JP 1.24 FUTURE ARCHITECTURES FOR OPERATIONAL FORECASTING: TWO-WAY INTERACTING SENSORWEB AND MODEL / ASSIMILATION SYSTEM

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1. INTRODUCTION

NASA's Earth Science Technology Office (ESTO) appointed NASA's Goddard Space Flight Center to perform an advanced concept study to identify science knowledge and technology improvements needed to enable skilled weather forecasts out to 14 days in the 2025 timeframe. Even recognizing that an "accurate" deterministic 14-day forecast would be extremely difficult to achieve, and might not be possible (Lorenz 1963, 1969), we nonetheless set out to examine how far one might push the limits of useful weather prediction, given assumed year 2025 technology advances and new forecast system architectures enabled by these advances. Today among operational forecast centers the limit of useful skill range is about 6.5 days. Thus, our charge was to double the current range of forecast skill to 14 days.

As a result of our efforts, we suggest how changes to current modeling and assimilation processes and infrastructure might be improved in the future to take advantage of new capabilities in computing, communications, artificial intelligence, and SensorWeb concepts. A full study report is available though NASA' Earth Science Technology Office (Clausen, et al 2002).

To put this task into context, Figure 1 compares three 500 hPa height Anomaly Correlation curves representing operational forecast skill in 1989, 2001 and 2025. Over the last decade, the range of useful prediction as measured by 500 hPa Anomaly Correlation (AC >0.6) has increased only by about a day and a half, despite advances in computing technology, data assimilation capabilities and new data sources. Comparing the gap (at AC=0.6) between 1989 and 2001 to the gap between 2001 and 2025 gives some feel for the enormity of the challenge of reaching even minimal forecast skill by 2025.

For 10–14 day weather forecasting to be operationally useful, advances are required on many scientific and technological fronts. We acknowledge, for example, that large investments are required in the numerical design and development of models and modeling systems, large scale development of Observing System Simulation Experiment test-bed and research capabilities, basic research on fundamental physical processes and their incorporation in models either explicitly or through parameterization. However, our discussion here is necessarily limited to a few aspects that relate to future abilities to provide and optimally use comprehensive observing of the atmosphere and surface in numerical weather prediction.

2. BACKGROUND

2.1 Modeling Challenges

As an initial value problem, a model predicted state of the atmosphere can be no more *inherently* accurate than the initial state; and from the initial time forward, differences between the real atmosphere and a model forecast (i.e. forecast error) must increase. Other factors excluded, extending forecast skill much beyond 10 or 12 days will require an initial starting point for the model that nearly perfectly describes the true state of the atmosphere. In the context of a global model, this would seem to be contingent being able to observe the 3-D atmosphere everywhere perfectly. This requirement alone points to the need for global space-based observing.

A fundamental recommendation of this study was to advocate global models at up to 1 km horizontal resolution. We believe that computational resources will, based on currently emerging technologies, be sufficient in the 2025 timeframe to operate very high resolution atmospheric models globally (1- 10 km grids). Although the computing requirements are higher (by 10^6), there are critical advantages. First, lateral boundary issues are obviated with a global domain. Second, importance of scale interactions in overall development of the atmosphere argues for global 1 km resolution.

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25 km was the coarsest horizontal resolution considered in this study, since some forecast centers such as ECMWF and NASA's Data Assimilation Office can already run a global model quasi-operationally at 25 km horizontal resolution.

Running a model at 1 km over the entire globe admittedly represents a brute force approach. The need for such resolution will be situation dependent. An alternative would be to run the model globally with a 25 km resolution, but invest in development of adaptive grid techniques that can automatically increase (or decrease) resolution as circumstances warrant. The computational resource savings that might result from reduction (if any) in numbers of grid points would have to be weighed against the overhead of managing, assessing and monitoring adaptive grid processes. Although adaptive grid techniques are employed extensively in aerodynamics and other engineering design work, the challenges for weather forecast models are much more complex and will require both significant investment in research on useful adaptive grid techniques as well as adaptive parameterization.

Our notional baseline model configuration was assumed to be a global mesoscale model with 100 vertical levels from the surface up to 80 km. Expressed in height coordinates, this would provide 100 m vertical resolution in the lowest 2km (planetary boundary layer), 250 m upward to 12 km, 500 m resolution up to 15 km, 1km resolution up to 35 km, 2km resolution up to 50 km, and 6 km resolution to 80 km. The lower mesosphere would serve as a buffering transition to the top of the model. The 250 m vertical grid spacing in the free troposphere was assumed to be able to resolve major structures comparable to what one sees resolved in a *typical* radiosonde profile.

Based only on numbers of grid points, commensurate time step adjustments and requirements for solving non-hydrostatic equations, our analysis suggests the need for a million fold increase over current day computing power in order to run this assumed model in an operational setting. However, taking into account the additional computational demands of more sophisticated parameterizations, coupled surface modeling, the multiplying demands of ensemble forecasting, and the enormous computational demands associated with data assimilation, it is not difficult to see the need for a 10^8 to 10^9 increase over year 2000 computing power to execute the complete assumed model and data assimilation system in a useful operational mode.

2.2 Observing Challenges

Our notional baseline observing system would be capable of providing an initial state for the free atmosphere that depicts horizontal and vertical structure "equivalent" to that which could be provided by today's radiosondes operating every 25 km, every three hours globally. This is not to say that we actually need radiosondes, nor even satellite-retrieved temperature, moisture and wind profiles every 25 km. No single current or future measurement system alone can prescribe the atmospheric state with the accuracy, reliability, frequency and coverage that we need. In any case, it is the combination of forward-integrated model state (at grid resolution), with all wind, temperature, moisture, cloud and other data from all sources at different times and resolutions and accuracies, optimally combined through the mathematical assimilation process that must yield this equivalency to radiosondes every 25 km every three hours globally.

Even though we suggest a 1 km grid model, we believe it is probably sufficient that initial state atmosphere structure information be provided at a 25 km horizontal resolution globally, as the model must be allowed to generate its own internally consistent structures down to grid scale -- over-prescribing detail would probably not helpful.

Table 1 lists, in decreasing general order of priority, observations thought to have most bearing on the 14-day weather forecasting problem. Most important are 3-dimensional structure of atmospheric temperature, moisture and wind, since to first order the evolution of the free troposphere depends on proper initial specification of these variables. A comprehensive discussion of the assumed observing system configuration and technologies is found in the complete ESTO report. It includes discussion of both terrestrially-based and space-based, and advanced future observing systems and technologies, including lidar-derived wind and pressure, hyperspectral imagers and sounders, radio occultation based retrieval, space-based precipitation and cloud radars and scatterometers, automated radiosonde, unmanned aerial vehicle, ACARS, driftsondes, dropsondes, and others.

2.3 Limitations of the Current Systems

Altogether, the coverage and timeliness of data from existing observing systems is insufficient to satisfy the input needs of our notional high-resolution global weather forecast system. Coverage issues can be addressed in terms of numbers and advances in new observing systems and technologies. However, beyond this are issues of *relevance and efficient use of data*.

From the perspective of our study, a fundamental (but addressable) limitations of current operations is that most world-wide operational observing schedules and observing protocols, both space-based and in situ, are "pre-set at the factory", and observations are made without regard for priority needs for those observations based on the meteorology. So current observing systems do not use resources efficiently -- making observations where they are not especially needed, or worse, unable to provide observations where and when they might be most useful. With current generation technologies there is very limited capacity or even thought that can be given to sharing information among observing system elements, and only limited capability to engage and reconfigure the observing system in response to real time needs.

3. TOWARD A NEW APPROACH

The central premise of this study is that it will be possible in the future to fundamentally improve on current operational processes by building in an additional feedback between the forecast model and the observing system, such that the observing system operates flexibly and is responsive to special data acquisition needs identified by the forecast model. Given opportunities to realize key technological advances over the next quarter century, this new feedback could significantly advance weather forecasting. The simplest implementation of such a feedback from model to observing system might merely involve increasing the frequency of data collections upstream of locations where the model predicts future development. A more complex implementation might involve targeting specific observations based on Kalman Filter or Singular Vector methods. To complete the feed–back loop, real-time reporting of observations to the model could help to quickly identify discrepancies and enable the model to be appropriately adjusted /corrected.

This interactivity is illustrated simply in figure 2. What is unique about this approach is that, unlike present day weather observing systems, this observing system (and by extension the sensors within it) will have access to knowledge beyond what individual sensors see in isolation. The SensorWeb will have access to information about the present state of the atmosphere globally and, most importantly to information about the probable *future* states of the atmosphere generated by the forecast model. This will enable observing strategies to be tailored to schedule critical observations of certain types at times and locations that will have highest impact on the ultimate forecast of the event. Observing requirements and schedules may likewise be relaxed in areas where the atmosphere is known or forecast to be slowly evolving, in order to conserve resources.

In principle, benefits of a coordinated near-real time two-way feedback of information between a Modeling & Data Assimilation System (MDAS) and Observing System can be realized with any level of assets.

In its construction, the MDAS development will be based on significant but evolutionary science-based improvements to current-day models and assimilation systems. The Observing System will draw on SensorWeb concepts.

4. ELEMENTS OF A NEW ARCHITECTURE

Figure 3 illustrates important functional elements of the overall year 2025 architecture and their interactions. These are described in the following sections.

4.1 Integrated Space-Ground Communications

A pervasive communications network, including a space segment, will ensure seamless interoperability between space, airborne and terrestrial platforms. The network will be both space-based (e.g., internet in space), ground based (series of ground stations to transmit/receive requests and data), seamlessly integrated with unified protocols. The land-based terrestrial telecommunications backbone network will continue to evolve tremendously in terms of speed and bandwidth. Important technology gaps are probably not a consideration for land-based communications. However, the satellite-to-satellite communications (RF and potentially Laser), and downlink requirements will tax our ingenuity throughout the next twenty-five years. The burdens of Space-to-Earth communications will grow on one hand due to the numbers of satellites and volumes of data envisioned. On the other hand, the ability to do more computational analysis and high-level information processing in space will alleviate some of this burden.

4.2 SensorWeb Based Observing

SensorWeb is an emerging concept that allows for intelligent virtual organization of multiple numbers and types of sensors (Space, Terrestrial, Fixed, Mobile) into a coordinated “macro-instrument”. The power of a SensorWeb is that information collected by any one sensor can used by other sensors in the web, as necessary to accomplish some coordinated observing mission. Adaptive behavior can be initiated throughout any or all assets of in Sensorweb by external inputs or by one or more of the members of the web itself. An embodiment of a SensorWeb (Lemmeran, et al., 2001; Delin & Jackson, 2001; Torres et al, 2002) may rely heavily on artificial intelligence, permit coordinated coincident observing from multiple perspectives, is driven by reconfigurable mission dependent software, may require advanced communication capabilities and protocols, and is enabled by real time “on-board” processing, analysis and decision-making.

Our SensorWeb observing system (at left in figures 2 and 3) must exhibit all of these advanced capabilities. Foremost, it must be able provide nearly continuous global coverage and must not be vulnerable to single point failures. So the architecture must be flexible, reconfigurable and able to adjust automatically to the addition or removal of individual spacecraft, instruments or other system components without compromising the operational mission.

The first functional mode of the observing system is to reliably collect, process and deliver the default routine global observations that the M/DAS needs to produce operational forecasts. Departures from this default mode will arise often based on a determination that an unanticipated event/or departure (from model forecast) has begun, that a future event is anticipated at a certain time and location that requires additional observations, or that a change in observational priorities/policy has been directed from the ground (ECS).

The second functional mode of the observing system is executing measurement strategies in response to needs identified *by the modeling system*. If the modeling system determines that additional observations are needed in key locations (i.e., targeted data collection), those requirements are conveyed the Observing System C^2, which calculates how to optimally manage and schedule observing assets as needed, and then elicits particular behaviors at the platform and sensor level.

The third functional mode of the observing system mode is to execute measurement strategies in response to needs identified autonomously by elements of the Observing System itself; for example, in cases where some incipient phenomenon has been detected that bears special attention or confirmation from other sources

There must also be sufficient on-board processing and storage so that individual spacecraft and instruments in the SensorWeb can autonomously recognize targets of opportunity, and alert other spacecraft and the model to meteorologically significant developments. Specifically driving on-board processing and storage requirements will be the need for on-board image processing, analysis, and pattern (change) recognition.

Just like space-based assets, ground-based observing systems are part of the SensorWeb, collecting in situ data, calibrating it, geo-locating it, quality-checking it, and reformatting it at the sensor or platform, and uplinking it via the global Earth-space communications network in near real-time to a collection point.

4.3 Modeling & Data Assimilation System (MDAS)

The M/DAS (right side in figures 2 & 3) is comprised of the model that generates the weather forecast, and the assimilation process by which observations are incorporated into the model. Together they comprise a sub-system whose essential feedback is a well established part of current day operational forecast cycle. Today this feedback is executed every six or twelve hours, each time resulting in a five-day forecast updated with most recently queued observations.

In the new framework, the M/DAS has an additional purpose. It will provide the SensorWeb with predictions of what individual sensors should expect to see at a given time and place throughout their next orbit (in space) or other observing period (terrestrial systems). Model predictions and actual observations will be compared in near real time; and in response to such real-time feedback from the SensorWeb, the model may automatically reconfigure itself, for example by modifying its parameterizations, or by adapting its grid resolution in order to better capture what has been observed.

Similarly, based on its own predictions and assessment of observational needs, the M/DAS will able to automatically request operational / behavior changes within the Observing System and among observational network elements. The M/DAS will be able to direct the SensorWeb, through a command and control system, to schedule specific targeted, complementary, time sequential, multi-view observations whose assimilation will especially improve model depiction and forecast, or will facilitate ongoing assessment of model forecast performance.

4.4 External Control System (ECS)

An External Control System (**ECS**) provides the interfaces for humans in the loop, implements security, and provides overall monitoring and control for the combined observing and modeling systems. ECS governs the implementation of human-directed policy regarding operation, prioritization and allocation of system resources. It is through ECS that the science community would be authorized to address and interact with components of the SensorWeb for research purposes.

4.5 Observing System Command & Control (C^2)

Much of the intelligence of the overall system will reside in the $\mathbf{C^2}$. Whether $\mathbf{C^2}$ functionality is provided for on the ground or in space, or is consolidated or distributed, was not determined. However, the magnitude and complexity of the $\mathbf{C^2}$ envisioned presents very complex challenges in the arena of software system engineering and artificial intelligence. More than all the technological challenges, this aspect of software engineering presents the greatest overall challenge in terms of scope, complexity and human labor investment.

The $\mathbf{C^2}$ system manages and directs all SensorWeb assets based on inputs from the MDAS, other users, and from the SensorWeb itself to collect data non-routinely as opportunities are known. $\mathbf{C^2}$ monitors the quality of the data that is being returned by the Sensor Web and automatically schedules additional or corroborating observations that might be needed to ensure high confidence in data quality. Based on requests, the $\mathbf{C^2}$ tasks the observing system to take observations as needed. If the total of observing requests exceeds the capability of the SensorWeb, the $\mathbf{C^2}$ will be able to prioritize and resolve conflicting requests.

An important capability for the observing system to have resident within itself, a sufficient degree of intelligence and analysis capability to independently recognize and characterize change relative to model predictions or previous observations. This requires that a given sensor or platform is able receive and utilize information from the ground about what the model has predicted and also what other sensors/platforms viewed aw on earlier overpasses of a particular area. Much of this communication will be coordinated by the $\mathbf{C^2}$.

4.6 Forward Model Observation Function

Since it is the differences between observations and models, whether viewed in geophysical parameter space or a radiance space, are what ultimately get assimilated into the model, an explicit "forward modeling observation function" will facilitate an apples-apples comparison of what a given satellite sensor (at a given place, time and viewing path) actually "sees", and the geophysical parameter the forecast model has projected. Most satellite-based measurements do not provide direct observations of a geophysical variable, but rather a radiometric or some other partial or indirect representation of the desired variable measurement. Making such comparisons often involves non-trivial calculations to convert the satellite measurement into a geophysical variable (retrieval process). The intercomparison may also involve converting a geophysical variable into the satellite radiance space (forward process) to be compared with the satellite radiance measurements.

In the forward process case, the forward model observation function will be able to transform MDAS' forecast atmosphere into *model forecasts of satellite observations* that each sensor on each platform should expect to see in its native sensor format throughout its upcoming orbit. This includes transforming model data to match any parameter space (e.g. radiance) and sensor viewing geometry. Because the modeling system "knows" the orbital parameters of each satellite, as new MDAS forecasts become available the current and forecast state information relevant to each satellite and sensor are delivered to each platform and instrument through the $\mathbf{C^2}$. Each satellite measurement can be geo-located and calibrated on-board, and compared to the forecast of that same measurement. These model data delivered to the platform will be for change detection, quality control or for providing first guess information for an on-board geophysical retrieval. Quality flags may be assigned indicating differences as meteorologically real & significant, or suspect, before passing processed data back to modeling system through the $\mathbf{C^2}$ for later assimilation.

An important related issue is not just whether a forward model observing function is needed (it isn't in all cases), but whether overall system efficiencies can be gained by moving these calculations from the ground to sensor platform. The trade involves consideration of the competing demands of doing geophysical retrievals or other calculations in space (requires significant on-board processing) and downlinking the processed observations, versus downlinking tens of thousands of raw uncorrected radiances for processing on the ground and placing greater demands on space communications infrastructure. With the trend toward hyperspectral remote sensing in general, it could be far less demanding to emphasize increased on-board processing than to downlink all radiometric data for ground processing.

4.7 Data Reduction and Quality Control

Data reduction includes geo-location, calibration, and correction, some of which will increasingly done on-board the observing platform. *Quality Control* (QC) of observational data, and the correctness of a decision to keep or reject data is traditionally one of the largest identifiable sources of forecast error. Data may be rejected for a variety of valid reasons: transmission errors, instrument failure, or contamination from the atmosphere (e.g., cloud contaminated satellite temperature retrievals). Operational quality control algorithms reject as much as 10% of available data -- a consequence of the threshold and statistical techniques employed. However, there are instances in which bad data pass the quality control and good data do not. Intelligent systems and protocols can be developed that can better distinguish between "bad" measurements and "valid outliers". Based on a global continuous data collection capability involving many types of complementary data from multiple platforms and perspectives, additional resources can be quickly tasked to provide additional observations to help decide whether to keep, reject, or replace suspect flagged data.

4.8 Targeted Observing Function

Besides the global Forecast Model and Assimilation Processes themselves, other functions critical to the architecture are shown under the M/DAS side of figure 3. Among the more interesting of these is a Targeted Observing Function which contains the software and operations that determine, based on current evolution of the model atmosphere, where and what observations will be most important for updating the model in order to optimize future forecasts. The Targeted Observation Function tasks the SensorWeb through $\mathbf{C^2}$ to acquire the desired observations, if possible. Targeting as used here has two contexts. First, determining which observations will produce the best forecast as measured in an "overall" sense. The second context refers to identifying specific observations based on their potential positive impacts in a specific location or region. The two approaches may not always be simultaneously achievable. From the point of view of supporting (for example) military operations at a target site, the second approach would have considerable value.

The implementation of a 'targeted observation control loop' would involve directed changes in the variety and schedules of data collections, and engage additional assets / sensors to observe at locations where perceived needs are greatest (i.e. where greatest forecast impacts from those data are likely to be realized). The decision to execute a specific observing strategy implementation might be driven by where and when a model predicts rapid significant future development, by where the model forecast shows greatest uncertainty (as revealed in ensemble forecasts), or by where observations reported real-time from the SensorWeb indicate deficiencies in model performance. The architecture proposed in this study is especially suited to the implementation of targeted observing strategies. The feed back between the observing system and modeling system enables targeting to actually be carried out!

Techniques for estimating where observations are most needed include the Ensemble Transform Kalman Filter (ETKF) (Bishop & Toth, 1999) that aims to predict the evolution of error covariances, and a Singular Vector (SV) method in which targeting is based on projecting initial errors (and correction thereto) onto rapidly growing modes identified by dominant singular vectors from an ensemble of model runs (Gelaro, et al, 1999).

The efficacy of model-guided targeted observing for synoptic weather systems was demonstrated in the FASTEX, NORPEX, CALJET, WSR99 and WRS00 field programs (Toth, et al, 1998, 1999; Gelaro, 1999; Szunyogh, et al, 1999). As a result, targeting strategies are being implemented operationally by the National Weather Service relative to Winter Storms (Toth, et al, 2001). The benefits of targeting observing in relation to hurricanes have also been operationally established (Burpee, et al, 1996).

5. ASPECTS OF OPERATIONS

5.1 Assimilation Frequency

Movement toward more frequent assimilation will enable large the benefits of the proposed architecture to be realized. Since the computational cost of data assimilation is related nonlinearly to the number of observations assimilated, frequent analysis of small amounts of data may in the end be more computationally efficient than infrequent analyses with large amounts of data. This is especially important in view of the tremendous increase of data acquisition and use that would be supported by the new architecture. Ideally, a true time-continuous assimilation system will evolve, a concept whose feasibility and benefits have been demonstrated (Ghil, et al., 1979).

An hourly assimilation cycle would take better advantage of the proposed continuous global satellite data collections. In current practice, only about 15% of all satellite data are assimilated operationally. While there are quality control issues, most satellite data are culled solely due to the inability of current assimilation (and computing) systems to accommodate the observations. Most operational forecast models are initialized at standard synoptic times -- every 12 hours – with asynoptic data queued in a 3 – 6 hour window up to assimilation time. This means that at least half of the satellite data are too old to be included, and even data that is 3 – 6 hours old may require correction for atmospheric state changes that have occurred during the several hour intervals between the observation time and initialization time, a process requiring expensive 4DVAR techniques. Assimilated hourly, observational “errors” related to the difference between the assimilation time and actual observation time are bound to be smaller, therefore requiring smaller, less disruptive (model shock) corrections. It will also be easier to detect when and where the model forecast and observations diverge, and thus to dispatch additional observations to such locations. Initial states derived hourly would serve as the starting point for short, medium and long-range forecasts.

5.2 Ensemble Forecasting

In the future, operational forecasting and observing strategies will depend not on a single model forecast, but on many, perhaps even hundreds of model forecasts being run in ensemble batches every six to twelve hours. The information provided by ensembles serves a number of purposes. For example, the ensemble mean may be assumed to be the forecast that is most likely to be correct; and the spread about the mean a measure of confidence in the forecast. Statistics derived from the ensemble forecasts also provide measures of reliability of model forecast first guess fields relative to observations, and thus the relative weight given to the first guess in constructing the next initial state analysis. And as already discussed, statistical information derived from properly designed forecast ensembles is useful for carrying out targeted observing.

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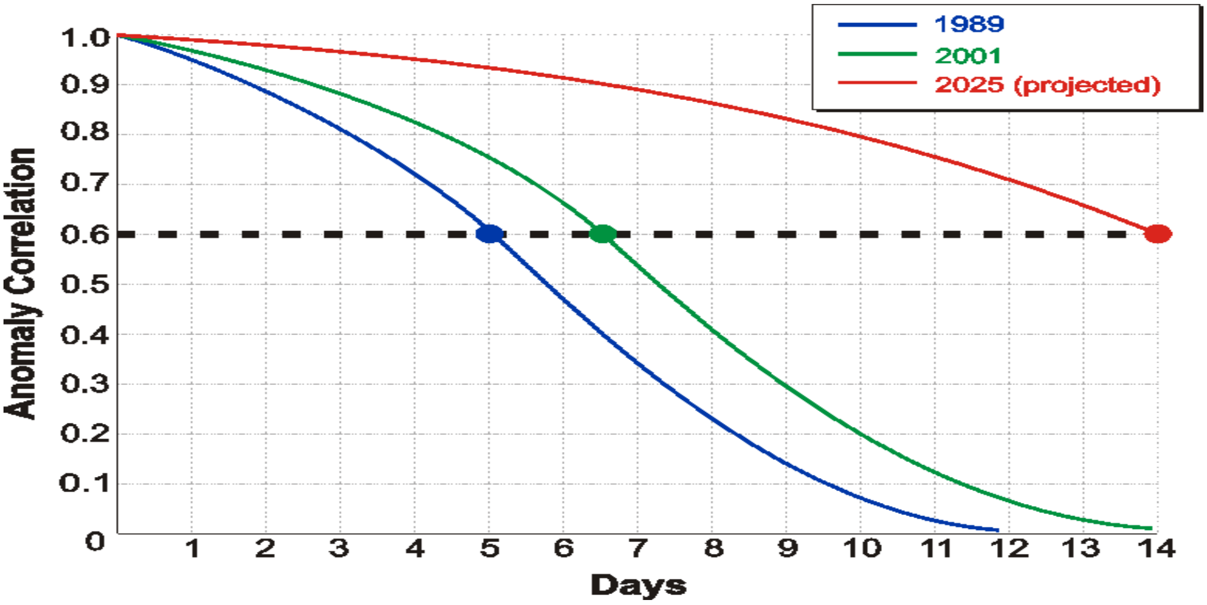

Figure 1. Illustration of decreasing anomaly correlation with length of forecast as a metric of forecast skill.

GLOBAL MEASUREMENT	Temporal Resolution	Horizontal Resolution	Vertical Resolution
3-D Atmospheric Wind Speed & Direction	3 hours	25 km	250 m
3-D Atmospheric Temperature (T)	3 hours	25 km	250 m
3-D Atmospheric Humidity (Td, RH)	3 hours	25 km	250 m
Barometric Pressure (Psfc)	3 hours	25 km	NA
3-D Precipitation (accumulation, rate, phase)	1 hour	1 km	250 m
3-D Cloud (water content, phase & other properties)	1 hour	1 km	250 m
Land-surface / Soil Moisture (LSM)	3 hours	25 km	NA
Land-surface / Soil Temperature (LST skin)	3 hours	25 km	NA
Land-Sea Snow-Ice (extent, depth & properties)	3 hours	25 km	NA
Sea Surface Skin Temperature (SST skin)	3 hours	25 km	NA
Planetary Boundary Layer (PBL) Height	1 hour	25 km	25 m
Aerosols (size dist., conc., & other properties)	6 hours	25 km	NA
Albedo (%)	3 hours	25 km	NA
Vegetation (e.g. NDVI)	1 week	1 km	NA
Surface Roughness (R_0)	2 weeks	1 km	NA

Table 1 Observational needs relative to the 14-day weather forecasting problem ranked by relative importance. Variables shown green are thought not to present significant technology challenges, but will be obtainable though evolution of current measurement technologies and systems. Variables shown red are difficult to carry out remotely and will require significant technological developments. In general these are the observations that will involve active remote sensors using such space-deployed Lasers (Lidar) and Radars.

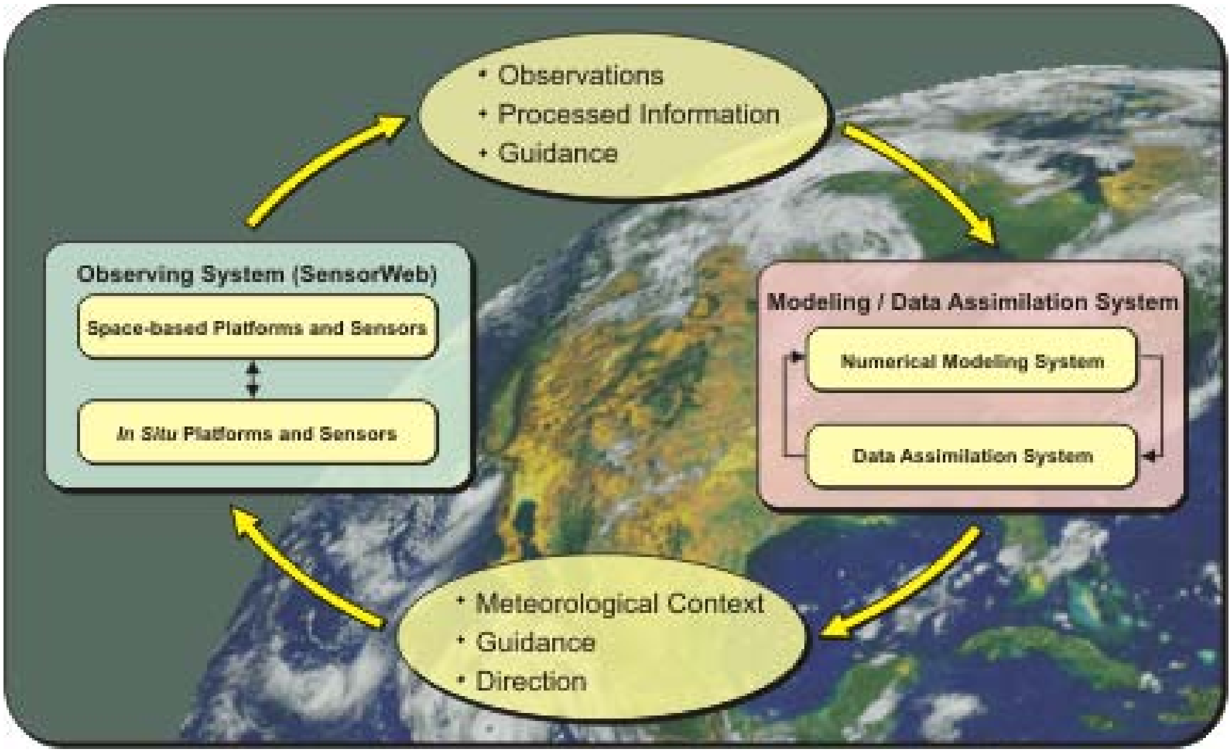

Figure 2. Two-way Interactive SensorWeb and Model / Data Assimilation System

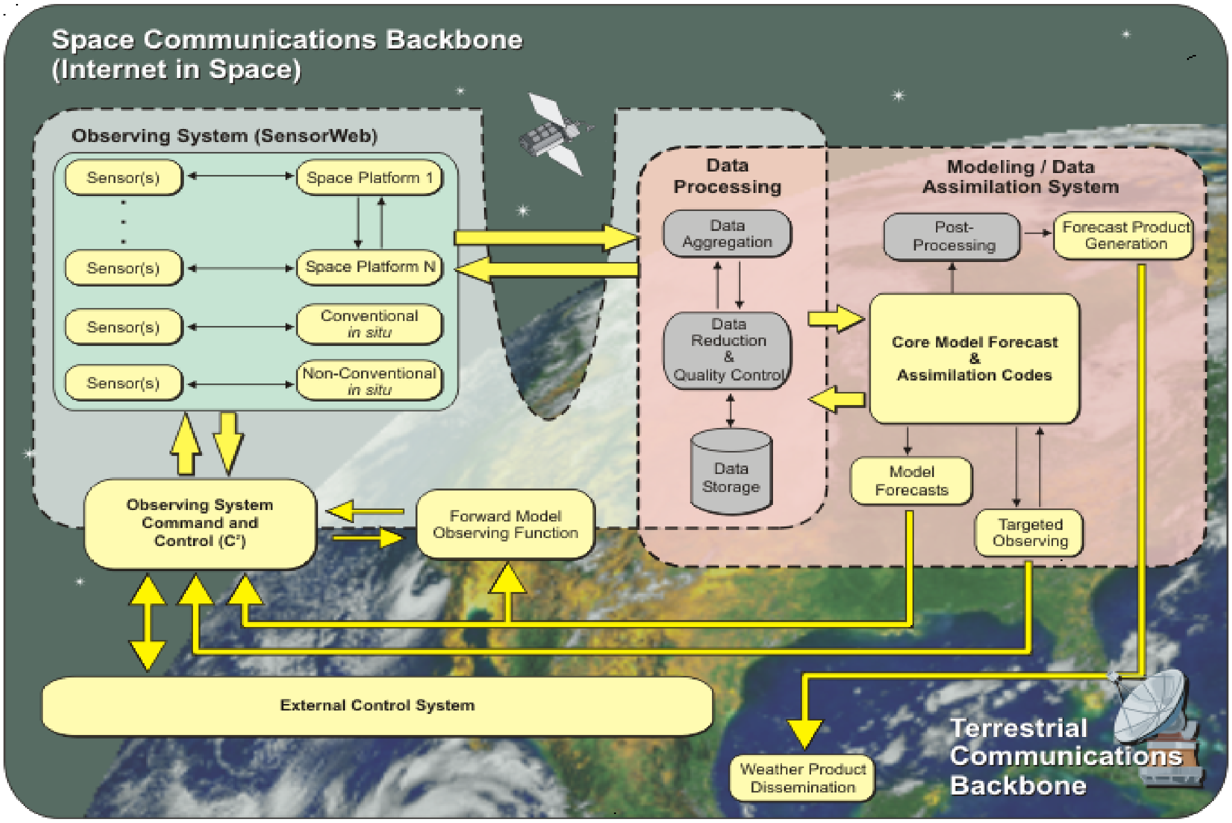

Figure 3. 2025 Weather Forecasting System Functional Architecture Concept

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Last Printed On:	9/30/2002 1:25 PM

As of Last Complete Printing

Number of Pages:	9
Number of Words:	5,373 (approx.)
Number of Characters:	30,628 (approx.)