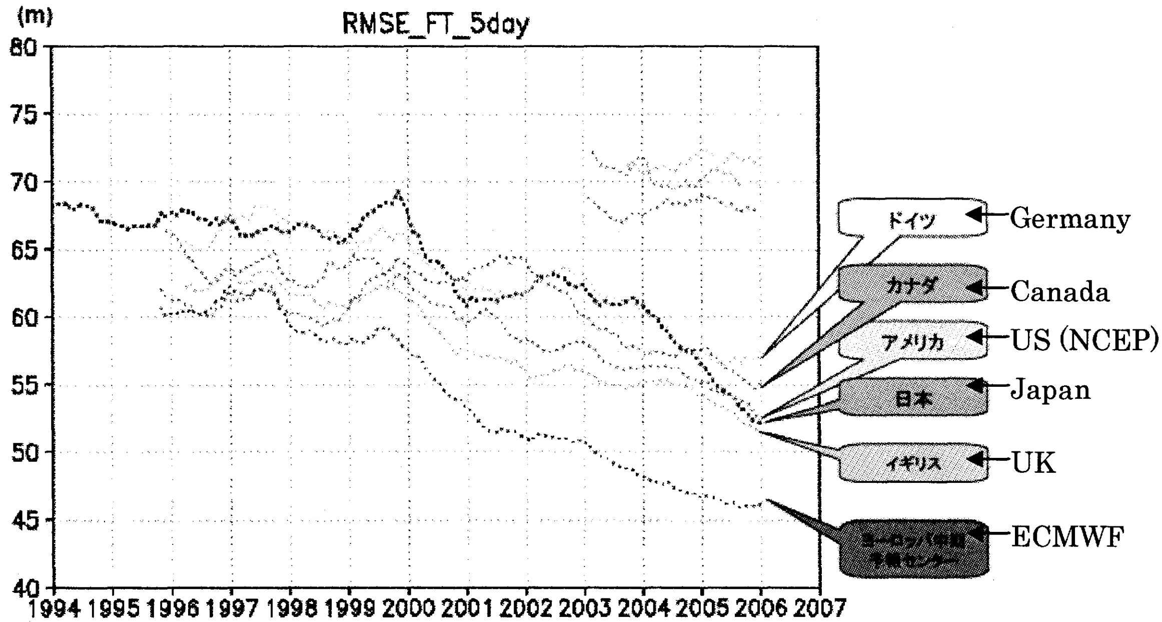
The basic concept of the current forecasting system stems from the 1900's. According to Shuman (1989), Vilhelm Bjerknes was the first to propose the idea of numerical weather forecasting in

1904, and Lewis F. Richardson proposed in his book, *Weather Prediction by Numerical Process* published in 1922, a method of computing discretized differential equations of the atmosphere. His proposal was not implemented due to problems in his computational scheme as well as the huge cost and time for calculations that had to be performed by hand in the 1920's. The first forecasting was implemented in 1955 in the US (National Weather Service 2006) and in 1960 in Japan (Japan Meteorological Agency 2007) after the first successful study of numerical weather prediction performed with ENIAC (Charney, Fjortoft, and von Neumann 1950). Numerical weather predictions have been developed in many countries along with the advancement of supercomputers (e.g. the Japanese case shown in Figure 2-2). Weather forecasting performance has been also developed in conjunction with the development of supercomputers. The historical development of weather forecasting performance is shown in Figure 2-3. The improvement of weather forecasting comes mainly from higher resolution of numerical weather prediction (NWP), improvement in describing the processes of the atmosphere by NWP models, new data (e.g. satellite data) and new techniques of the "analysis" step in the forecasting systems.



source: Muroi (2006)

Figure 2-2 Supercomputers in Japan Meteorological Agency



source: Muroi (2006) with modification

Figure 2-3 Root Mean Square Error (RSME)[2] of numerical weather predictions of 5-day weather at the 500hPa field (Germany, Canada, the US, Japan, UK, and ECMWF[3])

RMSE at the 500hPa field is often used for evaluation of NWP models (e.g. Japan Meteorological Agency (2006b)) Predictions with low RMSE are regarded as good forecasts.

2-2. Uncertainty in forecasting systems

Although weather forecasting has improved, it inevitably includes some uncertainty. This uncertainty comes from the inaccurate initial state of the atmosphere and incomplete modeling of natural processes in the atmosphere in numerical weather prediction (NWP) systems (National Research Council 2006). In addition, the chaotic nature of the atmosphere makes the uncertainty larger as the forecasting

[2] Root Mean Square Error (RMSE): A measure of total error defined as the square root of the sum of the variance and the square of the bias. (International Labour Organization et al. 2004)

[3] ECMWF: European Centre for Medium-Range Weather Forecasting

time becomes longer.

In practice, the uncertainty is included in the observation, the analysis, the numerical weather prediction (NWP) models, and the post-processes in forecasting systems shown in Figure 2-1. The observation embraces several kinds of errors such as a systematic errors (i.e. instrumental error), an accidental error (i.e. error of reading), or human errors (i.e. error in a reported location of a ship providing observation data (Okano et al. 2006). According to NRC (2006), NWP models in the forecasting process also provide additional uncertainty, which is derived from inadequate description of natural processes in the atmosphere and ocean such as cloud physics, radiation, turbulence, and surface processes. Another source of the uncertainty in NWP models is the coarse resolution used throughout the numerical prediction. If finer resolution NWP models were used, smaller scale of atmospheric phenomena the models could be detected. However, in reality, limited computer resources necessarily introduce small-scale phenomena that cannot be handled. There are other sources of errors from computation techniques of NWP models[4]. In addition, the chaos in the atmosphere makes the error larger as related to forecasting time (Lorenz (1963) and Lorenz (1969)). The chaos "appear[s] to proceed according to chance even though their behavior are in fact determined by precise laws" (Lorenz 1993, p.4). The chaotic character makes "small uncertainty in the starting point of a forecast or in the forecasting system … result in large differences as the prediction unfolds" (National Research Council, 2006, p. 112). Therefore, as

[4] Such as lateral and surface boundaries in the simulated fields, and approximation associated with the finite difference method (National Research Council 2006, p. 112)

the National Research Council (2006) declared, it is said that "[u]ncertainty is thus a fundamental characteristic of hydrometeorological prediction, and no forecast is complete without a description of its uncertainty." Handling of this uncertainty is as important as deterministic forecasting.

2-3. History of ensemble forecasting

2-3-1. Early History

According to National Oceanic and Atmospheric Administration (National Oceanic and Atmospheric Administration 2006), 1871 was when the first forecast with information of uncertainty was provided. Cleveland Abbe (aka "Old Probabilities")[5] issued a forecast with probabilities to the public ("Weather Synopsis and Probabilities").

> Synopsis for past twenty-four hours; the barometric pressure had diminished in the southern and Gulf states this morning; it has remained nearly stationary on the Lakes. A decided diminution has appeared unannounced in Missouri accompanied with a rapid rise in the thermometer which is felt as far east as Cincinnati; the barometer in Missouri is about four-tenths of an inch lower than on Erie and on the Gulf. Fresh north and west winds are prevailing in the north; southerly winds in the south. Probabilities; it is probable that the low pressure in Missouri will make itself felt decidedly tomorrow with northerly winds and clouds on the lakes, and brisk southerly winds on the Gulf. (National Oceanic and Atmospheric Administration 2006)

At the beginning of the 20^{th} century, Australian meteorologist W. E. Cooke introduced a numerical scale of certainty[6] attached to forecasts in order to "indicate, approximately, the weight or degree of probability which the forecaster himself attaches to that particular prediction." (Cooke, 1906)

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[5] He was a supporter of emerging services of weather forecasting in the US army.

[6] from "1: not at all likely" to "5: almost absolute certainty"

2-3-2. Theoretical advancement of ensemble forecasting

These disseminated probabilities in early years were subjective. Objective probability forecasting has been studied since the 1960's when Lorenz revealed the chaotic nature of the atmosphere. These studies focused on error in initial conditions and enhancement of the error through the forecasting process. Epstein (1969) assumed the uncertainty fits to stochastic functions such as Gaussian and considered the development of the error explicitly ("stochastic dynamic forecast") (Epstein 1969). Leigh (1974) set a variety of initial conditions based on a Monte Carlo method, and he estimated courses of forecasts simulated from the initial conditions. He concluded that his forecasting method was a "practical, computable approximation" of the stochastic dynamic forecasts (Leith 1974). This was the basic concept of ensemble forecasting, although the computational resources in the era were inadequate for practical weather forecasting.

2-3-3. The Post Process

"Post-Process" is an interpretation process done by computers from output of numerical weather prediction (NWP) to common weather elements such as quantitative precipitation, wind, and temperature. The post processes pick up several elements of numerical prediction outputs around a target point and produce specific weather elements at the point. Unlike NWP models, which are based on fluid dynamics of the atmosphere, the post processes are based on stochastic relationships between past observation and forecasts. Thus, the process requires less computational resources than the ensemble forecasting that requires multiple simulations. The first objective probabilistic forecasts made by a stochastic post-process model came into operation in 1969 (National Research Council, 2006). One of the common post-process techniques is the Model Output Statistics (MOS), which can calculate probability for any weather elements by stochastic methods with past observation and NWP model output. MOS can predict any elements if both past data and forecasts are collected. However, precipitation (probability of precipitation: PoP) was only the probabilistic forecast production for many years. Japan Meteorological Agency (JMA) followed the US after a significant delay; PoP in Japan began in 1980 (Japan Meteorological Agency 2007). JMA issues the level of confidence[7] of its weather forecast for a week, although the level seldom appears in general weather forecasting to the public except on the web pages of JMA[8].

2-3-4. Practical Advancement of ensemble forecasting

Significant advancements in computational resources made ensemble forecasting practical in the 1990's. Some of the earliest operational ensemble forecasting systems were implemented by the European Centre for Medium-Range Weather Forecasting (ECMWF) (Molteni et al. 1996) and the National Center for Environmental Prediction (NCEP) under the National Weather Service (NWS) in 1992 (Toth and Kalnay 1993, Tractona and Kalnay 1993). Currently, nine centers in the world operate ensemble

[7] The levels are letter grades from "A" (high confidence) to "C" (low confidence).
[8] http://www.jma.go.jp/jp/week/319.html (accessed February 14, 2007)

forecasting for mid-range[9] forecasts. Each center develops methods of adding perturbation to the "analysis" data in the forecasting process to produce multiple initial states for an NWP model. The NWP model predicts the course of the atmosphere from the initial conditions. The plot of all the courses from the initial conditions depicts the probability of the future state of the atmosphere (Figure 2-4). Sophisticated methods of producing the perturbed initial conditions should be developed in order to make the probability close to the reality of the atmosphere with the limited times of running an NWP model; the centers are now seeking such methods. The methods widely used in operational weather forecasting are the Singular Vector (SV) method (Molteni et al. 1996), the Breeding of Growing Mode (BGM) method (Toth and Kalnay 1993, Tractona and Kalnay 1993), and the Ensemble Kalman Filter (EnKF) method (Evensen 1994, Houtekamer and Mitchell 1998, Miyoshi 2005a)

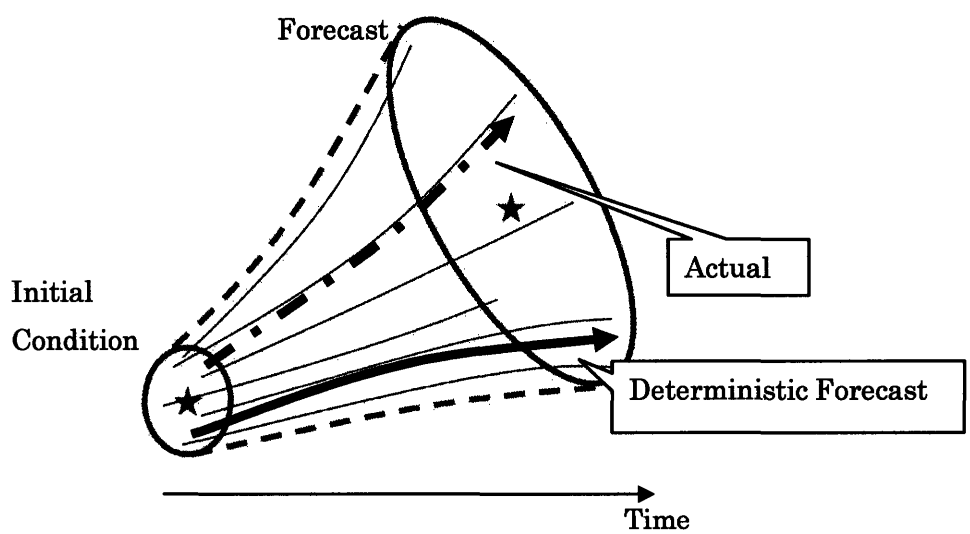

Figure 2-4 conceptual diagram of ensemble forecasting source: Miyoshi (2005b) with modification

9 "Mid-range forecast" means forecasting weather from between 72 hours to 10 days ahead of time.

2-3-5. Multi-Center Ensemble

When multiple centers began to operate ensemble forecasting, the study of utilizing outputs of multiple centers was proposed. Krishnamurti et al. (1999) suggested that deterministic hurricane track forecasts would be improved by the weighted mean of multiple NWP outputs (Super-Ensemble). Harrison et al. (1995) combined the deterministic NWP outputs of the UK Meteorological Office (UKMO) and the ECMWF to use as one ensemble forecasting system (Multi-Center Ensemble or Multi-Center Grand Ensemble). Richardson (2001) studied the "multi-model multi-analysis ensemble,"[10] which gathers analysis and numerical weather prediction (NWP) models from several NWP centers, to make a number of combinations of analysis data and NWP models to produce ensemble forecasting with a number of scenarios. Arribas et al. (2005) developed an experimental multi-center ensemble system by combining the deterministic forecasts of the nine operational NWP centers in the world and suggested that the system could be better than the ensemble system of the ECMWF. This kind of system is often called "Poorman's Ensemble Prediction System (PEPS)" (e.g. Buizza et al. (2003), Ziehmann (2000)), because it can be constructed by poor countries that do not have enough resources for numerical prediction.

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[10] So called by Mylne et al. (2002)

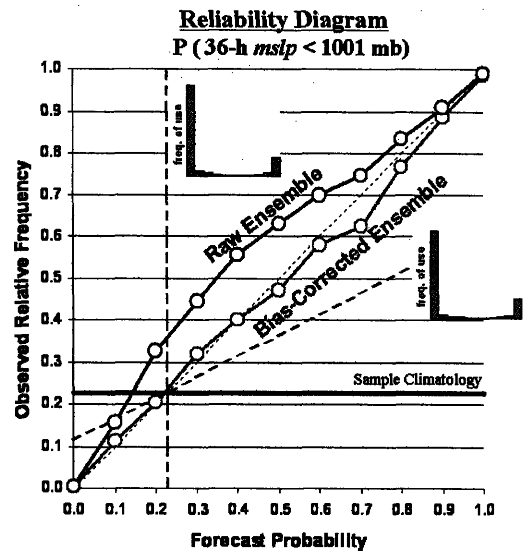
2-4. Current study topics of ensemble forecasting

2-4-1. Development of NWP models

Even if techniques of producing initial conditions for ensemble forecasting are improved, the probability of forecasting can not become close to the reality unless the NWP models accurately describe the processes of nature. The centers of numerical prediction have devoted themselves to improving their NWP models, to increase the resolution of the simulations, as well as the number of ensemble members in the ensemble forecasting system.

2-4-2. Post processes

The other way to overcome the inaccuracy of numerical weather prediction (NWP) models is a "Post-Process" calibrating of the NWP model outputs. Hamill claims three types of calibration (Hamill 2007): Model Bias Correction, Ensemble Spread Correction, and Downscaling. One of the calibrations is a "model bias correction" (1^{st} order calibration), which has the mean value of the ensemble system close to the reality. The amount of correction is determined by the past data of the observation and the forecasts. Eckel and Mass (2005) and Eckel (2007) showed that the bias-corrected ensemble members reflect the real probability of nature, as depicted in Figure 2-5.

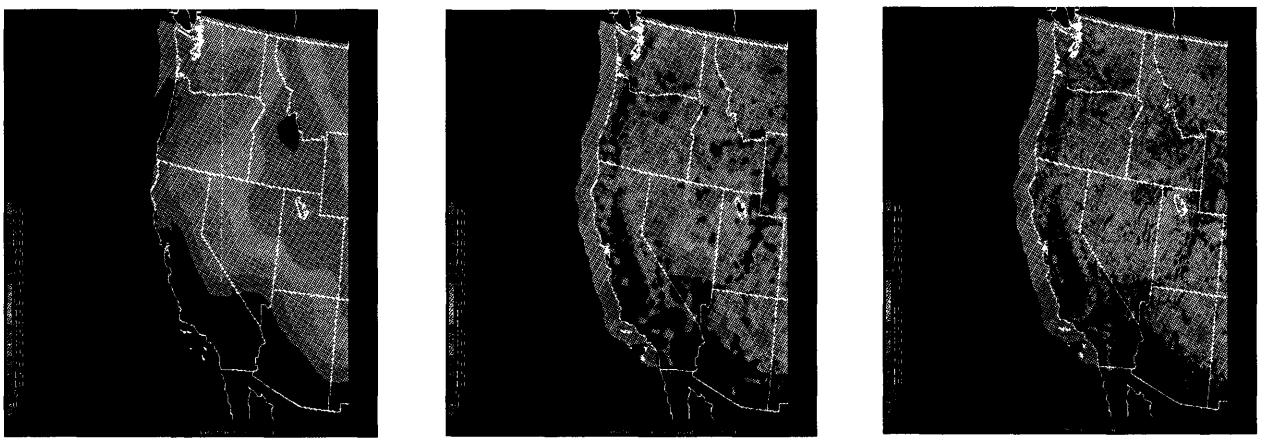


source: Eckel(2007)

Figure 2-5 Relationship between forecasted probability (FP) and observed frequency (OF)
A dotted line of FP=OF refers to the situation that probability of forecast is close to the observed distribution frequency. "Bias-Corrected Ensemble" fits closer to the line of FP=OF than "Raw Ensemble (without bias correction)" does.

Another calibration is "ensemble spread correction" (2nd order calibration). The ensemble members often spread too broadly or too narrowly compared with the observations. Some methods for this calibration have been proposed (e.g. Eckel and Walters (1998), Hamill and Colucci (1997)). However, they require a "large training period to build robust histograms" (Hamill 2007).

Another method is to translate model outputs into smaller-scale phenomena. The coarse outputs of NWP models cannot explicitly tell small-scale weather conditions such as wind in complex terrain, tornados, and limited-area severe rain. The "downscale" calibration from the coarse output to the small scale weather could capture the wind forecast strongly affected by the terrain and the potential of severe weather (Hamill 2007). Figure 2-6 shows an example of maximum temperature forecasting (Antolik 2006). An output of a statistical model that processes a NWP model output, MOS point forecasts, and terrain data are combined, and more detailed temperature forecast is produced.



(a)"First guess" field

(b) First guess + guidance at all available sites

(c) First guess + station forecasts + terrain

source: Antolik (2006)

Figure 2-6 Maximum temperature forecasting through the "downscaling" process

First of all, a generalized operator equation is derived by relating the NWP output to and historical sample of weather observations at station locations. One statistical equation is derived to cover the entire domain.

(a) First guess field: an output of the statistical model that processed an NWP model output

(b) First guess + guidance at all available sites: (a) is combined with MOS point forecasts at all station locations within the domain.

(c) First guess + station forecasts + terrain: by using high-resolution terrain data, (b) is adjusted according to weather element/terrain relationships observed in the data.

2-4-3. Multi-Center Ensemble

The World Meteorological Organization (WMO) is now planning and operating the research project THORPEX[11] which aims to accelerate improvements in the accuracy of 1-day to 2-week high impact weather forecasts (World Meteorological Organization 2007). Under THORPEX, ensemble forecasting is also being studied. THORPEX Interactive Grand Global Ensemble (TIGGE) is a subproject of THORPEX for collecting and utilizing the outputs of operational ensemble forecasts of all major numerical prediction centers in the world (World Meteorological Organization, 2005). Specifications and outputs vary with each center; thus, the combination of the various outputs might produce much better forecasts (e.g. early warning of severe weather).

The US, Canada and Mexico agreed upon the joint project of ensemble forecasting (North American Ensemble Forecasting System: NAEFS) in 2004 (Environment Canada 2007). They share the ensemble raw output to produce better forecasts. The system for exchanging data was implemented in 2006, and the participants expect that NAFES will be implemented for operational weather forecasting by 2008 (Zhu 2007).

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[11] THe Observing system Research and Predictability Experiment

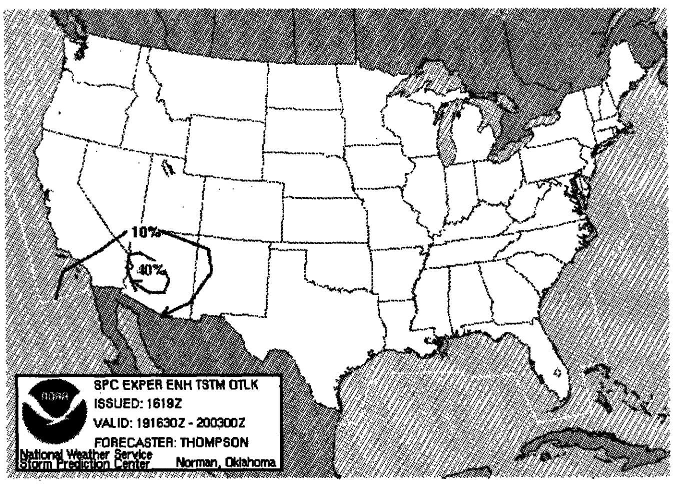
Chapter 3. Potential Use and Value of Ensemble Forecasting

Ensemble forecasting studies have shown that ensemble forecasting improves deterministic weather prediction such as hurricane tracking. In addition, each forecasted member in ensemble forecasting constructs a probability distribution function of each weather element. Weather forecasts (deterministic forecasts) are widely applied to risk management in various areas, such as retail businesses for demand prediction, the energy sector for effective operation, and risk communication for disaster management. This chapter discusses current issues of the use of ensemble forecasting in the US and Japan.

3-1. Current use of ensemble forecasting

Ensemble forecasting is often used for improving deterministic weather forecasts. Krishnamurti et al. (1999) demonstrated that errors of (deterministic) hurricane track forecasts were improved by using the weighted mean of the results of several numerical weather predictions. Ensemble forecasting also provides a probability distribution function of any weather elements handled by numerical weather prediction models and introduces several possible weather scenarios rather than only one scenario. Thus, ensemble forecasting can provide qualitative information with a quantitative level of confidence (Ahrens 2000), and can help forecasters decide upon their forecasts and help users (consumers) plan better actions.

Ensemble forecasting can also help users as well as forecasters to prepare for alternative possible scenarios. This preparedness can be important especially in the case of severe weather. Figure 3-1 depicts an experimental output of probabilistic severe weather outlook.



Source: Storm Prediction Center, National Weather Service (NWS) [12]

Figure 3-1 Experimental product of probabilistic outlook of thunderstorm (issued 1619UTC 2/19/2007)

The figure clearly indicates the possibility of a thunderstorm in Arizona and southern California, and such information can raise the awareness of users (and forecasters) about possible severe weather.

Although several experimental products of probabilistic information have been studied, products for the public have included only probability of precipitation (PoP) and the confidence index of weekly forecasts (only provided by the Japan Meteorological Agency (JMA)). Most weather forecasters including

[12] http://www.spc.noaa.gov/products/exper/enhtstm/ (accessed 1720UTC 2/19/2007)

public weather forecasters (i.e. NWS or JMA), private weather forecasting companies, and the news media do not provide any additional uncertainty information in weather forecasts. For example, deterministic weekly forecasts cannot be achieved partly due to errors in forecasting systems and to the fact that longer forecasts have larger uncertainties than short-term forecasts. However, weekly forecasts distributed through common media (e.g. on the Internet or TV), are recognized as deterministic by users. Weekly or longer forecasts on many web pages provide deterministic weather conditions, which look identical to one- or two-day forecasts, without displaying uncertainty information (National Research Council 2006).

3-2. Evaluation of ensemble forecasts

As discussed above, ensemble forecasts could improve deterministic forecasts (e.g. hurricane tracking) and provide probabilistic forecasts. However, there has always been the issue of verification, which is the process of assessing what are "good" forecasts (Wilks 2006).

Brier and Allen (1951) classify purposes of verification into three categories: administrative purpose, scientific purpose, and economic purpose. The administrative purpose is to compare the performance of operational forecasting between forecasters. The scientific purpose is to analyze the forecast errors to find weak points of the forecasting systems, and this analysis may contribute to better forecasting. The economic purpose is evaluation of forecast information in terms of monetary measures.

This evaluation is made by estimating the information value, which is defined as additional revenue or avoided loss thanks to the weather information that users received beforehand; the value indicates how much the forecast improves their decision making. Murphy (1993) also denotes three alternative categories: *consistency*, which is a subjective measurement in forecasters' minds comparing computation output and their judgments (e.g. poor consistency means that computed model results differ from forecasters' experience), *quality*, which is a "correspondence between the forecasts and the … [actual] observation," and *value*, which means "the incremental economic and/or other benefits realized by decision makers through the use of the forecasts."

For verification of deterministic forecasts, simple statistical measures such as mean error (ME) and root mean square error (RSME)[13] between forecasts and observation are widely used. Although these measures are also applicable to each numerical weather prediction (NWP) model output included in ensemble forecasting or averaged weather variables of ensemble forecasts, additional measures are needed to evaluate the entire probability distribution function predicted by ensemble forecasts. (COMET 2004)[14] Many kinds of evaluation measures have been studied[15], but most of them evaluate the difference between forecasts and observations (Wilks 2006).

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[13] Examples of ME: cold/warm, wet/dry, high/low, etc; RSME: "a measure of 'distance'" between observation and forecast (COMET 2004)

[14] COMET Project (Cooperative Program for Operational Meteorology, Education and Training) is an education and outreach program, established jointly by National Weather Service (NWS) and University Corporation for Atmospheric Research (UCAR).

[15] such as Brier Score, Brier Skill Score, Reliability Diagrams(Wilks 2006), ROC (Relative Operating Characteristic(Mason 1982; Mason 1982), Rank Histogram (Hamill 2001)

The economic value of forecasts is a primary metric from the viewpoint of forecast users. Users face the uncertainty of weather, and they utilize forecast information to support their decision making, which often results in monetary gains or losses. There is ample research in systems engineering about value of information in decision making or real options (De Neufville 1990, De Neufville 2006). De Neufville (1990) defines the value of information as "[t]he increase in expected value to be obtained from a situation due to the information, without regard for the cost of obtaining it" (p.330). This basic concept of information value is also applicable to weather forecasting.

3-3. Economic Value of Weather Forecasts: a simple case study

This section discusses the application of one of the economic evaluation methods to a case based on Murphy et al. (1982). The economic value of forecasts should be evaluated on a case-by-case basis (Murphy 1993); however, the following scenario provides a concrete example of measuring the economic value of forecasts.

Assume that fruit farmers during the frost season need to decide whether frost protection activities should be deployed every morning. If they do nothing on a chilly morning, their fruit will suffer from severe loss of buds due to frost. However, if they heat their field considering the possibility of a cold morning, it could be warm in reality and the cost to heat their field wasted. The heating cost and the loss due to frost damage following deterministic forecasts are illustrated in Table 3-1. When the forecast warns the farmers about the "cold" successfully, the farmers can protect the frost damage; the farmers just pay for the heating cost, which can be thought as a useful expenditure. When the forecast falsely warns the farmers of the "cold" (false alarm), the farmers have to heat their fields according to the false alarm; heating cost for frost prevention will be a wasteful expenditure. If forecasters did not warn against the cold morning but it is actually cold (failure of forecast), then the farmers lose their crop yield due to frost. Figure 3-2 describes the heating cost and monetary loss of crop yield associated with frost damage. The farmers try to minimize the total amount of "Lost revenue" and "Cost" (in the middle of the graph), and also tries to minimize the total cost of "L," "C(UE)," and "U(WE)", which are associated with weather, by using weather forecasts.

Table 3-1 Cost and loss of the fruits farmers

When the forecast says "cold", the farmers have to pay for frost prevention activities. The cost of prost prevention is useful when it is actually cold; it is wasteful when it is actually warm. When the forecast says "warm", but the actually it is cold, then the farmers suffer from severe crop loss due to frost.

Costs related to fruit farmers		
Deterministic Forecast	Actual: Cold	Actual: Warm
Forecast: "Cold"	Accurate/Successful Forecast ➢ Useful Expenditure • Cost of heating • Preventing the buds' damage	False Alarm (Inaccurate Forecast) ➢ Wasteful Expenditure • Cost of unnecessary heating
Forecast: "Warm"	Failure of Forecast ➢ Loss of crop yield • severe buds damage	

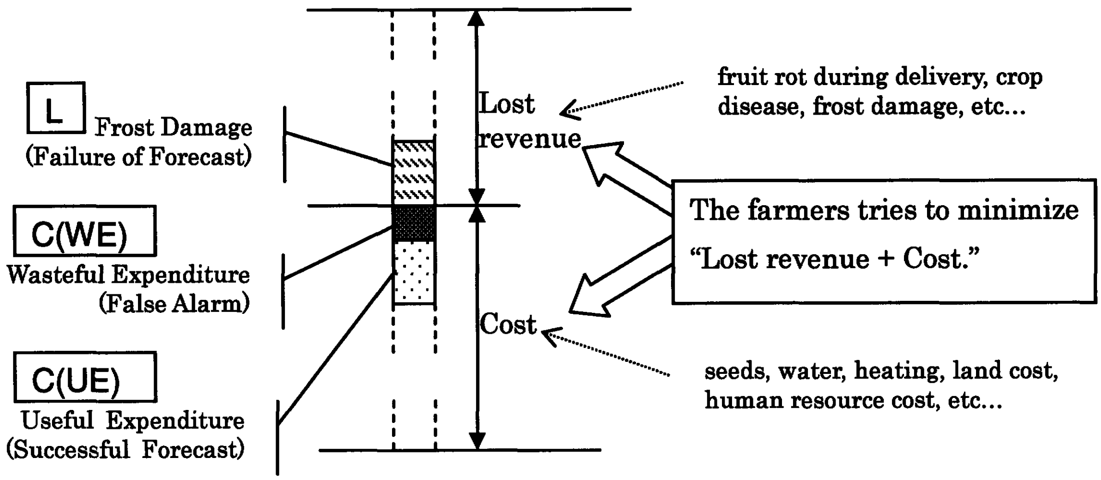


Figure 3-2 Structures of Cost and Loss revenue of the fruit farmers
The heating cost in accurate forecasts (useful expenditure) is denoted as "C(UE)"; the heating cost in false alarm (wasteful expenditure) is described as "C(WE)"; the monetary loss from bud damage due to frost are denoted as "L" respectively.

Table 3-2 Cost and Loss of the fruits farmers (2)
Using "C(UE)", "C(WE)", and "L", Table 3-1 can be simplified in Table 3-2.

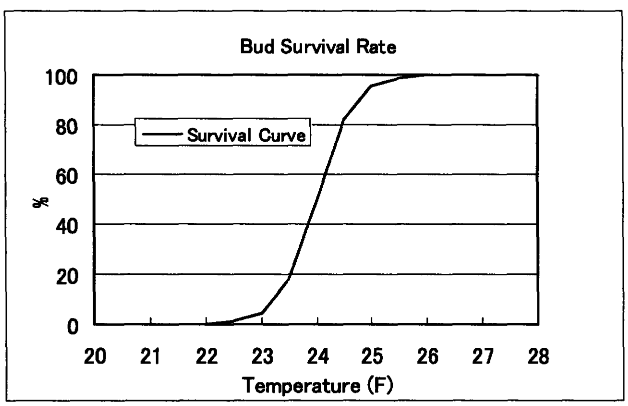
Costs related to the fruit farmers		
Deterministic Forecast	Actual: Cold	Actual: Warm
Forecast "Cold"	-C(UE)	-C(WE)
Forecast "Warm"	-L	

Table 3-2 describes the cost and loss structure in the case of deterministic forecasts, but it could also be applied to the case of ensemble forecasts, which provide a probability function of temperature (e.g., the probability of "Cold" is 80%). If the farmers have a threshold probability (e.g. probability of "Cold": 70%), and the probabilistic forecast exceeds the threshold, then they will deploy frost prevention activities. The cost and loss arising from the farmers' decision is shown in Table 3-3.

Table 3-3 Cost and Loss of the fruits farmers (probabilistic forecasts)

Costs related to the fruit farmers			
Probabilistic Forecasts		Actual: Cold	Actual: Warm
Probability of "Cold"	More than a threshold percentage that the farmers defined beforehand	-C(UE)	-C(WE)
	Less than the threshold percentage	-L	

Murphy et al. (1982) calculates "L" in Table 3-3 from the actual data of the relationship between temperature and bud loss rate of *red delicious apples*. For simplicity, this paper simplifies their data. Table 3-3 shows the relationship between temperature and bud survival rate.



source: Katz, Murphy, and Winklerb (1982) with modification

Figure 3-3 Bud Survival Rate of *red delicious apple*

This paper also models temperature based on Katz et al. (1982), in which the observation has a mean value (T_{ave}) of -2.2C° (36F°) and a standard deviation (T_s) of +3.6C° (=6.5 F°). The hypothetical observation and forecasts (T_{fcst}) are assumed as follows.

$$\text{Observation}, T_{actual} = T_{ave} + N_1(0, T_s)\text{; Forecasts, } T_{fcst} = T_{actual} + N_2(0, T_{err})$$

where T_{err} is the error of deterministic forecasting (T_{err} is defined 2.0 C°[16]), and $N_i(\mu, s)$ is a normal random function whose expected value is μ and standard deviation is s. Hypothetical ensemble forecasting used in this section consists of ten forecasts that have biases of ±1.0, ±0.8, ±0.6, ±0.4, ±0.2, respectively. The threshold temperature that distinguishes "cold" and "warm" is defined as 27 F°, below which temperature the rates of bud loss without any protection activities are 58.98% and 0.00%, respectively. Given these assumptions, scores of forecasts are computed through the Monte Carlo simulation. The score of the deterministic forecasts are shown in Table 3-4; the scores of ensemble forecasts, which change along with the threshold percentage of a "cold" forecast, are shown in Table 3-5 and Figure 3-4. The fruit farmers define the criteria of the probability (percentage) beforehand, and they take frost prevention activities when the probabilistic forecast of "cold morning" exceeds the criteria determining that "cold morning" is highly possible. The perfect forecast data is simply derived from the number of actual cold days and warm days. Because the false alarm and failure of forecast do not exist, the actual cold days = "successful forecast" days and actual warm days = the "No action, No cost, No losses" days.

[16] The current temperature forecast error is roughly between 1.5 to 2.5 C°. (Japan Meteorological Agency 2006a)

Table 3-4 Score of the deterministic forecast

Each cell denotes the number of days during a frost season that is assumed to have 100 days.

Deterministic Forecasting	Actual Cold	Actual Warm
Forecast Cold	26.1 (heating costs, avoiding loss)	9.1 (wasteful heating costs)
Forecast Warm	6.2 (severe crop yield loss)	58.6 (no action, no costs, no losses)

Table 3-5 Score of the probabilistic forecast

The score depends on the threshold ("p" in the figure) of a "cold" morning probability, above which the farmers will take frost-prevention activities; thus, the figure shows some cases of different p (p=0.8 and p=0.5).

Ensemble Forecasting (p=0.8)	Actual Cold	Actual Warm
Probability of "cold" > p	32.3	45.0
Probability of "cold" < p	0	22.7

Ensemble Forecasting(p=0.5)	Actual Cold	Actual Warm
"Probability of Cold ≥50%	32.1	26.3
"Probability of Cold < %	0.2	41.4

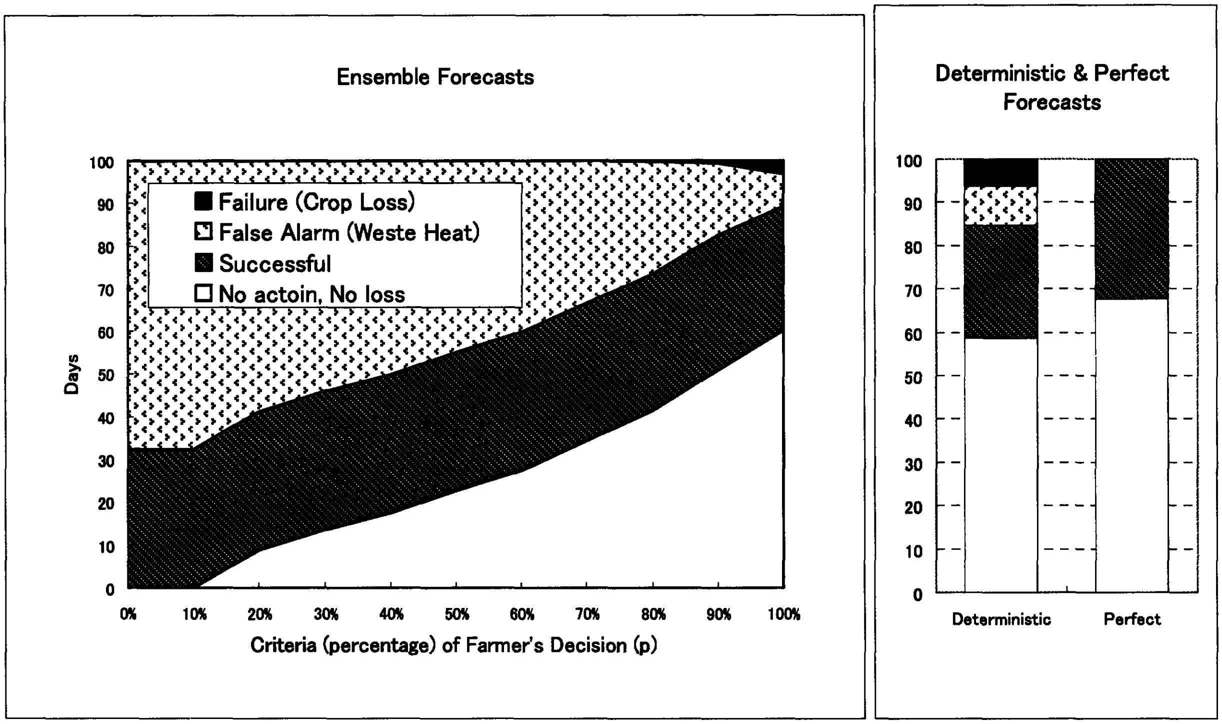


Figure 3-4 Score (days/100-day frost season) of ensemble forecasts, deterministic and perfect forecasts

Data is the same as Table 3-5. The farmers take frost prevention activities when the forecasted probability of the "cold" by ensemble forecasting exceeds the criteria (percentage) that the farmers determined beforehand. The graph indicates the relationship between the criteria (percentage) and the number of days during a 100-day frost season. The deterministic forecast data is from Table 3-4. The "perfect forecast" is a hypothetical forecast, which can always forecast perfectly. The perfect forecast data is only from the actual cold days and actual warm days, because there is no failure of forecasts, nor false error in the perfect forecast case.

Based on the scores above, the monetary values for the farmers are calculated by considering the heating cost, a potential value of the fruit[17]. Given that the potential value of crops is $10,000 without any frost damage, that the heating cost is $100 per day, and that the frost season is 100 days long, the "total cost" (= total of the heating cost and the loss due to frost damage (total C(UE) +total C(WE) + total "L") in Tables 3-1 and 3-3) will be measured. The total cost from the probabilistic forecast depends on the criteria (percentage) of the probability of "cold" forecasting. Figure 3-5 shows the relationship between revenue and the criteria of probability (percentage).

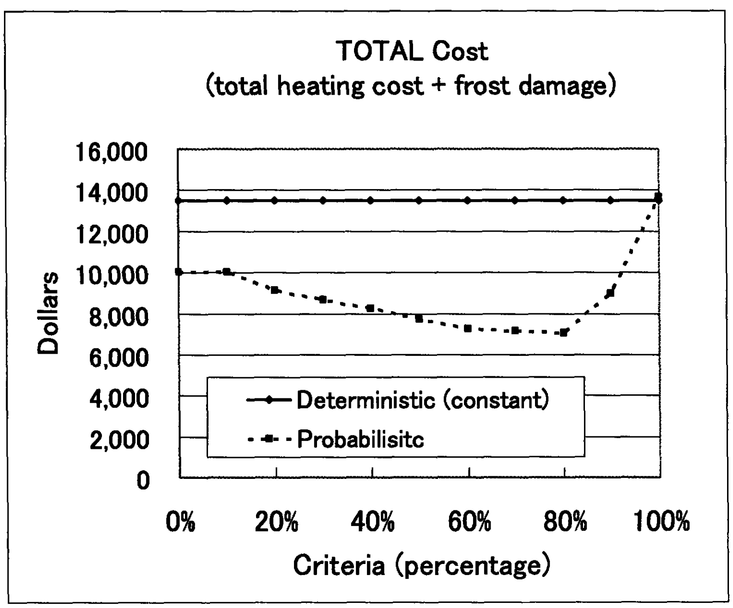


Figure 3-5 Total cost of the fruit farmers

[17] There are other fixed costs, such as information systems for expert systems of risk communication, but these costs are ignored in this case for simplicity.

The total cost based on the deterministic forecast is \$ 13,520 (constant with the criteria (percentage) that defines the action of the ensemble user (= the farmer)), and the total cost based on the probabilistic forecast varies with the criteria. The minimum total cost can be achieved when the criterion is 80% (the total cost: \$ 7,020). The comparison of the two total cost curves shows that utilizing a probabilistic forecast is preferable to deterministic forecasts as long as the criteria are from 0 % to 90 %; this implies that the ensemble forecasts can reduce the total cost compared with the deterministic forecasts, but at the same time, that the farmers should carefully decide upon the right criteria of the "cold" morning forecasts; otherwise, they might choose 100% as the criterion that is not preferable to them. In addition, the total cost in case of ensemble forecasts is less than \$ 10,000 (potential crop yield) when the criterion is between 20 to 90%. Thus, the farmers should also make sure that they can make a profit. Figure 3-6 shows shading for each part of total costs (C(UE), C(WE), and L) of Figure 3-5. It shows that the determinist forecasts cause huge crop loss "L" and shows that the ensemble forecasts can reduce both the wasteful cost "C(WE)" and crop loss "L" by carefully choosing the criteria.

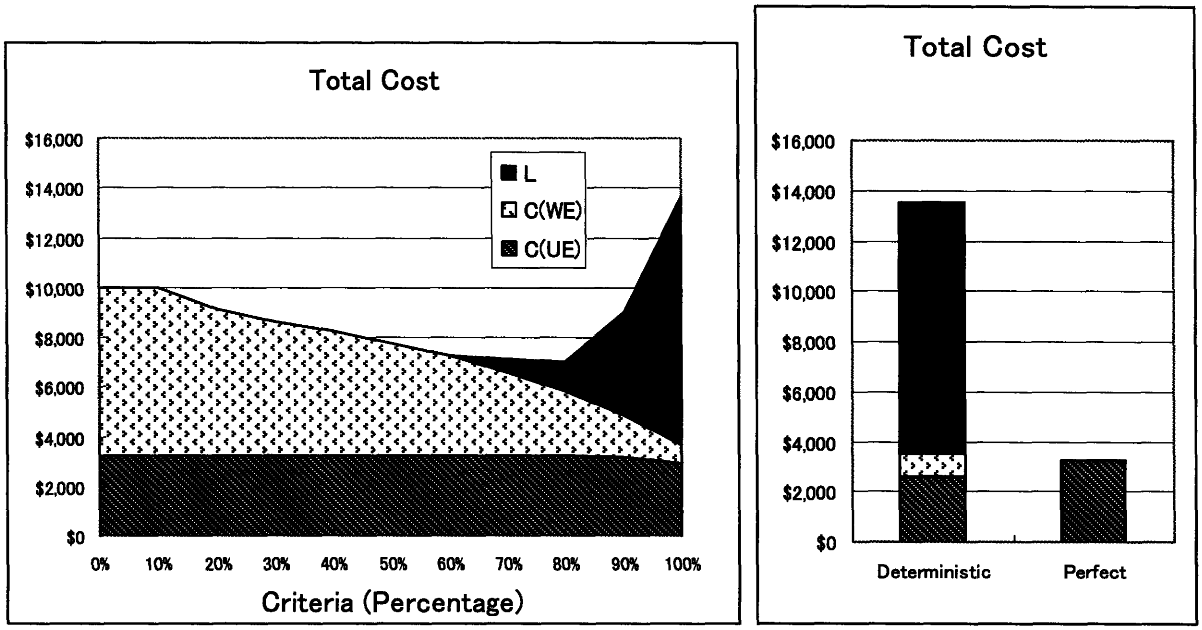


Figure 3-6 Each cost of the fruit farmers

(left: ensemble forecasts; right: deterministic and perfect forecasts)

These graphs describe the same data as Figure 3-5, but indicates with shading C(UE), C(WE), and L. C(UE): heating cost (useful expenditure); C(WE): heating cost (wasteful expenditure); L: Crop Loss (see Table 3-2 and Table 3-3)

Figure 3-7 shows another case, in which all the parameters are the same as the base case but the fruits have values of $1,000 and $100,000 (instead of the base case $10,000). The total costs, the preferability of the probabilistic forecast to the deterministic one, and the criterion that introduces minimum total cost are affected also by the fruit values. The fruit values are related to "L" in Tables 3-2 and 3-3; thus, the value of the forecasts depends on the unit cost "L." Figure 3-8 shows the other cases of a different heating cost, which is associated with "C(UE)" and "C(WE) in Tables 3-2 and 3-3. The graph shows that the value of the forecasts also depends on the unit cost "C" (="C(UE)"= "C(WE)"). The shapes of the graph in Figure 3-7 and Figure 3-8 are the same because total cost of this case is assumed to be a linear expression of "C" and "L." Assuming the cost-loss ratio (C/L), Figure 3-7 and Figure 3-8 imply that the ensemble forecasts are attractive to the fruit farmers in case of large C/L. In reality, however, the assumption of the linearity of the total cost is not always reasonable because there could be other costs such as warning computer systems of the farmers utilizing forecast data, or because the heating cost could change dramatically during the frost season due to an oil price change.

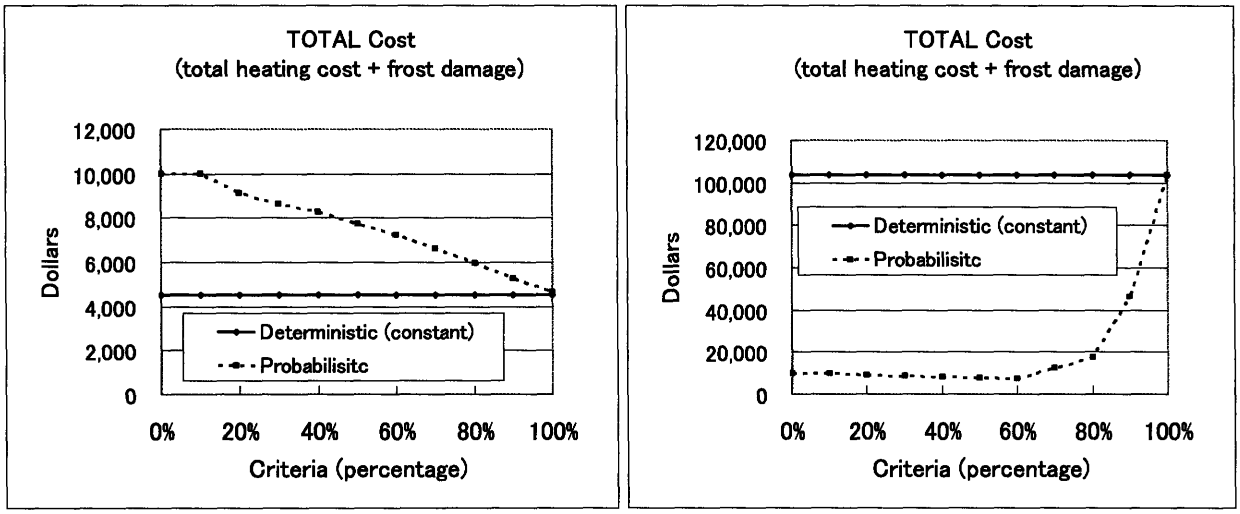


Figure 3-7 Total cost of the fruit farmers (different value crop: left $1,000, right $100,000)[18]

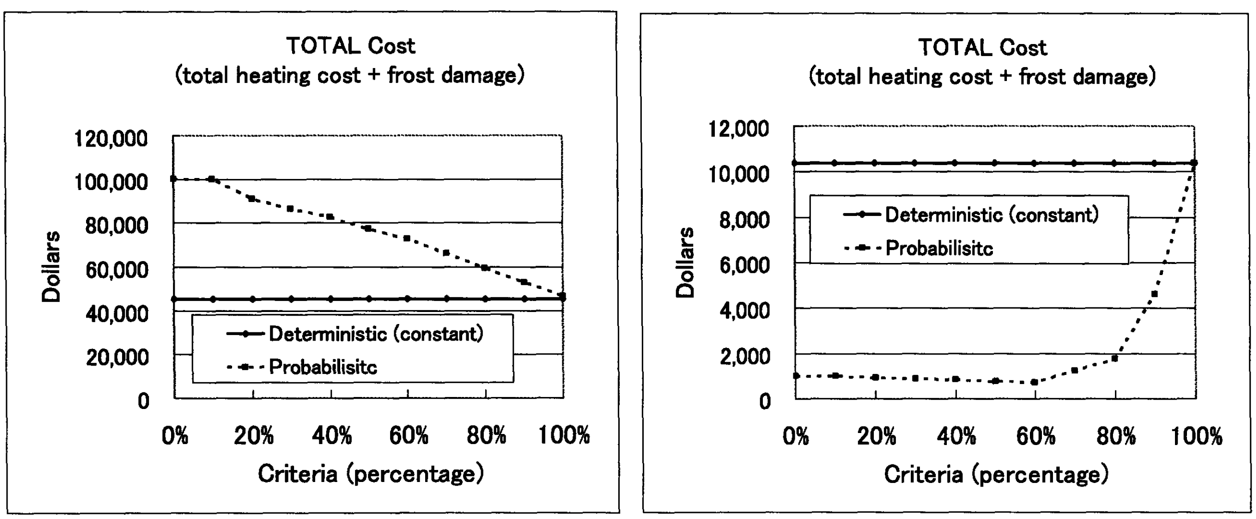


Figure 3-8 Total cost of the fruit farmers (different heating cost: left $1,000/day, right $10/day)[19]

[18] In reality, the left graph indicate that using either deterministic or probabilistic forecasts is not preferable.

[19] See the previous footnote.

In actual cases, the uses of forecasting are so diverse that valuable forecast information for some users with certain measures is not always valuable for others (Wilks 2006), and the value of forecast information in different decision making processes must be evaluated not by unique criteria but on a case-by-case basis (Katz and Murphy 1997a). These results imply that the raw data of each ensemble member (not single information --if any-- produced by a combination of ensemble members) should be utilized by any user in order to maximize the information value of ensemble forecasts.

3-4. Potential Use of Ensemble Forecasts: Risk Management

The previous section discussed the simple case of the use of ensemble forecasts. The fruit farmers could reduce the total cost by using the ensemble forecasts in some cases. Like the fruit farmers facing a risk of frost damage, any businesses may face some risks. Avoiding the risks would be one solution; however, this means also loss of business opportunities Thus, managing risks is an integral part for any business that copes with risks.

3-4-1. Risk Management

Many guidelines have been proposed for managing risks in various areas. For example, the National Institute of Standards and Technology (NIST) issued a risk management guide for information technology systems (Stonebumer et al. 2002). In Japan, the "Japanese Industrial Standard" published the standard of risk management not focusing on specific areas. The standard (JIS Q 2001:2001) provides principles and elements for the establishment of a risk management system, including the following four types of treatment of risks (Japan Standards Association 2001). One of the types is "risk avoidance," which means withdrawal from or non-involvement in issues related to risks. Prohibition of all cars in order to reduce traffic accidents is a possible example. Another type is "risk transfer," which is to "share with another party the benefit of gain or burden of loss for a particular risk." (JIS Q 2001:2001 [English version], p.2) Financial measures such as insurance are often used for risk transfer. The third type is "risk reduction," which is an "[action] taken to lessen the probability, negative consequence, or both, associated with a particular risk." (JIS Q 2001:2001 [English], p.2) Installing air-bags in cars for driver safety is one example. The fourth type is "risk retention": "an acceptance of the burden of loss or benefit of gain from a particular risk." It can be acceptable only when the risk is small enough to endure. Weather information can play important roles in perceiving risks and helping make the appropriate choices of risk treatment. Among the four types of risk treatment, weather information also plays important roles in operations of risk reduction and transfer, as explained in. he following sections.

3-4-2. Wind Energy Sector: Example of Risk Reduction

Wind energy is an alternative energy to fossil-fuel-based electricity. Due to global climate change and energy security issues, renewable energy has received much attention recently. President George W Bush mentioned in the State of the Union 2007 address the importance of renewable and alternative fuels (The White House 2007). Thus, development of these energy sectors is a pressing issue. These sectors seek reduction of energy generating costs, and stable supply of energy is needed. Energy supply and demand is affected by weather conditions. For example, temperature has an impact on energy demand. Among several kinds of renewable energy, the wind power is one energy resource that is affected by weather conditions. Handling weather risk both in energy production and energy demand is therefore an important issue for the wind energy sector.

i) Operating Cost of Energy Production

Electricity production by wind energy turbines is influenced by wind conditions. Energy generation companies make commitments for electricity generation one day in advance. The wind generators should consider how to operate the wind turbines effectively to meet this commitment as well as to minimize costs. Excess electricity production does not necessarily mean additional revenue, and the deficit of the committed electricity production turns out to be a penalty imposed on the wind energy company (Roulston et al. 2003).

Marginal cost of wind energy generation is generally cheaper than fossil energy, so the grid tries to utilize wind energy as much as possible. When the wind energy generation forecasts are "high," then the grid turns off/down fossil energy generation, and vice versa. However, if the forecast differs from the actual wind energy generation, some of the planned expenditure turns out to be a waste (lower left of Table 3-6) or the grid has to pay for extra generation from expensive resources such as fossil to clear the commitment (upper right of Table 3-6).

Table 3-6 Wind energy generation forecasts and activities of an energy grid company

	Grid Activity (Plan)	Actual Wind: Strong	Actual Wind: Weak
Forecast: Strong Wind & High Energy Genera tion	Turn off/down fossil energy generation. (Low planned expenditure)	Low planned expenditure & No additional expenditure	Low planned expenditure but **Loss of potential revenue** **Extra expenditure for additional energy (expensive energy) generation**
Forecast: Weak wind & Low Energy Generat ion	Turn on/up fossil energy generation. (High planned expenditure)	High planned expenditure but Actual expenditure should have been lower than the plan (i.e. **some of the planned expenditure turns out to be a wasted expenditure.**)	High planned expenditure & No additional expenditure

Ahlstrom et al. (2005) demonstrated the effective use of wind forecasts for assessing the impact on wind electricity generation costs at Xcel Energy, an electricity generation company serving 1.4 million customers in the northern Midwest of the US. The following is a description of the project of Ahlstrom et al. (2005). In 2004, the Minnesota Department of Commerce and Xcel Energy assessed the operation cost of new wind turbines, which can produce 1,500 MW and were to be integrated into Xcel Energy service network. Based on historical weather data and meteorological numerical weather prediction (NWP) models, wind forecasting data of the past several years with high resolutions of time and space was developed around the proposed areas for the new wind turbines in the states of Minnesota and South Dakota. The wind forecast data was processed into wind power generation forecasts using the "power curve," a relationship between power generation and wind. The power generation forecast data was combined with systems of scheduling the operation of turbines to achieve the most cost-effective operations of overall generation. The study concluded that the additional cost of integrating the 1,500 MW of wind generation into the existing Excel Energy service network was 0.46 cents/kWh, which is just about 1/20 of the current average retail price of electricity (Energy Information Administration 2006). The forecast data could also be integrated in the utility control center energy management systems (EMSs), and the data could play an important role in "mitigat[ing] risks and consequences of inadequate situation awareness in control centers" and "reduc[ing] costs through improved operators and dispatchers to manage wind variability" (Ahlstrom et al. 2005, p.62).

Ahlstorm et al. (2005) used conventional (deterministic) forecasts, not ensemble forecasts. The use of ensemble forecasting could have improved the efficiency of the operation. Ahlstrom et al. (2005) acknowledged that a large error in electricity generation forecasts in their study mainly stemmed from a forecast of the exact time when the wind would change significantly due to passage of weather fronts. Forecasting the exact time of a weather front passing is difficult, and the error of the timing can in turn result in a large error in electricity production forecasts. However, ensemble forecasting could estimate the possible time window of the passage of weather fronts more effectively because ensemble forecasting can consider multiple possible weather scenarios. The time window could help users to prepare for of the front passage effectively; without the time window of the front passage, users prepare for the front passage for too long or too short a time rather than the proper time window, and this improper time window results in unnecessary costs.

ii) Energy Demand Forecast

Wind forecast is useful for effective electricity generation, as discussed above. The use of forecasts plays an important role in surviving in a competitive electricity market. A common style of the business procedure in energy generation companies is shown in Figure 3-9. The demand forecast plays a critical role in the *Day-ahead market*, which defines possible revenues from electricity generation, so that accurate electricity demand forecasting may reduce the volatility of the business of the electricity generation companies.

1) *Day-ahead forecast*: Market participants forecast system load for each hour of the following day. ...
2) *Day-ahead market*: Generators and load-serving entities bid for producing and purchasing energy and operation reserves. ...
3) *Unit commitment*: System operator schedules an appropriate mix of generating resources to serve the load recognizing factors such as bid prices for energy, generator start-up and maneuvering constraints, and transmission congestion constraints.
4) *Real-time operation*: System operator adjusts generating resources to match actual system load in real time during the day of operation. ...
5) *Market Settlement*: Actual power generated and consumed is logged, and imbalances from scheduled values are financially settled, ...

Figure 3-9 Business process of electricity generation companies (Piwko et al. 2005)

The relationship between electricity demand forecasts and activities of energy grid companies is illustrated in Table 3-7, which looks slightly similar to Table 3-6. The grid tries to minimize generation that exceeds demands[20]. When the energy demand forecasts are "high," then the grid turns off/down generation facilities of expensive electricity, and vice versa. However, if the forecast predicts high demand but actual demand is low, some of the planned expenditure for high energy generation turns out to be a wasted cost (lower left of Table 3-7). In addition, if the forecast predicts low demand but actual demand is high, the grid either pays for extra electricity generation from expensive resources, such as fossil fuel, to meet the demand by any means or loses a part of the revenue that the grid would have

[20] In reality, the grid generates more than the demand as a reserve.

received in the case of perfect forecasts (upper right of Table 3-7).

Table 3-7 Energy demand forecasts and activities of an energy grid company

	Grid Activity (Plan)	Actual Demand: Low	Actual Demand: High
Forecast: Low Energy Demand	Turn off/down expensive energy generation (e.g. fossil energy). (Low planned expenditure)	Low planned expenditure & No additional expenditure	Low planned expenditure but **Extra expenditure for additional energy (expensive energy) generation or Loss of potential revenue**
Forecast: High Energy Demand	Turn on/up expensive energy generation (e.g. fossil energy). (High planned expenditure)	High planned expenditure but Actual generation expenditure is lower than the plan (i.e. **some of the planned expenditure turns out to be a wasted cost.**)	High planned expenditure & No additional expenditure

The energy demand forecast is generated by several kinds of data including day/time (day of the week and holiday), season (winter or not), temperature (Ramanathan et al. 1997), and humidity. Therefore, proper temperature forecasts are valuable inputs into electricity demand forecasts. Taylor and Buizza (2003) demonstrated the use of ensemble forecasts for demand forecasts. They developed demand forecasts[21] for England and Wales from a deterministic wind forecast and an ensemble wind forecast and compared them. They concluded that the ensemble wind forecast provided the better demand forecast (Figure 3-10).

The relationship between wind data and electricity demand is non-linear (Ramanathan et al. 1997). Under non-linear conditions, an expected value of outputs, each of which is derived from inputs through the function, is different from the output derived through the function from the expect values of the inputs. Regarding handling the non-linearity, Taylor and Buizza (2003) pointed out that "it would be preferable to first construct the probability density function for the weather-related electricity demand, and then to calculate the expectation" (p.62).

In another study, Roulston et al. (2003) also demonstrated, by using ensemble forecasts with post processes, that an ensemble wind forecast in Oxfordshire, UK, foretold one to ten days ahead, could allow higher revenue for wind energy producers than a deterministic weather forecast beyond one day (Figure 3-11).

[21] As for the modeling of electricity demand forecasting, they used the method of National Gird, which is responsible for electricity transmission in the research area.

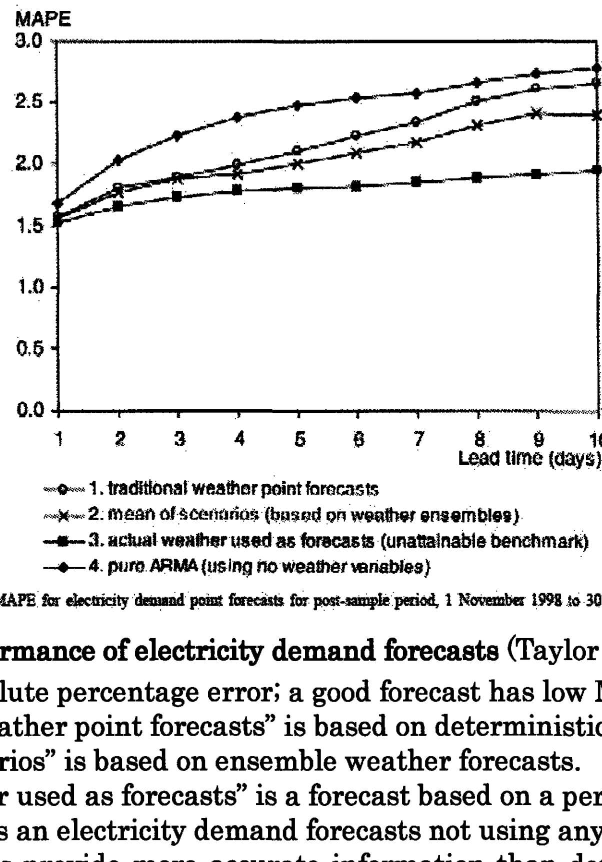


Fig. 3. MAPE for electricity demand point forecasts for post-sample period, 1 November 1998 to 30 April 2000.

Figure 3-10 Performance of electricity demand forecasts (Taylor and Buizza 2003)[22]

MAPE: Mean absolute percentage error; a good forecast has low MAPE.

"1. traditional weather point forecasts" is based on deterministic weather forecasts.

"2. mean of scenarios" is based on ensemble weather forecasts.

"3. actual weather used as forecasts" is a forecast based on a perfect weather forecast.

"4. pure ARMA" is an electricity demand forecasts not using any weather data.

Ensemble forecasts provide more accurate information than deterministic forecasts. "3" and "4" are reference cases of perfect forecasting and no forecasting.

[22] This article was published in International Journal of Forecasting, 19 (1), J. W. Taylor and R. Buizza, "Using weather ensemble predictions in electricity demand forecasting." 57-70. Copyright Elsevier (2003)

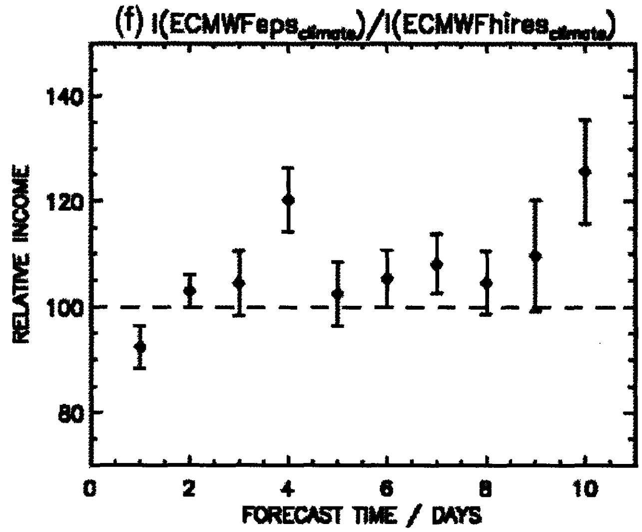


Figure 3-11 Net income (weekly mean) as a function lead time (Roulston et al. 2003)[23] Relative income means income by ensemble weather forecasting normalized by the income by high resolution deterministic forecasts.

[23] This article was published in *Renewable Energy*, 28 (4), M. S. Roulston, D. T. Kaplan, J. Hardenberg, and L. A. Smit, "Using medium-range weather forecasts to improve the value of wind energy production." 585-602. Copyright Elsevier (2003)

iii) Possible Role of the Weather Forecasting Sector

According to the article in *IEEE power and energy magazine* written by J. Charles Smith of the Utility Wind Interest Group[24], the wind energy cost has been reduced by 80% in the past 20 years (Smith 2005). The cost of the wind energy could be competitive with other energy sources such as natural gas, but is still higher than others, such as coal (National Grid 2006, Smith 2005). As a result, customers who want to use wind energy have to pay additional fees on top of a standard rate in many cases (Environmental Protection Agency 2006). Thus, the wind energy sector is trying to reduce cost by every possible means (Ahlstrom et al. 2005, DeMeo et al. 2005, National Commission on Energy Policy 2006, National Grid 2006, Piwko et al. 2005, Smith 2005, Zavadil et al. 2005). As discussed above, ensemble weather forecasts might allow economically efficient energy production through effective operation and more valuable energy demand forecasts, and help wind energy firms, grid operations, or both. The weather forecasting sector should recognize the fact that the weather sector can have a role in the renewable energy issues. Whether the weather sector should help the wind energy sector via ensemble forecasts would depend on the following two points: How much could better weather forecasts increase the true revenue of wind energy production? If the cost could be reduced, how much would the reduced cost attract customers? The weather sector should always evaluate these two factors when considering the

[24] Utility Wind Interest Group (UWIG) is an NPO established by utility companies. J. Charles Smith is the executive director of UWIG.

possible role of weather forecasts in the renewable energy sector.

3-4-3. Weather Derivative: Risk Transfer

Risk transfer also is commonly implemented in risk management. Insurance is a typical means of risk transfer. Companies or people that recognize a risk purchase insurance to cover the possible loss, and this insurance reimburses the loss if the loss happens in reality. Derivatives, which are "in finance, contracts whose value is derived from another asset, which can include stocks, bonds, currencies, interest rates, commodities, and related indexes" (Britannica 2007)[25], are also another technique of risk transfer. The difference between insurance and derivative is that the pay-off in insurance is based on financial loss but pay-off in derivative is not. Rather, it is based on an index of weather, such as cumulative daily temperature over the designed period. Derivatives have been used for managing the risks of price fluctuation of securities and foreign currencies, and they recently have been applied to not only the financial commodities but also to other commodities such as fuel. Today, derivatives have begun to deal with risks in other areas (Brealey and Myers 2000) such as weather, earthquakes, and the environment (Goto and Hihara 2002, Japan Meteorological Agency 2002).

Derivatives have several types that have developed over the past 30 years: Options, Futures, Forwards, and Swaps (Brealey and Myers 2000). This paper covers two types: options and swaps, based

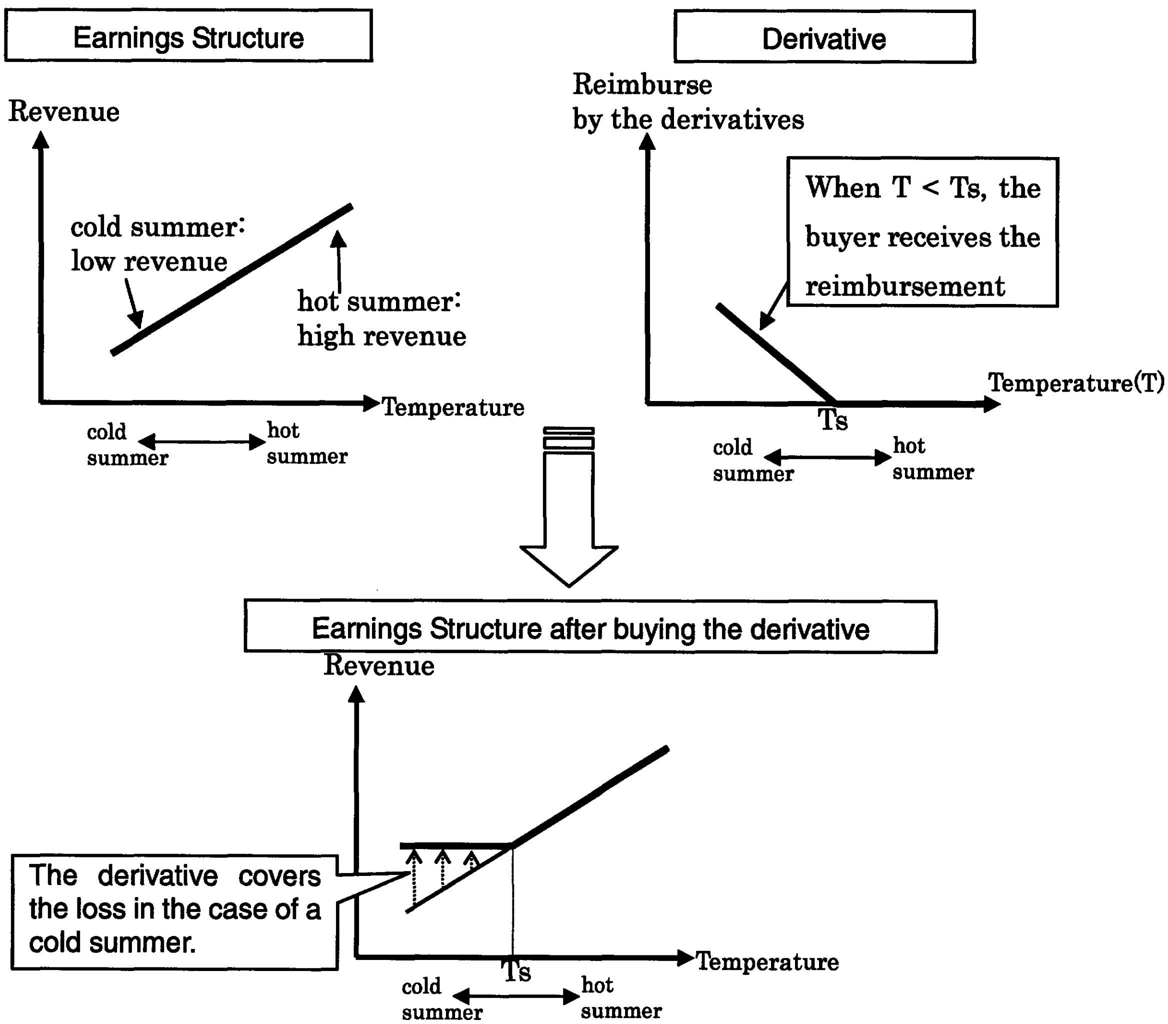
[25] "derivatives." Britannica Concise Encyclopedia. 2007. Encyclopædia Britannica Online. 12 Mar. 2007 Available from http://search.eb.com/ebc/article-9362563

on the discussion of Goto and Hihara (2002).

i) Option

Figure 3-12 illustrates the option, one typical type of derivatives. Assuming a company whose revenue increases with temperature in summer (e.g. electric companies and beverage manufacturers), the company has a risk of reducing its revenue in a cold summer. The company can buy a financial product (derivatives) that pays the company in the case that temperature in the summer is below the threshold degree (technically called as *strike*)[26]. Consequently, the derivatives reimburse the revenue loss due to a cold summer. In this case, it can be said that the risk of a cold summer is transferred from the company to the seller of the derivatives, i.e. financial institutions (brokers). In reality, the transaction cost associated with the derivatives is imposed on the company; therefore, the actual revenue of the company in the case of a hot summer is reduced by the transaction cost.

[26] This type of option is called a "put option." The option that reimburses in the case that the temperature is above the strike temperature is called a "call option."



(* In reality, the buyer's revenue is reduced by the transaction cost associated with brokers.)

Figure 3-12 Example of Options in Weather Derivatives

ii) Swap

The company in the previous section has a revenue structure a hot summer is preferable. On the other hand, for some companies a cold summer is preferable. For example, gas companies' revenue drops in the case of a hot summer and increases with a cold summer. This is partly because the heat requirement for boiling is reduced when the temperature is higher. Companies with opposite revenue structures affected by weather can exchange weather risks. This exchange of weather risk is called a *swap*. In this case, the companies do not need a financial broker as an intermediary agent. Therefore, theoretically, the transaction cost to brokers is non-existent, unlike with options. Figure 3-13 shows an example of a swap. A cold summer is favorable for the revenue structure of Company A; a hot summer is attractive to company B. When the two companies make a swap contract, in which A pays B in case of a hot summer and B pays to A in case of a cold summer, the revenue structures of both companies can become resilient to the summer temperature. In reality, since Tokyo Electric Power and Tokyo Gas made a swap contract associated with temperature in the summer in 2001, the swap contract related to weather risks has become shared (Goto and Hihara 2002)

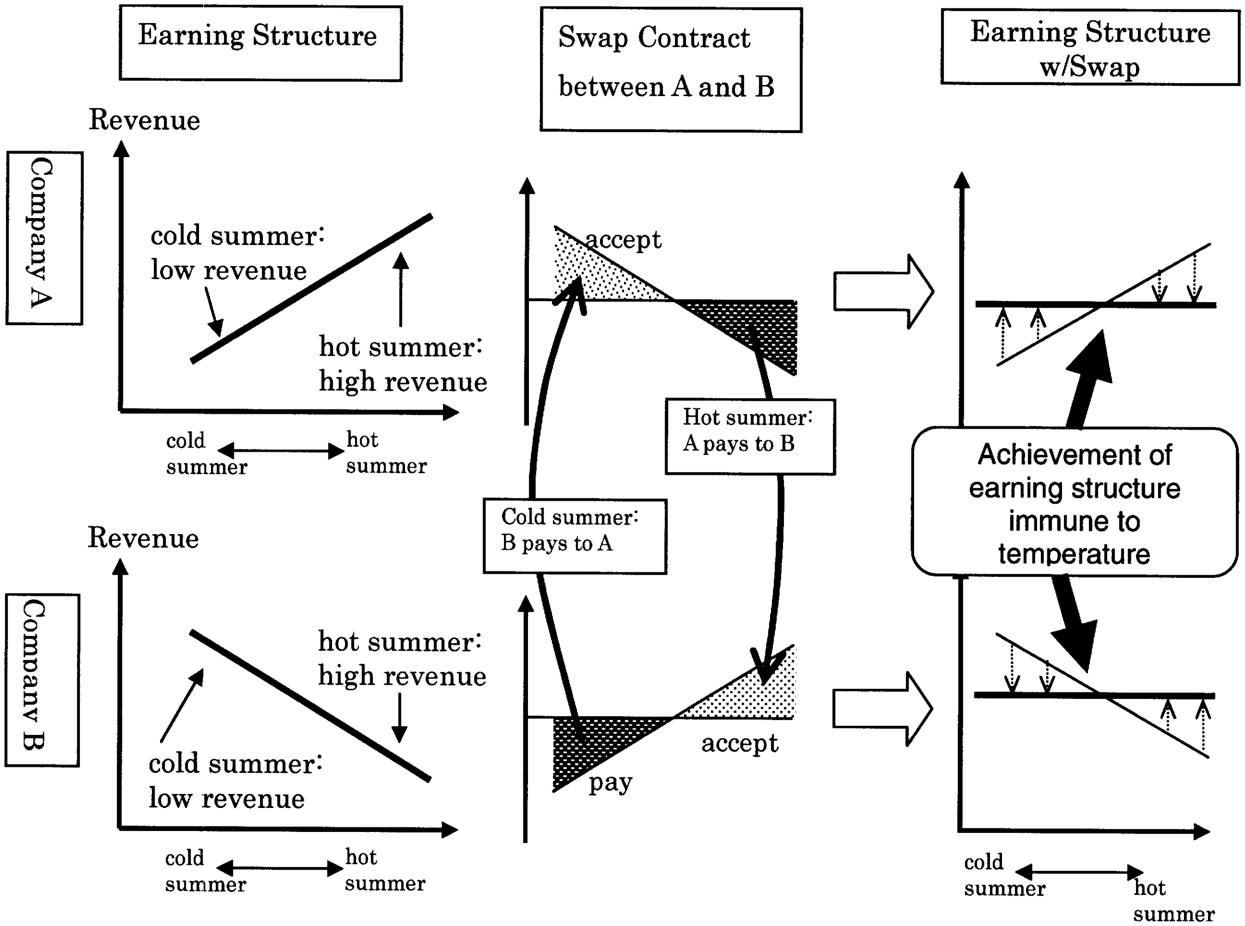


Figure 3-13 Example of Swap in Weather Derivatives

Weather derivatives are often contracted through over-the-counter trading because organizations have diverse sizes and risk characteristics. In order to trade the risks more easily, markets for exchanging weather derivatives were established by Chicago Mercantile Exchange (CME) in 1999 and by London International Financial Futures Exchange (LIFFE) in 2001. In CME, indexes called HDD (heating degree days) and CDD (Cooling Degree Day) are traded. HDD is calculated through a summation of "65F° minus daily average temperature"[27] over a period of time or a year. CDD is calculated through a summation of "daily average temperature minus 65F°"[28] over a period of time or a year. According to the Weather Risk Management Association (WRMA)[29], the number of the contracts has increased dramatically, from 4,400 in 2004 to 1 million in 2006, and the market size increased from $4.6 billion in 2004 to $45.2 billion in 2006 (Weather Risk Management Association 2004, 2006)

Currently, the pricing of derivatives is based on historical weather observation data in many cases, and sometimes based on a combination of forecasts (deterministic forecasts) and historical observation (Jewson and Brix 2005). However, some pioneering studies have displayed the potential use of ensemble forecasts in the pricing. Taylor and Buizza (2006), for example, used a probabilistic distribution function produced by ensemble forecasts for forecasting heating degree days (HDDs). They

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27 If the daily average temperature is lower than 65F°, data for the day is not added to HDD.
28 If the daily average temperature is higher than 65F°, data for the day is not added to CDD.
29 WRMA is an industry organization of weather risk management.

calculated the expected values of the put option from the HDD and compared the quality of the put option with a put option constructed in the usual way. As a result, they found that the ensemble-based payoff "outperformed" the payoff of the option constructed by a conventional method. Thus, in the near future, ensemble forecasting could become a powerful tool for weather derivatives to help forecast users transfer risk more effectively.

Exchanging weather derivatives can increase benefits to society. In economics, the exchange of financial products of risk adjustment in a market makes it easier for participants to exchange risks, reduces default risk or credit risk of contract partners, and increases transparency of pricing of the financial products. The nature of this exchange leads to reduced profit margins of the intermediates of risk transferring, and the cost savings can be invested in other more profitable investment opportunities. In the private sector, these opportunities may be a rate of return of investment, and in the public sector, the opportunities can be a social return. (Gale and Douglas 1991, Horne 1985) As for weather derivatives, they increase the liquidity of weather-related risks and work as financial risk adjustment products, and emerging markets of weather derivatives provide a place for exchanging risks. Thus, the two factors of evolution of weather derivatives and emerging markets of exchanging the weather derivatives can be beneficial for society.

Financial measures for risk adjustment including weather derivatives can be advantageous to society. So what is the role of the public sector in the market? I suggest that there are two roles, as Goto and Hihara (2002) have discussed. First, the public sector should be involved in the management and development of financial measures. This is because the innovations in the financial measures might be "public goods," which are "nonrival" and "nonexclusive." The nonrivality means that "for a given level of production, the marginal cost of providing it to an additional consumer is zero" (Pindyck and Rubinfeld 2005, p.665). The nonexclusiveness means "goods the people cannot be excluded from consuming, so that it is difficult or impossible to charge for their use" (p.665). Thus, the "public goods" inevitably allow additional consumers to be free riders when using the goods. In reality, Tufano (1989) studied 58 cases of new financial products from 1974 to 1986 and found that information about these new products was propagated to rivals of the innovators very soon, and the rivals mimicked the new products quickly. As a result, the innovators could not enjoy a long term advantage and were soon involved in price competition with their rivals. They might receive a large market share as a "first mover"; other than this, it is difficult for innovators to recoup the investment in innovations (Tufano 1989). When it is difficult for innovators to recoup such investments, their motivation is reduced, which leads to underinvestment in new innovations, although the innovations may enhance the utility of society. Therefore, the public sector should participate in managing and developing new innovations (Olson 1982, Shiller 1993, and Stigler 1971). Second, the state of weather risks handled by the derivatives should be described objectively, concretely, and accurately by indexes that are reliable and have no potential for manipulation. As for weather data, national weather forecasting organizations such as the Japan Meteorological Agency (JMA) in Japan and the National Oceanic and Atmospheric Administration (NOAA) in the US have accumulated observation data. The public sector, including such as JMA and NOAA, should keep a database of observations, minimize gaps in the observation data, refrain from altering the data, allow everyone to access the data easily, and prohibit any unethical activity such as acquiring the data before it is open to the public.

Chapter 4. Implementation of Ensemble Forecasting

The advancement of atmospheric science, mathematical science, and computational technology has enabled the seed of practical ensemble forecasting to germinate. Ensemble forecasting can reduce weather-related risks in some cases. However, the development and implementation of ensemble forecasting require substantial computational and human resources due to the characteristics of ensemble forecasting (e.g., huge data size, multiple numerical weather prediction (NWP) model runs). In order to promote this development, collaboration among weather-related organizations is needed. The chapter discusses the relationship among weather-related organizations and possible ways of collaboration.

4-1. Collaboration as a basic concept

Ensemble forecasting requires more computational resources and human resources than conventional forecasting. A numerical weather prediction (NWP) model has to run many times to create multiple weather scenarios that construct ensemble forecasts; therefore, ensemble forecasting requires more computational resources, including processors for calculation and storage devices for archiving calculated data, than deterministic forecasts. For example, according to Japan Meteorological Agency

(JMA) (2005), the resolution[30] of the current operational NWP model of JMA for deterministic forecasting is twice that of ensemble NWP models. The number of horizontal grid points of the deterministic NWP model forecasting global atmospheric motion is 51,200; the ensemble forecasting NWP model has 12,800 grid points, which is 25% of the deterministic forecasting model. It might look as if ensemble forecasting requires less computational cost; however, the ensemble model runs 51 times to produce multiple scenarios, while the deterministic forecasting runs only once. The large computational cost of operational forecasting implies a large computational cost of development as well. In addition, the development of ensemble forecasting requires specifications different from those of deterministic forecasts (e.g., moisture process and time limits for simulations), so the development is not accomplished as a byproduct of deterministic forecast development. Some of the development elements are analysis models, which produce multiple initial conditions; NWP models, which have different resolution from deterministic forecasting models; post processing, which adjusts distribution of weather elements such as temperature, wind, rainfall rate, and so forth; and user side application techniques such as cost/loss analysis that should be developed on a case-by-case basis, as discussed in Chapter 3. Due to the high cost, it would be difficult to develop ensemble forecasting systems within a single weather-related organization with a limited budget. Moreover, some prospective techniques of ensemble forecasting such as Poorman's Ensemble Prediction System (PEPS) require simulated results of not a single NWP model but different

[30] The finer resolution a NWP model has, the more detail atmospheric phenomenon the model can describe.

multi NWP models (Buizza et al. 2003; Ziehmann 2000); it is almost impossible for single organizations, which often have only one operational NWP model, to develop such ensemble forecasting systems by themselves. Thus, collaboration among weather-related organizations necessarily becomes important to developing and improving ensemble forecasting.

There are many weather-related organizations including public weather-forecasting organizations, such as the National Weather Service in the US and the Japan Meteorological Agency in Japan; private weather companies, such as The WeatherChannel and AccuWeather in the US and WeatherNews and Japan Weather Association (JWA) in Japan; and academia such as universities and national laboratories. The following sections discuss the relationship among these weather-related sectors and how they can collaborate with each other for better services of ensemble forecasting. Section 4-2 discusses the relationship between weather-related public and private sectors (e.g., NWS and WeatherChannel). Section 4-3 covers the relationship between the public weather sector and academia, and Section 4-4 deals with the relationship between academia and the private sector. The following sections covers the partnership among the sectors in ensemble forecasting (Section 4-5), international partnership (Section 4-6), and collaboration with non-weather sectors (Section 4-7). Some of the sections do not limit their discussion to ensemble forecasting but cover general situation in weather forecasting; nevertheless, they can embrace discussion of ensemble forecasting as well.

4-2. Public Organizations and Private Companies in the Weather Industry

Both private and public sectors do weather forecasting today; the collaboration between these sectors could contribute to the evolution of ensemble forecasting. However, the two sectors have raised a long-standing debate about public-private partnerships in weather forecasting. The private sector finds business opportunities in the public sector's forecasting activities, but at the same time feels the public sector's activities are a threat to its business. This section first analyzes the current situation of public and private forecasting, the relationship between the public and private sectors, and the possible resolution of the situation.

4-2-1. Forecasting by public organizations

1) Market failure in weather forecasting

Governmental forecasting organizations such as the National Weather Service (NWS) in the U.S. and Japan Meteorological Agency (JMA) issue seasonal, monthly, weekly, daily, and hourly (in hazardous weather) forecasts and warnings to the public today. The weather forecast plays important roles in public policy matters, such as disaster management, global warming policymaking, or defense force operations. The government is responsible for these areas in many countries because these areas have large "externalities," which in this paper means that the government's involvement maintains the large scale welfare of the public by protecting the life and property of the people; the cost of the government's involvement is considered smaller than the public welfare it ensures. In the case of weather warnings, the US Federal Communications Commission (FCC) rule "requires broadcasters to monitor at least two independent sources for emergency information, ensuring that emergency information is received and delivered to viewers and listeners" (National Weather Service 2005) (Federal Communications Commission 2005; Federal Communications Commission 2006); in Japan, the Basic Law on Natural Disasters or its related disaster prevention plan, the Broadcast Law, and the Meteorological Service Law ask broadcasters to disseminate warnings[31]. The warnings trigger and assist the disaster management activities of national and local governments.

Modern weather forecasting began in the late 19th century, and since then it has been developed by the government through continuous investment. Today, it costs $600-700 million/year for operational weather forecasting in Japan and $700-800 million/year in the US (Japan Meteorological Agency 2006c; National Oceanic and Atmospheric Administration 2007). This figure includes observation network systems including satellites, supercomputers[32], studies of atmospheric sciences and computer sciences for improving forecasting technologies, and the human resources cost for routine operations. The total cost is too high for private weather-forecasting companies to assume[33], and therefore,

[31] These rules order the Japan Broadcasting Corporation (NHK) to broadcast warnings.
[32] Weather forecasting requires super high-level performance computers. Among "the top 50 of supercomputers" in the world, eight computers are owned by weather-forecasting-related organizations (http://www.top500.org/list/2006/06/100).
[33] For example, Weathernews Inc., one of largest weather-forecasting companies in the world, makes about $100 million in revenue every year. The profit of the company is -5 to +6 million dollars/year, which is far less than the required cost for only an observation network of operational weather forecasting organizations.

a market could not exist only with private weather-forecasting companies. Moreover, air particles in the atmosphere move globally over national borders; therefore, a country's weather data should be collected internationally with coordination with neighboring foreign countries. Private organizations, shortsightedly trying to meet the demand for their direct customers, might not coordinate internationally.

Who would bear the cost if the government did not involve itself in weather services and the public did not have government-provided weather information? If only some people have weather information and others do not, what happens? Presumably, those who do not have it would cause more weather-related damages that society would have to pay for. Considering both the externalities of protecting the life and property of the public and the cost of forecasting processes, the governments themselves in many countries decide to take responsibility for the development and operation of weather forecasting and make forecasting a public good.

2) The general forecasting by public organizations

The previous subsection covers mainly the forecasts that are important for public decision makers such as disaster management. NWS and JMA and other governments' operational weather organizations are also issuing a general forecast, including non-hazardous general weather forecasts such as "fair weather." Technically, it seems impossible to divide the forecasting processes between hazardous weather and non-hazardous weather; it is impossible for the forecasting process to run only when a forecaster's intuition tells him a storm will happen, because it is only the forecasts themselves that let the forecasters know that the storm might happen. The fact that the weather forecasting processes of general weather and of hazardous weather are (almost) identical implies that the cost for the general forecast is very little in addition to that of the hazardous weather forecast. Moreover, the general forecast has some externalities derived from risk reductions related to our daily life, such as aviation safety, road management (against rain, snow, or strong wind), even our escaping from getting wet with rain, and the fact that the public accepts that the general weather forecast is issued by public organizations implies that such externalities exceed the "additional (very small) cost" of the general forecasts.

4-2-2. Weather forecasting by private sector

Not only the public sector provides weather forecasts. In reality, private weather forecasting companies also provide weather forecasts. Private companies are trying to meet their customers' specific and detailed needs, which public forecasts cannot meet. Such customers use the forecasts for a variety of needs, such as demand forecasts related to particular products, risk management of an energy sector, or crop management in agriculture. Other customers are broadcasting stations that distribute weather-forecasting programs to the public. Generally, the private sector collects weather forecasting data mainly from the public sector and processes it into customized weather forecasts. Some major companies seem to provide original forecasts by simply combining the public forecasts and other sources including their (somewhat) original ones[34]; others seem only to assemble the public forecasts. As mentioned above, the size of private operations (including observations, studies, or investments in simulation systems) is smaller than that of public sector operations; therefore, the private sector's business is evolving based on the fruits of the public sector.

4-2-3. Co-existence of both the private and the public weather sectors

Once the public sector establishes the industry, new business opportunities such as new niches are created for private forecasting companies who meet specific users' needs by utilizing the public sector's new products. However, private weather companies sometimes see the public sector's activities as a threat to their own business. The main objectives of the sectors are not the same. The NWS provides forecasts for "the protection of life and property and the enhancement of the national economy."[35] The private sector provides forecasts to customers. However, there is an area where both the public and private sectors exist in a general weather forecast. For example, we can find forecasts for any place in the US through a ZIP code search on web pages of both the NWS (http://www.weather.gov) and the Weather Channel (http://www.weather.com)[36]. Figure 4-1 shows the process of weather forecasting, coverage of the public and private sectors, and categories of forecast users. The bottom row includes forecast users,

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34 Weathernews Inc., http://weathernews.com/jp/c/support/

35 NWS mission http://www.nws.noaa.gov/hdqrtr.php

36 Generally, the significant difference in their weather forecasts would be difficult to detect because the private sector's forecasts are based on the data of the public sector to some extent.

who are roughly classified into government (responsible for disaster management), general public users, and specific users buying forecasts from private weather companies. The boundaries between the user categories cannot be assumed to be rigid, as the users of public and private weather forecasts inevitably overlap.

From the viewpoint of vertical integration in the process of weather forecasting in Figure 4-1, the public sector covers the whole process from observation to distribution. As for the private sector, some big companies have the analysis and NWP systems, but other many companies do not have analysis systems, NWP models, or postprocess systems; they sometimes interpret data obtained from the public weather sector. Comparison between the public sector and the (big) private sector indicates little difference in the area covered by the private and public sectors. However, the dotted lines and arrows showing weather data flow in Figure 4-1 indicate that the private sector strongly relies on the public sector.

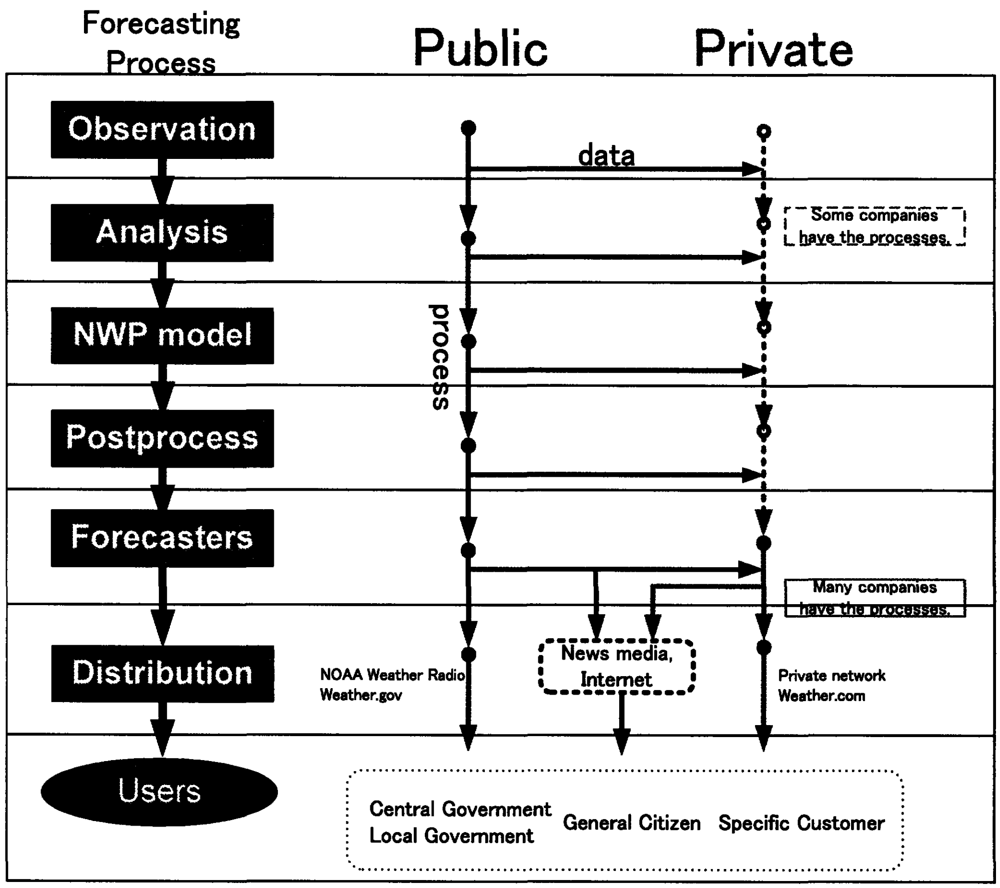

Figure 4-1 Public and Private Sectors in weather forecasting

The private sector's forecasting process often relies on the public sector's process, as it receives data from the public sector. Each sector has its own distribution channel (Public sector: NOAA Weather Radio [37], web site (weather.gov); private sector: private network, weather.com (WeatherChannel Inc.), etc). News media and other web sites also distribute weather forecasting information of the public and private sectors.

[37] NWS has a radio network for distributing hazardous weather warnings.

4-2-4. The debate over the relationship between public and private sectors

1) Discussion in Congress in the US and Japan

Weather information distributed via mass communications can be seen as a non-rival good in that even if someone consumes (receives) the weather information, it is still available for others. The forecasts are also regarded as non-excludable. This is because no one can prevent others from consuming the forecast due to the widespread dissemination. Public hazardous forecasts are required to be broadcast for free; the public sector's general forecasts are broadcasted via unencrypted media and can be received for free. In this sense, governments have decided to make weather forecasts common goods. As a result, all but those who have a need for more specific forecasts do not pay for weather information. Because this information is a public good, they can be "free riders."

The public sector develops the technology and produces weather forecasts for the public to meet the public needs; the private sector regards the public sector as a threat to its business. As a result of this co-existence, a long-standing debate about a public-private partnership in weather forecasting has existed. In 1991, the U.S. Congress issued legislation that the NWS would privatize some services and would not compete with the private weather companies (Department of Commerce 1991). For example, "in the late 1990's the Commercial Weather Services Association spearheaded a lobbying effort to change the NWS Organic Act and prevent competition with the private sector. These efforts have not succeeded, and the debate continues today." (National Research Council 2003, p. 17)

Just around the same period in Japan, the debate about government reform heated up. As a result of the discussion, governmental organization reform was implemented in 2001. The government's administrative reform panel discussed a "small government," and concluded that the JMA should limit its tasks in order not to compete with private firms.[38]

2) Dilemmas

The coexistence can be regarded as a subsidy of private weather companies that enjoy the fruits of the public sectors (e.g., observation data, forecasting data, and tips for practical forecasters) with little cost. On the other hand, this coexistence is seen as a constraint on the private companies' business. This situation produces a complex dilemma.

In Japan, web pages providing local forecasts customized by ZIP codes are all private companies' pages. JMA distributes its forecast through its web pages; however, it does not have the ZIP-based services. It was reported that one of the private companies objected to the enrichment of public services through the JMA's web pages when JMA first planed to provide weather information on its web pages (Yomiuri Shinbun 2002). It was also reported that the company was also the one that won a bid for constructing the JMA's web pages for disseminating forecasts (Japan Meteorological Agency 2002). The

[38] The Basic Law on Reforming Government Ministries (in Japan) (Ministry of Internal Affairs and Communications (Japan))

contract would give the company a chance to raise public awareness of the company's technical capability to take part in the systems of the JMA (e.g. Weather News Inc. (2000)).

The public sector also has faced a dilemma concerning this situation as well. The public sector devotes itself to developing and operating more accurate and useful forecasting than the private sector to serve the public better. Actually, casualties in Japan due to natural hazards number more than 150 people in FY 2005 (Cabinet Office 2006). Governments are responsible for protecting the life and property of the people. Thus, public forecasters are called upon for accurate and useful forecasts of natural disasters. However, there is an "institutional failure," in which the public sector's effort itself might generate political discussion about downscaling public forecasting. It is only the public sector that needs to work hard to develop weather-related technologies, because the private sector tends not to do this init the current environment (Section 4-2); technology development allows the public sector to provide new products to the public. However, the private sector often sees the issuance of a new product as a symbol of a threat to its business, even though the product is for public use. For example, rain forecasts provided by NWS are getting more detailed. The object of such forecasts is to support natural disaster management in case of flood. However, this implies that the customers buying a private detailed rain forecast for high fees might never buy the forecasts when similar data is disseminated as public forecasts. As a result, once politicians notice this situation, discussion of the privatization or downscaling of the public weather forecast may emerge. In the US Congress ordered the NWS to privatize fire weather services and frost weather services (Library of Congress 1996). The privatization or abolishment of some branches of the JMA is now being discussed under the Japanese Prime Minister (Office of Prime Minister 2007).

3) Possible solutions

The private sector finds niches or new products based on public forecasting; at the same time, it also feels the co-existence with the public sector can sometimes be regarded as an institutional failure, that is, a threat to its business. The public sector makes efforts to provide forecasts that have externalities mainly due to the *market failure* in weather forecasting market as discussed previously; at the same time, the public sector might face *institutional failure* in that the political discussion of its downscaling may arise, ironically, due to these efforts to serve the people. The following is a discussion about possible solutions to these dilemmas.

1. Clearer definition of the relationship between the public and private weather sectors

One plausible solution for the dilemma is setting a clearer wall between private and public sectors in weather forecasting. The expansion of the public sector's operation should be limited, and instead, it should be substituted or complemented by the private sector (sometimes through public grants) if the public's needs expand. The rigid definition, if any, of each area would make both sides focus on their own objectives without the interference of the other. For example, it is probable that more detailed rain forecasts for flood management, which could be developed with a little additional improvement of the existing JMA forecasting system, cannot be developed by JMA. Drastic transfer of technology and human resources to the private sector would be needed due to lack of basic technologies and skills in the current public sector. However, this transfer would take cost and time, which might delay development of new forecasts that could have saved more people in natural disasters. Moreover, there is also the problem of public services in that the seller of the detailed heavy rain forecasts would release them to only rich buyers[39] and they could not be used by JMA. In addition, the costs of transferring technology and human resources from the public to the private would emerge

2. Privatization of the public forecasting organization

Another possible solution is that the JMA or NWS becomes a private organization. In this case, there would be no difference between the JMA and other forecasting companies, though public money still would be invested for the public weather forecast, not always in JMA but sometimes in the public companies. However, there could be drawbacks. First, if policy makers such as politicians aim at small government, then the privatization for resolving the dilemma would become privatization for reduction of government expenditure on public forecasts. This situation can be regarded as a "common problem"

[39] Such as companies use the forecast to achieve better business performance.

between the "government" and "the others[40]" in that the "government" and "the others" fight each other over which one should pay less for public weather forecasts. Second, the privatized (formerly public) organizations would have technological skills and reputation far superior to other private weather companies. The business of existing private forecasters might face a critical situation.

3. Establishment of a semi-public-private institution

Another possible choice is establishing an institution that lies between the two sectors. The organization might be derived from both sides' resources (budget and human resources), and this organization covers the domain overlapped by both sectors. This solution would eradicate the futile discussion about the dichotomy between the private and the public[41]. This institution also would reduce duplicate investments in the overlapping field of both sectors. However, the same problem discussed in the previous solution appears here: whether "the government" or "the others" should pay less. This third party institution would also be a threat to private companies' businesses. In addition to these issues, there would be a problem of where the line separating the new public sector and the third party institution should be drawn within the current public sector.

[40] Some possible payers are the advertising companies, who attach ads to the forecasts.

[41] In Japan, "independent administrative agencies" were invented in 2001 in order to make the government smaller. Many former governmental organizations subaffiliated with the government ministries have been separated from the government into "independent" agencies. These agencies are regarded as non-governmental organizations, although their tasks were not to be changed and the workers were to be treated as government officials. However, the discussion faced severe bureaucratic resistance and severe worker resistance. It is my opinion that the separations in 2001 would have not been executed if the separate organizations would have to become purely private organizations.

4. Status quo

As a last comment on the discussions of these "prescriptions" there may be no *perfect* solution for the public/private dilemma. Each possible solution has not only advantages but also drawbacks so another possible idea is keeping the current status. The controversy could last forever; however, the private and the public sectors can and do co-exist today and "the weather is something people really take for granted" (Jon Lindsay, personal communication) under the current scheme.

4-2-5. Endless Debates for Resolution

Though the previous sections proposed some possible solutions, there might be no perfect solution because any possible solution has strengths and limitations. And the debate has been long-standing. For example, after the 1991 policy discussion in the US Congress to limit NWS tasks, the National Research Council issued the suggestion to revise the policy of 1991 (National Research Council 2003). Later, a former US Senator proposed a bill, named the "National Weather Services Duties Act of 2005,"[42] to limit the tasks of the National Weather Service to support the private sector (ABC News 2005, The New York Times 2005; Washington Post 2005). The bill fell through, but it was supported by private

[42] Library of Congress (2005)

weather companies including a weather company based on the senator's home state. (Commercial Weather Service Association 2005)

4-3. Public organizations and academia in the weather industry

Universities and national laboratories research the nature of the atmosphere and find scientific bases of improvement of weather forecasting. The theorization of the chaotic nature of the atmosphere by Professor Edward Lorenz in MIT is one example. Its chaotic nature prevents perfect forecasting, and the difficulty in forecasting due to the chaos ignited research on ensemble forecasting. Academia has contributed to the advancement of weather forecasting, from not only a theoretical perspective but also in a practical way. For example, in the US, Pennsylvania State University and the National Center for Atmospheric Research (NCAR) developed a numerical weather prediction (NWP) model that simulates meso-scale atmospheric phenomena[43]. The model, called MM5 (University Corporation for Atmospheric Research 2006), is widely used not only for just academic research but also for practical forecasting (e.g. Civil Aeronautics Administration, Taiwan (2007); NCAR (2007)). The wide range of research sometimes overlaps with the practical weather forecasting research by public (including military) operational weather forecasting organizations, and often allows for collaborative works of both sectors. For instance, the operational organizations and academia collaborate to develop the Weather Research and Forecasting

[43] In meteorology, meso-scale atmospheric phenomena have a typical horizontal scale of 2 – 2000 km, ranging from thunderstorms to hurricanes (Ahrens 2000).

(WRF) Model, which is "a next-generation mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs." (UCAR 2007) In addition, 21 % of 121 NWS offices are located at universities (National Research Council 2003), and these locations contribute to encourage exchange among academia and operational forecasting organizations.

As for ensemble forecasting in the US, the academic community plays an important role in the advancement of ensemble forecasting and promotion of knowledge sharing with the operational sector. For example, the University of Washington demonstrated computational simulations of meso-scale ensemble weather forecasting by the MM5 model (Grimit 2005); researchers and practical forecasters lectured on ensemble forecasting and its practical applications to forecasters in a short course of the American Meteorological Society in 2007 (American Meteorological Society 2007).

In contrast, the collaboration among the academic and operational sectors in Japan seems immature compared with the US. In Japan, there are actually some NWP models[44]; however, they are not so widely used as MM5 and WRF. Some researchers argue that the current research environment does not motivate academic researchers to develop NWP models (Muroi 2001). One claimed, for example, that even if a researcher develops a NWP model, the development itself is not appreciated among the Japanese academic society of meteorology. Academic research used by the models is fairly evaluated. In other words, developers are not highly valued, but users are. This research environment makes researchers tend

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[44] e.g. JMANHM (Saito et al. , 1266-1298) and CReSS (Tsuboki and Sakakibara 2001) for meso-scale simulation

to use NWP models already developed by someone else instead of developing the models themselves. As a result, JMA, which has developed NWP models for operational purposes, could be one of the most major developers of NWP models. For JMA, even if researchers just use the models but do not participate in development, use of NWP models by researchers is beneficial. This is because users might provide some feedback, even perhaps a bug in NWP computational programs, to JMA. However, unlike US NWP models, JMA models cannot be distributed freely to users because of an issue of intellectual property rights. JMA is a governmental organization, and the government regards the NWP models of JMA as government-owned properties and does not allow the models to be accessible for free by anyone (Yamada 2004). As a result, JMA orders users of NWP models to make a contract to "borrow" the models[45]. Along with the contract, if a user introduces new components into the JMA's models to improve the performance of the models, the user must report his/her new findings to JMA (Japan Meteorological Agency 2003). Users may feel annoyed that they have to make such a contract. Moreover, NWS models of the US (such as MM5 or WRF model) seem more attractive than the Japanese ones to users in that the US models allow users to download the model for free, without contracts. In reality, in the academic research community of meteorology, some researchers advocated reducing the transaction cost related to the contract and free access of the models (Yamada 2004). If the current situation does not change, it is probable that most researchers will use foreign models, and national models might become obsolete.

[45] Sample contract form is located on http://pfi.kishou.go.jp/open/shinsei.htm (cited Apr 8, 2007)

Another obstacle to research of NWP models is acquiring the weather data that are the initial conditions for a NWP model run. As discussed in Section 2, the "analysis" process prior to the NWP model run in weather forecasting prepares the data of the current state of the atmosphere (i.e. "analysis" data) as a starting place for NWP model simulation (an initial condition for a NWP model). In the US, many kinds of data produced in operational forecasting of NWS are accessible freely via the Internet (National Center for Atmospheric Research, 2007). However, in Japan, this seems not the case. In the US, following the law[46], many kinds of weather data, including NWP model outputs, are open to the public (National Research Council 2003), and the National Research Council (2001) also recommended the "preservation of full and open access to core data products." (p.5) In Japan, following the basic concept of the Meteorological Service Law, JMA is ordered to distribute all the weather data, such as raw "analysis" data and NWP model outputs, through the Japan Meteorological Business Support Center (JMBSC). JMBSC meets the demand of public weather forecasting companies by providing such raw data through a dedicated line connection. The users (public weather companies) do not pay a fee for the data itself; however, they have to pay for the maintenance cost of JMBSC systems and the personal lines. Some researchers have argued that researchers with little funding cannot afford to buy the data from JMBSC. The current data distribution scheme in Japan was set up in 1996, just before the Internet reduced data exchanging cost dramatically. In general, once a scheme comes into effect, it is difficult to revise it

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[46] OMB Circular A-130, 65 Federal Register 77677, December 12, 2000

(Foster 1999, Oye 2006). Also, in this case, the data provision scheme has been unchanged for years. One possible solution is for JMA and JMBSC to categorize users as commercial entities and others (such as educators and researchers). Commercial weather companies need data without lack and without delay; researchers or educators seem not to require such a high quality of service (high QoS: Quality of Service). The current JMBSC scheme focuses only on high QoS of data provision, and establishment of a low QoS service could be beneficial for educators or researchers. JMA and a research community recently tried to establish a new contract for data provision for educational and research use (The Meteorological Society of Japan 2007). Hopefully, the new scheme will allow researchers to exploit new study areas closer to practical weather forecasting, and will enhance collaboration between academia and an operational weather forecasting sector.

Other than exchanging the information of NWP models and providing weather data, the Japanese study environment in meteorology has another problem. In Japan, the distribution of weather forecasting to the public is regulated, and any people providing his/her own forecasts other than JMA must receive a license to forecast. The license system tries to prohibit the social disruption that comes from technologically unsound forecasts, especially in case of hazardous weather (Japan Meteorological Agency 2007). An applicant for the license should submit a forecasting plan including personnel assignments of his/her organization and demonstrating that he/she has systems efficient enough to receive data and to process and distribute forecasts. This license scheme seems to discourage incentives of researchers to study practical weather forecasting. In contrast, many universities in the US operate weather forecasting on campus. What is more, Pennsylvania State University produces forecasts for the *New York Times* weather page. Faculties of the universities regard the provision of forecasting as a precious opportunity for students to study meteorology (National Research Council 2003). In Japan, only one university provides weather forecasting by NWP models officially (Gifu University 2007); many meteorological departments of universities do not offer practical weather forecasting courses; and the gap between researchers and operational weather forecasting organizations could widen; it would become more difficult for the two sectors to collaborate.

In conclusion, three factors in the meteorological society of Japan, exchange of NWP model development information including the free access issue of NWP models, data provision to academia, and a forecasting license, have been discussed in this section. These factors discourage seem to researchers from studying practical weather forecasting. It is hard to change a scheme once it is fixed; however, if both sectors, academia and operational organizations, will collaborate to improve the current situation, then the future may be different.

4-4. Academic and private partnership

Academia in Japan does not have strong preference in practical weather forecasting due to the academic environment. This preference reflects the relationship between academia and private weather sectors. In the US, some companies utilize the MM5 model, which is widely used in the academic community, for their weather forecasts (National Research Council 2003). There are also some spin-off companies from universities such as AccuWeather (AccuWeather 2007). On the other hand, in Japan, it is hard to find the cases of a strong relationship between academia and the private sector. One example is a collaborative NWP model project between Toshiba Inc. and Nagoya University (Nagoya University Laboratory of Meteorology 2007). Conversely, a big Japanese private weather company works not with universities in Japan but with Oklahoma University in the US (National Weather Service 2005).

Considering that the private sector does not have enough funds for research in meteorology[47], it is almost impossible for the private sector to promote academic researchers in practical weather forecasting studies, and thereby change the preference in academia. The current apathetic relationship will remain until academia gets involved more in practical weather studies in the future.

4-5. Promotion of collaboration among the sectors

The current environment associated with weather forecasting does not give incentive to any weather sector (public, private or academia) for improving ensemble forecasting and making it widely used , although, as discussed in Section 4-1, because ensemble forecasting requires a huge cost, the weather sectors should collaborate to improve and utilize ensemble forecasting effectively. For the public weather sector, ensemble forecasting provides more accurate (deterministic) forecasts to protect the life

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[47] That is why tax is used for the research. see Section 4-2-1

and property of the public (e.g., hurricane tracking or probabilistic forecasts of tornados, severe rain and snow storms). However, due to the problematic relationship with private weather sectors, the public sector tends to hesitate to promote new services using ensemble forecasting. For academia, especially in Japan, the limited incentive to study practical weather forecasting might not provide scientific bases for improving ensemble forecasting. The private weather sector does not have enough capability by itself to develop ensemble forecasting. The following paragraphs discuss a possible solution for better collaboration especially in Japan. This solution seems to be arising from policy change in Japan, and this change has affected the environment in meteorology.

First, in 1998, the Basic Law on Reforming Government Ministries came into effect in Japan. This law ordered the elimination and consolidation of governmental organizations (Cabinet Office 1998). At that time, national laboratories and universities in Japan were owned by the government, and researchers and professors in the organizations were all government workers. The Japanese government has a human resource system of employment for life and promotion of seniority; this system seems to reduce competitiveness in academia. However, the organizations became separated from the government by the law, and researchers and professors became non-government officers.

In addition, the policy of distribution of research funds changed. The 1998 law also established the Council for Science and Technology and Policy (CSTP) in 2001. The council discusses science and technology policy under the leadership of the Prime Minister (Council for Science and Technology and

Policy 2007). In 2001, the Council issued a report of a general plan of science and technology, proposing that research funds of the government shift to competitive funds from equal budgets to researchers, and the policy change followed (Council for Science and Technology and Policy 2001). This shift in funding implied that researchers should be aware of their contribution not only to academia but also to society because competitive funds often reflect public needs. This change in research environment affected researchers even in meteorology, and some researchers declared their willingness to contribute to practical weather forecasting (Ohfuchi and Enomoto 2005).

Japan Meteorological Agency (JMA) as a public weather forecasting organization remained a part of the government after the Japanese government reform. JMA has a subordinate research institute (Meteorological Research Institute or MRI), and MRI also remained part of the government. However, in 2006, as a result of a policy discussion about trimming down governmental organizations, MRI decided to become an independent administrative institution, that is, to be separated from the government, within 5 years, following the cabinet decision on June 30, 2006 (Cabinet Office 2006). MRI, as a part of JMA, has devoted itself to research strongly related to JMA operation such as development of NWP models, climate change studies, and earthquake analysis and prediction studies. The separation of MRI might bring an opportunity for restructuring the current environment of the weather world.

First, MRI researchers will become non-government officers, and the fruits of researches in the future will not always belong to the government. Further discussion is needed about treatment of intellectual property rights in the process of separation of MRI and JMA; however, it is probable that the future development of NWP models in MRI can reside outside the government and that MRI researchers may share it within academia without contracts with the government. In addition, MRI is expected to make bridges from JMA to the academia and to the private sectors in meteorology, and this role was already discussed in *Establishment of a semi-public-private organization* discussed in section 4-2-4.3). As for bridging the gulf between JMA and academia, considering the policy change in weather data distribution from JMA to academia (with low Quality of Service (QoS), see Section 4-3), MRI, as a weather data distributor to academia, will be able to play a role in making such a bridge. As for collaboration with the private sector, MRI could take on collaborative work with private companies to better utilize weather products including ensemble forecasts.

The current situation of entities in the weather world does not embrace incentives to implement ensemble forecasting aggressively. However, social change, especially the separation of MRI, will have an impact on the situation. It is still unclear what the future will be; nevertheless, hopefully, the future situation will attract all weather sectors to collaborate for better weather services including ensemble forecasting.

4-6. International Collaboration

As discussed in Section 2, some ensemble forecasting techniques such as Poorman's Ensemble

Prediction Systems (PEPS) require multiple simulation results of multiple NWP models (Buizza, Richardson, and Palmer 2003; Ziehmann 2000). Few weather forecasting centers in the world have multiple operational NWP models for single purpose; therefore, several centers should collaborate to operate such ensemble forecasting. For example, as discussed in Section 2-4-3, the US, Canada, and Mexico implement a collaborative project of ensemble forecasting, called North American Ensemble Forecasting System or NAFES (Environment Canada 2007, Environmental Modeling Center 2006). They hold teleconferences once every two weeks (Yuejian Zhu (personal communication), 2006) and one of the developers of the project stated to the author that NAFES was going well. In the near future, other centers such as the Fleet Numerical Meteorology and Oceanography Center, a forecasting center of the US Navy, and the UK Meteorological Office (MetOffice) will decide whether they will join NAFES (Zhu 2007). Another international project of ensemble forecasting is TIGGE (THORPEX Interactive Grand Global Ensemble, see Section 2-4-3), which aims at both academic research and operational purposes. This project is led by the World Meteorological Organization (WMO), and asks many countries for their involvement in the project (WMO 2005).

Collaborative works are important for ensemble forecasting (and especially critical to PEPS). Participants probably expect not only to provide ensemble forecasting by combining simulation results of NWP models of many weather forecasting centers but also to receive feedback on strengths and weaknesses of their own NWP models by critiquing the performance of each center's model. However, some considerations remain. First, any collaboration among many countries requires huge diplomatic transaction costs, such as making an international agreement and holding an international conference, and the huge cost might reduce incentive to collaborate. In the NAFES case, developers in the US and Canada hold teleconferences once every two weeks. However, if many more than two or three entities join the project, would it be possible for all the participants to exchange information effectively? Lack of effective communication tends to result in a confusion of responsibilities, especially if a project is conducted by many entities. Finally, there is the free rider issue. It is likely that one participant that develops an NWP model will give up the development of its own models because it can still receive the results of other NWP models of foreign centers through the project. It is also possible that the countries that do not develop NWP models will never try to develop their own models because they can still receive the results of NWP models of other countries. Thus, it can be said that the international ensemble forecasting projects embrace effective improvement of ensemble forecasting; however, they also have the flip side of disincentive in terms of future development of NWP models of each country. The WMO and other weather-related organizations in the world should always consider both the pros and cons of the international collaboration to enhance the technologies of ensemble forecasting.

4-7. Collaboration with non-weather sectors

The value of ensemble forecasting is perceived on a case-by-case basis by users, as discussed in Section 3-3. Thus, effective promotion of ensemble forecasting to prospective users and development of new applications of ensemble forecasts requires communication and collaboration with potential users of the forecasts. However, each weather sector -- the public, academic, and private -- seem to be hesitant to enter into collaboration with non-weather sectors.

The public weather sector is afraid of promoting or developing a new weather service for fear of confusing the private-public partnership (see Section 4-2). The private sector also does not seem to invest in new services of ensemble forecasting because the weather information could be regarded as a "public goods."[48] The last hope is the academic sector. Some researchers in meteorology in the US have recently recognized the importance of the actual use and social impact of weather information. For example, the American Meteorological Society held a session discussing weather-related policy issues at its annual meeting every year since 2005 (American Meteorological Society 2007). The National Center for Atmospheric Research (NCAR) implemented a seminar course ("WAS*IS" project) for weather-related researchers and practitioners to acquire a new viewpoint from the socio-economic perspective on weather services (National Center for Atmospheric Research 2007). However, the activities are still in their infancy and are expected to grow as the time goes on. On the contrary, in Japan, such activities do not

[48] See page 64

seem to be appearing. It is the author's hope that researchers in Japan will also try, with users, to explore the potential uses of ensemble forecasting.

The author has often heard from many people that weather sectors have little money for research. In reality, the budget of JMA has remained almost unchanged or only slightly decreased over time, and researchers are concerned about the recent shift of national research funding sources from an equal basis to competitive funds (see Section 4-3). However, outside of the weather society, other funding sources might exist. For example, the Japanese government has special accounts outside of its general budgets. Each account is regulated by law and must be used for a specific purpose. Some of the areas that have special accounts are foreign exchange funds, road improvement, flood control, and development of electric power resources. The size of the accounts related to roads, rivers, and energy are about $ 30, $10, and $20 billion, respectively (JMA's annual budget is about $700 million). It was reported that an electricity-related account had some reserve funds (Misumi 2006). The energy sector needs valuable weather forecasting for effective operation of energy production, as discussed in Section 2; there might be a chance for new business exploration by the weather sectors. Thus, the weather sectors are expected not only to exploit meteorology itself but also to explore areas outside of the meteorological world that might be related to meteorology.

4-8. Toward Effective Implementation of Ensemble Forecasting

This chapter (Chapter 4) analyzed and discussed landscapes related to ensemble forecasting. This landscape includes relationships among stakeholders, such as the public, private and academic institutions, the effects from outside of meteorology such as the governmental policy of government downsizing (e.g. MRI separation from JMA), international projects, and potential collaboration with non-weather sectors. Even though some of the discussion in this chapter focuses not only on ensemble forecasting but on weather services broadly, the discussion has attempted to deal with problems in collaboration and to ask what might be drivers to resolve the problems. Collaboration is an important part of successful weather services as well as successful ensemble forecasting. The current situation in the meteorological society does not seem to favor collaboration for developing ensemble forecasting. However, changes from the policy arena might improve the meteorological society in the near future. One of the most important factors for successful implementation of technology-related policy is the "window" of time (Weigel 2005)[49], and today's policy change might be a good chance for the weather society to promote collaboration both within and outside of the weather world.

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[49] Major factors proposed by Weigel (2005) are "Issue Framing," "Stakeholders," "Technology/Policy Interactions," "Powers & Resources," "Channels," and "Window."

Chapter 5. Conclusion

Ensemble forecasting has been developed to overcome the difficulties in conventional deterministic weather forecasting. However, despite the achievements of ensemble forecasting techniques and efforts to put them into operation, the implementation and utilization of ensemble forecasting seems to be limited in society. The thesis discusses ensemble forecasting from the following viewpoints, a meteorological aspect (Chapter 2), potential use and value (Chapter 3), and policy for effective implementation (Chapter 4), in order to give an overall picture of ensemble forecasting and suggests the direction of measures to increase its utilization.

The combination of the inevitably imperfect "best guess" of the current atmospheric states and the chaotic nature of the atmosphere sometimes induces deviations of the forecasted weather from actual weather. The imperfect description of numerical weather prediction models in the forecasting process is another source of the deviation. The ensemble forecasting techniques have been developed to overcome this difficulty in forecasting. Although theoretical works stemmed from MIT Professor Edward N Lorenz in the 1960's, practical ensemble forecasting has been blooming since computer performance dramatically improved in the 1990's.

Ensemble forecasting provides probabilistic weather forecasting based on multiple weather scenarios. Conventional weather forecasting issues a single scenario, which sometimes fails to catch the actual scenario. Thus, use of ensemble forecasting could be different from that of conventional forecasting. One of the experimental products of ensemble forecasting is a probability map of severe weather outlook. Unlike the single scenario produced by deterministic forecasting, which might overlook low-probability severe weather, this product could help disaster management officers to prepare for the probable hazardous conditions. Another possible use is risk management in business. Among several types of risk management, uses of ensemble forecasting for risk reduction and risk transfer are mainly covered in this thesis. As for risk reduction, this thesis follows the concept of information value and real options, and demonstrates that the cost of frost prevention could be reduced by using ensemble forecasting rather than conventional (deterministic) forecasting; it can be said that ensemble forecasting is more valuable than conventional (deterministic) forecasting. Potential use of ensemble forecasting for an electricity generation sector, especially the wind energy sector, is also discussed in this thesis. Ensemble forecasting is expected to contribute to secure, efficient, and economical operations of electricity generation by providing proper forecasts of wind power generation and electricity demand. Risk transfer, which is executed by financial measures such as insurance and derivatives, could be made more sophisticated through the use of ensemble forecasting. These potential uses of ensemble forecasting imply that the positive effects of ensemble forecasting could exceed the costs of its implementation.

Implementation of ensemble forecasting requires huge costs, so collaboration within weather sectors and with non-weather sectors is a key factor in the effective implementation. Relationships between operational weather forecasting organizations (e.g. National Weather Service and Japan Meteorological Agency), which are responsible for public weather services, and other weather sectors, including private weather companies and academia, are discussed. The public-private relationship seems characterized by dilemmas in both the public and private sectors. As for the public-academic relationship, there are sound collaborations in the U.S. In Japan, the research environment and some policies (e.g. data distribution) may reduce willingness of researchers to study practical weather forecasting.

These current relationships among the three sectors in Japan seem somewhat deterrent to collaboration for the advancement of ensemble forecasting. However, policy change that happened outside of the weather world may change this situation. Following a science and technology policy change (e.g. a shift in funding toward more competitive research), some researchers tried to contribute to the public through better practical weather forecasting. Moreover, a task force under the Japanese Prime Minister is trying to downsize the government decided upon a separation of a research institute of Japan Meteorological Agency (Meteorological Research Institute) from JMA. This decision could affect the current weather world; it might be a good opportunity to revise the current policy. International collaboration is also important in effective development of ensemble forecasting, and in reality, some international projects are in operation. In order to make these projects successful, participants should be aware of increasing transaction costs as more participants will join the projects. Also, project participants have to heed a concern that the project might include an incentive not to contribute to the projects but to just receive fruits from the projects. Moreover, the weather world should pursue collaboration with non-weather sectors. The non-weather sectors are potential users of ensemble forecasting but have not yet realized the potential use and value of ensemble forecasting. If all these collaborations among the sectors work well, then ensemble forecasting can spawn the new generation of weather forecasting.

Finally, there are few researchers studying policy matters in the weather domain in Japan and even in the U.S. The author of this thesis hopes that this study can provide a vantage point on the weather world and help all the weather-related institutions to collaborate with each other and that the collaboration will improve weather services in the near future.

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