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Observing Systems Simulation Experiments:
Their Role in Meteorology

ALAN E. LIPTON

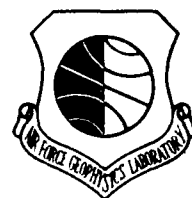
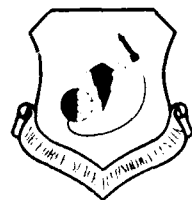


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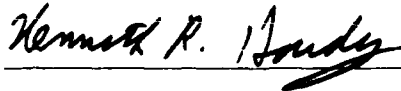
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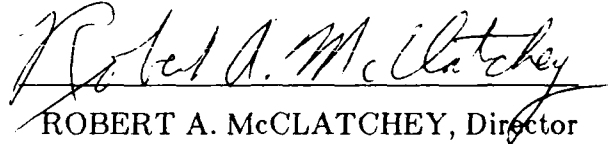
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This report provides an overview of the use of observing systems simulation experiments (OSSEs) in meteorology. We discuss the reasons that OSSEs have been adopted as a research tool and describe the experimental designs that have been employed. The history of OSSE applications is summarized, the apparent limitations of the method are listed, and future prospects of OSSEs are discussed.					
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Preface

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Observing Systems Simulation Experiments: Their Role in Meteorology

1. INTRODUCTION

This report deals with a particular class of simulation experiments — those designed to evaluate the use of data from a given observing system in numerical weather analysis and forecasting. Simulation of data is an attractive option when evaluating a proposed observing system for which no real data are yet available, or when the experiment requires reference to atmospheric observations that can be considered perfect.

It is inherent in atmospheric observing systems that their design involves sacrifice and compromise; we cannot observe the behavior of every molecule. Cost is usually the primary limiting factor. While it may be desirable to have another shipboard radiosonde station or another satellite, budgets require that some other observational element be eliminated to make such additions. Simulation experiments provide an educated basis on which to evaluate the trade-offs.

The planning of the Global Atmospheric Research Program (GARP) provided the initial impetus for use of observing systems simulation experiments (OSSEs). The U.S. Committee for GARP (1969) proposed a national effort in OSSE-based research as an aid in designing a global observing system. Ambitious requirements had been set regarding the accuracy with which the value of each atmospheric parameter

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should be either measured or inferred. Many OSSEs were conducted to help the planners decide on the best strategy to meet those requirements, given the limited resources of the program. Studies evaluated trade-offs between system components, such as polar-orbiting versus geostationary satellites (Jastrow and Halem, 1970) and wind versus temperature observations (Williamson and Kasahara, 1971). Estimates were made of the relationship between the error limits specified by GARP and the range and accuracy of the forecasts that could be derived from GARP-quality data (Jastrow and Halem, 1970). In particular, planners wanted to know the required accuracy, density, and frequency of observations (Kasahara, 1972).

The global observing system was implemented in the First GARP Global Experiment (FGGE). The size and diversity of the FGGE data set was unprecedented and, thus, the use of the data in numerical weather prediction presented new problems. For example, satellite-based sounders were new, and the data they produced had different error characteristics than the familiar radiosonde products. Advances were needed in the technologies of objective analysis and assimilation. Simulations allowed researchers to begin testing methods (for example, synoptic versus four-dimensional assimilation; Jastrow and Halem, 1973) before the FGGE data were available. This type of study has remained relevant into the 1980's as new remote sensing systems have been proposed (for example, Kuo, *et al.*, 1987).

Another FGGE-inspired purpose for OSSEs was to check the consistency of observational system requirements. There was concern that the FGGE requirements for wind data were too lenient relative to the temperature requirements, and that the inconsistency would lead to a misappropriation of resources (Jastrow and Halem, 1970). Anold and Dey (1986) recommended that this kind of consistency check be included in the design of satellite instruments. For example, a satellite instrument designer may have to compromise between ground resolution and noise amplitudes. If the satellite data are to be used in a numerical model, the compromise should be made in light of the model's response to these variables.

2. OSSE DESIGNS

There is considerable variety among the OSSE designs that have been employed, but the basic steps are as follows: First, a "reference atmosphere" is defined by integrating a numerical model, and a history of this atmosphere (its temperatures, winds, etc.) is archived. Second, simulated observations of the reference atmosphere are made by taking history data at selected locations and times and adding "error" perturbations. The observing system characteristics are accounted for in this process.

Third, the observed data are assimilated into another numerical model analysis and (possibly) forecast cycle. Fourth, the results of the second modeling exercise are compared with those of the reference integration. The differences are assumed to be similar to the errors that would occur if the real observing system were used in modeling the real atmosphere.

The components of an OSSE are diagramed in Figure 1, which illustrates both the processes and the products that are involved in an experiment. The "truth" or "nature" model run produces the reference atmospheric data. If a general circulation model (GCM) is used in the experiment, the duration of the run is on the order of several weeks and the initial condition (A, in Figure 1) may be the product of a multi-week spinup from a static, uniform atmosphere. If a forecast model is used, the run duration is on the order of hours or days. The resulting history data perfectly represent one four-dimensional atmospheric state that could occur if the atmosphere were actually governed by the model equations (U.S. Committee for GARP, 1969). Thus, the data are dynamically consistent with each other, and they can be available at whatever spatial and temporal resolution may be needed for simulating observations or verifying forecasts. These requirements could not be met by using analyses of real data to specify the reference atmosphere.

The perturbations to the history data virtually always include a random component, and sometimes they include a systematic component. Random perturbations should account for noise that arises in the collection and processing of data and for errors that result when sub-grid scale weather features make observations unrepresentative of grid-volume averages. Systematic errors may stem from instrument miscalibration or a biased response of the observing system to particular atmospheric conditions. One example is a cool bias in atmospheric temperature data when retrievals from infrared satellite sounders are contaminated by cloud effects. This type of error may be systematic with respect to both horizontal and vertical orientations. Other vertically systematic errors occur when the vertical resolution of a sounding system is deficient and smoothing results.

Objective analysis and initialization are the means by which simulated observations are assimilated into an experimental analysis/forecast cycle. The simulated observations generally are incomplete — not every parameter is specified at every model grid point. Therefore, the simulated assimilation process depends in part on a set of initial data (B, in Figure 1). For realism, condition B should be substantially different from condition A. It might be some arbitrary atmospheric state, or it might be based on data from a source other than the observing system of interest.

In early OSSEs it was customary to use the same numerical model to create the reference atmosphere and to conduct the simulated analysis/forecast cycle. These

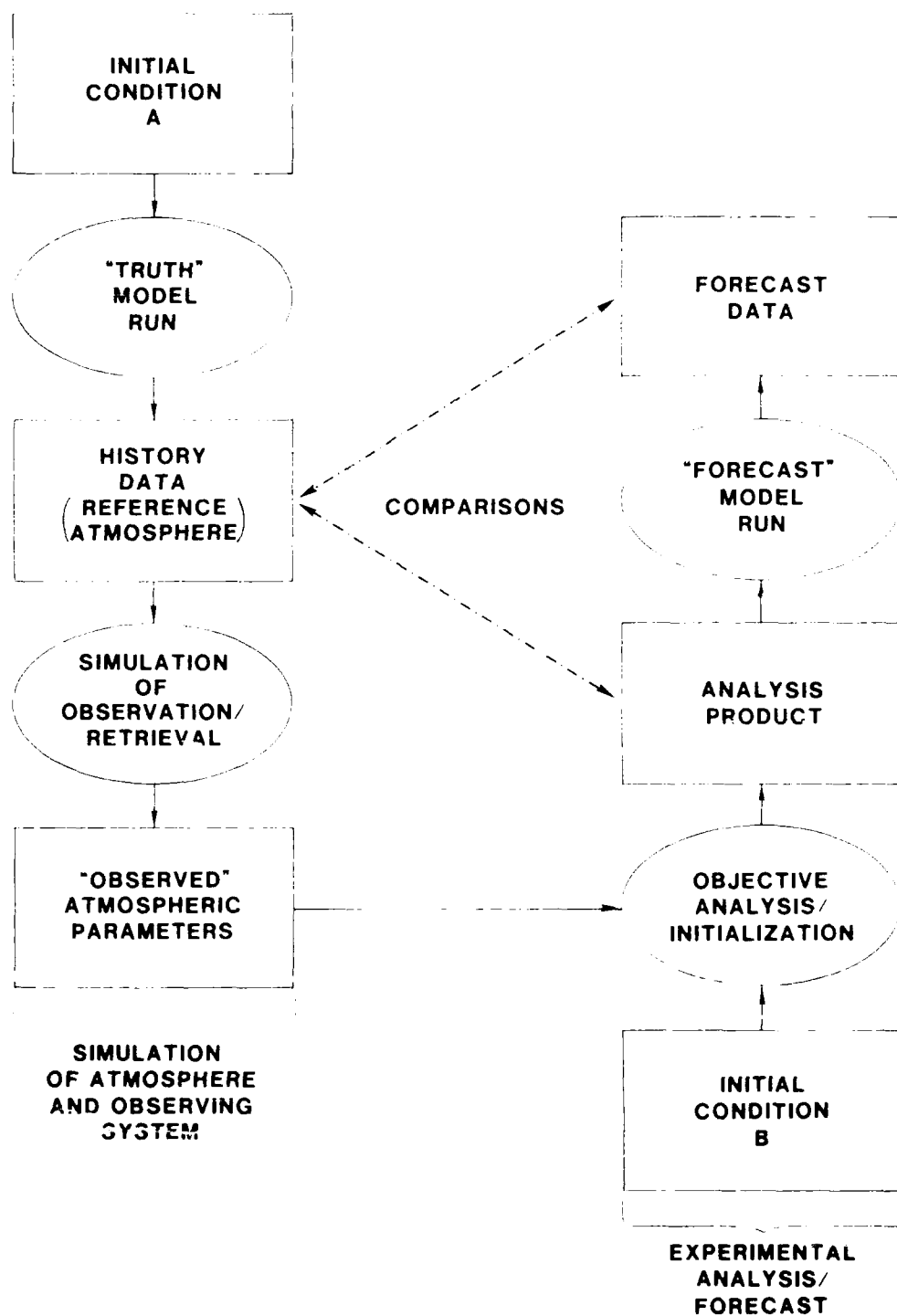


Figure 1 A schematic of an OSSE. Boxes represent data, ovals represent processes, and arrows indicate the flow of information.

became known as "identical-twin" experiments. Williamson and Kasabara (1971) suggested that estimates of analysis/forecast errors would be more realistic if a highly sophisticated model were used to create the reference atmosphere and a simpler one made the analysis/forecast, given that the real atmosphere is more complicated than any numerical model. Modeling errors stem from inaccurate treatment of physical processes and from computational error and thus, they suggested that the forecast model have degraded resolution and physical parameterizations. This is commonly referred to as a "fraternal twin" approach.

Definitions of the term OSSE generally emphasize evaluation of weather forecasts, but many OSSE studies have focused on weather analyses, without making forecasts. The two possible foci are represented by the dashed lines in Figure 1. The distinction is not always clear because OSSE analyses are done on a model grid as the basis for numerical forecasts, and some (four-dimensional) assimilation methods involve model integration. Analysis-oriented experiments are relatively direct, since analysis errors depend only on the data and the assimilation system, which OSSEs are intended to evaluate. Forecasts indicate the ultimate effect of analysis errors, but forecast error statistics also depend on the sophistication of the forecast model relative to the reference atmosphere.

3. APPLICATIONS

Charney, *et al.* (1969) pioneered the use of "induction" experiments in relation to GARP. The object of induction OSSEs is to test the accuracy with which one meteorological variable can be induced in a model by continuously inserting data from "observations" of another variable. In particular, Charney *et al.* explored the possibility of using a long time sequence of satellite-derived temperature soundings to induce winds, making wind observations unnecessary. A GCM was used in an identical-twin design. Their simulated observations consisted of atmospheric temperature data covering a 60-day history of the reference atmosphere. The data were used in four-dimensional assimilation experiments, with data insertion intervals ranging from 1 to 24 hours. In these experiments the wind "errors" were large initially, but their average values decreased asymptotically over the 60-day period in response to the repeated correction of the mass field. An insertion interval of 12 hours produced the smallest asymptotic wind error.

This work was extended by several studies. Jastrow and Halem (1970) considered the effects of varying coverage of satellite data. Their simulated data corresponded to realistic satellite orbits and scan patterns. A pair of polar orbiters could provide

sufficient data for wind induction, but geostationary data alone were insufficient. A combination of the two was better than either alone. Williamson and Kasahara (1971) investigated the converse process of inducing temperatures by insertion of wind data. They experimented with varying insertion frequencies and related the asymptotic error levels to noise magnitudes in the observations. Error levels were found to be a function of latitude, implying that observation strategies should not be the same all around the globe. Kasahara and Williamson (1972) attempted to determine what minimum combination of observations would satisfy GARP requirements everywhere and found that the preferred strategy was to observe winds in the tropics and temperatures in higher latitudes.

A distinction of Kasahara and Williamson's (1972) work was that they considered the effects of systematic observation errors, finding them to be more detrimental than purely random errors with the same root-mean-square value. However, the error distribution they used (global, symmetric about the poles) was not realistic for satellite-based soundings.

Jastrow and Halem (1970) applied their OSSE results to the question of internal consistency of GARP data requirements. They observed that, if the GARP requirement for temperature data were met, winds could be induced from temperatures with an accuracy exceeding the GARP wind data requirements. This conclusion was reinforced by Williamson and Kasahara's (1971) study.

All of the early GARP-related OSSEs were identical-twin experiments. Results of later studies suggested that the early results had been interpreted too liberally. Williamson (1973) performed fraternal-twin experiments in which the resolution of the GCM that created the reference atmosphere was finer than the one used for induction. Asymptotic error values for induced winds and temperatures were much larger with this approach than with identical-twin experiments. Results also depended on the particular model used in the study. Jastrow and Halem (1973) showed that contradictory results of three independent OSSEs appeared to stem from differences in model resolution. Comparisons such as these were helpful in designing later OSSEs and in interpreting their results.

In the 1980's OSSEs have dealt with a variety of topics. There has been considerable interest in a proposed satellite-based lidar for wind measurement around the globe, which might be expected to greatly enhance prediction skill in regions with few rawinsondes. Dlouhy and Halem (1984) helped to relate possible limitations in lidar data coverage to the usefulness of the data in numerical forecasting.

OSSEs have been used to study existing observing systems as well as proposed ones. Daley and Meyer (1986) developed an OSSE procedure to estimate the error in our current global analyses as a function of height and latitude. By relying on a

simulation approach they had perfect reference data against which to compare analysis results. They listed three alternative experimental methods, all using real data, that could have been used for their study. However, they concluded that the OSSE method was preferable because the assumptions and inferences on which the alternatives depended were less reliable than those involved in an OSSE.

The applications mentioned above were all global-scale studies, and most of them employed GCMs. In recent years there has been heightened interest in mesoscale observing systems, and several mesoscale OSSEs have been done. These have generally been identical-twin experiments with a model that has a regional domain. The objective of Kuo and Anthes' (1984) study was similar to that of Daley and Meyer (1986) in that they evaluated an observing system that had already been implemented. In particular, they investigated the accuracy with which heat and moisture budgets could be computed from AVE-SESAME data. They estimated the magnitudes of errors from specific sources and drew inferences regarding the design of future special-purpose observing systems.

Kuo, *et al.* (1985) evaluated the accuracy of trajectory models used in studying pollutant dispersion. Their results indicated that "the current synoptic network and observational frequency over North America are inadequate for accurate computation of long-range transport of episodic events". They concluded that it would be more cost effective to increase the observational frequency than to enhance the spatial resolution of the existing network. Analysis methods were evaluated to determine the effect of using optional simplifying assumptions.

Mesoscale OSSEs have included induction experiments. Kuo and Anthes (1985) were looking toward a proposed network of ground-based remote wind profilers when they tested a method for inferring the mesoscale temperature distribution from nearly-continuous wind observations. Possible network configurations were evaluated, and options were tested regarding the combination of profiler data with other types of data (Kuo, *et al.*, 1987). The latter study concluded that both wind and temperature information are needed to produce good forecasts at the mesoscale.

An OSSE provided the first testing ground for the Gal-Chen, *et al.* (1986) assimilation method for mesoscale satellite-based sounding data. They found that forecasts could benefit from increasing the frequency of geostationary sounding observations such that data would be taken hourly. They also assessed the importance of gaps that arise in retrievals from infrared sounder data when clouds are present.

Oceanographers have used OSSEs with approaches similar to those of mesoscale meteorologists. A group of researchers from the Naval Ocean Research and Development Activity (NORDA) studied the potential use of a satellite-based sea-

surface altimeter in a series of OSSEs with a numerical model covering the Gulf of Mexico (Hurlburt, 1986; Thompson, 1986; Kindle, 1986). The focus issues in their work were: 1) inference of subsurface information from surface data, 2) spatial and temporal sampling requirements, 3) the feasibility of synoptic data assimilation, and 4) evaluation of the impacts of uncertainty in the data. Both identical- and fraternal-twin experiments were used.

4. LIMITATIONS

OSSEs are inherently complicated. There are several major steps in the process and each involves assumptions and uncertainties. Kasahara (1972) pointed out that this makes OSSE results difficult to interpret. For example, the peculiarities of an analysis system may either enhance or detract from the apparent value of an observing system as applied to modeling. This type of problem also occurs (but to a lesser degree) in experiments that use real data instead of simulated data (Tractor, *et al.*, 1981; Atlas, *et al.*, 1982).

Several limitations of OSSE studies are related to the dependence of the results on the particular numerical model employed. At the extreme, OSSE results can be valid only if the model is sufficiently similar to the atmosphere that it can simulate the meteorological phenomena of interest. For example, tropical observing systems cannot be evaluated with a GCM that lacks the forcing mechanisms for tropical convection (Jastrow and Halem, 1970).

Given an adequate model, the limits on interpretation of results depend heavily on how the model is used in the OSSE. Identical-twin experiments are particularly limited. Part of their problem is the compatibility issue addressed by Morel, *et al.* (1971). Data simulated from a numerical model run are highly consistent with the slow normal modes of that model. If the same model is used for an analysis/forecast, the data should be very readily assimilated. If, on the other hand, the data come from a system (for example, the real atmosphere) with different normal modes, the data might be poorly assimilated. Beneficial effects of the data depend on thorough assimilation. Thus, identical-twin results may depend on an unrealistically good *a priori* fit between the data and the model dynamics.

A second limitation of identical-twin experiments is that they cannot give reliable estimates of real-world forecast errors. Analysis errors depend on many factors, including the quality of the observing system, but the growth of those errors during an identical-twin forecast run depends only on the predictability of the model

atmosphere (Williamson, 1973). By predictability, we mean the tendency for two nearly-identical initial states of a model to yield very different forecasts after a long integration. In reality the forecast error grows due to model imperfections as well as predictability limits.

Fraternal-twin experiments can account to some degree for the imperfections of forecast models relative to the real atmosphere. However, even this experimental design has limitations since the atmosphere is more different from a model than any two models are from each other. Forecast errors are likely to be underestimated since there is much in common among the ways models parameterize the physics of the atmosphere (Jastrow and Halem, 1973).

To evaluate an observing system by simulation, the error characteristics of the observational data must be accurately represented. Unrealistic methods have been used in most OSSEs to introduce error to observations of the reference atmosphere. The conventional approach is to add random and/or systematic errors to the reference data according to the expected behavior of the observing instrument. This works poorly when the observations are from remote sensors. In satellite-based temperature soundings, for example, the vertical and horizontal structure of errors in retrieved temperatures depends on many meteorological factors and on the retrieval algorithm. For remote sensors it is more realistic to go through the intermediate steps of simulating the observed data (for example, radiances) from the history of the reference atmosphere and then retrieving the meteorological data (for example, temperatures). Atlas, *et al.* (1984) described in detail how this can be done. This method also has limitations, however, because radiance simulation requires detailed information about cloudiness — more detailed than forecast models can provide directly. Inferences and assumptions are needed.

The several steps in conducting an OSSE require a large amount of computer time, even for relatively simple experimental designs. Therefore, researchers typically rely on a single analysis/forecast for each treatment in their experiments. This approach yields less reliable results than repeated analysis/forecasts with different meteorological conditions (Arnold and Dey, 1986), which allows for computing ensemble statistics. This issue may be particularly important for mesoscale OSSEs because a relatively narrow range of meteorological conditions can occur within the time and space limits of a single mesoscale analysis/forecast.

5. PROSPECTS

Despite the limitations of OSSEs, they are a useful means to evaluate current and proposed observing systems and analysis methods. In many instances there is no better alternative. One issue to be considered, however, is the cost of OSSEs in terms of human and computer time. If the purpose is to determine whether to install a proposed observing system, and an OSSE would cost more than the system, then it would be best to skip the OSSE and go ahead with installation (Arnold and Dey, 1986).

When an OSSE is worth the cost, researchers must design the experiments carefully and exercise great restraint in interpreting their results. The OSSE's design must be logically related to its purpose and objectives, and all these aspects of the experiments are constrained by the limitations inherent to OSSEs. For example, if a satellite-based wind-sensing lidar is being planned, one conceivable purpose for an OSSE is to learn the accuracy of forecasts that would result from using the lidar data in a state-of-the-art forecast model. This purpose is unrealistic given the limitations of OSSEs discussed earlier. Furthermore, the fraternal-twin approach is not an available design option for evaluating state-of-the-art models. A more realistic purpose would be to determine whether it is likely that lidar data would have a significant beneficial effect on forecasts. In addition, OSSEs can be very useful for intercomparing forecasts made with varying amounts and qualities of lidar data.

It is possible to draw valid conclusions about an observing system only if the observed data are realistically simulated. For remote sensors it will generally be necessary to make retrieval of meteorological parameter values a part of the OSSE procedure. Once meteorological data are simulated at the observation sites, a realistic method must be used to interpolate the data to the model grid.

The horizontal and vertical resolutions of the model must be compatible with the observing system being evaluated. If the resolvable scales of the model are broader than those of the observing system, then some information may be wasted and the OSSE will not be a fair test of the system's value. The resolution must also be sufficient to simulate the relevant meteorological phenomena.

Experimental designs generally should be fraternal-twin rather than identical-twin, so that the results can be interpreted most broadly. The relative simplicity of identical-twin experiments make them preferable in some situations, such as initial testing of an analysis technique (for example, Gal-Chen, *et al.*, 1986). When the analysis/forecast model can be considered perfect the OSSE results are relatively easy to interpret; there are fewer possible sources for any errors in the analysis. If a method shows promise in an identical-twin experiment, then fraternal-twin and/or real-data experiments should be employed to further evaluate the method.

Most OSSE designs have relied on simple, objective measures, such as root-mean-square errors, for evaluation of analysis/forecast results. This is understandable given the large quantities of data involved. Interpretations of statistics such as these should include tests of significance (Arnold and Dey, 1986). Whenever possible, it is advantageous to make subjective evaluations also, which may bring to light meteorologically significant features of the results that could be hidden in simple statistics. It is also helpful at times to stratify the results (by latitude, for example) to highlight the effect of the observing system on a particular region or under a limited set of meteorological conditions.

There is reason to believe that future meteorological research will include many OSSEs. There has recently been strong interest in using new, remotely-sensed data in numerical models, and in combining datasets from different sources within the context of a model grid. Certainly modeling applications will be a major consideration for future observing systems. In this regard, one major limitation of OSSEs, model dependence, is becoming less acute. The models available to researchers are growing in number, sophistication, and variety, and the growth of computer power makes it possible to increase the realism of many parts of the OSSE process.

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