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The Tracking and Analysis Framework (TAF): A Tool for the Integrated Assessment of Acid Deposition

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Abstract

A major challenge that has faced policy makers concerned with acid deposition is obtaining an integrated view of the underlying science related to acid deposition. In response to this challenge, the U.S. Department of Energy is sponsoring the development of an integrated Tracking and Analysis Framework (TAF) which links together the key acid deposition components of emissions, air transport, atmospheric deposition, and aquatic effects in a single modeling structure. The goal of TAF is to integrate credible models of the scientific and technical issues into an assessment framework that can directly address key policy issues, and in doing so act as a bridge between science and policy. Key objectives of TAF are to support coordination and communication among scientific researchers; to support communications with policy makers, and to provide rapid response for analyzing newly emerging policy issues; and to provide guidance for prioritizing research programs. This paper briefly describes how TAF was formulated to meet those objectives and the underlying principals which form the basis for its development.

Introduction

With the passage of the 1990 Clean Air Act Amendments, the United States embarked on an acid deposition control policy that has been estimated to cost at least $2 billion. As part of the Act, the National Acid Precipitation Assessment Program (NAPAP) was asked to evaluate the status of implementation, the effectiveness, and the costs and benefits of the acid deposition control program created by Title IV of this Act and to determine if additional reductions in deposition are necessary to prevent adverse ecological effects. In support of this mandate, the Tracking and Analysis Framework (TAF) is being developed for NAPAP as an integrated assessment tool which has as its goal the integration of credible models of the scientific and technical issues into an assessment framework that can directly address key policy issues.

TAF should be viewed as not just a model, but rather as a flexible framework for modeling and integrated assessment. Effective integrated assessment requires iterative refinement, adaptation and restructuring of technical models for purposes of policy evaluation. No single model will be adequate for all purposes. As science progresses, new understanding will justify revised or new models. It is therefore desirable to compare the implications of several different model formulations, based on different scientific views. As new policy questions emerge, information needs will evolve. New and urgent questions may require simple models that can be created, adapted, and executed rapidly. Longer-term questions may allow for the development of more elaborate models that take longer to create and analyze. The goal for TAF is to develop a framework that will allow a variety of models to be developed, and to coexist in a flexible, yet coordinated, manner.

Integrated assessment is a complicated activity requiring the participation of many different people and organizations with a multitude of different perspectives and interests. With this in mind, a team has been brought together composed of researchers from the DOE national laboratories, universities, private companies, and non-profit research institutes. In order to develop a credible analysis tool in a relatively short period of time, TAF is being based upon the Acid Deposition Assessment Model (ADAM) developed by a team of researchers (many of whom are involved in the current TAF effort) at Carnegie Mellon University during the mid 1980s[1,2]. Both ADAM and TAF are implemented in the DEMOS modeling software, which explicitly includes uncertainty, and lets reviewers easily access and review all models, variable, equations, assumptions[3] with a variety of model exploration and "what if?" capabilities.

Objectives of TAF

A major challenge in performing a comprehensive assessment is to bridge the gap between science and policy. Since 1980, over $1 billion has been spent on technical and scientific research to understand the effects of air pollution in general, and of acid deposition in particular. From this context, TAF should be viewed as a framework for creating a functional linkage of technical models and information that can be used to bridge the gap between science and policy. The bridge needs to facilitate travel in both directions: Policy should be informed by the best available science; and scientific research should be focused on which issues are relevant to answering the policy questions of most concern or interest. This framework has three primary objectives:

1) *To support coordination among scientific researchers, including NAPAP Working Groups*: Given the vast range of scientific issues and disciplines involved, research efforts can easily become fragmented and incompatible. The framework for integrated assessment should help to define interfaces between research groups, specifying issues of interest and coordinating the levels of geographic or temporal aggregation specified in the research or the type of detail being sought.

2) *To support communication with policy makers:* The framework should integrate and summarize the existing scientific knowledge into forms that directly address the policy issues of current concern.

3) *To provide guidance for prioritizing research needs:* The framework can help to identify which gaps and uncertainties in the existing science are most critical to the key policy questions, and hence can guide scientific research to focus on those areas where a better understanding will be of the most immediate value to decision making.

Effective integrated assessment requires iterative refinement, adaptation and restructuring of models. No single model will be adequate for all purposes. As science progresses, new understanding will justify revised or new modules. Policy makers and scientists will want to compare the implications of several different versions for selected modules, based on different scientific views. As new policy questions emerge, the relative importance of various portions or features of the models will evolve. New and urgent questions may require simple models that highlight the details of one aspect of the issue but which can be executed rapidly. Longer-term questions may allow for the development of more elaborate and detailed models that take longer to create and analyze. The aim for TAF is to develop a framework that will allow a variety of models to be developed, and to coexist in a flexible, yet coordinated, manner. The author's goal here is to present a prototype for such a framework. This goal should not be obscured by details of the current implementations or "versions" of individual modules that have been linked for this illustration.

The key requirements for a framework for integrated assessment are to:

- to provide comprehensive linkage of the key scientific/technical components
- to be technically credible
- to contain data to track compliance with Title IV of the 1990 CAAA
- to support cost-benefit-effectiveness analysis
- to represent and analyze uncertainty
- to identify sensitive indicators and to detect trends
- to be transparent and traceable

We will now briefly discuss the manner in which TAF addresses each of the above issues.

Providing Comprehensive Linkage of Components

A comprehensive assessment of the costs, benefits, and effectiveness of the CAAA Title IV requires consideration of many issues. Figure 1 shows the top level of the current TAF, with its graphical network of linked and interrelated issues. This figure shows the model as an influence diagram. This influence diagram is intended to represent the situation from the perspective of U.S. public policy (as opposed, say, to the perspective of an electric utility manager, or of an individual consumer).

The rectangular box labeled *Emissions -control policies* represents a decision strategy (or "policy variable"). It is identified as a decision because it is directly controlled by U.S. government policy, initially by the CAAA 1990, and subject to extension or modification by potential future legislation or executive direction. Evaluating decision strategies, including past legislation and proposed new policies, is one of the goals of the assessment.

The rounded boxes represent "chance variables" — that is, quantities that are uncertain, and are not directly controllable. The uncertainty arises from limitations in our scientific understanding and our ability to predict. In Figure 1 boxes with a thick outline represent components of the linked framework that contain detailed models in the current TAF. Boxes with the thin outline in Figure 1 represent components that do not now contain a completed linked model. Eventually, all boxes in this diagram needed to address the key policy questions would contain more detailed models. In some cases, several alternative modules might be constructed for a single box to reflect alternative scientific viewpoints and models.

Some issues are relatively well understood, such as the costs of installing and operating new emissions-control technologies — although even these costs can be subject to significant uncertainty. Others — such as the effects of atmospheric pollutants on human health and on global climate — remain subjects of major controversy. A comprehensive assessment should include all effects that have been identified as credible possibilities by reputable scientists. It must be recognized, nevertheless, that some of these topics may not currently be appropriate candidates for full quantitative modeling, due to the lack of understanding or to controversy over the appropriate structure and mechanism.

Technically credibility and reduced form modeling

Previous attempts to develop integrated assessment models have at times been criticized as lacking sound scientific foundations due to the degree of simplification[4,5]. The challenge is to reconcile the need for models to be based on the best available scientific data and models, yet to be small, agile, flexible, and comprehensible. With TAF, this challenge is met by having each module be a "reduced-form" model based directly on the best available detailed scientific model and data.

Reduced-form models (RFMs) are simplified models, intended to approximate the behavior of larger, more complicated models or data sets. They are simplified in containing fewer variables, less mechanistic detail, or higher levels of aggregation. However, their performance is calibrated against or fitted to the performance of the detailed "parent" models. Hence, the quality of the approximation can be measured, and the uncertainty from the approximation can be quantified and compared with the uncertainty introduced by other model components or the natural variability involved in some environmental features.

In integrated assessment, it is generally necessary to link several models together — the outputs of one are matched to the inputs of the next. Typically, problems arise because the detailed models are at different levels of aggregation. For example, emission projections may be by season for each power plant; but, the atmospheric transport model may need emissions on a daily basis aggregated by 20 kilometer grid-square. It also often happens that the file formats and platforms for the technical models developed by dispersed research teams are incompatible. Moreover, the models may be so large that it is too expensive and time-consuming to run them for many different scenarios, especially to handle uncertainty using Monte Carlo or other commonly used techniques. It is often impractical to reconfigure and rerun such state-of-the-art models every time a new policy problem arises.

The use of reduced-form models lets one avoid these problems, provided the reduced-form models are designed explicitly to use compatible levels of aggregation and file formats. As with any model, selecting the appropriate levels of aggregation or problem "dimension" is critical in designing reduced-form models. Key issues include:

- *Temporal resolution*: For daily, monthly, seasonal, annual, or multiyear periods.
- *Spatial resolution:* By point source or receptor, by 20 kilometer grid square, by state, or by region.
- *Treatment of uncertainty:* Sample size for Monte Carlo, or the set of discrete scenarios.
- *The number and type of other aggregation dimensions*: ,Such as chemical species, receptor types, and emissions trajectories.

It is not essential that successive revisions or refinements of the RFMs for a given scientific issue or component use identical resolution and aggregation. For example, in the earlier TAF prototype, projected utility plant SO_2 emissions are aggregated by state for the RFM that predicts control costs. The effects RFMs use a variety of receptor sites. The key is that the outputs of each module can be easily aggregated or disaggregated, without undue loss of precision, to meet the needs for the inputs of the next module. TAF contains some general aggregation functions to facilitate these conversions.

RFMs may be developed or formulated in a wide variety of ways. Four different ways which have been utilized in the development of previous TAF modules are: regression curve-fitting to the results of a detailed model, developing normalized input-output matrices obtained from full form (detailed) models, utilizing curve fitting to a collection of observed data values, and model restructuring at a higher level of aggregation.

It is important to remember that the design of each RFM requires consideration of the existing detailed models and databases, and the requirements of the other modules with which the RFM must be interfaced. Selection of the appropriate aggregation levels often requires negotiation among the designers of the related modules. Typically, judgments about what levels of detail are necessary are made by scientists and modelers, based on hunch. Since RFMs can include quantitative measures of the uncertainty introduced by the approximation, it is possible to compare the uncertainty due to approximation to uncertainty from other sources. The goal should be to design each component RFM to be as simple as possible, so long as the uncertainty approximation is not out-of-proportion to the uncertainty contributions from other sources. This balance can and should be investigated empirically. Preliminary experience[6] suggests that in the parameter uncertainties are often so large, that quite simple RFMs may suffice. If so, the dilemma between desired scientific precision and small, flexible models may be easy to resolve.

Containing data to track compliance with Title IV

To reliably track compliance, monitor effects, and predict future effects, it is essential that TAF have the most accurate and up-to-date data available. Two kinds of databases will be required:

- *Unit Compliance Database (UCD)*: A collection of unit-specific data and information focused on the quantity of pollutant emissions generated by each affected emitter, and the resulting cost of Title IV compliance
- *Receptor Characteristics Database (RCD)*: A collection of receptor-specific data characterizing the baseline conditions and the nature and level of existing or projected environmental impact attributable to the emission of acid precursor species

Figure 2 shows the relationships of these two databases to the reduced form models. The UCD, through the specification of emission-reduction scenarios and emissions trajectories over time, will be the driver of TAF. These scenarios could represent "what if?" policy options or the past observed emissions. Reduced-form models (such as for atmospheric transport and deposition, aquatic resource acidification, or visibility impairment) project the environmental effects of these emission trajectories. These projected effects are stored in the RCD, for comparison with actual observations of environmental indicators. This use of TAF (from left-to-right in Figure 2) corresponds to predictive applications, an example of which would be the prior assessment of the change in deposition patterns associated with a proposed emissions trade.

Alternatively, TAF can be applied in support of monitoring activities. This application is represented by right-to-left movement in Figure 2. Monitoring data on the changing condition of human or environmental receptors can become the inputs to the reduced-form models. The reduced-form models may then be used to develop the most cost-effective detection programs, for example, or to evaluate the relative effectiveness of actual emission reductions. In order for NAPAP to meet its Congressional mandates, TAF will need to be used to support both predictive and monitoring analyses.

Supporting cost-benefit-effectiveness analysis

As was mentioned in the introduction, NAPAP is mandated by Congress to assess the costs, benefits, and effectiveness of the provisions of the CAAA Title IV. TAF's use in tracking and forecasting changes in emissions, costs, and environmental effects will provide direct analytical support for this mandate. It will be useful to perform such cost-benefit-effectiveness analysis at national and regional levels, as well as examining specific decisions and actions by emission sources and regulatory agencies.

A major innovation of CAAA 1990 was the introduction of trading in emissions allowances. Monitoring this trading and its effects will be an important part of NAPAP's activities. Using TAF, the net benefits and environmental effects of a single trade can be illustrated. For illustration, the first such trade announced will be examined. In this trade, Wisconsin Power and Light (WI) sold emissions allowances to Duquesne Light (PA) and the Tennessee Valley Authority (TN). Figure 3 compares the marginal cost of emissions reductions in dollars per ton of SO_2 with the announced prices of the emissions allowance for each of the three states involved. The costs estimates presented in Figure 3 are generated by TAF's statewide control cost model, and are only illustrative. Nevertheless, they are consistent with the trade, suggesting that the high marginal control costs in Pennsylvania and Tennessee would make the allowances very attractive to Duquesne Light and TVA; the low control cost in Wisconsin make selling the allowances attractive to Wisconsin Power and Light. The difference between the control cost and the sale price of allowances is an indicator of the net value to each utility, a net value that may translate into increased profit for the utility or decreased electricity rates for its customers.

Because this trade will reduce emissions in Wisconsin, and increase emissions in Tennessee and Western Pennsylvania in a relative sense, environmental effects in the Northeastern U.S. may be increased relative to the no-trade scenario. Figure 4 predicts the resulting change in wet deposition in two sensitive receptor sites, the Adirondack mountains and Western Pennsylvania. Again, it should be noted that are numbers shown in the figures are from preliminary models contained in TAF and are presented to illustrate the analysis capability being built into TAF.

Representing and analyzing uncertainty

Uncertainties are represented in TAF by probability distributions. Methods to express and propagate uncertainties are discussed below. Because uncertainties are represented characterized and explicitly included, it is possible to represent and examine issues that are poorly understood. Where a quantity is uncertain or controversial, it is possible to express the range of values by a probability distribution and the assessment can proceed accordingly. This approach substantially expands the set of issues for which quantitative models can be an appropriate tool relative to approaches that are limited to deterministic representations. Almost every aspect of acid precipitation and the effects of CAAA 1990 is subject to uncertainty. Uncertainties arise from a wide variety of sources, including these:

- *Organizational behavior* — e.g., How will emission sources respond to the changes in technology, markets, and regulation?
- *Technology* — e.g., How well will new control technologies perform? How much will they cost?
- *Variability* — e.g., How will wind and rainfall patterns vary over time?
- *Scientific quantities* — e.g., What are atmospheric oxidation rates of SO_2 to sulfates, or the sensitivity of fish to the acidity of their environment?
- *Scientific models* — e.g., What are the differences between Eulerian models of atmospheric transport and simpler diffusion models? How should we choose among them?
- *Model approximation* — Practical computational models use finite temporal and spatial resolutions, e.g. by year and by 20km grid square. What errors might these approximations produce?
- *Valuation* — e.g., What is the value of improved visibility or reduced breathing difficulties? How can we establish monetary equivalents for such values?

Morgan and Henrion[7] contains a taxonomy of types of uncertainty and detailed discussion of approaches to handle them. Uncertain results may be displayed in TAF in several forms. Figure 5 illustrates how probably bands, including interquartile and 90% credible intervals are applied to an initial visibility model.

The value of representing uncertainty

The majority of current models, both scientific and policy-oriented, provide no explicit representation of uncertainty. This omission often substantially reduces the value of models, particularly when the uncertainties are so large. Uncertainties are expressed in TAF, wherever possible, in the form of probability distributions. Explicit representation of uncertainty in the form of probability distributions provides a variety of benefits[7], of which the most important for TAF, are:

- *Qualifying data and model results:* Explicit uncertainty provides a clear quantitative indication of the precision and reliability of the inputs and outputs of each module, and of the model as a whole.

- *Identifying key uncertainties*: Explicit uncertainty allows direct comparison of different sources of uncertainty, to identify their relative contributions to the uncertainty in the results.
- *Guiding research priorities:* Comparison of the contributions of different uncertainties can be used to guide future allocation of resources towards those areas of science where further research is likely to be most valuable in reducing the uncertainty in the results.

Methods for propagating uncertainty

There are two main approaches to propagating probability distributions through models to estimate the probability distributions induced on the outputs of interest:

Type 1: *Probability trees, decision trees, and discrete-valued influence diagrams.* These methods require all continuous quantities to be approximated by discrete quantities. Their computational complexity (time to calculate) increases exponentially with the number of uncertain quantities.

Type 2: *Monte Carlo and related random sampling methods.* These methods can handle continuous or discrete quantities. Their computational complexity is linear in the number of uncertain quantities for predictive reasoning for any given precision in the output distribution. For Monte Carlo methods, the precision in the estimate of the output distributions is a function only of the sample size, and not of the number of uncertain inputs.

TAF and similar models for integrated assessment contain both continuous and discrete variables, are primarily or exclusively predictive (not diagnostic), and may contain thousands of uncertain variables. For these reasons — especially the last — such models should use Type 2 (Monte Carlo/random sampling) methods for propagating uncertainty.

Analyzing uncertainty to identify key sources

A key reason to represent uncertainty is to be able to compare the various sources of uncertainty to discover which really matter — that is, which contribute significantly to the uncertainty in the results — and which do not. Standard methods of sensitivity analysis examine how small changes in each input affect the output, but ignore the wide variation in amounts of uncertainty. *Uncertainty analysis* is a form of sensitivity analysis that considers both sensitivity and uncertainty. One valuable approach to uncertainty analysis that works well in models using Monte Carlo and other sampling approaches is sometimes called *importance* analysis. The importance of inputs is measured and compared by the rank-order correlation of the random sample of values for each input with the corresponding sample of output values. When the inputs are correlated, partial correlations should be used.

Figure 6 shows the results of a example importance analysis for the key uncertain parameters in TAF's lake-acidification component. The first parameter, *Average rain acidity (pH)*, is the input to this module from the preceding module that predicts precipitation acidity. The remaining eight variables are parameters of the reduced-form model for regional lake acidification. Uncertainty about each parameter was characterized by a subjective probability distribution. Figure 6 charts the rank-order correlation of each of these parameters with a key output of this module, *the fraction of regional lakes with pH<5.5.*

It is clear that variable 7, the mean weathering factor, contributes a great deal of uncertainty. Variables 3, 4, and 5 are also important. Variable 1 ranks 5th — which is interesting, since the uncertainty in variable 1, the rain acidity, embodies and represents the entire uncertainty from all earlier parts of the linked framework model, including emissions, atmospheric transport, and atmospheric chemistry. Again, it must be noted that the specific numbers are only illustrative. This example is intended to demonstrate the types of insight that may be obtained from such uncertainty analyses.

Identifying sensitive indicators and detecting trends

Some effects of atmospheric pollution and acid deposition are much easier to detect than others. For example, the acidity of mountain lakes in the Adirondacks was one of the first indicators to be noticed, because an effect on a sensitive receptor will be larger and easier to measure. On the other hand, measuring the effect of air quality on tree survival is much more difficult, for a variety of reasons. There are many factors affecting the health of trees, (including drought, insect pests, and climate), and it is very hard statistically to separate out and attribute causality to air pollutants. Stressors may also combine in non-linear ways to affect tree health. Effects may be mediated through complex soil chemistry and tree biochemical processes with lag times of many years. Key issues in determining the sensitivity of an indicator include:

- *Ease of and precision of measurement*
- *Sensitivity:* The magnitude of the change in the indicator for a unit change in emissions
- *Variability:* The natural variability in the indicator, considering the background noise, in which the change must be detected
- *Time lag:* The time between the change in emissions and the effect on the indicator

It is desirable to detect changes in environmental effects due to reductions in emissions as early as possible. Ultimately, TAF should help identify which indicators are likely to show the effects the soonest, so that monitoring efforts can be focused on those. Since detecting changes requires extracting a signal from an uncertain and noisy background, explicit representation of the underlying variability is critical to identifying early indicators.

Developing transparent and traceable models

A common complaint about computer models — be they scientific or policy models — is that they are too complicated and too poorly documented to be understood, verified, or trusted. Typically, model documentation is created and updated separately from the computer model, with the result that it becomes inconsistent with the model it is supposed to document. Since a major objective of TAF is to support communication and coordination among scientists and policy analysts, an essential requirement for TAF is that the models be documented clearly and consistently.

In TAF, the diagrams showing the model structure and text explaining what variables and equations represent, and documenting the sources of assumptions, are all integral with the computer representation of the model. In this way, the team that builds and refines a model can most easily write and update the documentation simultaneously. This approach minimizes the chance of inconsistency and incompleteness in documentation. It also means that a reviewer can inspect the model code and its explanation together, all in the same environment.

TAF, the choice of demos for implementation has made this requirement easy to meet. The model is created and accessed as a hierarchy of influence diagrams. The influence diagrams directly show the key variables and modules and their dependencies, expressed by the influence arrows. Each component model appears as a single box per node in its parent diagram. A double-click on the node will open up the diagram for the submodel, as in Figure 7. In this way, the hierarchical modular structure is depicted by the hierarchy of diagrams. Each variable is documented by a "card" (Object window), containing a set of attributes describing the variable. One such card is illustrated in Figure 8.

Conclusions

This paper has outlined a strategy for NAPAP to develop the capability to meet its Congressional mandates. A framework being developed for integrated assessment has been described that is soundly based on the best available scientific models and empirical data, yet small enough for comprehensive uncertainty analysis, and flexible enough to be rapidly reconfigured to address new policy issues. The key to reconciling these apparently conflicting requirements is the development of reduced-form models for each key component.

In the implementation of TAF, it has been demonstrated that it is possible to meet these requirements in a practical software system. It should be noted that several of the modules now in TAF have not yet been fully implemented. The concentration of the current research effort is on developing an initial framework which links emissions, transport, deposition, aquatic and visibility effects, and control costs. There is a considerable amount of work remaining to be done to develop a comprehensive version of TAF that has usable numbers and models for all components.

The TAF structure and fundamental capabilities also could serve as the pattern for an integrated assessment tool for addressing the policy issues associated with other environmental problems, such as global change, which involve complex, linked environmental interactions subject to rapidly evolving scientific understanding.

In a further effort to share TAF-related research, information on the TAF project, including draft models and the DEMOS modeling software, is being made available over the World Wide Web via internet (http://www.lumina.com/taflist/taf.html).

Acknowledgements

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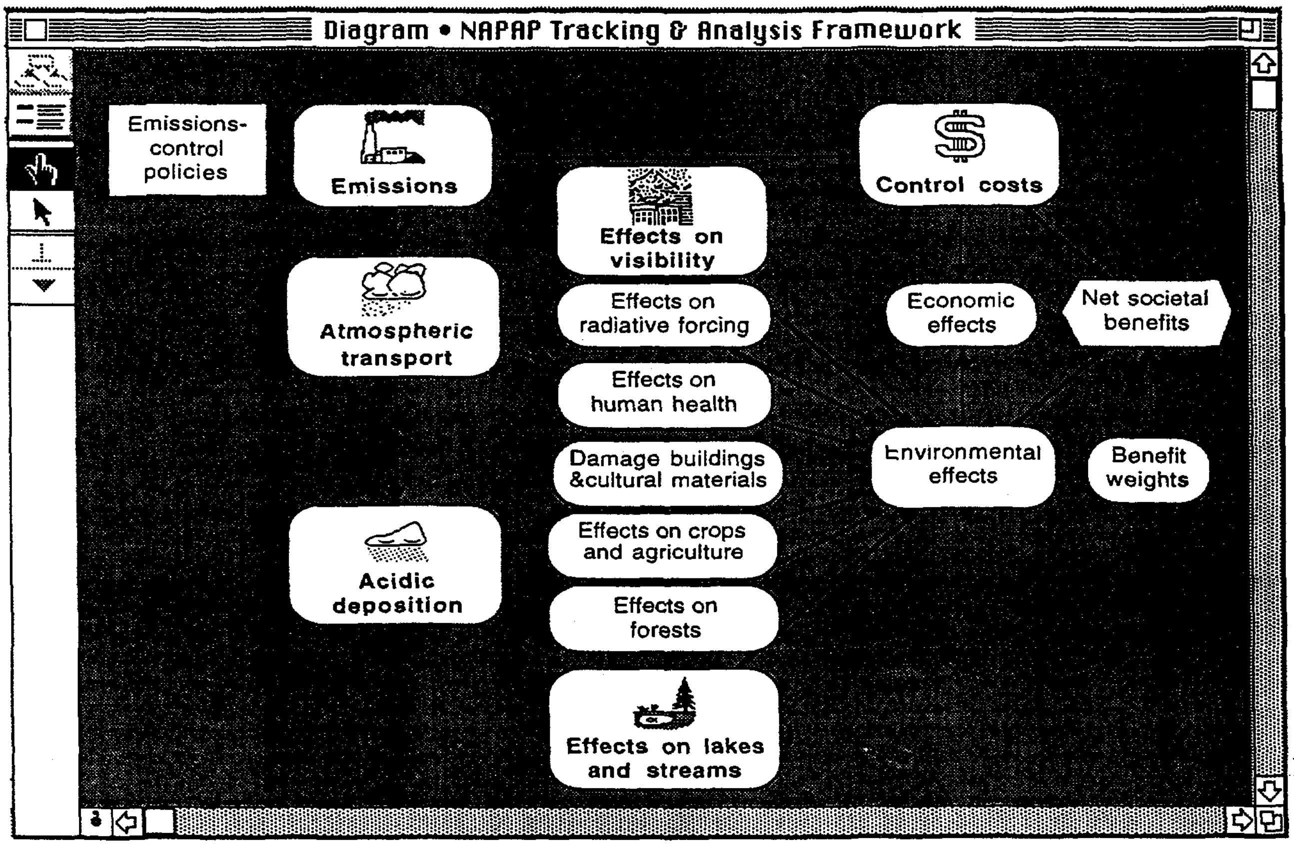

Figure 1: Top-level organization of TAF in the form of an influence diagram

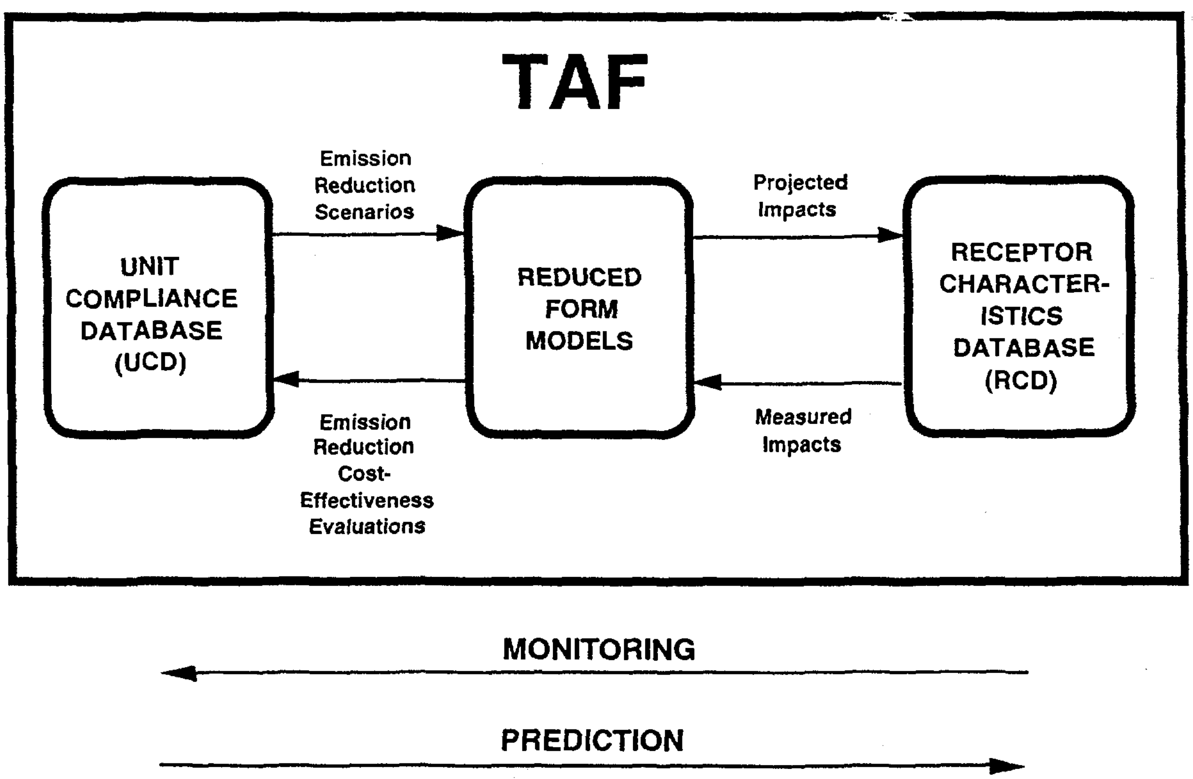

Figure 2: These three main components of TAF relate to one another in two different modes of operation.

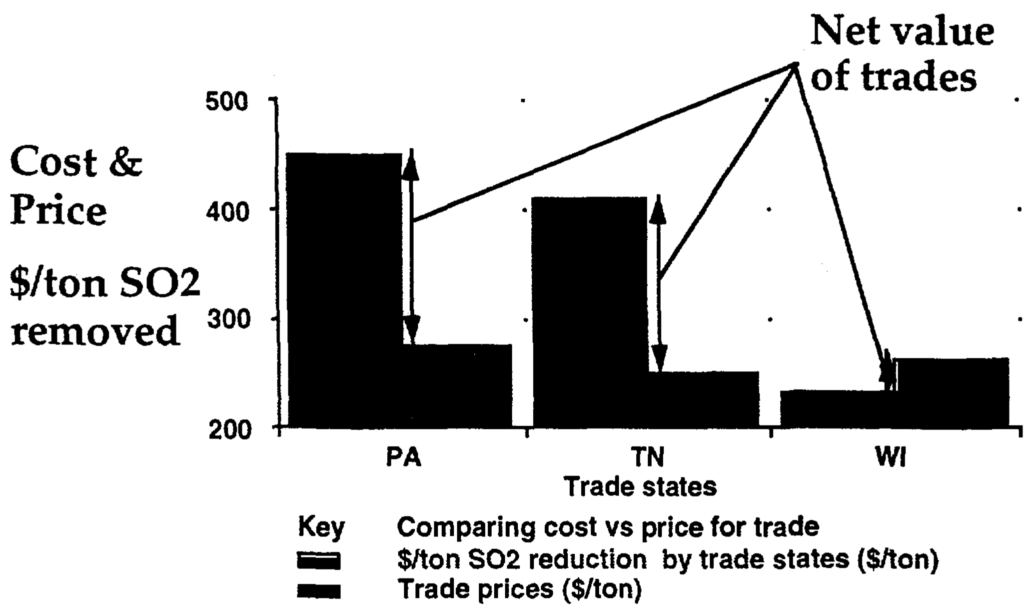

Figure 3: In the first emissions allowance trade, Wisconsin Power and Light (WI) sold emissions allowances to Duquesne Light (PA) and Tennessee Valley Authority (TN). This chart compares the statewide marginal cost of reducing emissions in dollars per ton of SO_2 (estimated by TAF) with the trade prices in dollars per ton. It suggests that the transaction had positive value for all three companies — Control costs were much more than the allowance price in PA and TN, but were less in WI. Note the numbers presented are purely illustrative.

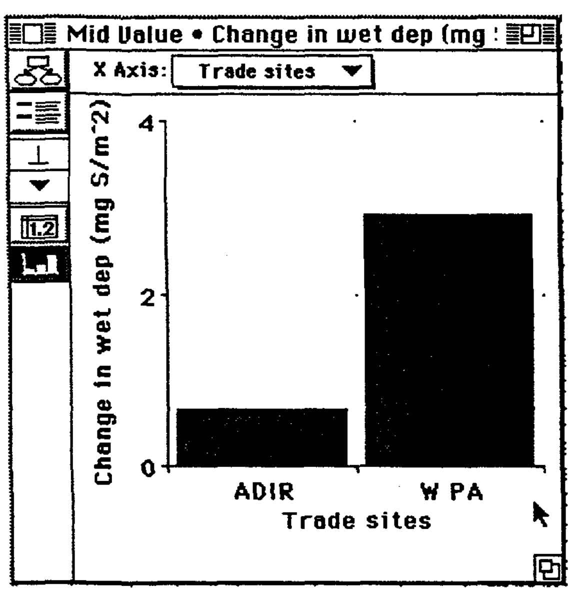

Figure 4: The emissions trade in Figure 3 will increase emissions in Tennessee and Western Pennsylvania relative to a no-trade alternative. This chart (produced by TAF) forecasts the resulting increment in wet deposition of sulfur (in micrograms per square meter per year) in the Adirondacks (ADIR) and Western Pennsylvania (W PA) due to the trade.

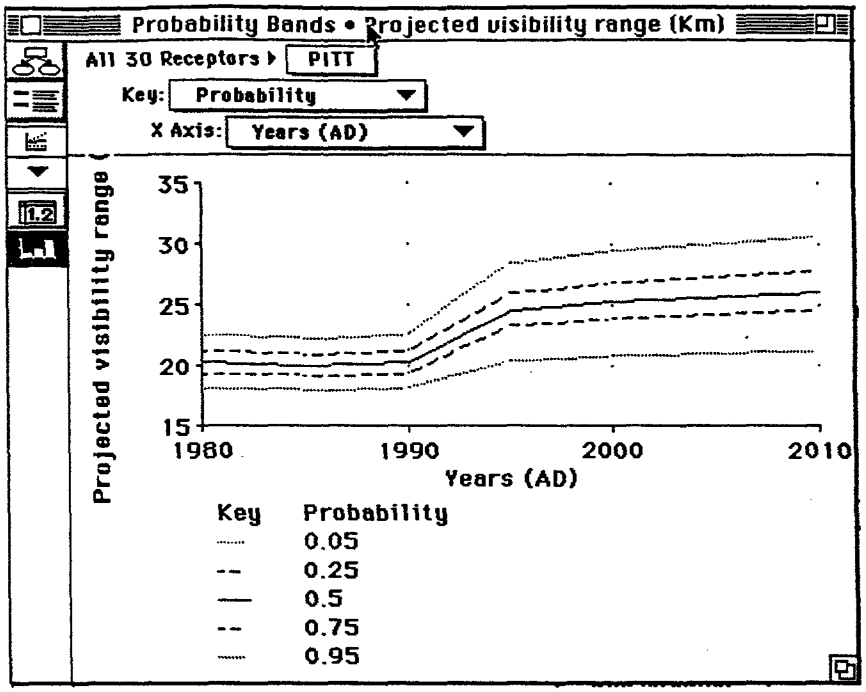

Figure 5: Probability distributions on projected range of visibility over time are displayed as probability bands, with 90% credible interval (outside lines), and 50% or interquartile interval (dashed lines, around the median (central line).

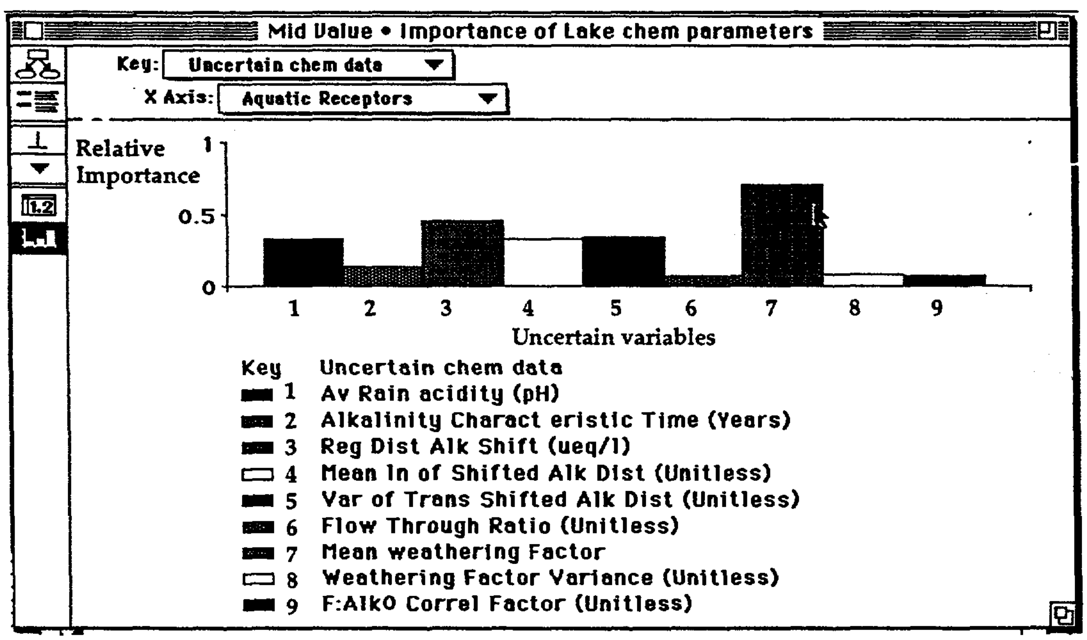

Figure 6: Analysis of the relative importance of the uncertainty in each of the input parameters of the lake chemistry model to the uncertainty in the fraction of lakes with pH<5.5. The bars show the rank-order correlation of each uncertain input with the output.

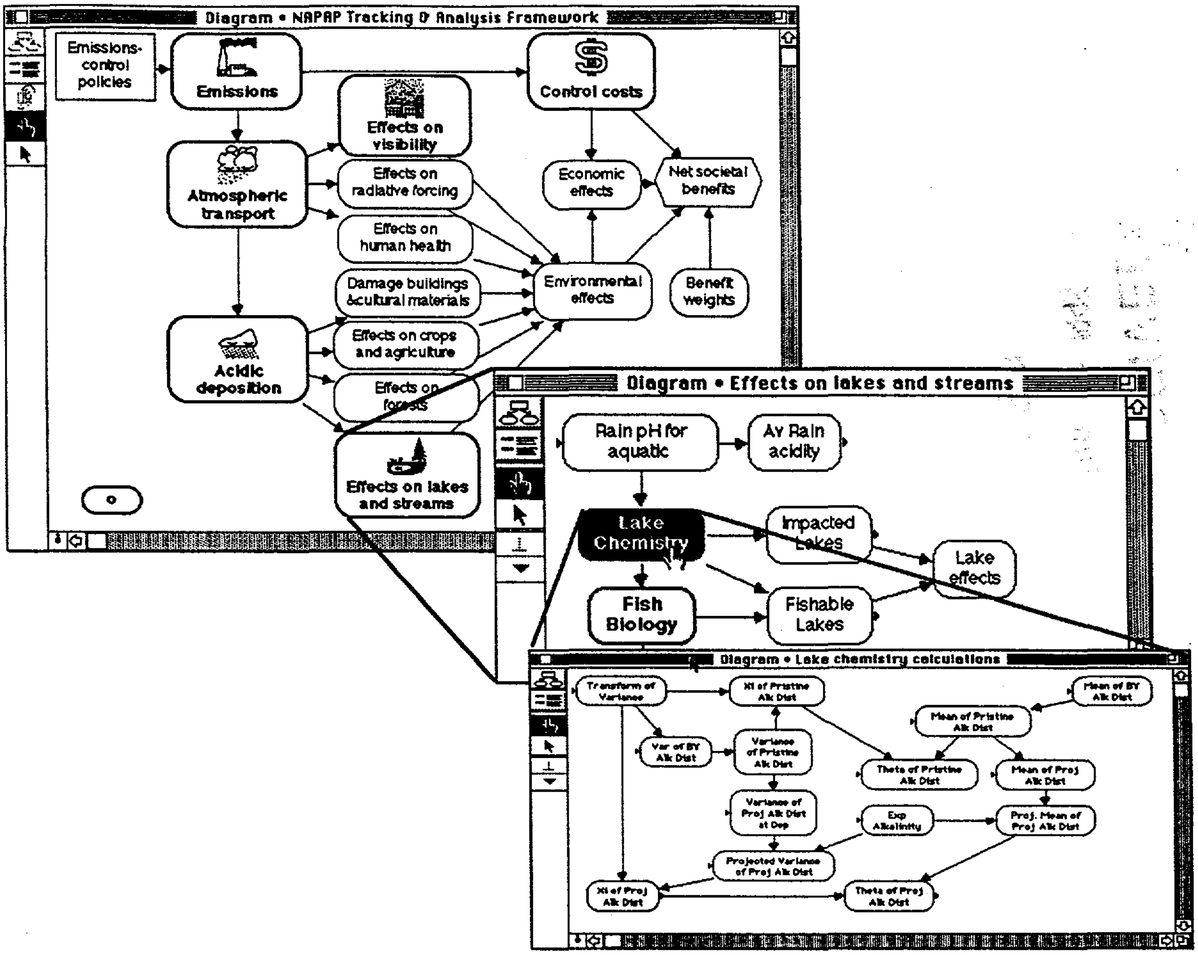

Figure 7: The model hierarchy in TAF. Double clicking the mouse on a model node opens up the diagram for that model.

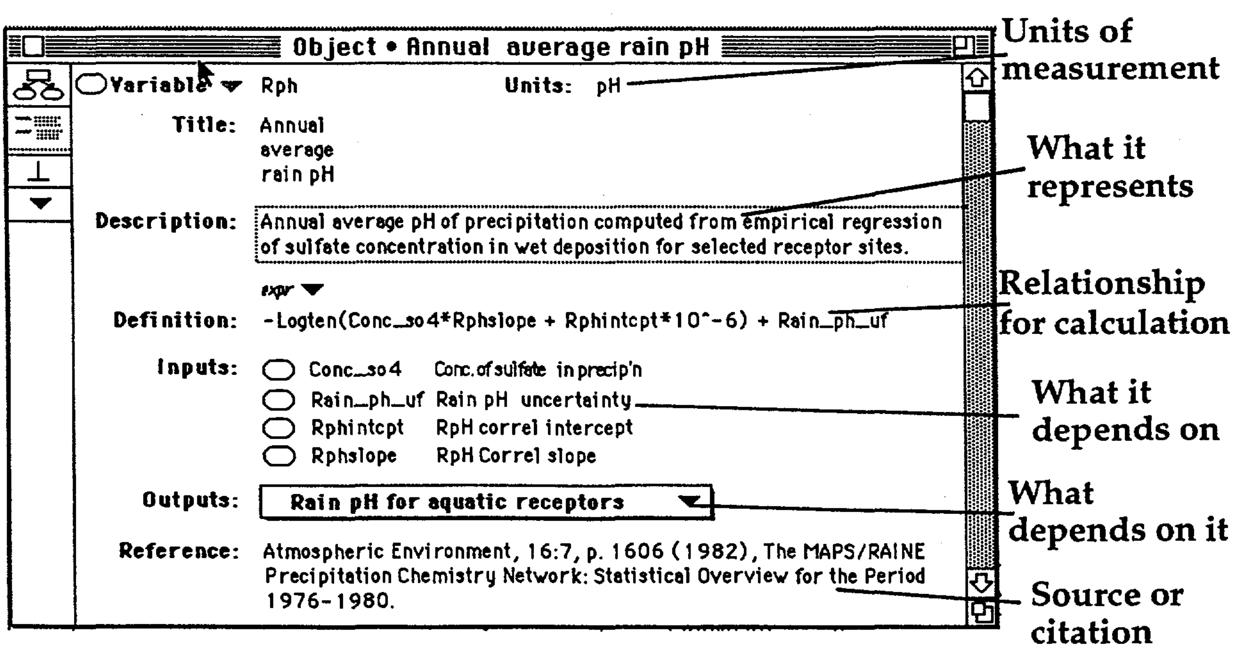

Figure 8: Each TAF variable is documented internally with a card like this which shows the key information about the variable.