Using Architecture Modeling to Assess the Societal Benefits of the Global Earth Observation System-of-Systems

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Abstract—An enterprise architecture for the Earth Science activities of the National Aeronautics and Space Administration (NASA) was developed to assist in assessing the capacity of scientific instruments in meeting the needs of society. It can also help them develop the right investment strategies and help scientists and engineers in their planning for system development, especially for complex space-based environmental sensors. This architecture model can be easily extended to the Global Earth Observation System-of-Systems (GEOSS). In fact, it was constructed with GEOSS in mind to ensure that NASA's observation systems can be readily mapped into the GEOSS structure. The architecture contains about 3000 elements that are involved in earth science research: observation sources, sensors, environmental parameters, data products, mission products, observations, science models, predictions, and decision-support tools. The science models use observations from the space-based instruments to generate predictions about various aspects of the environment. These predictions are used by decision-makers around the world to help minimize property damage and loss of human life due to adverse conditions such as severe weather storms. The architecture is developed using both traditional and nontraditional systems engineering (SE) tools and techniques. This paper will describe additional methods needed for the SE toolbox.

Index Terms—Architecture, Earth observation, Global Earth Observation System-of-Systems (GEOSS), system-of-systems (SoS).

I. Introduction

THE GLOBAL Earth Observation System of Systems (GEOSS) qualifies on all seven attributes for a system-of-systems (SoS):

1) operational independence of the component systems;
2) managerial independence of the component systems;
3) geographical distribution;
4) emergent behavior;
5) evolutionary development;
6) self-organization;
7) adaptation.

These attributes were synthesized by Sage and Biemer [1] from other research and studies [2]–[12]. Most SoS that have been described in the literature have four or five of these attributes. Therefore, it is worthwhile to study those SoS instances

that have all the attributes present. Modeling of SoS has been addressed by some [12], [13]. Metamodeling of SoS has been addressed rarely [13], [20]. Recently, there has been a growing interest in SoS concepts and strategies. However, it still remains a difficult venture for most. To address this weakness in the systems community some have proposed the formation of an international consortium on SoS engineering [14]. This paper describes the efforts at NASA to architecturally model and characterize their systems of systems with the intent to expand this model to incorporate the multi-national portfolio of Earth observation systems.

II. Earth Science and Observation

NASA's Applied Sciences Program has the primary goal of enhancing its partners' decision-support capabilities by enabling expanded use of Earth science results, information, and technology. NASA's partners have a mission to serve their management and policy responsibilities to society. For example, the National Weather Service has a responsibility for providing up-to-date, accurate weather forecasts throughout the United States. NASA performs much of the basic research that allows the National Weather Service to achieve their mission. (See http://science.hq.nasa.gov/missions/earth-sun.html.)

From our vantage point above the Earth, we can view the Sun and Earth as a whole system, observe the results of complex interactions, and begin to understand how our planet and star are changing. Working with its domestic and international partners, NASA provides accurate, objective scientific data and analysis to advance our understanding of Earth–Sun system processes.

Learning more about these processes will enable improved prediction capability for climate, weather, and natural hazards. By *studying the Sun and Earth as a system* and employing an *end-to-end strategy* to assure that all the information, understanding, and capabilities derived from its research are fully realized, NASA is striving to develop a scientific understanding of the Earth–Sun System and its response to natural or human-induced changes.

Earth system science has six main areas of focus as illustrated in Fig. 1 [17]. Each focus area competes for a limited amount of funding for science projects. It is not always easy to determine the best investment strategy that will guide proper research activities and have the maximum benefit for society. We are developing an enterprise architecture as the means to establish the right investment strategies and to help scientists and engineers

Fig. 1. Earth system science.

Fig. 2. Application of national priority.

Benefit Areas Related To Earth Observations

TABLE KEY

H = High level of importance to benefit area
M = Medium level of importance to benefit area
L = Low level of importance to benefit area

Earth Observations
Note: This list of observations is not meant to be comprehensive

Societal Benefit Areas								
Weather	Disasters	Oceans	Climate	Agriculture	Human Health	Ecology	Water	Energy
M	H	H	M	H	M	H	H	L
M	M	L	M	H	H	H	M	M
L	L	H	H	H	H	H	M	L
L	H	L	M	H	H	H	M	L
M	M	L	H	H	H	M	H	L
M	M	M	H	M	M	M	H	M
H	H	H	H	H	H	H	M	H
L	H	H	H	H	H	H	H	H
L	H	H	M	H	H	H	H	L

Row labels (left column):
Land Elevation/Topography; Land Use/Land Cover (Crops, Forests, Urban, etc.); Ecosystem Parameters (Health, Diversity, etc.); Fire (Detection, Extent, Severity); Soil Moisture; Ice and Snow (Cover and Volume); Land and Sea Surface Temperature; River Runoff (Volume, Sediment, etc.); Water Quality (Contamination, Spills, etc.)

Fig. 3. Benefit areas related to earth observations.

6) understand the effect of environmental factors on human health and well-being;
7) develop the capacity to make ecological forecasts;
8) protect and monitor water resources;
9) monitor and manage energy resources.

A. Mapping of Earth Observations to Benefits

As you can see in Fig. 3, the mapping between societal benefit areas and types of earth observations is relatively complex [19]. The purpose of the enterprise architecture is to capture the details of these relationships in such a way as to facilitate analysis and assessment.

B. Integrated System Solutions Architecture

The basic elements of the Applied Sciences Program are connected in the manner shown in the Integrated System Solutions Architecture illustrated in Fig. 4. The decision-support tools are operated by NASA's partners to make policy decisions and management decisions.

For example, the Federal Emergency Management Agency must decide how to prepare for and mitigate the impacts of natural disasters such as hurricanes. The National Weather Service must decide when to issue a hurricane warning and local governments must decide when to issue evacuation orders.

All of these decisions can have societal benefits in terms of millions of dollars of property loss averted and in thousands of human lives saved. These decision-support tools depend on having timely access to the right data about the environment.

IV. ENTERPRISE ARCHITECTURE DEVELOPMENT

We are using the same six-step process shown in Fig. 5 that was used in development of the Enterprise Architecture for the National Oceanic and Atmospheric Administration (NOAA) [20], [21].

in planning for system development, especially for complex, space-based environmental sensors.

To assist in this analysis 12 application areas of "national priority" have been identified as illustrated in Fig. 2. Each of these application areas has a suite of decision-support tools for use by decision-makers [18].

These decision-support tools are provided with environmental predictions from models of the land, ocean, ice, and atmosphere. The earth science models receive raw and processed data from many sensors around the world—satellite, suborbital, and in situ ground-based platforms.

III. SOCIETAL BENEFITS

The Interagency Working Group on Earth Observations has identified the following nine major areas of societal benefit:
1) improve weather forecasting;
2) reduce loss of life and property from disasters;
3) protect and monitor our ocean resources;
4) understand, assess, predict, mitigate, and adapt to climate variability and change;
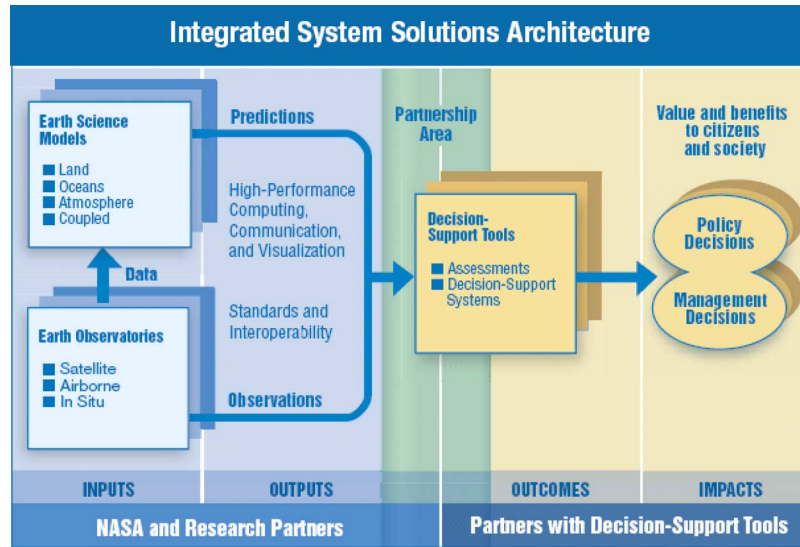5) support sustainable agriculture and combat land degradation;

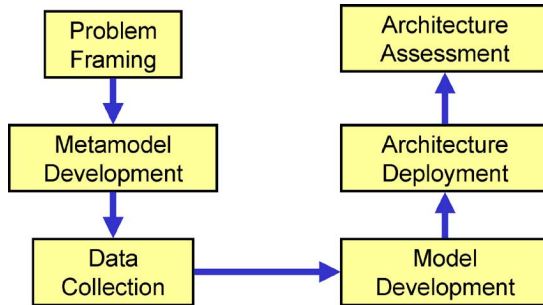Fig. 4. Integrated system solutions architecture.

Fig. 5. Six-step process for architecture development.

The first step of problem framing is the most important step since it sets the stages for all subsequent efforts. Starting with the wrong problem definition is often the cause of inadequate results when the "solution" is implemented. Problem framing techniques have been found to be quite beneficial in avoiding rework and getting more useful results.

Problem framing starts with a business analysis task that involves the following activities:
1) identify purpose of the architecture;
2) identify the "business questions" to be addressed by the architecture;
3) establish business priorities.

It is important to establish the business priorities since there is rarely enough time to address all the business questions in the time allotted. After you have the business questions identified, you must then develop the conceptual definition of the problem, usually in the form of a conceptual information model.

It typically takes about 20% of the total architecture project effort to do the problem framing step. Then it will take a few weeks to develop the metamodel. Metamodel development is usually necessary since it is not common to find an existing metamodel that fits the architectural situation.

The metamodel will be custom tailored to fit the specific business questions identified during problem framing. Sometimes it is possible to find a metamodel template that is close to what you need and then you merely need to modify the template. But often it is easier to start from scratch than to modify an existing template.

A. Earth Science Problem Definition

Some of the relevant business questions identified during the problem framing activity for the Earth–Sun System Architecture Tool are listed as follows.
1) How does NASA Earth–Sun Science Research contribute to meeting the operational needs of NASA's partner agencies?
2) How are the replacement of aging systems or the establishment of new sensors prioritized?
3) How does each Integrated System Solution contribute value to Society? What are the potential outcomes?
4) How can NASA's research assets contribute to meeting the needs of the GEOSS?

B. Conceptual Schema

Business questions identified during the Problem Framing step lead to the conceptual schema illustrated in Fig. 6. The blocks in this diagram represent entities inside the model while the lines represent relationships between the entities.

C. Metamodel

The results of conceptual analysis described previously were then converted into a formal metamodel in the Metis architecture modeling tool (see http://troux.com/products/) as illustrated in Fig. 7. The steps in creating the conceptual schema and the metamodel are further described in [13].

V. ENTERPRISE ARCHITECTURE MODEL

Data was collected by NASA on the 3000 architectural elements and the Metis tool was populated as shown in Fig. 8. The model includes 60 current and future spacecraft and 35 other airborne and ground-based observatories. These observatories contain 438 instruments that produce 471 data products which, in turn, feed into 241 Earth science models. The model outputs provide data for 28 decision-support tools.
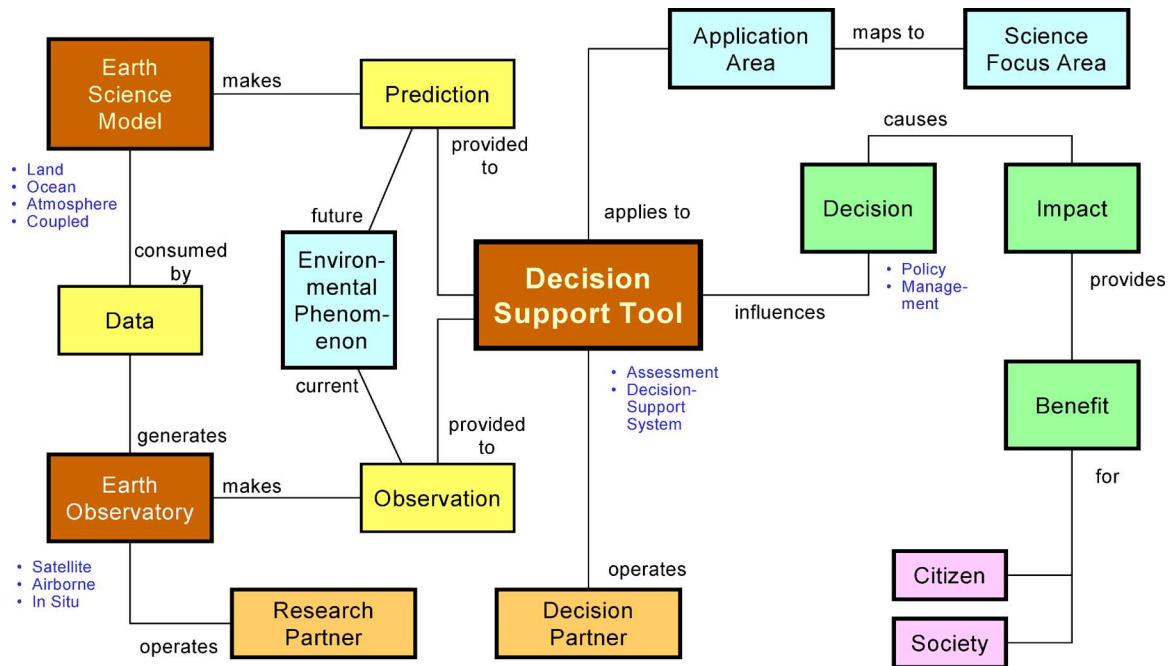
Fig. 6. Conceptual schema for the Earth–Sun system architecture.

Observatory > Instrument > Product > Model > Tool > Outcome > Benefit Areas
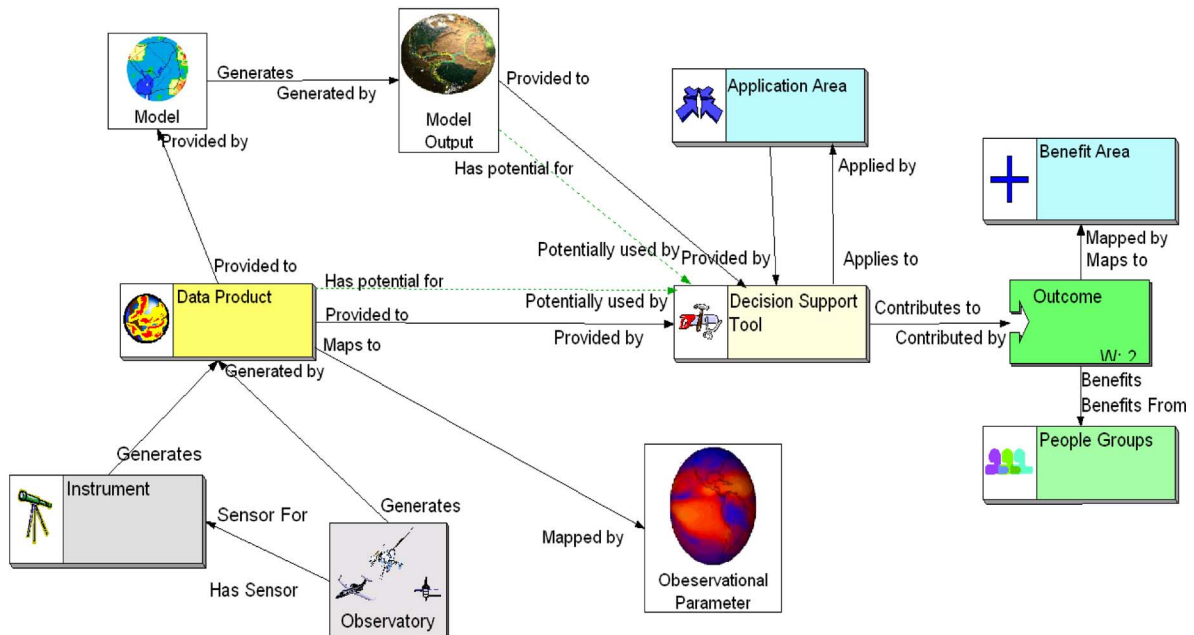

Fig. 7. Metamodel entities and relationships for the Earth–Sun system architecture.

VI. HURRICANE PREDICTION EXAMPLE

To illustrate how the model works, we will show an example of the enterprise elements involved in a hurricane prediction scenario. An overview of this example is shown in Fig. 9.

A. Earth Observation Satellites

There are two Earth-observing satellites that look at different factors of tropical cyclones (i.e., hurricanes) to help generate better forecasts. The observations and predictions derived from these two satellites are shown below. Tropical Rainfall Measuring Mission (TRMM) focuses on the intensity of tropical rainfall, which is indicative of whether a cyclone is weakening or strengthening. It also is valuable in improving hurricane track forecasting through the integration of its rainfall measurements into hurricane forecast computer models.

QuikSCAT contains a scatterometer that measures both the speed and direction of winds near the ocean surface. It is being
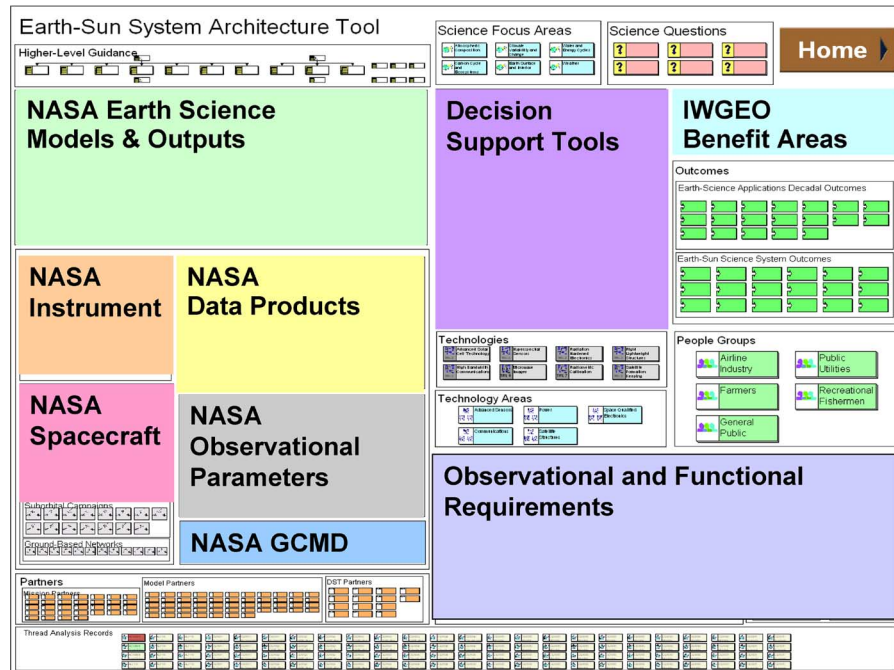
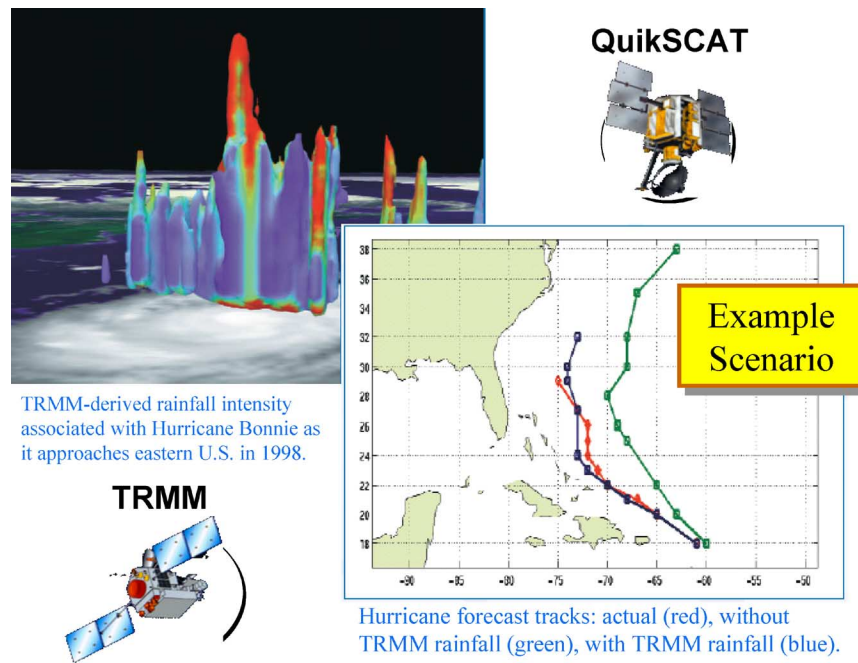Fig. 8.   Architecture model for the Earth–Sun system architecture tool.

Fig. 9.   Hurricane prediction example.

used by NOAA's Ocean and Tropical Prediction Centers to improve the monitoring and forecasting of hurricanes. QuikSCAT observations have been incorporated into operational global weather analysis and forecast systems.

B. Decision-Support Solutions

NASA, NOAA, and the Department of Defense work together in the Joint Center for Satellite Data Assimilation to provide the best hurricane development and landfall track information possible for decision-support purposes. The Tropical Prediction Center (a division of NOAA's National Center for Environ-

mental Prediction) uses output from several computer models to help forecast and track the path and intensity of tropical cyclones. The assimilation of Earth observing satellite measurements, along with other model enhancements undertaken by NOAA, have led to a vast improvement of model precision in recent years.

C. Mission Thread

Fig. 10 shows how the elements of this hurricane prediction "mission thread" interact to provide value and benefit to society. Notice there are many other observatories, models, and
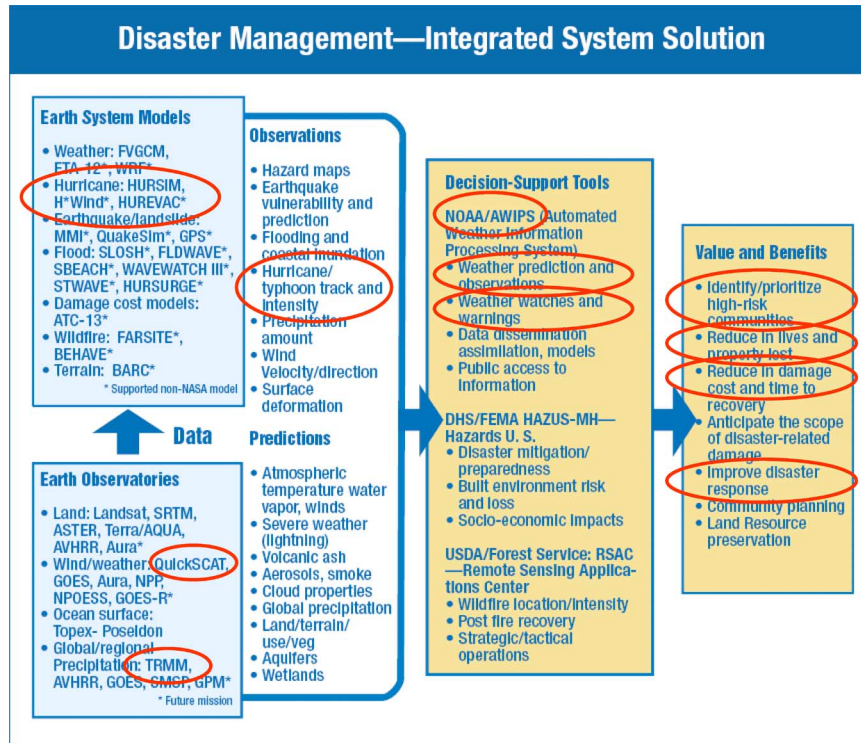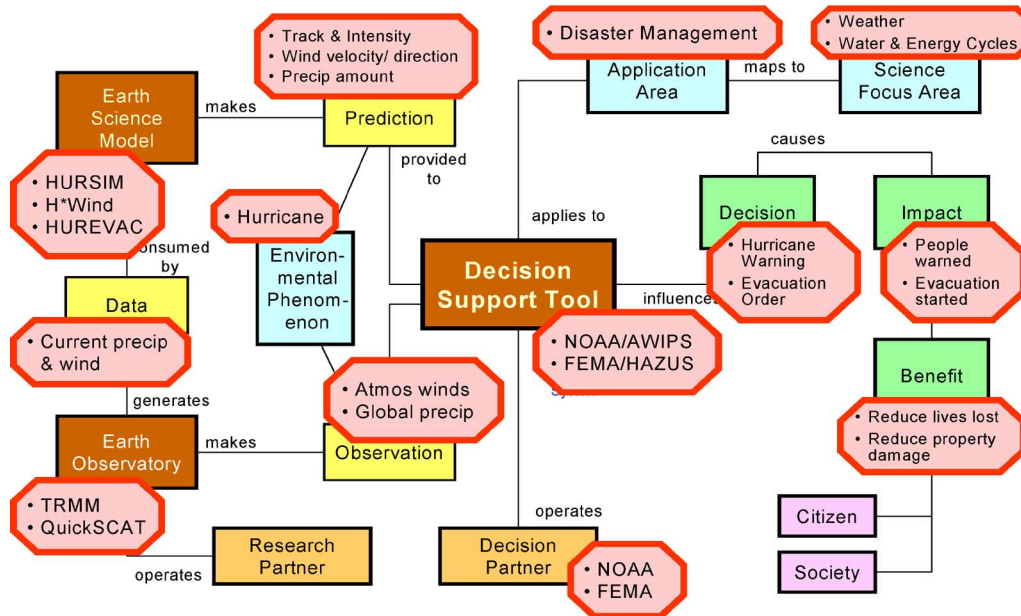
Fig. 10. Hurricane prediction mission thread.

Fig. 11. Modeling elements for hurricane prediction example.

decision-support tools involved in Disaster Management. This thread only deals with determination of intensity and tracks of hurricanes and typhoons.

The elements identified previously can be mapped into the conceptual schema that becomes the basic structure for the Earth-Sun System Architecture. The basic elements are illustrated in Fig. 11. Note that many of the same elements are involved in other mission threads. For example, precipitation rates are also used for basic seven-day weather forecasts, flood warnings, climate assessments, and so on.

You can use the enterprise architecture tool to identify the architectural elements relevant to the TRMM and QuikSCAT missions. The same information that would take a human analyst weeks or months to collect can be identified in seconds using the tool. A visual representation of the information is displayed by the tool (see Fig. 12).

This visualization greatly enhances the suitability of this information in addressing enterprise management issues and concerns. It makes it much easier to make business decisions and the quality of decisions is usually enhanced.
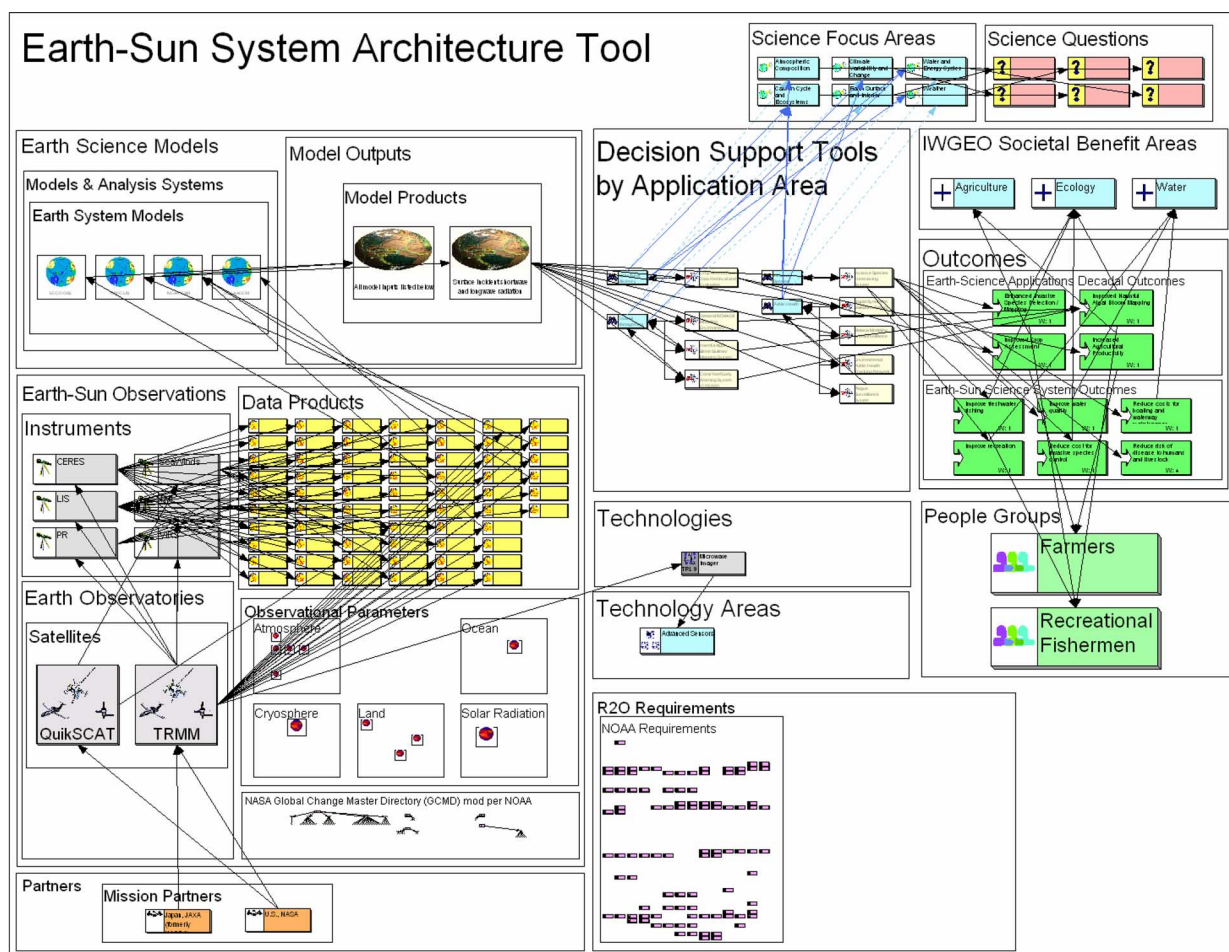
Fig. 12.   Model elements associated with QuikSCAT and TRMM satellites.

D. Decision Support

As you can see in Fig. 12, there are nine decision-support tools (DSTs) involved with these two missions. We can then determine the potential outcomes from making decisions with the DSTs and identify the expected benefits to society. The tool also addresses particular science questions as shown in the upper right-hand side of Fig. 12.

The lower right-hand side of Fig. 12 shows the operational requirements from other government agencies that can potentially use the results of NASA research. There is a research-to-operations (R2O) initiative that will use this tool to determine how best to transition research results to operations.

We can extract this information in table format and export as a comma-separated variable (CSV) formatted file as illustrated in Fig. 13.

To demonstrate further, let us say we want to determine which elements are related to the QuikSCAT mission. Within seconds the tool generates the view shown in Fig. 14. This allows us to investigate the data products generated by the satellite and how these impact Earth system models downstream.

VII.   Summary

Enterprise architecture tools and techniques are useful for helping high-level managers understand the elements of the enterprise they manage. The Metis tool is suitable for this type of

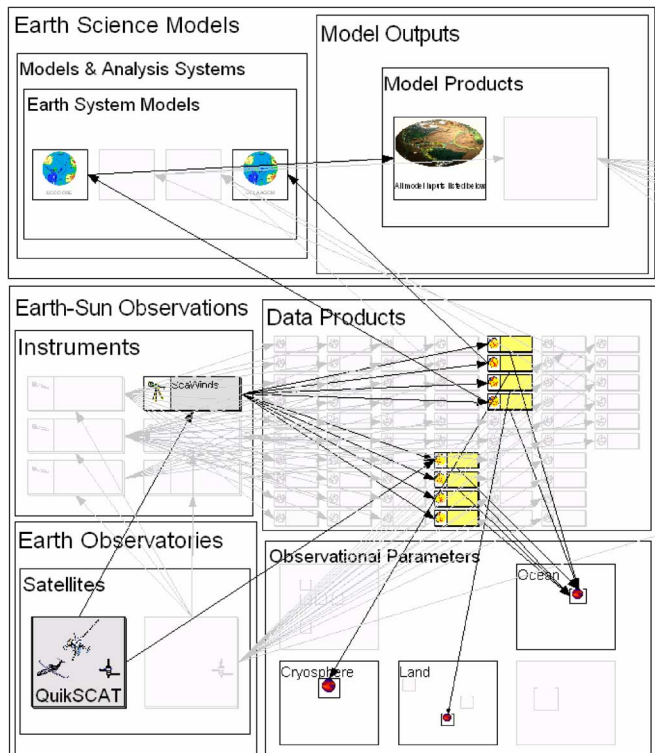Fig. 13.   Data exported for analysis.

Fig. 14. QuikSCAT query results.

modeling and can be easily customized for each particular situation. It has good analytical capabilities and allows for quick visualization of the results.

Systems engineering traditionally operates within system development projects. However, systems engineering with its normal toolbox of techniques has much to offer at the enterprise level. It does require systems engineers to look beyond their traditional mindset of gathering requirements and allocating these to system components. The "system" of interest in this case is the entire enterprise and often this enterprise can truly be global in scale.

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