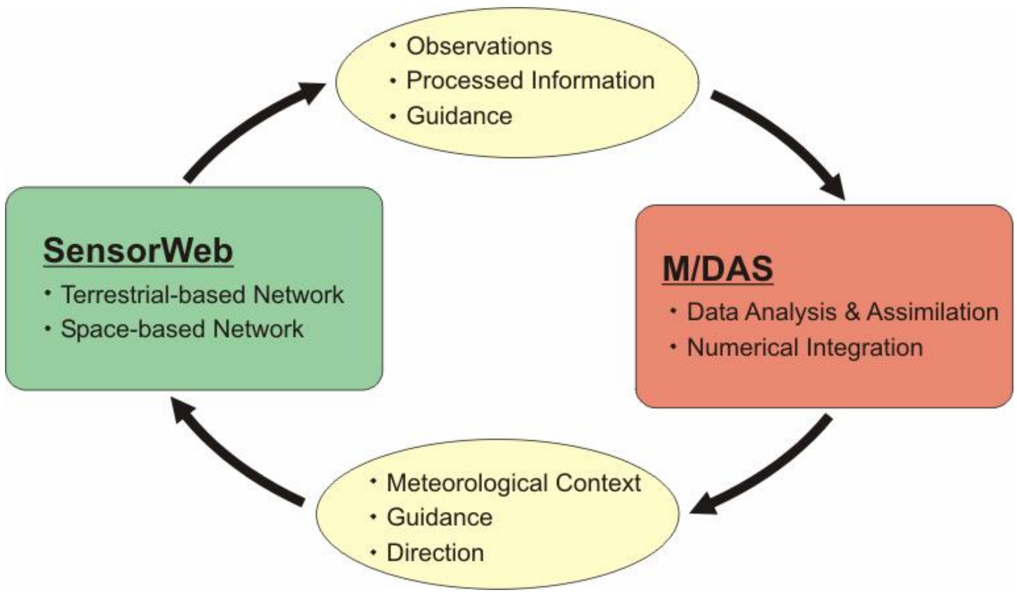
Advanced Weather Prediction Technologies: Two-way Interactive Sensor Web & Modeling System

Phase II Vision Architecture Study



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A report prepared for
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Acronyms

ABI	- Advanced Baseline Imager
ACARS	- Aircraft Communication Addressing and Reporting System
AIRS	- Atmospheric Infrared Sounder
AMDAR	- Aircraft Meteorological Data Reporting
AOC	- NOAA Aircraft Operations Center
ASOS	- Automated Surface Observing System
AVN	- Aviation model
AWIPS	- Advance Weather Information Processing System
CALJET	- California Landfalling Jets Experiment
CERES	- Clouds and the Earth's Radiant Energy System
CONUS	- Continental United States
COSMIC	- Constellation Observing System for Meteorology, Ionosphere, and Climate
COTS	- Commercial-Off-The-Shelf
ECMWF	- European Center for Medium Range Weather Forecasting
ECS	- External Control System
EDR	- Environmental Data Record
FASTEX	- Fronts and Atlantic Storm-Track Experiment
FOV	- Field of View
GAINS	- Global Air-ocean IN-situ system
GEMSEC	- GSFC Mission Services Evolution Center
GIFTS	- Geosynchronous Imaging Fourier Spectrometer
GFS	- Global Forecast System model
GOES	- Geostationary Operational Environmental Satellite
GPM	- Global Precipitation Measurement
GPS	- Global Positioning System
HES	- High-Resolution Environmental Sounder
HPC	- NCEP Hydrological Prediction Center
IASI	- Infrared Atmospheric Sounding Interferometer instrument
IFPS	- Interactive Forecast Preparation System
LAPS	- Local Area Prediction System
LEO	- Low Earth Orbit
MAPS	- Mesoscale Analysis and Prediction System
Mesonet	- Mesoscale Observing Network
MSAS	- Mesoscale Surface Analysis System
METAR	- Meteorological Aviation weather Report
METOP	- (European Operational Polar Orbiting Weather Satellite)
MDAS	- Modeling and Data Assimilation System

MODIS	- Moderate-Resolution Imaging Spectrometer
NCAR	National Center for Atmospheric Research
NCEP	- National Centers for Environmental Prediction
NCO	- NCEP Central Operations
NDFD	- National Digital Forecast Database
NOAA	- National Oceanographic and Atmospheric Administration
NORPEX	- North Pacific Experiment
NPOES	- National Polar Orbiting Environmental Satellite System
NSF	- National Science Foundation
NRC	- National Research Council
NWP	- Numerical Weather Prediction
NWS	- National Weather Service
OSE	- Observing System Experiment
OSSE	- Observing System Simulation Experiment
PACJET	- Pacific Landfalling Jets Experiment
RASS	- Radio Acoustic Sounder System
RRW	- Rapid Refresh WRF model
RUC	- Rapid Update Cycle
SSCS	- Storyboarding and Scenario Case Study
SREF	- Short Range Ensemble Forecast
TCA	- Transformational Communications Architecture
TDRSS	- Tracking and Data Relay Satellite System
TES	- Tropospheric Emissions Spectrometer
THORPEX	- THe Observing-system Research and predictability experiment
TPC	- Tropical Prediction Center
TRMM	- Tropical Rainfall Measurement Mission
UAV	- Unmanned Aerial Vehicles
VAD	- Velocity Azimuth Doppler (Radar winds)
4DVAR	- Four Dimensional Variational Assimilation
WFO	- Weather Forecast Office
WMO	- World Meteorological Organization
WRF	- Weather Research Forecast Model
WSR	- Winter Storm Research

Executive Summary

A May 2002 Phase I ESTO report entitled "*Advanced Weather Prediction Technologies: NASA's Contribution to the Operational Agencies"* suggested that given the opportunity to realize key technological advances over the next quarter century, it may be possible in the future (2025) to significantly extend the skill range of model based weather forecasting via a direct two-way feedback between numerical weather prediction models and a Sensor Web based observing system.

The purpose of this Phase II study was to validate and refine the functionality and relationships among the components that made up the Phase I (2025) framework architecture. In both the Phase I and Phase II study reports, is presented an advanced and very notional weather forecast system architecture whose realization is well beyond present capabilities, and is focused on a post-NPOESS era. These companion studies focus less on whether the suggested operational improvements *will* be made (determinations that must be guided by the results of research programs such as THORpex). Rather, most of our energies were devoted to thinking about how they might be done, and to anticipate what contributions NASA might make in developing the underlying system infrastructure and advanced technologies that will be needed, even if not yet recognized or under serious consideration by the weather operations community.

Just as NASA has had official responsibility for developing the satellite systems that NOAA eventually operates, we think that NASA can similarly make important contributions by investing in other advanced technologies and capabilities envisioned in this report that will benefit operational forecasting in the future. This is consistent with NASA's strategic view of its role as engaging in R&D that supports operationally oriented government agencies.

In order to better define the workings of the two-way interaction, the Phase approach II was to examine the Phase I (2025) functionality of the architecture and exercise elements of the architecture and interactions between these elements in more concrete terms in the context of documented real-world forecast situations. Specifically we looked at well-documented actual forecast situations in which the operational forecast system failed, and assessed how these failures could have been addressed in the two-way interactive Sensor Web and Modeling / Assimilation system. We characterized the space- and ground-based assets and capabilities anticipated to be available in the 2015 time frame, and used these in carrying out 1-day and 5-day actual weather forecast case scenarios, to validate or identify problems with assumptions about the functional organization and interfaces, overall system performance, and expected forecast impacts. It was is expected that this analysis would result in both an improved 2025 vision architecture and more informed suggestions regarding mid-term development pathways to the 2025 vision.

Lessons learned from the scenario exercises helped guide additional refinements and next level of detail for the overall two-way interactive architecture, and to identify and prioritize technology gaps, emphasizing information system functionality and other mid-course technology investments that would enable demonstration or realization of important functionalities inherent in the two-way interactive architecture by 2015.

The main elements that comprise the Phase II Sensor-Web-based Weather Forecast System Architecture are: (i) an Observing System, (ii) a Modeling and Data Assimilation System (MDAS), (iii) Forecast Operations (including weather data user communities), (iv) an External Control System and (v), a Communications, Command and Control System. All these components are intended to interact via an all-important pervasive communications fabric and data grid. *The graphic at the end of the executive summary depicts, at a very high level, the main concepts and operating components of the two-way interacting Sensor Web and model weather forecast system.*

The most significant changes to the original Phase I architecture were related to the explicit acknowledgement and inclusion of the role of human forecaster and user communities. In Phase II, we describe a system that includes four distinct targeted observing or feedback loops to the observing system. Largely autonomous feedback between the observing system with itself and the feedback between the model and observing system were introduced in the original study. The two new feedbacks enable humans to address the observing system in a targeted observing sense, and suggests an impetus for new generations of automated and intelligent tools that extend the intellectual reach of decision makers to integrate information real-time.

We determined at that human observing requests would be vetted through a much more capable External Control System facility than envisioned in Phase I. We also backed off on the level of autonomy allowed to the two original non-human feedback loops. This was thought necessary, since conflicts between model or sensor web generated observing requests and human generated observing requests would be significant enough that they would need to be resolved within a common policy framework provided by the External Control System.

Among agencies, and even within NASA, perceptions vary regarding what a sensor web is, how it functions, and how it is organized. This report offers an alternative, potentially useful view of a Sensor Web. The prevailing NASA notional Sensor Web refers only to the observing system elements. The new view is broader, including as part of the Sensor Web, non-observing assets that interact with the observing system to carry out a mission. We think that this view, supported by the taxonomy described in Section 7, might lend useful rigor to thinking about Sensor Webs.

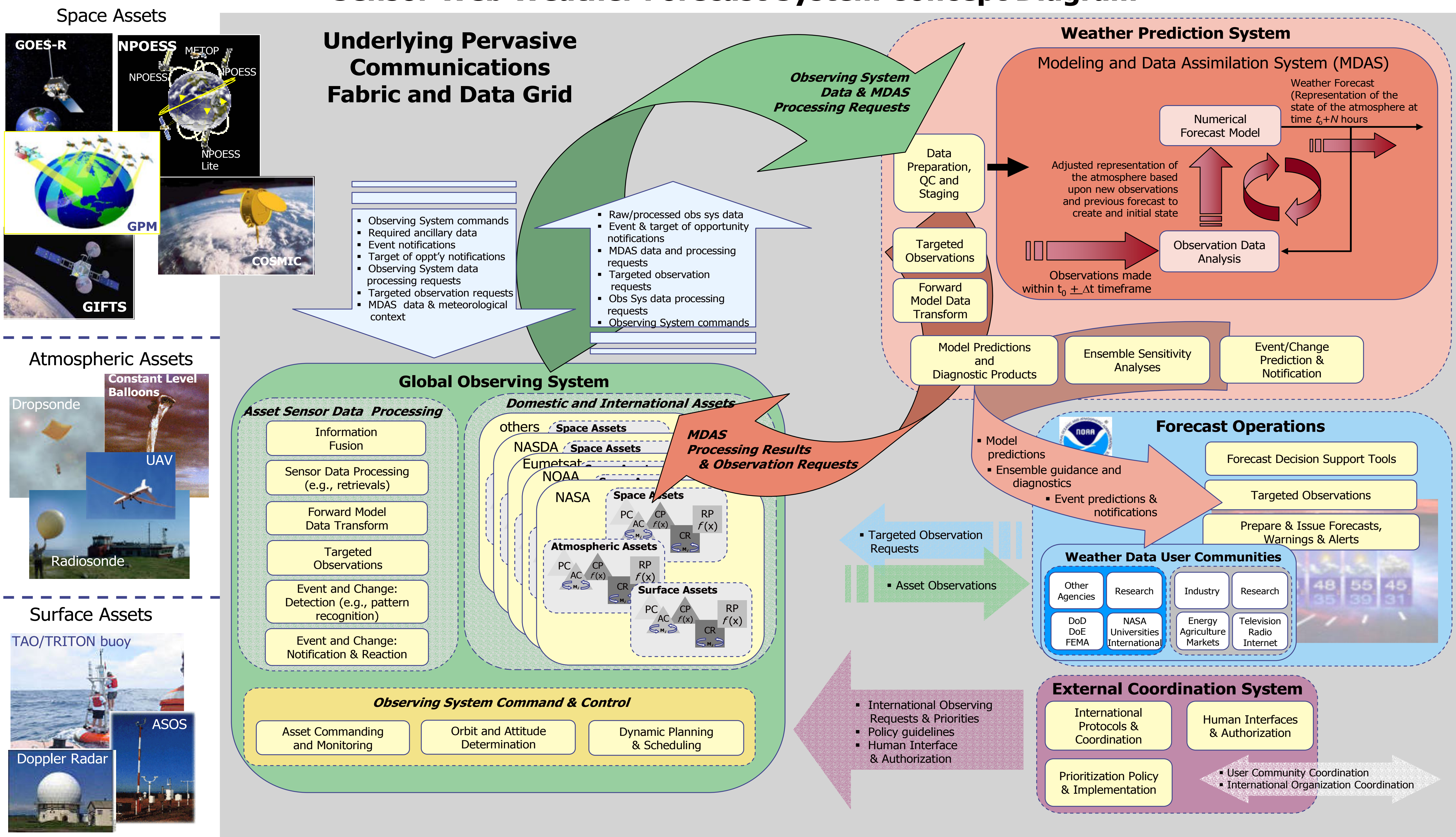
Many of the advances deemed critical for both 2015 and 2025 instantiation of key functionality of a two-way interactive Sensor Web based weather forecast modeling system architecture will necessitate advances in hardware (notably space-based hardware), information technologies (that facilitate seamless information exchange), and communications mediums and protocol technologies. Some of these may require two or perhaps three decades to mature before they can be “operationally” deployed to comprehensively satisfy all functional and performance requirements and to ensure a sufficiently robust operations concept. Other technologies will evolve rapidly and independently, without the need for extraordinary unilateral NASA investments, since broader efforts by industry, academia and the Federal Government are gathering momentum in key areas, notably terrestrial-based grid computing, dense wavelength division multiplexed (DWDM) wideband fiber optic terrestrial communications, and sophisticated information exchange standards which are being driven largely by the increasingly competitive needs of electronic commerce and newly emerging real time, network centric defense program initiatives.

The most significant challenge to developing a weather forecasting solution are developing the large scale deep infrastructure on which almost al of the more advanced proposed forecast system functionality depends. These are fundamentally in the areas of:

a. Communication technology & infrastructure
b. Interoperability
c. On-board computing and processing
d. Technologies and operational infrastructure
e. Decision support tools

As significant as science, technology and engineering challenges are, progress toward meeting the challenges presented in the Phase I and Phase II weather forecasting architecture studies also depends critically on large-scale coordination among organizations and agencies.

Sensor Web Weather Forecast System Concept Diagram



1. Introduction: Origin, Purpose & Scope of Phase II

In a series of 2025 Vision workshops, NASA identified strategic challenges surrounding the future acquisition of key science observations and related data products needed to support future Earth system monitoring and model-based prediction of Earth System behavior. Two-Week weather prediction was one of fourteen defined science requirement scenarios to help planners focus and prioritize future investments in technologies that will be needed to realize the Earth Science Enterprise 2025 Vision. In 2001, Goddard Space Flight Center was tasked by ESTO to perform a study to identify the science applications and technology improvements needed to enable skilled weather forecasts of 10 - 14 days in the 2025 timeframe. In May 2002, GSFC submitted its study results as an ESTO report entitled "*Advanced Weather Prediction Technologies: NASA's Contribution to the Operational Agencies*"[1], available through the ESTO office at NASA GSFC. That report, which presented a unique coupled "sensor-web" and weather forecast model system framework concept that could significantly extend the skill range of model based weather forecasting, is the starting point for this Phase II study.

The central aim of this Phase II study is to refine and define the functionality and relationships among the components that make up the Phase I (2025) framework architecture. The approach of this follow-on study considers the 2025 architecture and its derivatives in the context of established medium-range forecasting scenarios, and assesses the benefits / improvements that may be realized for 1-5-day forecasts in the 2015 timeframe. It is expected that this analysis will result in both an improved 2025 vision architecture and more informed suggestions regarding mid-term development pathways to the 2025 vision.

Our Phase II study approach was to:

- Re-examine the high level architecture for a two-way interactive forecast model – sensor web developed under the Phase I study, and make refinements based on recent new information and understanding gained since then.
- Identify and characterize the space- and ground-based assets and capabilities anticipated to be available in the 2015 time frame.
- Use assumed 2015 technologies and infrastructure and realistic 1-5 day weather forecast case scenarios to exercise the 2025 architecture, in order to validate or identify problems with assumptions about the functional organization and interfaces, overall system performance, and expected forecast impacts. Develop an operational concept for 2015.
- Use insights and lessons from the scenario exercises to help guide additional refinements and next level of detail for the overall two-way interactive architecture
- Identify and prioritize technology gaps, emphasizing information system functionality and other mid-course technology investments that would enable demonstration or realization of important functionalities inherent in the two-way interactive architecture by 2015.

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1 Clausen, M, M.. Kalb, G. McConaughy, R. Muller, S. Neeck, M. Seablom, and M. Steiner et al., "Advanced Weather Prediction Technologies: NASA's Contribution to the Operational Agencies," unpublished. A study report prepared for NASA's Earth Science Technology Office, May 2002.

2. Review of Phase I Architecture

The Phase I study was motivated by the goal of achieving skillful two–week weather forecasts. Since 14 days represents the theoretical limit of deterministic prediction, a two week forecast is an ambitious goal. Thus, to even consider the possibility of achieving predictive skill out to fourteen days, we recognized in Phase I that it would be absolutely necessary (although still not sufficient) to specify the initial state for a numerical model that would nearly perfectly describes the actual state of the atmosphere. We also believed that achieving such long range (14 day) forecast skill would be contingent on high resolution global modeling. It was reasonable to conclude that global space-based observing would have to be a significant part of any solution.

In the Phase I study, we examined at a high level how changes to the current operational infrastructure as well as to current modeling and assimilation processes might be improved in the future to take advantage of new capabilities in computing, communications, artificial intelligence, and Sensor Web concepts. The main contribution of the Phase I was to suggest that given opportunities to realize key technological advances over the next quarter century, it will be possible in the future to significantly advance weather forecasting fundamentally by building a direct two-way feedback between the forecast model and the observing system. In such a system, the observing system will operate flexibly and be responsive to special data acquisition needs identified by the forecast model. This interactivity is illustrated simply in figure 1.

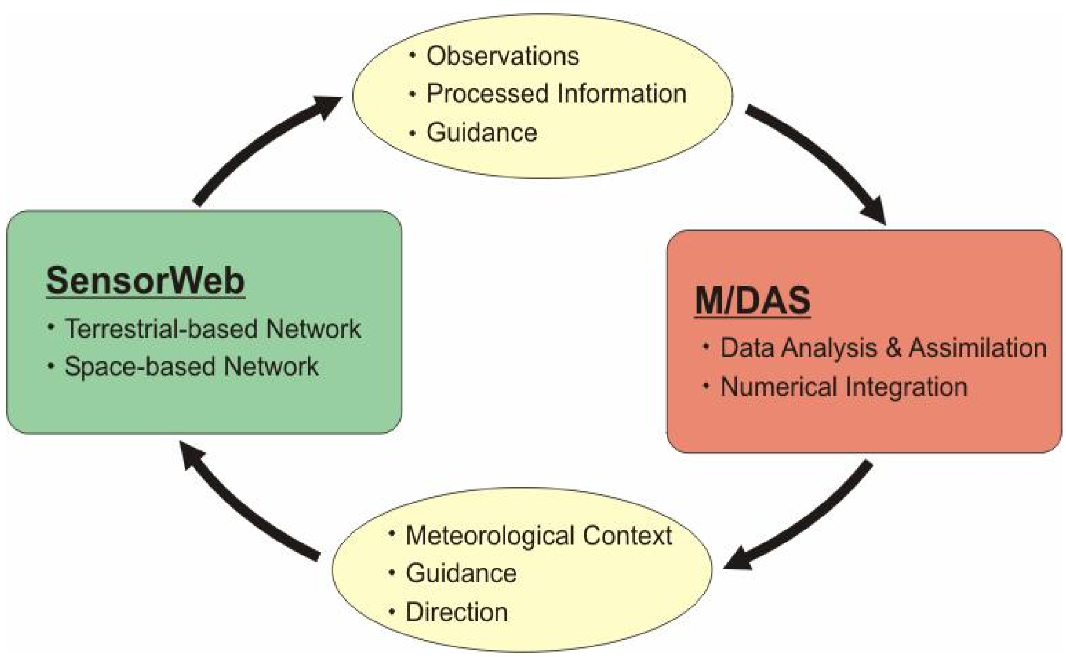

Figure 1. Original concept for a two-way Interactive Sensor Web and Model / Data Assimilation System

Implementation of such a feedback between model and observing system could be as simple as increasing the frequency of data collections upstream of locations where the model predicts future development, or as complex as targeting observations with mathematically sophisticated analysis of model ensembles. 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.

The novelty of 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 Sensor Web 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 allow observing strategies to be tailored to schedule critical observations at times and locations that will have highest impact on the subsequent forecasts of the event. Likewise, in order to optimize resources, observing requirements may be relaxed in areas where the atmosphere is forecast to be slowly evolving and the impact of these observations would be only marginal.

Functional Elements of Phase I Architecture Concept

The first stage of the phase II study was to re-evaluate and drill down into the functioning of, and interactions among, the major components elements identified in the phase I study. The final Phase I study architecture is redrawn here as figure 2. It is an elaboration on the underlying two-way Sensor Web modeling system feedback of figure 1. This section is a shortened description of the basic elements of the Phase I architecture and the intended functionality and interactions among those elements. A complete discussion is found in the Phase I report.

Sensor Web Based Observing

The Sensor Web concept involves intelligent virtual organization of multiple numbers and types of sensors (Space, Terrestrial, Fixed, and Mobile) into a coordinated "macro-instrument". The power of a Sensor Web is that information collected by any one sensor can used by other sensors in the web, to accomplish a coordinated observing goal. Adaptive behavior can be initiated throughout any or all assets of in Sensor Web by external inputs or by one or more of the members of the web itself. A Sensor Web [2] [3] [4] may rely heavily on artificial intelligence, involve coordinated observing from multiple perspectives, be reconfigurable to the particular mission, require advanced communication capabilities and protocols, and be enabled by real time "on-board" processing, analysis and decision-making. Autonomy is an important element of the Sensor Web concept. The observing system (at left in figures 1 and 2) is intended to invoke all these Sensor Web attributes.

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2 Lemmeran, L., K. Delin, F. Hadaegh, M. Lou, K. Bhasin, J. Bristow, R. Connerton and M. Pasciuto: "Earth Science Vision:Platform Technology Challenges". IEEE Geoscience and Remote Sensing Symposium (IGARSS), Sydney, Australia, June 2001.

3 Delin, K.A. and S.P. Jackson, 2001: The Sensor Web: A New Instrument Concept. SPIE Symposium on Integrated Optics, San Jose, CA, January 2001.

4 Torres, E., M. Schoberl, M. Kalb and G. Paules, 2002: "The Earth Science Vision: An Intelligent Web of Sensors", 53rd International Astronautical Congress/ COSPAR joint session on Earth Observation Sensors and Technologies, International Aeronautical Federation, October 10-19, 2002.

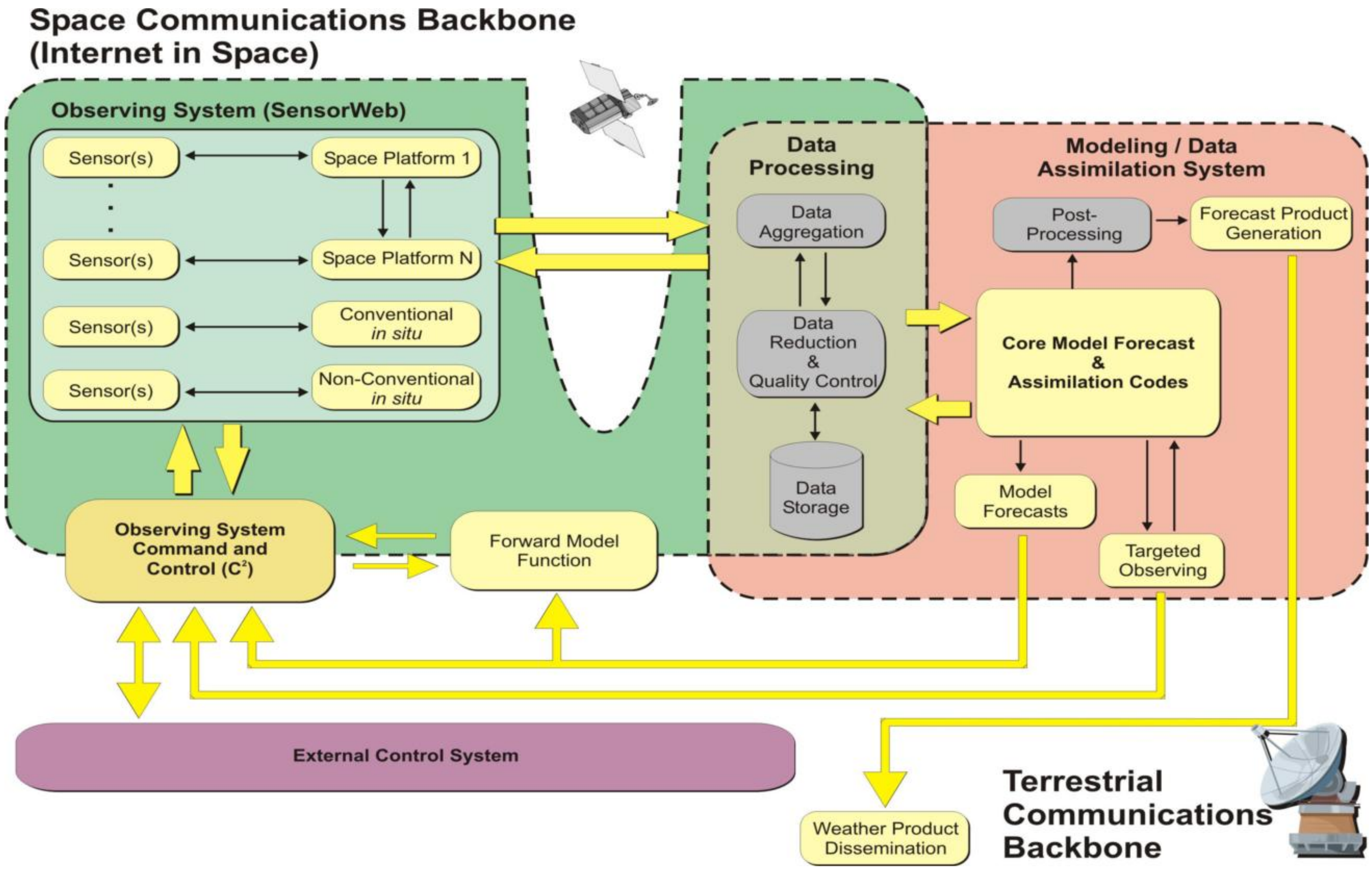

Figure 2. Final Phase I 2025 weather forecasting system framework, showing important components and interactions.

For the stringent *14-day* forecast mission, not only must an observing system be able to meet requirements for nearly continuous global coverage, it must not be vulnerable to single point failures. The architecture of the observing system must be flexible, reconfigurable and able to automatically adjust to the addition or removal of individual spacecraft, instruments or other system components without compromising the operational mission

The baseline role the "Sensor Web-based" observing system envisioned in Phase I is to deliver on the routine global observations that the Modeling / Data Assimilation System (**MDAS**) needs to produce operational forecasts. Departures from routine observing would be initiated based on a determination that: some unexpected development has been detected and interpreted, that observed departures from a model forecast(s) are increasing in certain areas, that significant future events are anticipated by a model at a time and location requiring more intensive observation, that divergence among successive or ensemble model runs suggest greater uncertainty in some areas, or that a change in observational priorities/policy has been directed by a human overseer (perhaps as embodied in the External Control System).

According the framework laid out in Phase I, tailored dynamic responses to such situations could eventually be carried out autonomously with the aid of two internal feedbacks that involve: a) the observing system feeding actionable information to itself, and b) the modeling system feeding actionable information to the observing system. "Actionable" means that the observing system is required and able to dynamically adapt its behavior in response to the information provided. The second of these feedbacks was referred to as the "targeted observing" loop in the phase I study.

The observing system would carry out with a high degree of autonomy, observing strategies in response to needs identified by elements of the Observing System itself. An example would be a case in which one sensor detected potentially some incipient phenomenon that requires special attention or confirmation from other observing assets. This functionality is predicated on sufficient on-board processing and storage so that individual spacecraft and instruments in the Sensor Web might be able to autonomously recognize important targets of opportunity, and alert other spacecraft and the model to meteorologically significant developments. The need for on-board image processing, analysis, and pattern (change) recognition will drive on-board processing and storage requirements.

The observing system also executes non-routine measurement strategies in response to needs identified by the modeling system. If analysis of model output determines that special observations are needed in some areas, those requirements are conveyed *(in Phase I)* to the Observing System Command & Control (**C^2**), which aims to optimize scheduling of observing assets to accommodate the requests, and then generates commands to elicit behaviors at the platform, senor and observing system level.

*Modeling & Data Assimilation System (**MDAS**)*

The **MDAS** (right side in figures 1and 2) is composed of the model(s) that generates the weather forecast, and the assimilation process by which observations are incorporated into the model. Together they comprise a sub-system whose interactions are already a well-established part of present day operational forecast cycle. However, in the new framework, the **MDAS** has an additional purpose of providing the Sensor Web 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 Sensor Web, 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 **MDAS** will be able to automatically effect modes of operation / behavior within the Observing System and among observational network elements. The **MDAS** will be able to direct the Sensor Web *in Phase I*, through an intelligent command and control infrastructure (**C^2**), to schedule specific targeted observations whose assimilation will especially improve model depiction and forecast, or will facilitate ongoing assessment of model forecast performance.

For Phase II we project the likely state weather prediction modeling in the 2015 timeframe through analysis of National Weather Service / NOAA planning documents, presentations and the open literature. This detailed assessment of 2015 capabilities is provided as **Appendix A**).

*External Control System (**ECS**)*

In Phase I it was recognized that there was no mathematically based guarantee that the complex, fully autonomous control system envisioned would necessarily be self-optimizing, that is, always converge to produce superior forecasts. However, our assumption was that any actionable (and logical) feedback in a system is better than no feedback, and that if properly formulated, the two-way Interactive modeling and observing system concept should be capable of providing substantial benefits. An External Control System (**ECS**) was introduced to allow human monitoring (and control as needed) of the combined observing and modeling system performance. In Phase I, **ECS** also was viewed as the high level venue for implementing human-directed policy as regards security, prioritization and allocation of system resources among user organizations and interests. In Phase II, **ECS** was considered in greater detail, and ultimately given a significant role in the overall framework.

*Observing System Command & Control (**C^2**)*

We recognized that usual system engineering operations functions such as communications with observing assets, monitoring, telemetry, planning & scheduling needed to be performed, but they would need to be much more highly integrated and sophisticated than what is practiced today. The magnitude and complexity (intelligence and autonomy) of these functions, how and where (e.g. centralized vs. distributed, space vs. ground) they would be performed was part of the trade space, and could not be considered in detail independent of a fuller definition of the architecture and performance required of the Sensor Web. So in Phase I many functions were, as a temporary convenience, placed under a single **C^2** or "Command & Control" to be dealt with later.

In Phase I the "command & control" was assumed to house most of the intelligence of the overall system. Under Phase II, **C^3** will would be capable of optimizing non-routine observing, but merely carry out on instructions drawn from pre-scripted strategies provided to it through the External Control System. In other words much of the intelligence originally ascribed to **C^2** in Phase I might be shifted elsewhere, notably to the **ECS** whose capabilities under Phase II are enhanced relative to Phase I.

That the expression "command & control" in phase I was not in precise accordance with its normal engineering usage was a point of confusion in phase II discussions. In phase II **C²** was changed to "Communications, Command and Control" (**C³**); however, we were not able to perform a very substantial drill down on these functions in the allotted time.

Forward Model Function (Model Data Transform)

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 proxy 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 <u>any</u> 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 <u>forecast</u> state information relevant to each satellite and sensor are delivered to each platform and instrument. 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 model verification, 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 and significant, or suspect, before passing processed data back to modeling system for later assimilation.

This function is considered critical in the overall system architecture. In Phase II, It has been renamed to Model Data Transform in an attempt to avoid confusion with the phrase "forward model" as used in radiative transfer (although that <u>is</u> a subset of what is intended under the new label).

Data Reduction and Quality Control

In Phase "data reduction" refers to operations such as geo-location, calibration, and geophysical retrieval, much of which in the future, enabled by continued advances in miniaturized computing and storage, could most certainly be done at the observing platform. Today, virtually all quality control and processing of observational data that is destined for forecast offices or for assimilation into prediction models takes place on the ground at centralized repositories / processing facilities. Whether and how much processing might be done at the observing system level, and whether it would be beneficial, would come down to a trade-off between the cost of on-board processing (computing in space) versus the cost in dollars and performance associated with down-linking increasingly voluminous raw data streams to the ground where processing will always faster and cheaper by at least an order of magnitude.

Data and information processing depicted in figure 2 refers *only* to that processing associated with making observations usable by the forecast models, and therefore was situated in figure 2 to imply that these functions would be shared between the observing system and modeling in proportions that must be highly situation dependent and not easily generalized. It is also important to explain that figure 2 is a *functional* diagram. It addresses *what* happens, but not necessarily where. So, the correct interpretation of figure 2 is not whether processing is performed in space or ground (after all, Sensor Web is space *and* ground based), but whether processing is performed at the sensor/platform level or performed external to the observing system. Today, virtually all data processing is centralized at ground facilities; and concerted efforts to process data in situ are few and limited. This need not be the case.

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). As a consequence of the threshold and statistical techniques employed, current operational quality control algorithms reject as much as 10% of available data. 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 in principle be tasked to provide additional observations that help decide whether to keep, reject, or replace suspect flagged data. We believe the Phase I framework would enable this.

Targeted Observing

The “Targeted Observing” referred to <u>in Phase I</u> involves determining, based on internal dynamics of the model atmosphere, where and what observations will be most important for updating the model in order to optimize future forecasts. 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. The decision to execute a specific observing strategy implementation might be driven by where and when a model predicts rapid and 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 Sensor Web indicate deficiencies in model performance. There are a variety of techniques for estimating where observations are most needed based on analysis of model ensembles [5] [6] [7] [8], and the efficacy of model-guided targeted observing has been operationally established with respect to winter storms and hurricanes.

Perhaps the main innovation in the phase I study is the idea of a forecast system architecture designed largely to enable operational expression of model-based targeting observing. This and some other ideas from the Phase I study, interestingly are beginning to be explored in proposed decade-long international research efforts like THORpex [9].

Aspects Of Operations

Movement toward more frequent assimilation will enable 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 since the new architecture would enable and require tremendous increases in data acquisition. Ideally, a true time-continuous assimilation system will evolve, a concept whose feasibility and benefits have been demonstrated [10].

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. 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

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6 Majumdar, S.J., C.H. Bishop, I. Szunyogh and Z. Toth, 2001: Can an Ensemble Transform Kalman Filter predict the reduction in forecast error variance produced by targeted observations? *Quart. J. Roy. Met. Soc.* 127, 2803-2820.

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8 Gelaro, R., R.H. Langland, G.D. Rohaly and T.E. Rossmond, 1999: An Assessment of the Singular-Vector Approach to Target Observations Using the FASTEX Dataset. *Quart. J. Roy. Met. Soc.*, 125, 3299 – 3328.

9 Program Overview: The Observing System Research and Predictability Experiment THORpex, Melvyn Shapiro and Alan Thorpe, September, 2002. http://www.angler.larc.nasa.gov/thorpex/docs/thorpex_plan13.pdf

10 Ghil M., M. Halem, and R. Atlas, 1979: Time-Continuous Assimilation of Remote-Sounding Data and Its Effect on Weather Forecasting. *Mon. Wea. Rev.*, 107, 140 – 171.

observations diverge, and then target additional observations accordingly. Initial states derived hourly would serve as the starting point for short, medium and long-range forecasts.

The Phase I study concluded that in the future, operational forecasting and observing strategies will depend not on a single model forecast, but on many model forecasts being run in ensemble batches. 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 reliability measures 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. Statistical information derived from properly designed forecast ensembles is useful for carrying out targeted observing. Different ensemble sets may be required for each of these purposes.

3. The Phase II Architecture

Background

The ESTO 2025 weather study identified and described the architectural components for a sensor web-based weather forecast system that was characterized by a highly automated (and ideally, completely autonomous) "system of systems". Particularly noteworthy, the architecture emphasized the use of negative feedback (i.e., reinforcing), closed-loop processes to facilitate the dynamic interchange of information and to provide real-time control interaction between two of its principal subsystems: a weather observing system, and a modeling and data assimilation (MDAS) system. An underlying infrastructure, termed the "communications fabric and data grid", provides a variety of widely distributed communications and data services to move, exchange, store, locate, and retrieve many different forms of raw and processed sensor data, ancillary data and metadata, and node command, control, and operating state information.

The 2025 weather architecture was revisited and further refined and described in this follow-on study. In particular, this study peeled back layers of the onion to reveal additional details and key inner workings of the architecture's components. This study also investigated those elements of the 2025 architecture that might be realized in 2015 (in whole or in part) given a suite of observing system assets (i.e., spacecraft missions, and atmospheric and ground sensors) and "non-observing assets" (e.g., MDAS and numerical weather forecast modeling systems) that are expected to become available in approximately 12 years. For those information technologies or observing system assets that are not presently planned to become available in 2015, recommendations have been made for NASA investment areas. Investments in new technologies that are on the critical path for a 2015 implementation of the architecture will help to ensure that the full-featured Sensor Web-based weather forecast system can be realized by 2025.

Approach for the Phase II Study

Phase I arrived at a conceptual two-way interactive Sensor Web and predictive model that we believed in principle might be capable of extending the useful range of long-range (12-14 days) prediction. Since numerical weather prediction is an initial value problem, any improvements at ten to fourteen days could only occur with comparable improvements for shorter-term weather forecasts. Thus, Phase I provides a framework potentially to result in benefits at all forecast time scales. However, which architecture components and interactions that would be most important would depend on the time and space scales being forecast. For example, for a 3 – 5 day forecast, model-based targeting elements might be most important; but in a 6– 36 hour forecast situation, real-time feedback from the observing system to the model is more likely to be important. The Phase II study was to examine this by invoking real world forecast situations as scenarios that would exercise various elements and interactions within the architecture.

One of the limitations of the 14–day study was that, as a purely conceptual exercise, it necessarily involved educated speculation on almost every relevant future technological capability from constellation management, to computing technologies, to communications, to observing technologies. In other words it was built by assumptions on top of assumptions. This Phase II study builds on the previous study, by adopting as a starting point the sensor web architecture developed in Phase I. However, in order to bore down into the deeper meaning of the two-way interaction, we believed it was important in Phase II to control the speculative elements in order to examine the architecture functionality in more concrete terms. Our approach to this was to:

1. Focus on forecast problems and forecast time scales that we already know are tractable (as opposed to the two week forecast). For the case scenarios we considered forecasts of phenomena whose evolution and prediction encompassed time scales ranging from one to five days.

2. Limit speculation on observing system to capabilities that are well-understood extensions of current technologies. Specifically, we considered of research and operational space-based observing systems that already exist, or are being planned now for operational deployment or implementation in the 2010 – 2015 time frame, including NPOESS, GOES-R / GIFTS, GPM and Radio Occultation Sounding methods, UAVs.

3. Examine well-documented actual forecast situations in which the operational forecast system failed, and assess how these failures could have been addressed in the two-way interactive Sensor Web and Modeling / Assimilation system.

In short, by selecting a forecast range known to be tractable, by naming the scenarios and phenomena of interest up front, and knowing the class of observations that will or should be available (and needed in our scenarios), we would focus more clearly on how the entire system must operate and be designed in order to provide the needed coordination among space and terrestrial based observing systems, and operational weather forecasting and modeling systems

Even prior to the scenario exercise, at the start of phase II we recognized that a number of refinements to the phase I architecture were needed that were not addressed or only partially addressed in Phase I. Among these were needs to: explicitly show feedbacks between the observing system and itself as a sensor web; explicitly integrate human-based forecast operations as part of the overall architecture; clarify and develop the roles of the External Control System, and; clarify and develop the functionality of the “Command and Control” (**C²**). These and other issues were addressed in Phase II.

Figure 3 represents the final Phase II improvements in the overall architecture, including those made both before and as a result of the scenario exercise (figure 3 should be compared with figure 2 reproduced from the Phase I study report).

The main components elements comprise the Sensor-Web-based Weather Forecast System Architecture depicted in figure 3 are: (i) an Observing System, (ii) a Modeling and Data Assimilation System (MDAS), (iii) Forecast Operations (including weather data user communities), (iv) an External Control System and (v), a Communications, Command and Control System. All these components are intended to interact via an all-important Pervasive Communications Fabric and Data Grid.

Although figure 3 depicts the principal functions associated with each of these five elements, the reader should not infer *where* a particular function might reside. For example, "Event and Change Detection", a functional component of the "Observing System", may be implemented for and reside with a sensor node or asset (e.g., a spacecraft's on-board computer). Alternatively, a function may reside in one or more traditional ground-based computing nodes. Determining factors will include the computing and local storage requirements, and the need for ancillary data and its potential impact on the asset's concept of operation [11].

11 For example, if a spacecraft requires ancillary data to perform feature recognition, one will need to determine the impact upon communications uplink bandwidth, link availability, etc to provide the required information to the spacecraft's OBC.

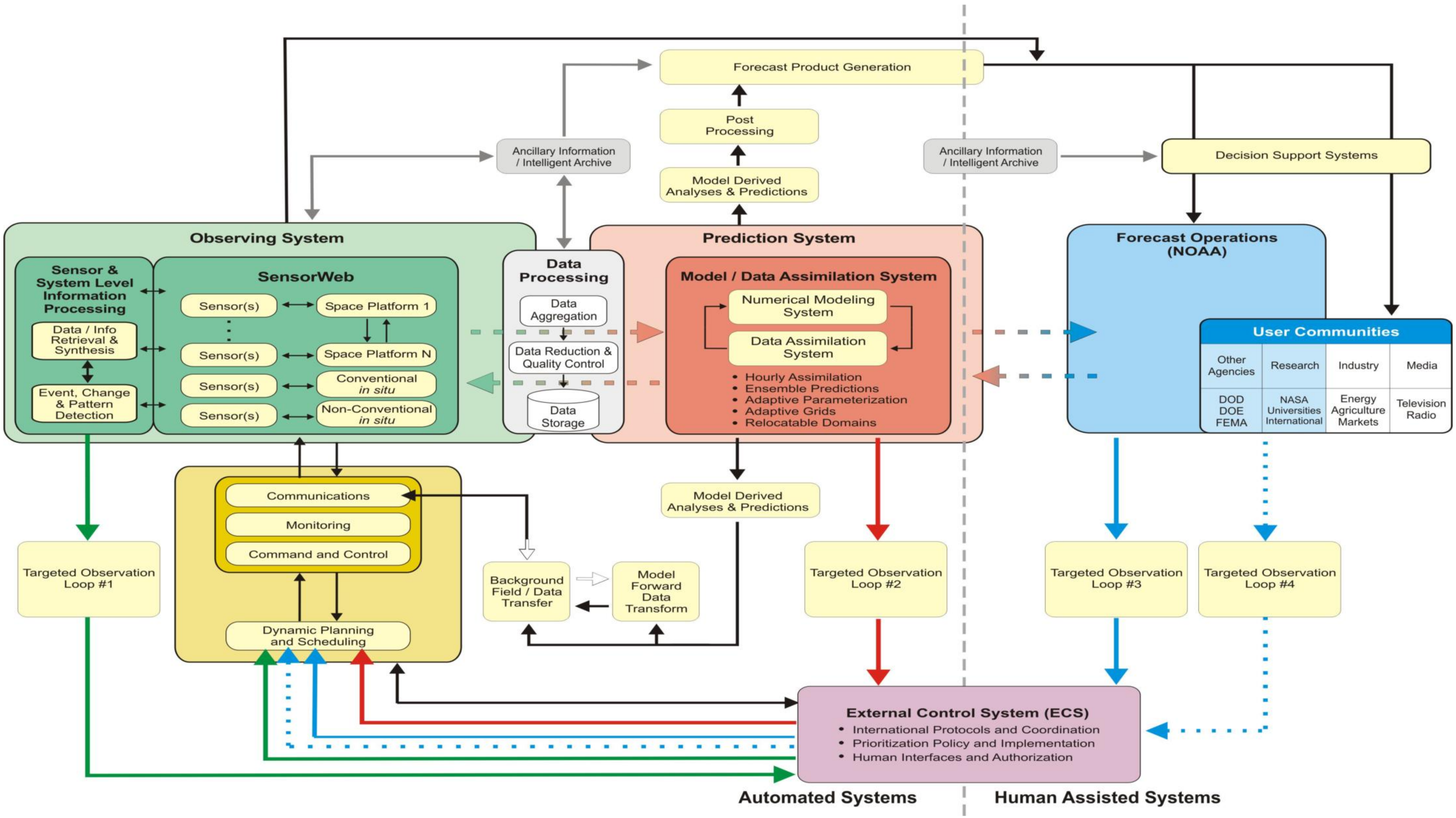

Figure 3. Two-way Interactive Modeling and Sensor Web Based Weather Forecasting System Architecture from Phase II study.

Description Phase II Architecture Functionality

The following sections describe key system functionalities from the perspective of the Phase II study exercise.

The overall two-way interactivity between the observing system and the modeling system is fundamental to the architecture in Phase I and Phase II. Below we review the intended the functionality of this major feedback (referred to now as Targeted Observing Loop #2) and the feedback between the observing system and itself (now Targeted Observing Loop #1) . We also introduce two added feedbacks with the observing system that engage the human forecasting and user community.

The functions associated with Observing Loops #1 and #2 from the Phase I study, with recent refinements, are listed in text boxes below. In Phase I, these feedbacks were thought of as potentially capable of operating autonomously without significant human intervention. In Phase II, it was determined that in the near term (2015) and longer term (2025 +), some level of human oversight would be necessary except in trivial implementations of these feedbacks. This oversight would come about though interactions with the newly considered External Control System.

Targeted Observing Loop #1 involves the ability of the Sensor Web to interact with itself. Among the intended functionalities are:

1. Observing based on automated detection, extraction, recognition and characterization of phenomena or spatial (vertical or horizontal) structures with actual or potential meteorological significance, and their changes over time
    - Directly observed variables & parameters (e.g. temperature, humidity, surface T)
    - Derived or calculated variables, descriptors, proxies (e.g. static stability, gradients, ozone-pv)
    - Static representations (feature detection; linear, spiral, etc.)
    - Time sequential representations (change detection; expansion, rotation, rates of)
2. Observing needed to supplement or complement other observations, or as required to enable calculation of derived quantities
3. Observing needed for quality control / or to confirm suspect observations
4. Observing to support ongoing scheduled calibration / validation of space based instruments
5. Observing in anticipation of developments based on codified empirical human experience
6. Observing in anticipation of developments based on self-learned empirical rules

Targeted Observing Loop #2 involves the ability of the Sensor Web to receive and act on instructions generated by the numerical model prediction system. Among the intended functionalities are:

1. Targeting providing additional "strategic" observations to help confirm / refine previous model predictions that have indicated some specific meteorologically and operationally important development
2. Directed observing based on proximity to analyzed or forecast development and structure of specific evolving phenomena
3. Targeted or enhanced observing to provide additional observations in areas where model(s) predict specific rapid, as yet uncharacterized changes, suggesting or leading potentially to the development of meteorological important features and structures
4. Enhanced observing driven by unfavorable real-time comparisons of observations relative to numerical model analyses & predictions [failure to validate]
5. Observing in anticipation of specific developments of interest that derive from numerically or theoretically-based model predictions (Targeting observing driven by theoretically-based, MDAS-based calculations)
6. Targeting based on ensemble-derived model sensitivity to observation input (location & type)
7. Enhanced or accelerated observing Targeting based on ensemble-derived model forecast uncertainty
    - Intra-model ensembles (physics based, resolution based, Initial Condition based)
    - Inter-model ensembles (super–ensembles)
8. Observing to enable discrimination of best model and model characteristics from among a number of ensemble members [also super-ensemble members]
9. Directed observing in response to divergence of specific solutions among models
10. Directed observing in response to vacillation of specific solutions in successive same-model runs (d prog / d t).

Here we discuss some implications of explicitly including human-based forecast operations within the overall framework. Most notably we define two additional feedback Loops #3 and #4.

FEEDBACK LOOP 3: Forecast Operations – Sensor Web Interaction

At present, most weather observations are acquired on fixed schedules at more or less fixed locations. Forecast Operations personnel have little direct influence or means to change observation system behavior except in relatively simple ways. Neither the majority of current observing systems nor supporting technical and organizational infrastructure permit independent or coordinated ad hoc tasking of even small numbers of assets. It has only been recently, that the value of human-directed targeted observing (aircraft) in the context of winter Atlantic storms was field-proven [12] [13]. This is a simple example of human-interactive observing that is operational within NWS. Still, the decision making process is cumbersome, and the lead time between recognizing that targeted observations would be useful and the time aircraft can be actually deployed is at least twelve hours. In the future, with near real-time communication and flexible integrated Sensor Web based observing, the time scale of request-response could be measured in tens of minutes, not hours. Advanced, intelligent decision support tools will be necessary to enable human teams to efficiently recognize the opportunity and need to make a decision, and to quickly extract and analyze the information most necessary to make specific observing recommendations. This level of functionality is what is envisioned in Targeted Observing Loop #3.

Targeted Observing Loop #3

Target Observing Loop 3 gives forecasters within the agencies responsible for forecast production and dissemination the ability to request special observations or observing modes as needed to improve operational forecasts.

In addition to decision aids needed to enable fast interaction between forecasters and the observing system, other automated decision tools and techniques will be needed for forecasters to make special observing recommendations relying on facilitated analysis of larger numbers of model ensemble forecasts. In some cases, forecasters may even be able to direct special model runs based on facilitated analysis and comparison between observations and model predictions. This is the type of interaction indicated in Figure 3 by the dashed arrows between the MDAS and Forecast Operations Components. The way we envision human forecasters interacting with the observing system and modeling system are illustrated below in figure 4.

12 Toth, Z., I. Szunyogh, S. Majumdar, R. Morss, B. Etherton, C. Bishop, S. Lord, M. Ralph, O. Persson, and Z.-X. Pu, 2000: Targeted observations at NCEP: Toward an operational implementation. Preprints of the 4th Symposium on Integrated Observing Systems, 10-14 January 2000, Long Beach, Ca, in print.

13 Burpee, R., J. Franklin, S. Lord, R. Tuleya and S. Aberson, 1996: The Impact of Omega Dropwinsondes on Operational Hurricane Track Forecast Models. *Bull. Am. Meteor. Soc.*, 77, pp 925 – 933.

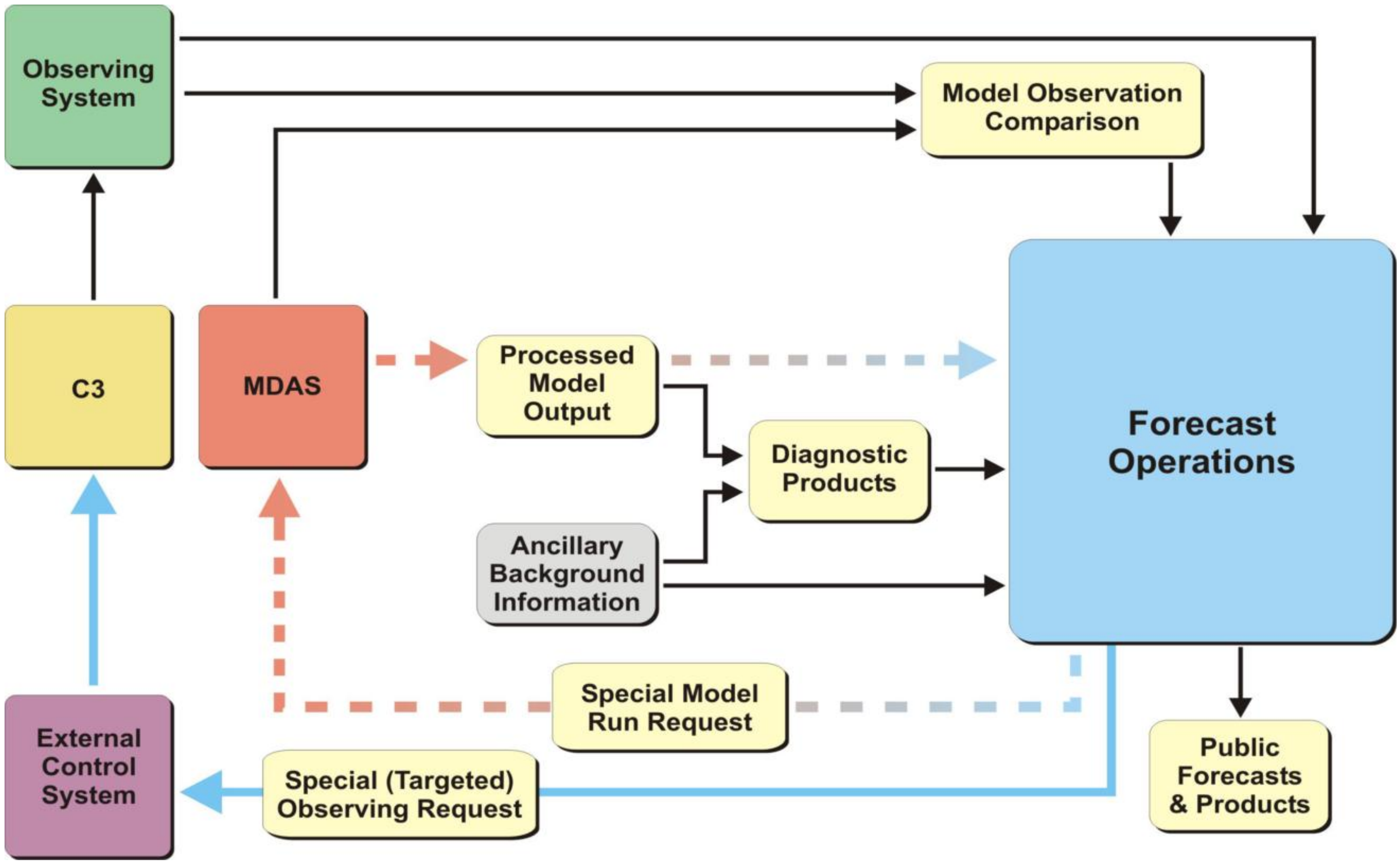

Figure 4: Relationships between Forecast Operations, Sensor Web and Modeling System relative to overall system architecture functioning.

FEEDBACK LOOP 4: User Community - Sensor Web

Targeted Observing Loop #4 provides for the ability of entities other than those directly responsible for operating the system and generating operational public forecasts, to influence data collections to meet their specific needs. Because the entire system probably will evolve as a cooperatively owned and operated capability involving other interests from academic to commercial who may have legitimate and competing needs for addressing the system with targeted observing requests, control of all decision making regarding access and use of the observing system may not fall under a single agency.

Targeted Observing Loop # 4 involves

The ability of entities/ organizations other than those directly responsible for operating the system or generating operational public forecasts, to influence data collections to meet their specific needs. This includes:

- University and Research Community
- International Weather Agencies
- Government Agencies, including Military, Homeland Defense
- Commercial Weather Products and Value-Added Vendors

External Control System

In Phase I the External Control System was defined as a set of functions that execute human–based policies regarding access to the Sensor Web and resolving issues of competing priorities among groups nationally and internationally. Looking beyond 2025, in Phase I we assumed in that the main feedbacks (Targeted observing operations) in the overall system would be able to operate with minimal human direction.

However, given the additional explicit involvement of human forecast operations and user communities, greater consideration needed to be given to human-based controls and, specifically greater functionality of the External Control System. At the end of the Phase II study, it was determined that **ECS** become the place where ***all*** targeted observing requests (#1, #2, #3, #4) are assessed against established priorities and asset availability. In this expanded view, in a resource-limited situation, human forecasters will compete with model driven and Sensor Web based observing requests. This fact that some negotiation is therefore required, , led to the decision to have both observing loops #1 and #2 not be completely autonomous but work through the ECS.

The process illustrated in Figure 5 is as follows: Observing requests from any of the four targeted observing loops are received by the ECS, where it is authenticated and assigned a priority based on the privilege of the requestor and the urgency of the request (e.g., military operations, imminent loss of life and property). Every submitted request includes information about the type of observation requested, when and where, specific observing assets to be addressed if known, the level of processing required of information to be returned, where to notify the requestor, and a time period through which the request remains valid. With this information in hand, based on system asset state information continuously pushed from monitoring, an initial assessment is made with regard to the *logical feasibility* of the request based on assets that *might* be available and capable in principle of fulfilling the request, and based on the priority of the request relative to pressing operational demands and other special requests. If passing these general tests, ECS actively queries **C³** Planning and Scheduling to confirm actual status and availability of specific assets meeting the request parameters. Throughout the process the requestor is automatically informed of the status of his request with indication given if any aspects of the request are unlikely to be accomplished. The requestor may have the ability to give a final approval to proceed or to scale back or terminate the request.

Assuming final approval, **ECS** generates the instructions that the **C³** will then translate into commands to be issued to the observing components throughout the Sensor Web. As illustrated in Figure 5, the expanded ECS may also coordinates and ensures that any ancillary services (e.g. data transformations) and ancillary data (e.g. algorithm coefficients, first-guess information) that may be needed in order for the observing instructions to be carried out at the observing platform come together. Ideally, both the observing request and supporting ancillary information are staged to the **C³** for transmission to the observing platform as a package.

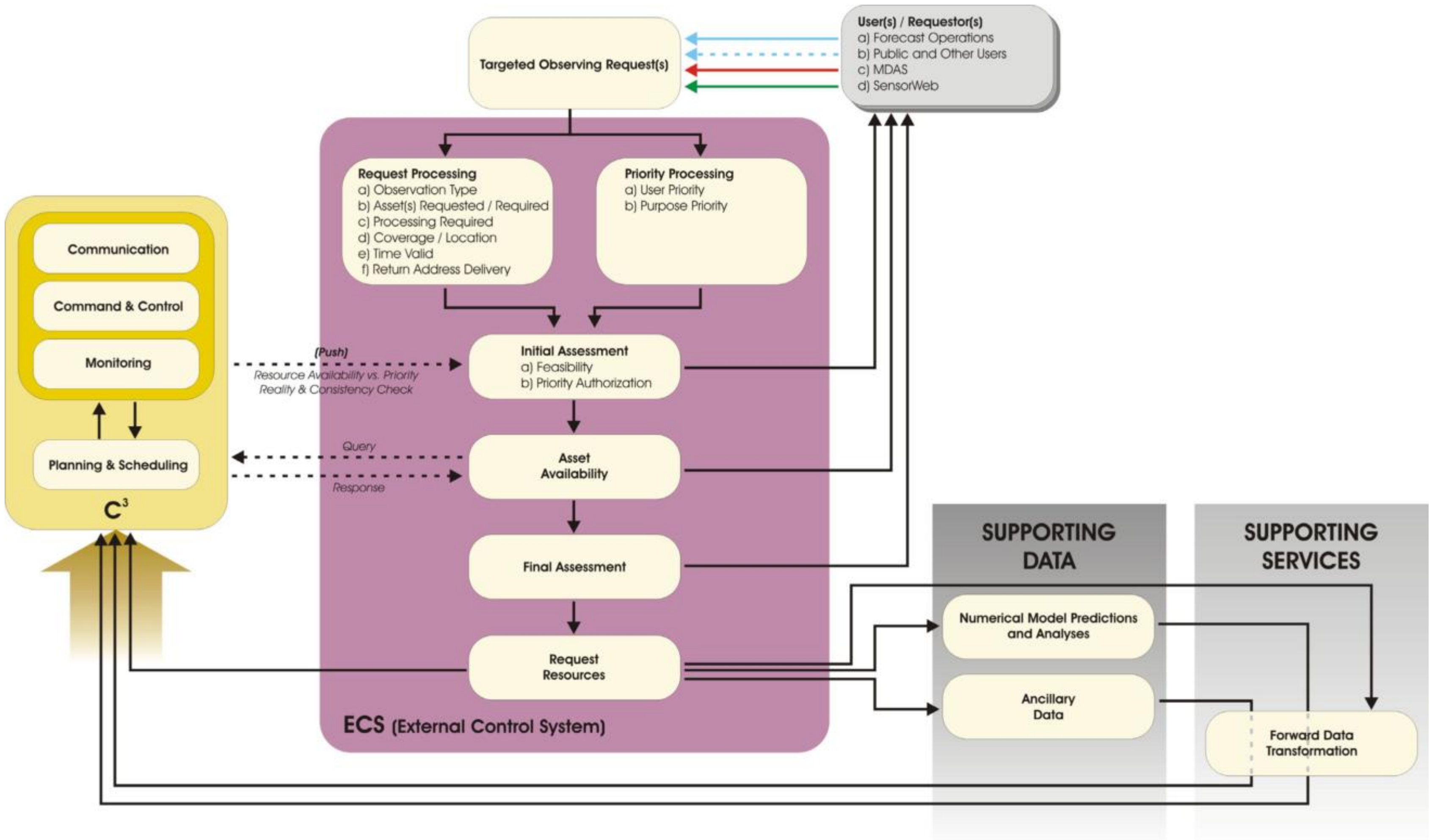

Figure 5. Process Flow and Role of the Phase II External Control System.

Decision Support Aids

Figure 3 includes decision support systems. The AWIPS system in use today by the National Weather Service brings large amounts of data and model diagnostic products to the forecaster's screen, but integration of those data is largely limited to the capacities of human operators. There is yet little or no provision for taking advantage of intelligent, autonomous feature or pattern recognition. Out intention is to suggest new generations of automated, intelligent, integrative tools that extend the intellectual reach of decision makers to integrate information real-time. Such tools might point out model or observational trends or highlight relationships among variables that may not be apparent because of their subtlety, complexity and volume of information. An example of where this might be valuable is in inter-comparing and assessing the future performances of different forecast models based on recent past performances, or assessing the information content from large numbers of ensembles. New tools can be developed that specifically facilitate human initiated targeted observing requests (Targeted Observing Loop #3) particularly those that involve interpreting ensembles. Tools could greatly facilitate targeting decisions, which today are usually the result of intensive consultation by committees of individuals even though the observations themselves are presently relatively simple and limited.

Decision Support Aids as expressed in figure 3 is also intended to address new communities, from researchers to homeland security and natural hazards agencies, who are users of weather information, but who need to see it integrated with other information in order to impact decisions in actual real world applications. These new users of weather information may not only be able request specific observations (Targeted Observing Loop #4), but they may be also levy requirements for decision support aids developed specific for their interests.

Ancillary Data

Ancillary Data is *supporting* information needed to carry-out any of the major functions in Figure 3. Although it is shown in two places, its availability is assumed in the long run to be pervasive through the communications fabric. It is ancillary only in the sense that it is needed by some other asset to carry out its own purposes. The reference is generally to data and information that is available remotely needed either because it is too voluminous to be stored locally, is might be needed only infrequently, or is created or refreshed dynamically by other components and assets in the system. Ancillary information may reside anywhere within or external to the forecasting system architecture. Today, such data resides in designated ground-based repositories.

Given the declining cost, increasing capability and physical footprint of storage media, it is increasingly likely that much information will be stored with the observing platforms that use it most, or stored with the asset that creates it. It may also be possible that a component of the architecture may require simultaneously pieces of information stored in different locations, and an intelligent agent, facilitated by the communications fabric, will to bring those data together as needed by the requestor. The agent may even anticipate the request, and store until it is called for. In either case, a pervasive communication fabric and data grid infrastructure allow information to be readily exchanged.

Ancillary data could be comprised of almost anything. An example of could be historical / climatological information used to provide first guesses for geophysical retrievals, or baselines for assessing model predictions or observations to support quality control, calibration or event and change detection functions. Such information might have the form of registered images, pattern detection and analysis routines or as statistical information. Other types on ancillary information might include parameter and co-efficient sets needed to update or tailor forecast model parameterizations to match observations, or uploadable programs or scripts needed to carryout specific observing modes in support of a research experiment.

Background Field/ Data Transfer and Forward Model Data Transform

Background Data Transfer refers loosely to the process by which Atmospheric state information (or "meteorological context") is conveyed to the observing system. Model generated background data (fields, profiles or point information) created by the prediction model(s) are forwarded to an observing platform or asset (through **C³**) to be used as first guess information for geophysical retrievals or as a contextual aid in assessing observation and model performance. The information conveyed might be derived from a "current state" analysis or prediction generated by the Modeling & Data Assimilation System (MDAS). It might be raw model output, or it might be first transformed to match observing system geometries and parameter spaces as suggested in figure 3.

An example of contextual information might be model-derived fields of a convective instability parameter (such as Lifted Index), or even model predicted convection. Such fields might be remapped (or transformed) to satellite observing geometry and used to intensify satellite (and terrestrial) based observing and processes in such areas identified as areas at high risk of storm development. Another example would be simulated radiance fields computed from the model forecast (transformed), that could be compared with actual satellite radiances as part of a change detection script.

Model & Data Assimilation System

Figure 6 is presents a slightly different perspective on the relationship between the MDAS and other components of the overall architecture. It is different from the phase I vision of a single very high-resolution global model. It is a reasonable projection of current operational practices and evolutionary plans involving a hierarchal modeling framework whereby large coarser scale models provide boundary and initial conditions for models whose domains are smaller, whose resolutions are finer and whose physics may be more detailed and tuned to represent specific phenomena.

However, we suggest greater functionality in which the coarser scale models may automatically initiate execution of finer scale models based on self-recognized deficiencies in coarse model performance relative to observations, or simply self-recognition that higher resolution may be required to better represent poorly resolved phenomena or events that are likely to occur that will not be best represented by the coarse model. It is predicated on the ability for the phenomena and structures that are either observed or developed in a coarser scale model to be inventoried and automatically classified as a particular category of "event" that merits a particular action or not. As an example, a global domain coarse model indicating strong baroclinic development with the suggestion of severe weather potential may trigger a nested higher resolution model focused on a specific region. A synoptic or regional model might trigger a very high-resolution local model somewhere; the coarser model would provide boundary and initial conditions, and would specify location, resolution, time step, simulation start and stop times, and even physics packages and parameters. Evidence of tropical instability in a model might trigger a high-resolution model with physics appropriate to capturing incipient hurricane development.

Also shown in figure 6 a pathway whereby human forecasters are able to initiate regional or local models on demand. This is consistent with NWS plans that will allow Weather Forecast Offices to run their high-resolution mesoscale models locally (Local Area Prediction System, based on MM5). At each scale, any number / permutations of different forecast models with variations in physics, vertical or horizontal resolution could be run as carefully constructed ensemble sets that would be analyzed to support decision making regarding: a) weighing observational error relative to forecast error in the process that create the "best analysis"; b) determining a maximum likelihood "best forecast" solution from among ensembles, and c) supporting targeted observing analysis. Targeted observing would also be based on consideration of the significance of actual phenomena being generated in the forecast models. For example, a forecast of major cyclogenesis would probably result in requests for intensified observing upstream of the identified area, or trigger more focused model runs as described above, independent of any parallel ensemble-based targeting.

Gridded model analyses or forecasts would be the source of state information providing first guess and other situational meteorological context that must find its way to the observing system (and specific assets within it) in order for the observing system to be able to fully exercise its intended functionality. The analysis of model data to discern event situations or phenomena would be performed within the "Observing Requests" function inside MDAS, and the nature and priority justification of the request would be part of the metadata instruction set that goes ECS to be vetted against policy, priority and reasonableness criteria.

Given the details of a specific observing request, ECS would have a knowledge base enabling it to "understand" the associated requirements for model-based contextual and ancillary data and any transformation requirements as was shown in figure 5. However, these data are not required to go through ECS directly. ECS just identifies and communicates to relevant parts of the system what data and processing services are needed to fulfill an observing request, and when and where the information is to be staged for communication to the impacted observing assets.

A significant level of observational analysis and processing is assumed to occur potentially at the observing system and observing platform. In routine or default observing mode, the observing systems feed the operational models with observations that will be formatted and staged for assimilation. But at a more sophisticated level, which goes to the heart of the two-way feedback, higher level analysis of sensor web observations aims to support the continuous assessment of model performance, by comparing observed states and patterns of change with those expected based on model (context) information. This type of information is to provide guidance that could result in changes to model operations such as triggering nested regional or local models.

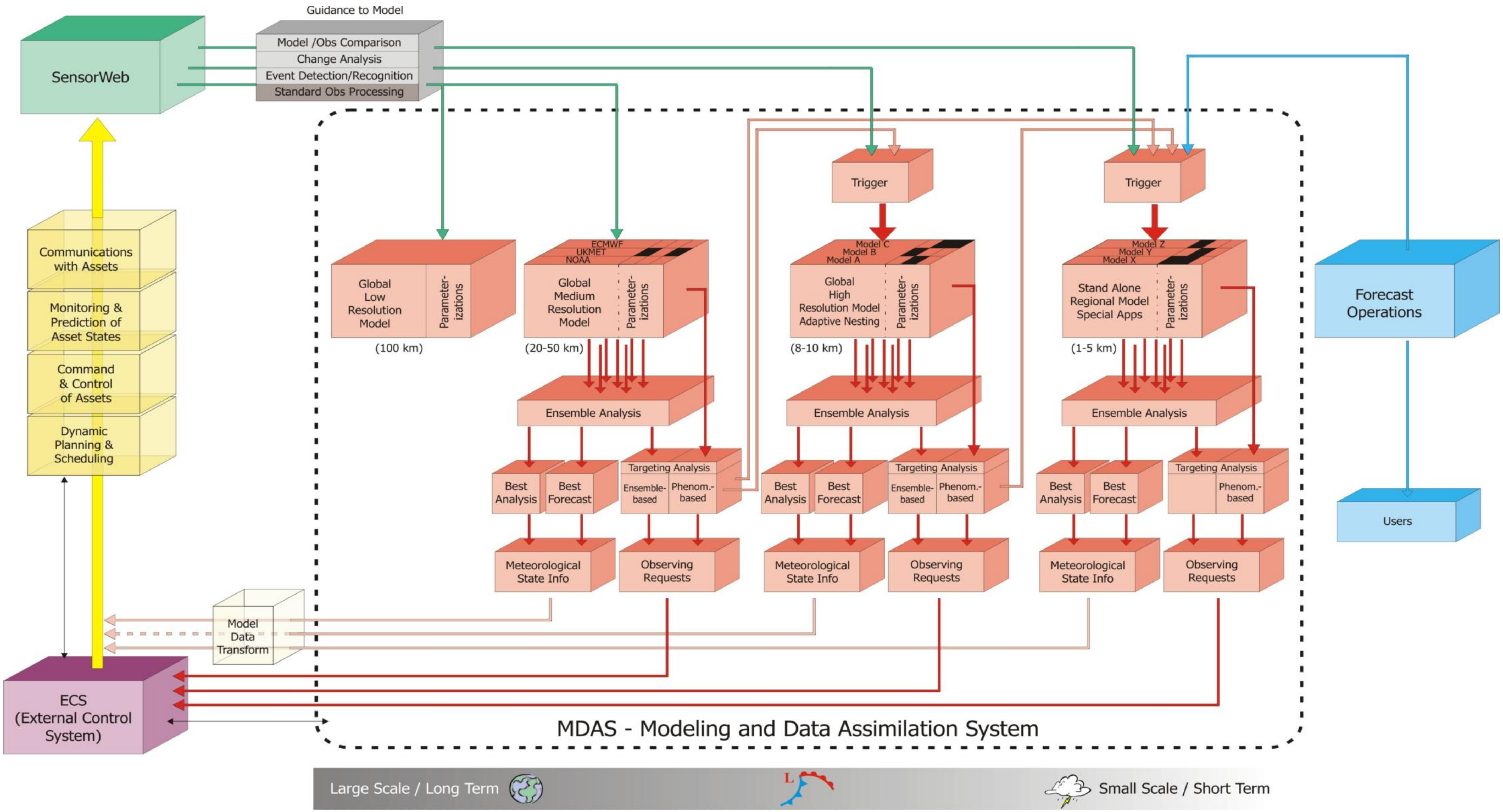

Figure 6. Model and Data Assimilation System (MDAS) processes and key interfaces with other overall forecast system architecture components.

4. Concept Evolution Overview

The evolution of the main concepts for the two way interactive Observing and Modeling system is illustrated in Figure 7 (a-e). It shows process and information flow among observing–modeling-forecast–dissemination elements of the forecast system at different stages of the Phase I and Phase II studies. Today (figure 7a), information flow is one-way: Observations are made available both for assimilation into forecast models, and for direct analysis by government forecasters and users in government and private sectors; Model (**MDAS**) products provide input to government forecasters and to value-added providers; Government (**OPS**) forecasters disseminate forecasts based on human interpretations of models and data. There is little information flow in the other direction (feedback), or even the capacity for the system to accommodate or act on such information. That is, operational forecasters cannot directly impact operational aspects of either modeling or observing, and the results of models cannot change operational observing.

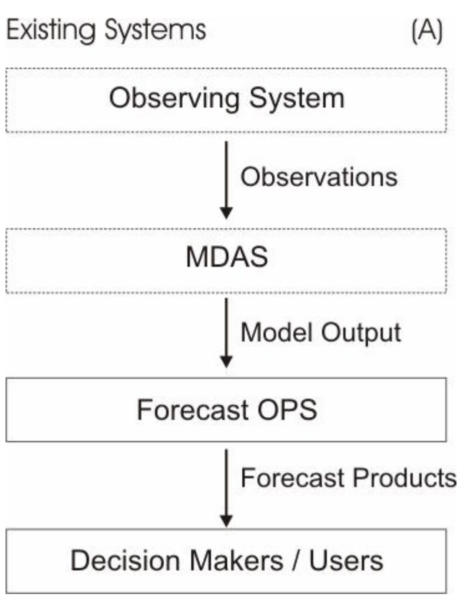

Figure 7a

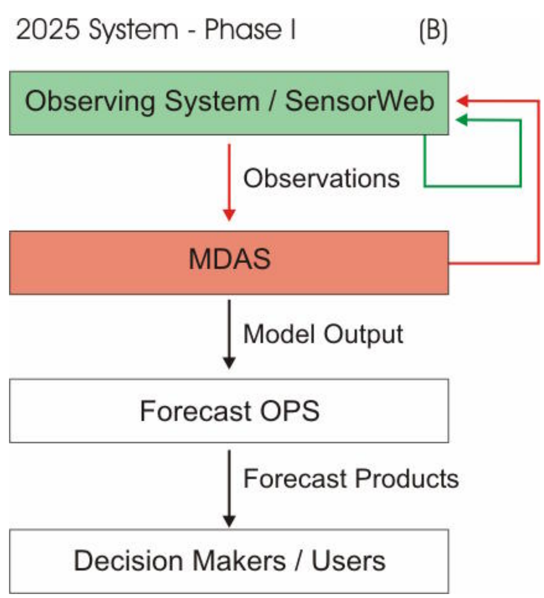

Figure 7b

Figure 7b shows feedback loops #1 (green) and #2 (red) conceived in the phase I study. Figure 7c shows these same two loops relative to major functional blocks in the Phase I architecture. Notably, in Figure 7c the **ECS** was not well defined in Phase I and is shown unconnected to the rest of the architecture. Targeted observing loops are shown as fully autonomous interacting directly through a command and control (**C**^{2}) utility independent of specific human controls. Forecast Operations and interactions with the user constituencies were not considered in the Phase I 2025 vision (and so are shown in black ands white). Figure 7c corresponds directly with Figure 2.

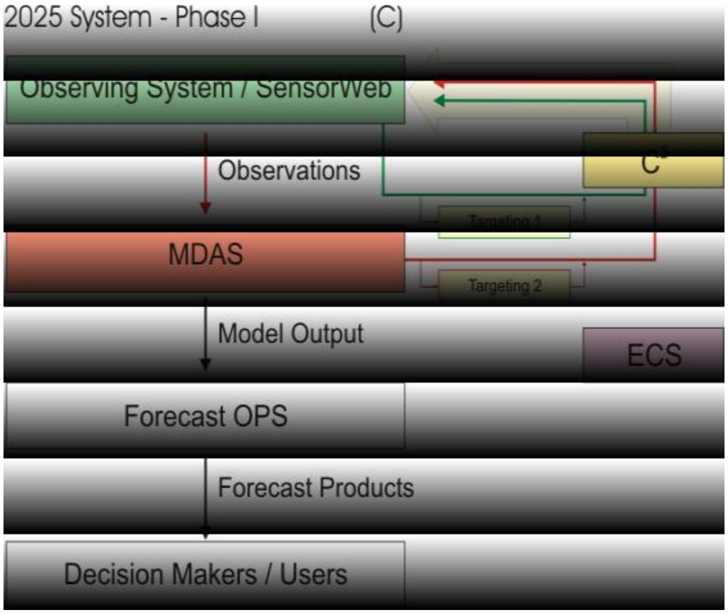

Figure 7c

The first Phase II architecture refinement (figure 7d) shows observing Loops #1 (Red) and #2 (Green) still operating independent of specific humans controls. However, the role of human forecaster and user communities has been added with targeted observing loops #3 (Blue solid) and #4 (Blue dashed). Human observing requests are first vetted through an External Control System facility.

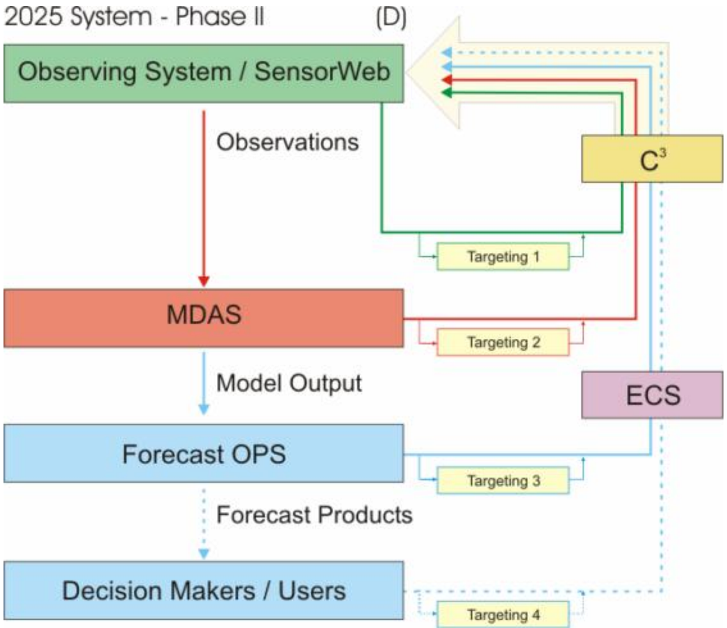

Figure 7d

Figure 7e, which corresponds to figure 3, shows the key functionality and relation among large components of the architecture at the end of Phase II, and following completion of the scenario study. The only major change as a result of the scenario study (between 7d and 7e) was that *all* targeted observing requests (Loops #1, #2, #3, #4) must first be assessed by a much more capable External Control System. This limit to autonomy was thought necessary, since conflicts between model or sensor web generated observing requests and human generated observing requests would be significant enough that they would need to be resolved within a common policy framework provided by the external control system. The only other change as a result of the scenario study was to explicitly acknowledge two-way interactions between the modeling & assimilation system and human forecast operations.

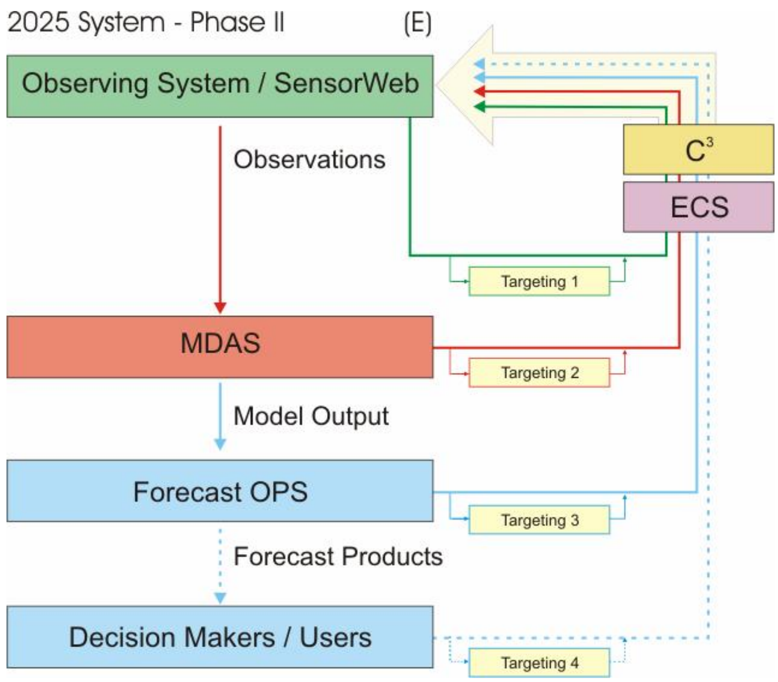

Figure 7e

Figure 7 (a-e) Graphical depiction of the evolution from Phase I through Phase II of key feedbacks among elements of the overall forecast system architecture.

In summary, Figure 7e (which corresponds to figure 3) represents a future capability in which traditional stove-pipe information flows and overall system performance (forecast skill) are enhanced by four distinct targeted observing feed back loops, representing: a) the ability of the observing system to feed actionable information to itself (Red, Targeted Observing Loop #1) b), the ability of a numerical weather prediction model & assimilation system to drive alternative observing strategies and observing system behavior (Green, Targeted Observing Loop #2) , c) the ability of human forecasters to levy specific observing requirements and observing system behaviors, (Blue, Targeted Observing Loop #3) and, d) the ability of external/ non-governmental communities to levy specific observing requirements and observing system behaviors (Targeted Observing Loop #4, blue dashed line). Feedback loops #1 and #2 were addressed in the Phase I study. Phase II add Loops #3 and #4, recognizing the need to explicitly incorporate human judgment and controls.

5. Trends & Developments Relating to Phase I Vision

As reflected in the discussions of the Phase II study team, this section briefly comments on trends and advances that are relevant to the feasibility of implementing aspects of a two-way interactive sensor web and modeling forecast system. Some of these are very recent developments since the Phase I report; others were ongoing, but about which the Phase I study team was not aware at the time. Despite many practical, fiscal and political challenges, there is some basis to believe that given continued advances against these trends, significant functionality of the type envisioned in phase I could be demonstrated in prototype within 25 years.

Very High Resolution Global Modeling

Many of the assumptions made in the Phase I study were regarded skeptically at the time of the Phase I study. For example, several modeling experts were uncomfortable with the proposition that it would be feasible to run a global mesoscale model at 1 – 10 km resolution operationally. But the NWS' own long-range plans [14,15] anticipate coupled atmosphere-ocean models running at these resolutions. The Earth Simulator Center in Yokahama, Japan has reportedly already begun routinely running a 10 km global model for weather and longer-term climate research. So the computational power needed for global very high-resolution models will probably continue to evolve steadily. The real computational requirement challenge will be the need for running significant numbers of ensembles on an intensive operational schedule.

There was discussion about whether it is more sensible to run full resolution global models or rely on nesting strategies. The current practice is to run nested models that use boundary conditions from coarser resolution models covering a large domain. The coarser model provides the boundary conditions to nest smaller domain models in steps of sequentially higher resolution. When dealing with very long-range (two week) forecasts, as in the Phase I study, a high-resolution global model is needed to eliminate small errors associated with imperfections in specifying lateral boundaries. Since the objective of the Phase II study is an improvement of a one to five-day forecast with the computing resources available in 2015, nesting models might be the most desirable solution.

In Phase II the MDAS is comprised of a hierarchal sequence of models from global to local scale. These models can relate to one another in semi-autonomous fashion, such that observed or predicted events by one model can automatically initiate and define domains and configurations of nested models. In addition, we allow for local forecasters to initiate local/or sub-regional forecast models, as part of a feedback between the MDAS and Forecast Operations (human) components of the overall forecast system architecture. These notions to some extent reflect automation improvements to existing practices, and are philosophically consistent with the National Weather Service's long-range plans.

14 NRC Report, "A Vision for the National Weather Service: Road Map for the Future (1999), National Academy Press, Washington D.C (http://www.nap.edu/openbook/0309063795/html/5.html,copyright)

15 National Weather Service Science and Technology Infusion Plan: A Roadmap to 2025, October 2001, U.S. Department of Commerce

Globally Coordinated Earth Observing

An assumption of the Phase I study was that a globally integrated observing system capable of providing nearly continuous 25 km coverage was needed for significant long-range forecast skill improvement to be achieved. This requirement was based on the perceived need for continuously updated and stringently quality controlled initial states for long-range model predictions. Additionally, it envisioned that all space-based weather observing assets, whether owned and operated by the U.S. or by other nations would be part of a system unified by common protocols and access, and perhaps under the control of a common international authority such as the WMO.

Although obvious and numerous political realities would make this difficult today, although long range plans for national interagency and international cooperation for an interoperable global weather observing system are being discussed today that might bear fruit in the 2025 timeframe. Specifically, this is seen in a recent draft NOAA/ NESDIS strategic plan document [16], wherein it is recognized that "A truly integrated global observation network exceeds the capability of any one country or any one agency. As a result, international and interagency cooperation is necessary to address duplication, omission of existing and planned environmental observing systems. A first step towards building an integrated global observing system is to garner support from senior-level government representatives to promote the value of a global Earth observation system that integrates space-based and in situ observations. U.S. led efforts such as the July 2003 Earth Observations Summit [17] demonstrate our commitment..."

In addition, specific plans for international coordination of weather observing system standards to facilitate a truly interoperable global observing system are beginning to take shape. A first step to international standardization and collaboration is the Initial Joint Polar Satellite System, in which EUMETSAT and NOAA will provide (2005) for joint operation of polar orbiting weather satellites.

The trend is such that in the future all weather observing and forecasting activities will involve sharing not only global observing resources and data, but sharing of authority for determining priority uses of those resources among various international, governmental (including research, hazards and defense) and non-governmental (including civilian forecasting) interests. A means for resolving competing priorities among various interests is assumed to reside within the External Control System.

Dynamic Data Driven Application Systems

NSF's Computer and Information Science & Engineering Directorate has sponsored several workshops to bring together applications (from medicine to traffic control, to economics) that would be enabled by the ability to implement two-way feedbacks between predictive simulation models and measurement systems. The goal of these efforts is to evolve a common conceptual and analytical system framework dubbed "Dynamic Data Driven Application Systems" (DDDAS).

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16 NOAA/NESDIS, May 22, 2003, "Priorities for the 21st Century: A Strategic Plan for NOAA's Satellite and Information Service for FY 2003 – 2008 and Beyond

17 Reference: http://www.earthobservationsummit.gov

Quoting from NSF reports [18]…"the new paradigm seeks to establish capabilities where the simulations can be used to steer the experiments (measurements) or the field data collection or mining process. Such a synergistic feedback control loop between simulations and measurements is a novel technical direction with high potential payoff in terms of creating applications with new and greatly enhanced capabilities..... The data driven aspect of these problems pertains to the closed loop between applications, algorithms and data. The incoming data stream can be used for dynamic decision making and for adapting the underlying models of the phenomenon".

The Phase I two-way interactive Weather Forecast System framework maps perfectly to these efforts and exemplifies, for an emerging NSF community, the conceptual feasibility and usefulness of interacting simulation and measurement feedback systems.

Pervasive Interoperable Communications and Computing

The 2025 architecture assumed the existence of a pervasive computing and communication infrastructure with seamless interoperability among observing system elements, and wideband communications system involving a network of nodes distributed from ground to space that will enable immediate availability of data from all observing assets to the Forecasting System, and a similarly robust feedback loop between the modeling system and the observing system. All this is predicated on migration toward a global set of standards in the long term, and *investment in development of tools and frameworks that allow near interoperability in the shorter term*.

It is not clear that in the 2015 timeframe a communications network will be able to provide the required ubiquitous wideband connectivity for all 2015 weather observing assets, and connectivity between the observing system and the weather forecast system ground components. However, a wide variety of wired, Dense Wavelength Multiplexed (DWDM) optical or "Lambda" network, wireless technologies (e.g., 802.11b, 802.11g) exist or are emerging to facilitate terrestrial and atmospheric-based communications. The emergence of grid computing [19, 20, 21] and an Open Grid Services Architecture, may serve as an effective starting position for designing and implementing aspects of the 2015, and eventually a 2025 Weather Forecast System.

Communications is the foundation of most of the functionality of the proposed weather forecast infrastructure. This functionality depends on many technological advances and infrastructure, but among these, *the communications infrastructure is paramount, and should be among the highest priorities in terms of technology investment strategies. Not surprisingly, many organizations and many fields of endeavor recognize the extraordinary importance of an interoperable communications system.*

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18 NSF sponsored workshop on Dynamic Data Driven Application Systems: "Creating a dynamic and symbiotic coupling of application / simulations with measurements/experiments" [March 8 – 10, 2000 Report available at: http://www.cise.nsf.gov/div/eia/fdar_ema/dd_das/index.html]

19 The Anatomy of the Grid: Enabling Scalable Virtual Organizations; Ian Foster, Carl Kesselman, Stephen Tuecke; International Journal of Supercomputer Applications, 2001.

20 The Physiology of the Grid: An Open Grid Services Architecture for Distributed Systems Integration; Ian Foster, Carl Kesselman, Jeffrey Nick, Stephen Tuecke; Draft; http://globus.org/research/papers/ogsa.pdf

21 Distributed Computing Research Issues in Grid Computing; Henri Casanova; UCSD; material not dated

The Transformational Communications Architecture [22] (TCA) is a new internet-like space network communications architecture being studied by DoD in partnership with NASA. A TCA-like solution may offer the required functional and performance characteristics needed for an extensive highly interoperable sensor web network. This architecture proposes to use a wideband optical backbone (e.g., 100Gbps), using five optically linked geosynchronous spacecraft, in conjunction with multiple optical and RF satellite crosslinks. IPv6 routing and circuit switched communications are planned to be supported. Although the operations concept and protocol selection is presently being evaluated, TCA is envisioned to provide Internet-like services to meet a wide variety of node communications bandwidth requirements and to accommodate stationary as well as mobile terrestrial (e.g., individual war fighters) and atmospheric (e.g., aircraft, UAV) nodes [23]. A TCA-like architecture, tailored to meet the specific needs of the weather forecast system of 2015, and eventually, 2025 has the potential to accommodate command and control and information interchange between individual spacecraft and groups of atmospheric assets such as radiosondes, dropsondes, ACARS, UAVs, and ultra long duration balloons, as well as stationary and mobile sensor assets. *Therefore, NASA should continue some level of support and participation in TCA activities.*

Other considerations and alternatives for implementing future space communications architectures that could facilitate real time, dynamic sensor web interactions were presented at the June 2003 Space Internet Workshop [24]. Until a TCA (or TCA-like) solution is realized, interim solutions for providing operational IP space communications through TDRSS have begun. NASA's GPM (Global Precipitation Measurement mission) is planned to be the first operational IP user in 2008 [25]. The Internet Engineering Task Force's (IETF) Mobile Ad hoc Networks (MANET) working group is addressing how to "standardize IP routing protocol functionality suitable for wireless routing application within both static and dynamic topologies". NASA's Glenn Research Center has presented how MANET may be applied to space and surface systems [26].

Trends in NWP, Data Assimilation, Adaptive Observing

A review of the short and long range plans of several operational weather centers [27,28,29,30] indicate a number of trends in the field of numerical weather prediction. One is a major investment in forecast products based on model ensembles. Another is development of more complex models that account for coupling or interdependencies between the evolution of atmosphere, ocean and land surface processes. Increased spatial resolution and more accurate representations of physical

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22 Reference: http://sunset.usc.edu/gsaw/gsaw2002/s8/canderson.pdf

23 Protocol stack presented in: http://scp.grc.nasa.gov/siw/presentations/Session_E/E_05_Mineweaser.pdf

24 http://scp.grc.nasa.gov/siw/presentations.html

25 http://scp.grc.nasa.gov/siw/presentations/Session_E/E_07_Israel.pdf

26 http://scp.grc.nasa.gov/siw/presentations/Session_D/D_09_Oldham.pdf

27 Review of NCEP Production Suite: Recent Changes and Plans, Dec. 11-12, 2002. http://www.emc.ncep.noaa.gov/NCEPreview2002/index.htm

28 NWS Science and Technology Infusion Plan (STIP) Review, Sep. 17-18, 2002.

http://205.156.54.206/ost/stip02/stip02agenda.html

29 Simulation et Prevision du Temps. 9th ORAP Forum, EC M RWF, Dominique Marbouty, Mar. 21, 2000.

30 Requirements for Observations for Regional NWP, World Meteorological Organization, Commission for Basic Systems Open Programme Area Group on Integrated Observing Systems, Expert Team on observational data requirements and redesign of the global observing system, fourth session, Geneva Switzerland, Jan. 28- Feb. 1, 2002

processes in NWP models will continue. All these depend on substantial increases in computer power.

The increased complexity of models both in physical realism and in their modes of operation have motivated development of more unified model architectures that are comprehensive and integrate capabilities among major operational forecast centers (NOAA/NCEP / WRF; UK Met Office / Unified Model) [31]. Concurrent with these changes will be increased availability of satellite and in-situ observation from future sensors. Finally, it is recognized that the degree of improvement in weather forecasts that can be realized by these advances is critically dependent on corresponding advances in data assimilation and adaptive observation strategies.

Bolstered by results obtained in FASTEX, NORPEX and WSR targeted observing programs, a new proposed 10-year international research program THORpex, would aim to demonstrate many of the same concepts in the Phase I study, especially as regards model-based targeted observing, globally coordinated observing, adaptive parameterization and use of new highly integrated satellite and terrestrial observing systems. THORpex [32, 33] aims to field-test more advanced targeted observing systems, emphasizing adaptive coordination of new generations of satellite sensors such as hyperspectral sounders (NPOESS) with new generations of in situ devices to achieve optimal initial states for forecast models. It will emphasize medium and extended-range forecasts.

We were encouraged that the major premises of THORpex seem to validate the Phase I vision, especially as it anticipates the need to begin considering a framework that would enable such capabilities in a future operational setting. Consistent with the Phase I 2025 vision, the THORpex documentation confirms that such functionality is still in the research stage, and large-scale operational programs based on these ideas are decades away. *However, we believe that NASA might seek to exploit opportunities to work in concert within THORpex to prototype component technologies and functionalities of the two-way interactive forecast system, and to integrate these components in ways that could ultimately enable more advanced future operational weather forecast capabilities.*

6. SCENARIO CASE STUDY

The objective of the scenario exercise was to help clarify thinking on 2025 architecture functions in light of realistic tractable (1-5 day) forecast situations, and infrastructure and technologies that might be reasonably projected for 2015. In the paragraphs that immediately follow, we describe the "realistic" technology and infrastructure assumptions by which the storyboard exercise might be bounded. These consisted of technological, scientific and programmatic conditions that would be operative in the 2015 timeframe. We describe below the scenario selection process and storyboard methodology, lessons relative to the potential operational use of the forecasting system

31 Da Silva, et al, 2003: "The Earth System Modeling Framework", IEEE Geoscience and Remote Sensing Symposium (IGARSS), Sydney, Australia, June 2001.

32 http://www.wmo.ch/web/arep/wwrp/THORPEX/THORPEX.htm

33 http://www.mmm.ucar.edu/uswrp/thorpex/THORpex_wmo.pdf

architecture, and conclusions about 2015 technology readiness. **Appendix C** contains the detailed summary of storyboard analysis.

2015 Technology / Capability Assumptions

2015 Weather Operations

Leading up to the scenario exercise, estimates of operational weather forecasting technologies and procedures likely to be implemented in the 2015 time-frame were developed based on reviews of current and future plans for global and regional weather forecast operations as described by the U.S. National Weather Service (NWS) [34], NOAA/NCEP [35, 36], European Centers for Medium Range Weather Forecasting (ECMWF) [37] and the World Meteorological Organization (WMO) [38]. A baseline was established for key aspects of the operational forecasting process: observation system, modeling and data assimilation system (MDAS), adaptive observations, and forecast operations. The likely forecast product suite and frequency of products available in the 2015 and 2025 time-frames were based on an assessment of the trends, priorities and feasible technological evolution in observing sensor systems, computer resources, modeling techniques and operational procedures. A complete discussion and analysis of these capabilities is presented in **Appendix A**.

Assumed 2015 Observing System Capabilities

By 2015 we do not expect enough in the way of organizational or technical capability to support any significant semi-autonomous coordination among observing system elements, a key element of the 2025 vision. The required ubiquitous (i.e. “anywhere, anytime”) communications capacity and infrastructure, and platform level hardware or software will simply not be available in 2015. This is easily predicted since the systems scheduled for deployment in the 2015 era, which are at the prototype / demonstration stage have virtually no design capacity to support such high level functionality. Space-based operations present extraordinary challenges. On the ground however, it is reasonable to believe that in 2015 the terrestrial-based communications infrastructure could support addressable, taskable ground-based observations, such as pre-positioned remotely triggered radiosondes or UAV deployed dropsondes.

The evolutionary systems and capabilities we recognized as valid for the 2015 scenario case study were as follows. For the space segment we recognized capabilities embodied in: NPOESS, GIFTS,

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34 A Vision for the National Weather Service: Road Map for the Future (1999) http://www.nap.edu/openbook/0309063795/html/5.html,copyright 1999,2000 The National Academy of Sciences

35 The Use of Targeted Observations in Operational Numerical Weather Forecasting. Winter Storm Reconnaissance Program, Hua-Lu Pan, Zoltan Toth, I. Szunyogh, NOAA/NCEP EMC *http://sgi62.wwb.noaa.gov:8080/ens/target/wsr.html*

36 . Review of Global OSEs and OSSEs, Implementation/Coordination Team on Integrated Observing systems, 2nd session, WMO, Geneva, 14-18 October 2002.

37 Simulation et Prevision du Temps. 9th ORAP Forum, European Center for Medium Range Weather Forecasting, Dominique Marbouty, Mar. 21, 2000.

38 Requirements for Observations for Regional NWP, World Meteorological Organization, Commission for Basic Systems Open Programme Area Group on Integrated Observing Systems, Expert Team on observational data requirements and redesign of the global observing system, fourth session, Geneva Switzerland, Jan. 28- Feb. 1, 2002.

GOES-R, GPM, CALIPSO, AQUA/TERRA, LANDSAT 8, QuickScat, Hyperion and other hyperspectral, ALI, and SPOT 5. For the surface-based (or surface-launched) segment we considered Precipitation Radars, Conventional Surface Observations, Automated Surface Observation Systems, Automated Radiosondes, Automated Ocean Buoy data, Ship Reports, Lightning Location Network, and Radar Wind Profilers. For an airborne segment we considered ACARS, Constant Level / Drift-sonde Balloon, and commercial aircraft deployable drop-sondes. A more complete characterization and projection of 2015 generation observing assets is provided in **Appendix B**.

The truly revolutionary new capability for 2015 will be the ability for new GPS radio-occultation methods to provide virtually 3D global coverage for atmospheric temperature and moisture. A globe-spanning satellite network, COSMIC [39], is now being developed for this purpose through a U.S.-Taiwan partnership based on a University Corporation for Atmospheric Research system design. COSMIC is expected to provide atmospheric temperature and moisture profiles at 3,000 locations daily. Even though the accuracy of these retrievals will not match the point accuracy and other characteristics of radiosondes, they are an important step to providing truly global coverage, including vast stretches of ocean inadequately profiled by radiosondes. The occultation soundings have different characteristics, such as larger effective footprint, than radiosondes and satellite profiles. But, they promise to provide greater total coverage, and since they are not strongly affected by cloud cover, better sampling of critical cloudy regions than conventional satellite IR sounders.

Scenario Selection and Methodology

As a conceptual exercise, the Phase I study involved speculation on almost every relevant future technological capability from constellation management, to computing technologies, to communications, to observing technologies. In order to better define the workings of the two-way interaction, an important activity in Phase II was to examine the functionality of the architecture in more concrete terms by invoking real world forecast situations that would exercise elements of the architecture and interactions between these elements.

In selecting scenarios for this study, we considered that most forecast failures can be traced to deficiencies in one or more of five categories: communications, data availability, data accuracy or quality control, data analysis and synthesis, and decision support systems. We selected candidate scenarios based on cases involving well-documented forecast failures traceable to one or more of these categories.

We sought cases first that had recognizable operational and/or economic significance. And since our objective was to exercise the architecture, we focused individual cases that would exercise more than one aspect of the architecture, and cases that collectively would exercise all aspects of the architecture. Six candidate cases were considered on the basis of several interrelated attributes, namely: a) the scale of phenomena (*mesoscale, regional or synoptic*) being forecast; b) the required forecast lead-time (e.g. *1 day vs. 5 day*); c) dependency of forecast success on need

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39 http://www.ucar.edu/communications/newsreleases/2002/cosmic.html

and availability of upstream data; d) reliance on space-based observing segments; e) the nature of observation targeting (*model-based vs. observation-based*); and f) the importance to forecast success of real-time feed back and supporting communications.

The attributes of these six cases are summarized in Table 1. Because time and scope constraints, we resolved to restrict ourselves to detailed analysis of just two: a 3-5 day forecast scenario and a small-scale 1-2 day scenario each of would exercise the architecture in different ways and on different time and space scales. For the first scenario we desired a situation involving a long wave synoptic scale wave pattern originating over the Pacific Ocean, whose eastward propagation and development over a three to five day period sets up conditions for strong development of an U.S. East coast [winter] cyclone and/or severe winter weather. The forecast accuracy of this large-scale 3-5 day development would emphasize the need for a global modeling capability, heavy reliance on satellite observations over the data-void Pacific Ocean, and targeted observing strategies based on model-ensemble based theoretical calculations. We thought that East Coast snowstorms would be good candidates for our consideration, because of their economic impacts and their fundamental predictability based on mid-latitude dynamics that models handle well.

WINTER STORMS INVESTIGATED BY STUDY TEAM				
Storm	**Dates**	**Area Affected**	**Formation Region**	**Significance**
1993 Superstorm	Mar. 13-14, 1993	US Gulf Coast/East Coast	Short-wave origin in Canada; deep surface low in Gulf	Huge economic impacts. Large scale trough and unusually large low pressure system generally well-forecast up to five days out, but with differences among various operational models.
Blizzard of 2000	Jan. 24 -26, 2000	US SE, Mid-Atlantic, and NE	Short-wave origin in Eastern Pacific; surface low deepens in US SE	Large economic impacts. Recognized as major failure of operational systems. Long and short range forecasts inaccurate.
Millennium Snowstorm	Dec. 27 - 30, 2000	US Mid-Atlantic and NE	Short-wave origin in Canada; Alberta clipper system with secondary development of SE Coast	Unexpected heavy snowfall in DC area. Major failure in 1-2 day forecast originating (mainly) from inadequate SST measurements
Front Range Snowstorm	Oct. 24 - 26, 1997	Colorado	Deep cut-off low in Rockies	Extreme heavy snowfall in Central CO. Amounts underpredicted (by factor of 2) lots of local variability. Higher resolution, meso-scale modeling would have improved forecasts.
Lake-effect Snowstorm	Nov. 26 - 27, 1996	Western New York	Trough crossing Great Lakes region from Canada	Unexpected heavy snowfall in Western NY. Under-forecast of upper trough intensity originating in data sparse region.
Northern Plains Snowstorm	Jan. 6 - 8, 1989	North Dakota	Short-wave origin in Eastern Pacific or Canada; surface low develops in Wyoming	Record snowfall in Dakotas and western Minnesota. Entire snowfall event ended prior to primary cyclogenesis forecasted.

Table 1. Winter storms considered by the study team.

For the second scenario, we desired a situation involving a small synoptic scale or regional scale forecast of some significant phenomena. The rationale was that being on the East Coast of the U.S., conventional observations are plentiful upstream, so the requirement for satellite data, while still important, is relatively less severe, and the emphasis shifts somewhat from data availability to the integration of that data and the operationally driven requirement for fast feedback between the model and SensorWeb. With a 24-hour forecast cycle and the regional nature of the desired forecast, the requirement for the architecture to interact with human-based forecast operations is fully exercised in scenario 2. In addition, observational targeting is more likely to be empirically based with data selection and targeting driven from within the Sensor Web or by local forecasters.

Tables 2 and 3 summarize our preliminary analysis of the six cases. For each case we attempted to identify and document what factors might have been responsible for missed forecasts, and to relate the identified problem areas to architectural components that would address the problems. In table 3, an “x” indicates that the problem area was specifically cited by reference documentation; an “x/o” indicates it is inferred (but not specifically stated) in the reference documentation, and an “o” indicates a study team member drew the conclusion after reviewing the reference documentation. It is evident from table 3 that there are many common problem areas. Probably the most widely documented storm was the Blizzard of 2000, and it is not surprising that many of the problem areas were called out in this research. Similarly, the 1993 Superstorm had considerable documentation and although generally well forecast, a number of problem areas were identified. Table 4 shows what 2025 architecture components would address the problem identified in table 3 and table 5 provides references for the storm research.

SOURCES OF FORECAST PROBLEMS IDENTIFIED IN RESEARCH							
Problem Area	**More Detail**	**1993 Superstorm**	**Blizzard of 2000**	**Millennium Snowstorm**	**Front Range Snowstorm**	**Lake-effect Snowstorm**	**Northern Plains Snowstorm**
Initial & Boundary Conditions	Forecast errors rooted in inadequate specification of IC/BCs in models	o	x	x (SST)		x	x
	Forecast sensitivity to initial data (cutoff)	x					
Operational Forecasting Procedures and Processes	Conflicting model guidance and lack of confidence in models led to uncertainty in forecasts	x	x	x			
	Inadequate tools to detect forecast trends and compare with observations	o	x	x		o	
	Model biases are not well-understood			x			
	Intermediate model results are not distributed to forecasters			x			
Higher Resolution Modeling	Higher Resolution modeling would have improved forecasts		x		x	x	
	Higher resolution event tracking nested model would have improve dforecasts		x		x		
	Higher vertical resolution would have captured critical tropopause structure and dynamics	x					
Data Assimilation	More frequent data assimilation would lead to inclusion of observations faster and more rapid update of forecasts.	x	x				
	4D-Var assimilation with changing model error statistics would have improved forecasts		x				
	More robust Quality Control (QC) needed, operational QC excluded key observations		x				
Model Physics	Better convective parameterization would have improved precipitation and intensity forecasts	x	o		x/o	x	
Observations	Targeted observations would improve forecasts	o	x			o	o
	Assimilation of precipitation data would improve forecasts		x				
	Auxiliary data sets (e.g., SST) can have major impacts on forecasts			x			

Table 2. Sources of forecast deficiencies identified for each candidate case scenario.

PROBLEM AREAS IDENTIFIED IN RESEARCH		2025 ARCHITECTURE COMPONENTS ADDRESSING PROBLEM AREA								
Problem Area	More Detail	Observing System	Data Processing	MDAS	Targeted Observations	Forward Model Data Transform	Command and Control	Forecast Operations	External Control	Comment
Initial & Boundary Conditions	Forecast errors rooted in inadequate specification of IC/BCs in models	x	x	x	x	x	x	x	x	Specification of IC/BC fundamental to accurate forecasting at all scales. Entire system designed to respond to this need.
	Forecast sensitivity to initial data (cutoff)			x						MDAS will support hourly data assimilation to include new data more quickly into products.
Operational Forecasting Procedures and Processes	Conflicting model guidance and lack of confidence in models led to uncertainty in forecasts	x	x	x	x	x	x	x	x	Entire system is designed to improve forecasts at all scales. This should increase confidence and narrow discrepancies among products.
	Inadequate tools to detect forecast trends and compare with observations	x	x	x				x		Forecast centers will be equipped with better tools to detect trends using data from the observing system and MDAS.
	Model biases are not well-understood			x				x		MDAS performance will be translated into useful decision aids for forecasters.
	Intermediate model results are not distributed to forecasters			x				x		MDAS archived data will be accessible to operational forecasters.
Higher Resolution Modeling	Higher Resolution modeling would have improved forecasts	x	x	x						MDAS models will have higher spatial and temporal resolution. At the same time, spatial and temporal resolution of observations will increase.
	Higher resolution event tracking nested model would improve forecasts			x						MDAS will support event tracking through nested modeling.
	Higher vertical resolution would have captured critical tropopause structure and dynamics			x						MDAS models will have higher vertical resolution.

Table 3. Architecture component potentially involved in addressing sources of forecast problems.

PROBLEM AREAS IDENTIFIED IN RESEARCH		2025 ARCHITECTURE COMPONENTS ADDRESSING PROBLEM AREA								
Problem Area	**More Detail**	**Observing System**	**Data Processing**	**MDAS**	**Targeted Observations**	**Forward Model Data Transform**	**Command and Control**	**Forecast Operations**	**External Control**	**Comment**
Data Assimilation	More frequent data assimilation would lead to inclusion of observations faster and more rapid update of forecasts.	x	x	x						MDAS data assimilation will occur at least hourly. Observing system and data processing system will make measurements available more quickly than today.
	4D-Var assimilation with changing model error statistics would have improved forecasts			x						MDAS assumes 4D-Var data assimilation or equivalent
	More robust Quality Control (QC) needed, operational QC excluded key observations	x	x	x	x	x	x	x	x	Entire system designed to improve description of the ICs/BCs by incorporating as many observations as possible. Targeting strategies will be used to collect more observations where measurements differ from expectations and where forecasts are most sensitive to input data.
Model Physics	Better convective parameterization would have improved precipitation and intensity forecasts	x	x	x						Higher resolution modeling and convective parameterization consistent with model resolution will result in improved modeling of precipitation.
Observations	Targeted observations would improve forecasts	x	x	x	x	x	x	x	x	The system supports targeted observing initiated by the observing system, MDAS, forecast operations, (and the user community)
	Assimilation of precipitation data would improve forecasts	x	x	x						The observing system will include 3-D precipitation measurements and these data will be assimilated in the MDAS.
	Auxiliary data sets (e.g., SST) can have major impacts on forecasts	x	x	x						The observing and data processing systems will provide more measurements of auxiliary data than the present system; these data will be used by the MDAS.
	Lack of sufficient density of profile data	x	x	x						The observing system will provide more frequent, higher resolution profile data. The MDAS system will assimilate these data.

Table 4. Architecture component potentially involved in addressing sources of forecast problems. (continued)

Based on our investigation of these six cases, we decided on the “Blizzard of 2000” (January 24-26, 2000). This case was so rich in terms of its forecast challenges, we decided that it could alone provide enough material to exercise most (but not all) the major features of the advanced architecture. First, it is a case of a major forecast failure that had huge economic impacts, and as a result has been extensively studied. It embodies both extended and short-term forecast challenges as regards predictability, targeted observations and forecast confidence at different spatial and temporal scales. The “Blizzard of 2000” is the best example of a storm that had Pacific Ocean origins and several days later impacted the US south and east coast.

The fact that short-range and medium-range forecast situations were linked dynamically to one another in time, provided an opportunity to demonstrate how the forecast system emphasis and functioning would adapt from longer- to shorter-range forecasts, in the context of one weather event. The fact that scenario 1 (Pacific Long-wave development and 5 day forecast horizon) culminates in scenario 2 (East Coast Cyclogenesis, short forecast horizon) reflects real-world scale dependency of the small-scale weather development on a priori large-scale development.

REFERENCES FOR STORM RESEARCH	
STORM	**REFERENCE**
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	Uccellini, et al., 1995: Forecasting the 12 - 14 March 1993 Superstorm, Bull. Amer. Meteor. Soc., 76:2, pp. 183 - 199.
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	http://www.emc.ncep.noaa.gov/mmb/research/blizz2000/
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	NOAA/NCEP Archives. jifmemo: [Fwd: Notice of INTENT to Change: New SST in Meso Eta] http://www.ncep.noaa.gov/cgi-bin/lwgate/public/lwgate/JIFMEMO/archives/jifmemo.0101/Subject/article-9.html
	Eta Model Parallel Change Log. http://www.emc.ncep.noaa.gov/mmb/mmbpll/eta.log.para.html
Front Range Snowstorm	Poulos, G. et al., 2002: A Rocky Mountain Storm. Part 1: The Blizzard- Kinematic Evolution and the Potential for High-Resolution Numerical Forecasting of Snowfall. Weather and Forecasting, 17, 955 - 970.
Lake-effect Snowstorm	Lackmann, G., 2001: Analysis of a Surprise western New York snowstorm. Weather and Forecasting, 16, 99-115.
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Table 5. References for the storm research.

West Coast and East Coast observing and forecast challenges are quite different. For an East Coast case with a 1-day forecast lead time, conventional upstream observations are plentiful so the requirement for satellite data, is relatively less important than in the case of a 5-day lead time forecast needing information from a data sparse Pacific ocean. A shorter forecast horizon also shifts the emphasis from issues of data un-availability to integration of data, to operational need for quick feedback between the model and Sensor Web to accommodate more efficient decision support, and human-based data selection and targeting.

To the extent the January 2000 linked cases do not touch *every* aspect of the architecture, other cases such as the March 13-14, 1993 storm would be drawn upon in discussions to focus more deeply on how the proposed architecture could address other forecast challenges such as inadequate model parameterizations, spurious forecast impacts of assimilation data–cutoff, and limitations related to use of statistically-based quality control of observations.

The selected East Coast scenario(s)do not explicitly address how the architecture would address forecasts for smaller scale weather events such localized thunderstorms or tropical storms. We are confident that the key observing system and model feedback would have the potential to address smaller scale weather developments using real-time observations linked to very small resolution models. However, specific implementations of the architecture that would address convective time-scales and resolutions would require a separate scenario. Similarly, for tropical storm prediction the architecture would probably need to be exercised in ways that are so fundamentally different that it would be likewise outside the resources available to this study.

The reader is directed to **Appendix C** for a complete summary of the Scenario Case Study Exercise.

Results and Lessons Learned

The Storyboarding and Scenario Case Study (SSCS) activities provided a way to analyze the temporal dependencies among architecture components as well as the functionality of these components. The storyboard process thus required us to address and define notional schedules for observing and non-observing assets and to make reasonable assumptions for processing timelines.

The SSCS activities also provided a way to examine how components might work together at different stages of the evolution of the winter storm event from five days out to one day out. For example, in the medium to short range (2 to 5 day) forecasts, event detection and model-based Sensitivity Analyses (SA) were the primary drivers for targeted observing. The regions of targeted observing were generally thousands of kilometers from the eventual location of the fully developed storm, and the collections were taken days before the storm formed. Data from targeted observing entered the assimilation process over a period of several hours, leading to gradually better initial conditions for the forecast models and consequently better forecasts. The longer lead times (2-5 days) also allowed greater flexibility in scheduling assets.

In contrast for the very short range forecast horizon (<24 hours), targeted observing was based upon collecting data in the vicinity of a well-defined storm track, over a time window ranging from only a few hours to several hours from the time of the storm passage. Then, once the storm developed, the need for targeted observing came from automated and computer-aided comparisons between observed and predicted storm structures, especially precipitation and wind patterns. In the short-range scenario, mesoscale very short-range (MVSR) forecasts were run frequently (hourly), with nested grids centered on the storm location. The assimilation for each MVSR run contained data from the targeted observing along the storm path.

The SSCS activities pointed out the continued need for in-situ measurements of wind, temperature and moisture data in the presence of clouds, which are critical to establishing reliable initial conditions for the forecast models. In many cases targeted observing will be required over the ocean and in cloud-covered areas. However, the reality was that aside from cloud drift wind measurements from space-based assets (which only provide information where clouds are present and do not provide vertical profiles of wind data), the assumed 2015 observing capabilities still would only support winds would be from rawinsondes, dropsondes, land-based sounders, and instrumented commercial aircraft, with coverage still severely limited even in 2015 (rawinsonde and sounder measurements are typically taken from land areas, dropsondes are dispersed through special operations by aircraft, and commercial aircraft tend to fly along well-defined routes and at high altitudes). Satellite-based measurements of temperature and moisture profiles will rely primarily on microwave- and infrared-based techniques, which are less accurate in the presence of clouds. Satellite GPS and RF techniques may have more success in the presence of cloud cover, but it is unclear how the observation schedule could be altered to support targeted observing.

The SSCS exercise emphasized the *need for data flow between every major element* of the architecture. The role of the ECS was expanded and clarified. The functional dependencies of the various layers of each architectural element were better defined. For example, the breakdown and description of tools and utilities needed within MDAS and Forecast Operations to facilitate targeted observations for weather events (such as the winter storm) were more clearly focused.

The scenario exercise was performed after *initial* refinements had been made to the Phase I architecture as characterized in figure 7d. Contrast this with figure 7e and figure 3 that reflect changes as a result of the scenario exercise. From an architecture perspective, the most fundamental impact of the scenario exercises was to back off the Phase I notion that feedback loops #1 (Sensor Web – Sensor Web) and #2 (Model - Sensor Web) could or should operate with complete autonomy from human controls, which was admittedly a very lofty goal. To support additional feed back loops #3 and #4 (Forecast Ops – Sensor Web), we invoked a strengthened External Control System to screen human observing requests against priority policy and asset availability. It became clear from the scenario exercises that humans would be competing against the [semi-autonomous] model and Sensor Web for the same limited resources. Therefore, it was decided that *all four* targeted observing feedback loops would need to go through the External Control System, and priorities issues settled there. This is what is finally shown in figure 3 and figure 7e. Beyond this, only minor additional adjustments to the overall architecture framework were thought needed as a result of the scenario exercise.

Conclusions relative to Technology Readiness in 2015

This section discusses 2015 Weather Forecasting System capabilities relative those envisioned for 2025 in the following areas: Observing System, MDAS, Forecasting Operations, ECS, and the Communications Infrastructure. The assumed 2015 capabilities are consistent with the 2015 scenario description contained in **Appendix C**.

Observing System

The 2015 observing system will include advanced versions of today's sensor systems, e.g., NPOESS, GOES-R, etc., but the missions will likely remain stovepipe and schedule-driven and the highly interactive relationships among sensors and platforms depicted in the 2025 architecture will not exist. A major consequence of this is that targeted observing, although much more prominent in 2015 than today, will *not* be nearly as autonomous and interactive among sensors as envisioned in the 2025 architecture. In addition, shortfalls will still remain in the ability to measure some parameters, e.g., wind soundings and temperature and moisture soundings in the presence of clouds. These shortfalls in 2015 will necessitate the use of dropsonde measurements from aircraft over data sparse regions and rawinsonde and profiler collections over ground locations. It is anticipated that more control of these assets will be possible in 2015, however. In addition, by 2015 it is assumed that the data collected by these assets will be made available to the system almost immediately; this will require new quality control and data reduction procedures relative to the present. Today, measurements from rawinsondes are made available to forecast models only after a complete sounding is made—often 2 hours after launch.

MDAS

Advances in computing, modeling, and data assimilation from now until 2015 will continue to drive models towards higher resolution, more frequent data assimilation, incorporation of more data and data types (e.g., precipitation and clouds) into assimilations, improved parameterizations, and more and better use of ensembles. These improvements will be on-track with 2025 expectations. By 2015, its is anticipated that automated procedures will be in place to identify and track significant weather “events” and the ability will exist to modify MDAS and observing system schedules (to some extent) in reaction to these events. Although it appears that by 2015 significant progress can be made in automating and facilitating these procedures, it will take time for personnel to “trust” the automated decisions made by the system. As a result, considerable human monitoring and interaction is still expected in 2015.

Forecast Operations

Today’s forecasters require improved utilities to compare observations with model forecasts, so that they can judge the quality of the model forecasts, choose among models, and prepare the best forecasts for the public. They also need to make these comparisons more frequently. This means that observations need to be available more quickly in a useable form and forecast products, even intermediate products, need to be made available more quickly. Since there is strong need for these capabilities today, it is likely that some of this will be in place in 2015. It is unclear; however, how much Forecast Operations will be able to impact the observing system and MDAS by 2015. For example, although Forecast Operations may be able identify performance problems with a given model for a given meteorological event, its ability to feedback this information quickly to MDAS and affect its schedule and parameterizations in time to produce better forecasts for the event may be limited. Similarly, although observed differences between model forecasts and observations may suggest to forecasters that additional observations should be taken over a particular region and time, the ability to affect the collection schedule of 2015 observing assets will be limited. These issues will have the most impact on short-range forecasts. The scenario description contained in Section 4 takes the view that Forecast Operations will have much more freedom to alter rawinsonde launch schedules to support medium- and short-range forecasts. For long range for forecasts, where there is more time and flexibility in schedule, it is anticipated that Forecast Operations will play a major part in target observing by 2015, which will impact long- and medium-range forecasts.

ECS

The 2025 architecture suggests that ECS play a strong role in coordinating multi-agency and multi-national collection and modeling operations. It is anticipated that a start at this will be possible by 2015, but the ability for example to impact satellite collection activities of assets controlled by other nations may be limited due to the anticipated stovepipe nature of missions and the absence of procedures in place to handle such requests. In the scenario described in **Appendix C**, it is assumed that multi-national rawinsonde collection schedules can be altered through ECS.

Communications Infrastructure

By 2015 it is assumed that the latency of data from virtually all assets will be reduced considerably relative to today, through more frequent data transmission and more rapid processing of data. As a result, measurements will be available more quickly to support the more frequent data assimilation cycles expected in 2015. Similarly, MDAS and Forecast Operations will have the facilities to review forecast products more easily and frequently, and will be able to quickly impact the collection schedules of some observing assets. The emphasis on speed through reduced latency and rapid feedback between the MDAS, Forecast Operations, and the Observing System means that a robust communications infrastructure will need to be in place by 2015.

7. Sensor Web Re-Visited: A Framework Taxonomy

In this section, we offer an alternative, potentially useful Sensor Web taxonomy. DoD and NASA Sensor Web concepts are similar in some respects but they are also quite different in other aspects. Even within NASA (and within our study Team) perceptions vary regarding what a sensor web is, how it functions, and how it is organized. At present there is little rigor in terms of defining a Sensor Web. The vision presented in this section evolved in parallel with the Phase II study and reflects the contributions of team member Stephen Talabac, NASA/GSFC. Note that it provides a different view of the Sensor Web than was assumed going into the Phase II study (see page 11 of this report), and different from that assumed for the scenario exercise.

Whereas the prevailing NASA notional Sensor Web refers only to the observing system elements, the view presented in this section is broader, including as part of the Sensor Web, non-observing assets that necessarily interact with the observing system to carry out a mission. Thus, for example, a weather model used to assimilate observations is just another node (although a different type of node) that comprises the Sensor Web. We think that this view, supported by the taxonomy described in this section, might lend rigor to thinking about Sensor Webs. Below we characterize sensor web architectural components for the 2025 weather forecast system architecture in view of this taxonomy and the interactions between sensor web nodes [40]", and describe some key properties of the sensor web viewed as a "system".

Sensor Webs and Sensor Networks: Background and Overview

Sensor Webs are envisioned to employ sophisticated and significantly more effective measurement techniques and observing strategies with which to monitor the intrinsically dynamic behavior of a wide variety of naturally occurring (e.g., wild fires, hurricanes, harmful algal blooms) and human-

40 The term "node" as used in this report is synonymous with "asset" or "platform". Representative examples include spacecraft, radiosondes, moored or drifting buoys, and fixed weather stations. However, as will be presented and described, two other forms of nodes can exist: computing nodes and data storage nodes.

induced (e.g., atmospheric and ocean/coastal zone pollution, malicious CBR [41] releases) events and phenomena. In contrast to today's "stove-piped" mission ops concepts and their (predominately) passive observing strategies, future environmental observations should be conducted with a view toward more systemic engineering solutions coupled with novel science measurement techniques that emphasize the use of sophisticated, interconnected assets and sensors that are able to autonomously reconfigure themselves and apply dynamic, highly coordinated observing strategies. *The ability to reconfigure itself in ways that continuously tend toward optimizing science measurements, as a direct reaction to the dynamics of the phenomenon being monitored, uniquely characterizes the Sensor Web.*

Since the sensor web (sometimes referred to as a "sensor network [42]") concept is new, and the properties that characterize it are still evolving, a high level definition or description is useful. A new description is:

> *A sensor web is a distributed, organized system of nodes, interconnected by a communications fabric that behaves as a single, coherent instrument. Through the exchange of measurement data and other information, produced and consumed by its sensing and non-sensing nodes [43], the sensor web dynamically reacts causing subsequent sensor measurements and node information processing states to be appropriately modified to continually ensure optimal science return.*

The Sensor Web must be viewed as a "system". It is composed of multiple, potentially heterogeneous, *in situ* and remote sensing nodes, deployed on or below the surface "skin" of the Earth, within the atmosphere, and/or in space. Computing and storage nodes that have no sensors, complement the sensor nodes. The underlying communications fabric that facilitates the exchange of information throughout this system can be instantiated in many different ways. In fact, implementation of the communications fabric will vary considerably depending upon a Sensor Web's unique functional and performance requirements. Measurement data and other information (e.g., node state information) produced by the sensor nodes serve as inputs to numerical model nodes or to populate data warehouse nodes with observational measurement data or perhaps derived information. Similarly, sensor nodes possess the ability to access (near) real-time observations from other sensor nodes, as well as results from numerical model nodes and information (e.g., derived "mined" information) stored or produced by data warehouse nodes. Sensor nodes may use this externally generated information to modify their internal information processing state(s) and adjust subsequent measurement techniques in ways that tend to maximize the return of only the most useful and significant measurement data to scientists, policy makers, and emergency management decision support systems. *The negative feedback loop that serves to continually modify sensor web observing and information processing states is the critical new component that will yield a substantial improvement in our ability to better understand the forces and dynamic interrelationships that drive the formation, behavior, and evolution of a wide variety of environmental phenomena.*

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41 Chemical, biological, radioactive

42 The terms "Sensor Network" and "Sensor Web" are frequently used by DoD and NASA respectively and are sometimes used interchangeably. Although the former tends to focus on wireless, low power, *in situ* sensing devices, and the hardware technologies and communications protocols that will be required to implement them, there is considerable overlap in the capabilities of these new forms of observing systems.

43 Representative examples include*: event detection and feature identification notification messages; numerical prediction forecast model results; MDAS requests for new measurements, etc.*

In contrast to present day observing systems, sensor nodes will make measurements, locally process this data, interact with other nodes by exchanging observational data and other information (e.g., predictive model results, node information processing states), and then autonomously react to the measured values and other information by modifying subsequent sensor node measurement and information processing states. The potential benefits of this new closed-loop approach are especially noteworthy. It is envisioned that sensor web observing systems will: (i) maximize the return of only the most useful scientific measurement data; (ii) minimize overall system response time when monitoring rapidly evolving or transient phenomena; (iii) directly utilize predictive numerical model forecasts by performing targeted observations of model-sensitive regions to identify significant precursor patterns or features *prior to their actual emergence*; and (iv) perform near-real-time synthesis or “fusion” of information from multiple sensor nodes and predictive numerical forecast models.

It is important to recognize that a Sensor Web-based weather observing system is not therefore “just a distributed data collection system”. In contrast, such systems are characterized by multiple, geographically distributed, independent nodes (e.g., spacecraft, radiosondes, *in situ* weather stations, buoys, etc.) that make measurements and periodically (perhaps continuously) report raw sensor data to a central site where the measurement data are collected, reformatted, calibrated, earth located, quality controlled, and then combined and processed in various ways to produce higher level science “products”. Distributed data collection systems have existed for many years: they are in fact the principal means today with which environmental parameters are measured and reported. To distinguish them from the Sensor Web, prominent properties of distributed data collection systems are: (i) sensor nodes typically possess a single measurement mode; (ii) measurement data flow is primarily “unidirectional” (i.e., from the sensor node to one or more processing and data storage nodes); and (iii) little if any information transactions take place between nodes. In such systems, closed loop negative feedback reactive control mechanisms that take advantage of real time, dynamic information interchanges amongst pairs or several sensor nodes, or between sensor nodes and data processing nodes (e.g., data assimilation systems) and predictive numerical models [44], do not exist. In contrast to the Sensor Web, distributed data collection systems lack the all important ability of its constituent sensing and non-sensing nodes to routinely exchange, and then dynamically react to, sensor measurements, event notifications, state changes by other nodes, model results, and other forms of processed information.

The sensor web is uniquely able to change the measurement modes and processing states of its constituent nodes in real- or near-real time. The sensor web’s dynamic behavior is derived by exploiting the ability of its sensor nodes to change one or more of their measurement or processing states: e.g., spatial, temporal, and/or spectral resolution as summarized in the table 6 below.

44 e.g., Models for: weather forecasts; algal bloom formation and growth; volcanic ash plume dispersion

State Change	*Representative Examples and Applications*
Spatial	❑ Make measurements or perform processing at ***different locations*** ▪ An *in situ* mobile sensor node (e.g., an Unmanned Aerial Vehicle, an autonomous coastal marine craft) moves to a new location to make measurements ▪ A remote sensing node (e.g., a gimbaled spacecraft instrument) points to a new measurement location ❑ Make measurements with ***different areal coverage*** *(e.g. Field of View (FOV) or Region of Interest (ROI)* ▪ Spacecraft instrument performs a targeted observation at a geographic region of interest with a FOV that is commensurate with the scale of the phenomenon it is observing ▪ Doppler radar changes its elevation angle to make measurements at different altitudes in the atmosphere. ❑ Make measurements or perform processing at a ***different resolution*** ▪ Change spacecraft instrument sensor node from coarse resolution per pixel (e.g., 4 Km) to finer resolution (e.g., 1 Km) per pixel.
Temporal	❑ Change a sensor node measurement or data processing rate (e.g., change the imaging of a region on the Earth image from every 1 hour to every 5 minutes; change numerical forecast model execution from every 6 hours to every 1 hour) ❑ Change measurements (e.g., Doppler radar) or processing (e.g., data assimilation, forecast model) from a periodic (perhaps a schedule-driven) rate to an event-driven, aperiodic, rate.
Spectral	❑ Select or process a subset of all available spectral band measurements in direct relation to the unique characteristics of the phenomenon

Table 6. *The sensor web is uniquely able to change the measurement modes and processing states of its constituent nodes in real- or near-real time.*

Sensor node state changes are a direct reaction to the specific dynamics of the phenomenon being observed. A change in the state of one or more sensor or non-sensing nodes in the system may initiate changes in the state of other nodes. A viable Sensor Web architecture must be able to periodically modify its node data collection and information processing strategy by changing a node's spatial, temporal, and/or spectral measurement operating modes, and local processing algorithms, commensurate with new observations. Information produced by a node is reported to one or more other nodes using any one, some, or all of the following methods: *"deterministic", "triggered", or "on demand"*.

Deterministic reporting simply means that a node makes information (sensor data; a sensor state message; etc.) available at predictable times. This does not necessarily mean the information is reported only at fixed intervals (e.g., once per hour); it could be at those times when, for example, it can be predicted that a spacecraft will come into contact with a ground station, or perhaps when ensemble forecast model runs diverge significantly due to a sensitivity to a specific atmospheric state. *Triggered reporting* occurs when a node detects a predefined event, measurement, statistical correlation, or perhaps a new operating state that warrants appropriate information to be immediately reported (e.g., detection of a sensitive atmospheric region causes a model-initiated observation request message). *"On demand" reporting* occurs when a node receives a request (from one or more other nodes) to immediately report specific information. The ability of the nodes that comprise the Sensor Web to possess one or more of these reporting modes will determine the characteristics and sophistication of the communications media and protocols (e.g., peer-to-peer) that will be required, the degree of complexity of node interactions, selection of the best overall system topology (e.g., fully connected mesh, hierarchical, etc), and resultant Sensor Web information throughput and performance.

Particularly noteworthy, and a key component of the 2025 weather architecture that has been described in the preceding sections of this report, is that observing system node changes may also be initiated by *predictions* of precursor conditions for certain meteorological phenomena. The sensor web-based weather forecast system's architecture possesses the unique ability to initiate predictive, model-driven measurements. In these instances it is not known whether a specific phenomenon (e.g., a severe storm) may form at some future point in time: in fact, its emergence may be critically dependant upon the formation or evolution of a significant atmospheric feature or condition whose formation and evolution is ultimately governed by very small, but non-linear mechanisms. This problem is particularly challenging for chaotic systems such as the atmosphere: the result of executing model ensembles can yield very different future states of the atmosphere if initial conditions for the model runs are only slightly perturbed. Only a sensor web-based architecture has the inherent ability to dynamically react to these feature-sensitive regions and cause the observing system to make highly targeted measurements in an attempt to force model ensemble predictions to converge and thus yield a more consistent and reliable forecast.

It is important to recognize that a meteorological sensor web will not evolve as a large, monolithic, all-encompassing observing, MDAS, and forecast system. Instead it is far more likely that there will exist a wide variety or "spectrum" of many, and possibly highly specialized, sensor web classes. These sensor webs may range in capability and scale from those that are simple and small, driven by comparatively straightforward automation techniques, to large, complex systems that are autonomously guided by sophisticated algorithms and goal-oriented heuristics.

For example, a sensor web may be composed of a coastal zone fleet of dozens of highly coordinated autonomous surface craft making *in situ* measurements of harmful algal blooms, environmental pollutants, ocean currents, or warm and cold eddies. At the other end of the spectrum, a sensor web may consist of a large and sophisticated fleet, or constellation, of formation flying spacecraft capable of performing a wide variety of coordinated atmospheric measurements. The spacecraft sensors may be able to change one or more of their spatial, temporal, or spectral measurement modes. These representative sensor webs will likely perform their environmental monitoring independent of one another. However, like communications networks that can be joined by routers and bridges to create a single, interoperable

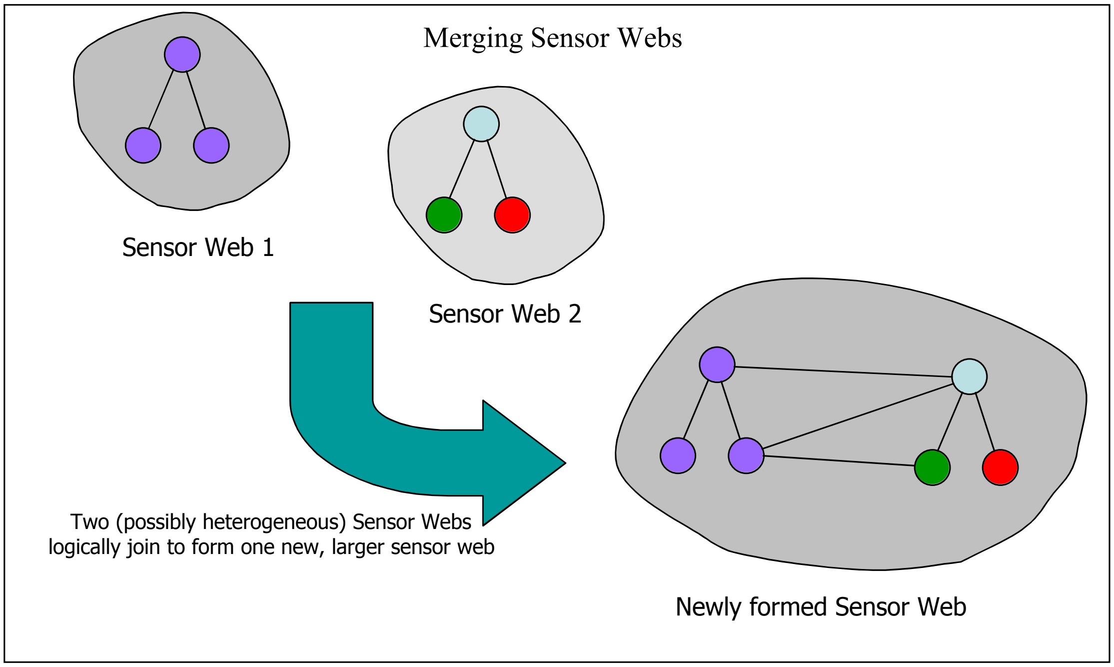

Figure 8. Illustration of larger Sensor Web comprised of smaller Sensor Webs.

communications network, smaller, and otherwise independent sensor webs may similarly join (i.e., logically merge) to form a larger integrated single observing system to perform coordinated remotely sensed and *in situ* measurements of a coastal region (See Figure 8). Although the architectural components that comprise individual sensor webs will be identical, each sensor web must be able to be implemented in a way that satisfies its unique measurement, performance, and operations concept requirements. As with communications protocol stack architectural models, it is also likely that not all architectural components may be required to implement a particular form of sensor web. In these instances, although the sensor web architecture may define all components and their functions, some functions may not be required to be implemented and may simply serve as “place holders”.

The sensor web architecture must take into account disparate remote sensing and *in situ* measurement platforms or nodes (e.g., spacecraft, unmanned aerial vehicles, ultra long duration balloons, underwater or surface-going autonomous vehicles, airport-based weather stations, etc), having widely varying sensor measurement and associated error characteristics, and very different observation vantage points (i.e., in space, within the atmosphere, and on or below the Earth’s surface). The architecture must permit nodes to aggregate, be replaced, upgraded with new hardware or software, and it must accommodate automated rerouting of information from failed or degraded nodes over time. The architecture must also be scalable to ensure that any significant changes (e.g., a large increase in the number of sensor nodes) will not significantly reduce overall system throughput and response time. This is significant because it is envisioned that the sensor web concept will play an increasingly important role in support of a wide variety of highly integrated, near real time decision support systems (DSS). As with large networked computers, a sensor web architecture must accommodate different sensor web topologies and node relationships (e.g., hierarchical versus fully connected mesh; different node clustering relationships such as master-drone, or peer-to-peer; etc), different command and control mechanisms (e.g., centralized versus distributed), and, as noted earlier, permit two or more sensor webs to logically combine and merge to form a new and larger Sensor Web observing system. The latter may be a temporary configuration to serve the needs of a particular set of observations, or to make measurements of complex interactions. A sensor web of atmospheric sensors may be required to temporarily merge with an otherwise independent sensor web cluster of autonomous marine surface vessels to better assess ocean-atmosphere boundary conditions. After all required observations are performed, the larger integrated Sensor Web may then reform itself into the two original and independent smaller subnets. Some of these concepts are illustrated below.

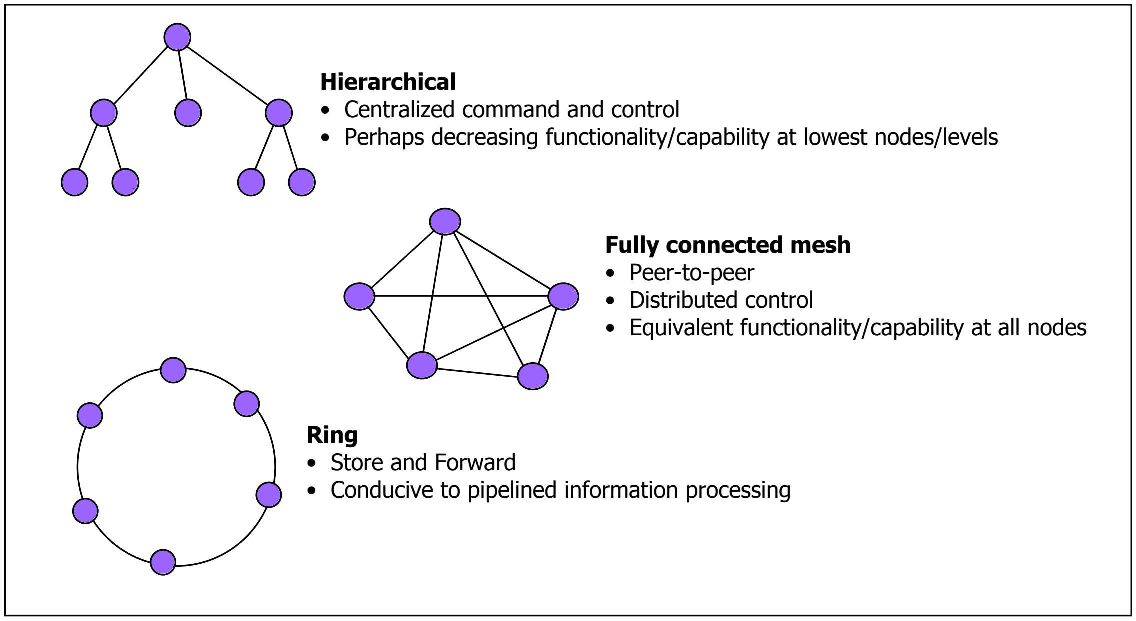

Figure 9. Several Sensor Web Architectures**.**

The ability of each otherwise independent sensor web, or “subnet”, to successfully communicate and exchange measurement data and other information (e.g., event notification messages) will rely upon an underlying suite of information technologies. These include communications protocols, and “glueware” or “middleware” software with which data and information can be seamlessly exchanged between sensor subnet nodes. Data and metadata representation standards will be critical elements to ensure all data and information can be exchanged with syntactic and semantic ease.

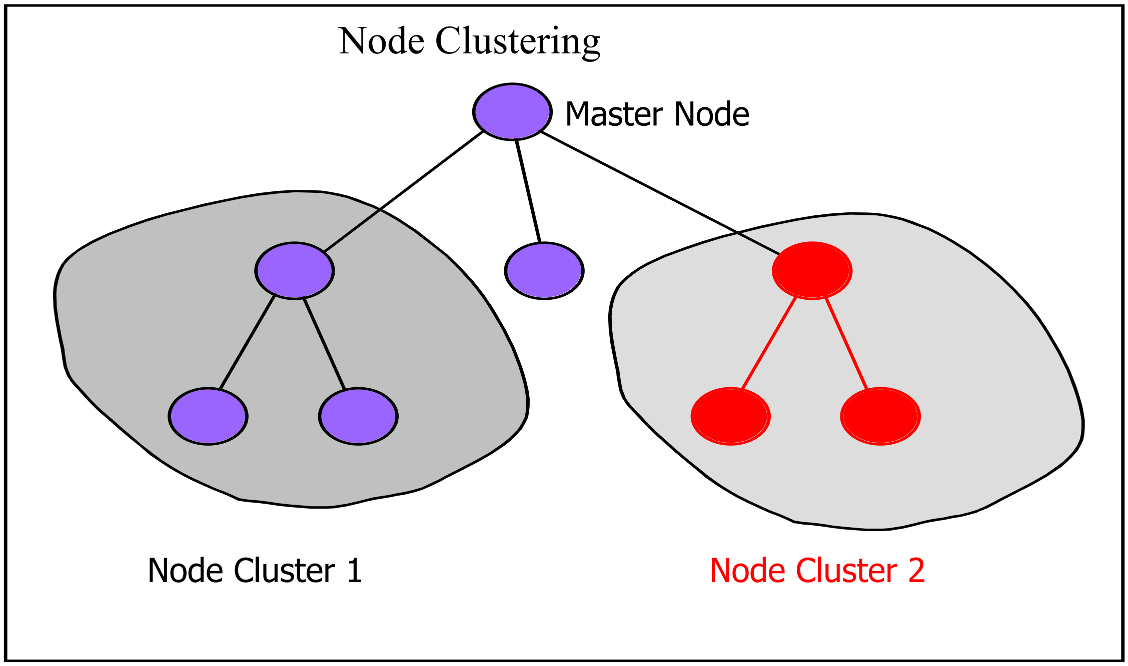

Figure 10. Illustration of Sensor Web node clustering.

Node Taxonomy and Characteristics

A sensor web may be constructed using three fundamental node types: ***sensor nodes***, ***computing nodes***, and ***storage nodes***. This taxonomy is illustrated in the figure below. Each has the ability to receive, produce, and otherwise exchange measurement data and other information by means of the communications fabric and data grid. The fabric encompasses the wide variety of available communications mediums (e.g., terrestrial land lines, microwave relays, and constellation communications satellite links; radio frequency, free-space optical, multimode fiber optics, and various forms of copper-based mediums) and a wide variety of available and emerging communications protocol suites (e.g., IP, UDP/TCP, FTP, SNMP, CCSDS, Bluetooth, wireless 802.11g, etc) that will be required to exchange information and to provide an infrastructure with which to perform node command and control.

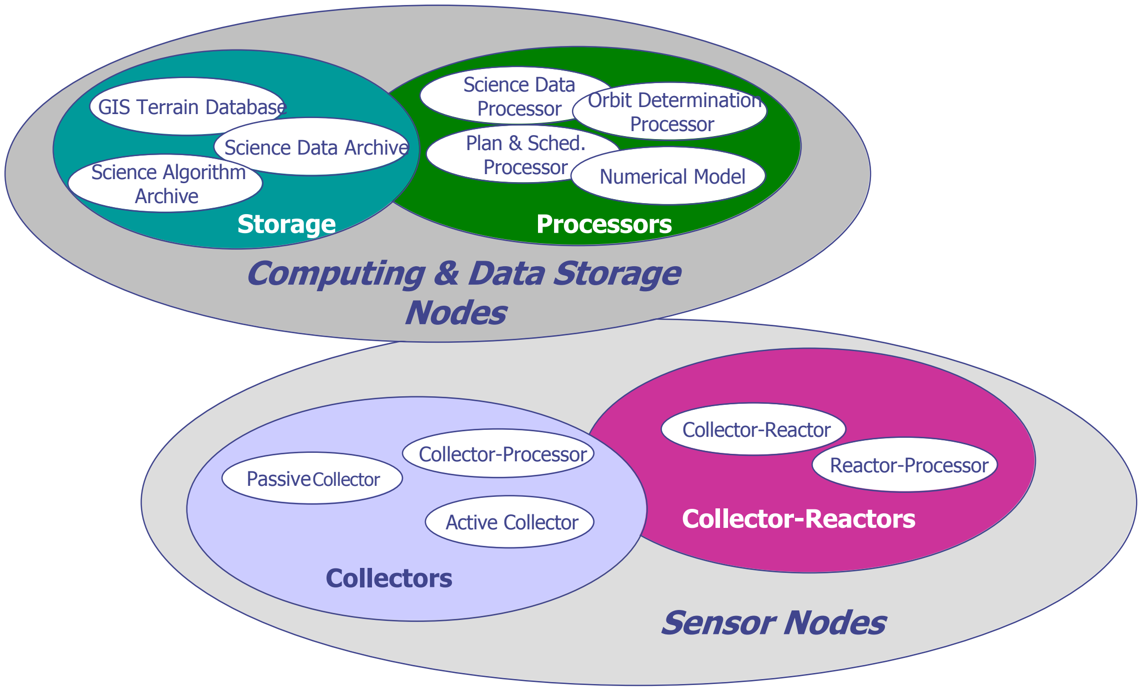

Figure 11. According to the proposed taxonomy, all Sensor Web nodes are characterized functionally as Storage, Processor, Collector, and Collector-Reactor nodes.

As the name implies, a ***sensor node*** has one or more instruments with which it can make *in situ* or remotely sensed measurements. The sensor web must accommodate many different types of sensor nodes with each able to perform different measurements: remotely sensed photon energies; *in situ* chemical, acoustic, and metrology measurements (e.g., strain gauges, laser range finders). Since the sensor web's strength is derived from its ability to exchange and synthesize measurement data from a wide variety of sensors, data representation information technologies (e.g., XML-based mark-up languages) will be required.

Computing and storage nodes do not have sensors. By collecting data and information from sensor (or other computing or storage) nodes, computing nodes use their suite of algorithms to transform the collected sensor data from one form to another and make that processed information available to other nodes via the communications fabric and data grid. An example of a computing node is a numerical prediction weather forecast model. Model outputs are, however, represented by a set of parameters and values that are not "sensed" by sensor nodes. A model may, for example, produce a mapped temperature field at some latitude and longitude grid scale. Sensor node measurements however (e.g., a spacecraft's IR sensor) are represented by "counts" (quantized to 10 bits for example) and its coordinate system, typically represented by pixels and scan lines, will be in a geometry as viewed from space. These IR counts have to therefore be calibrated, transformed to radiances and then to temperatures, and then earth located by mapping the pixels to the corresponding model's latitude, longitude grid coordinate system. Computing nodes (e.g., a forward model transform processor) provide the necessary translation service so that, for example, a spacecraft may be able to compare, in real time, the predicted model temperatures at time *t* with the actual spacecraft sensor measurements at that time.

Storage nodes provide other sensor web nodes with raw and processed measurement data that has been stored in some repository. In the future, "intelligent archive [45]" storage nodes may continuously mine meteorological or climatology storage repositories and provide derived information, such as historical trends, that can be used to refine where sensor nodes should make targeted observations in anticipation of the formation of significant atmospheric phenomena.

The table below presents a proposed taxonomy of sensor nodes and their characteristics.

Sensor Node Type	*General Characteristics*	*Sensor Sub-type*	*Representative Capabilities*	*Examples*
Collector	❑ Has one or more distinct, well-defined, measurement states ❑ Measurement state is internally selected by a simple algorithm that cannot be modified (e.g., low rate vs. high rate data collection). ❑ Able to collect and transmit science data measurements from its sensor suite. ❑ Unable to receive, and therefore cannot react to, data that is transmitted by another node(s).	❑ Passive Collector	❑ *Collects* raw sensor data ❑ One measurement state ❑ *Reformats and transmits raw sensor data* and node state data sufficient to meet comms fabric transmission requirements	❑ Tipping bucket rain gauge ❑ On-orbit multispectral instrument with fixed FOV, constant pixel resolution, & always "ON"
		❑ Active Collector	❑ *Collects* raw sensor data ❑ Two or more measurement states selectable by the node ❑ *Reformats and transmits raw sensor data* and node state data sufficient to meet comms fabric transmission requirements	❑ Spacecraft selects high resolution Visible and low resolution IR for daytime passes, and vice versa for nighttime passes. ❑ River gauge selects high rate measurement mode when it measures increased water flow rate.
		❑ Collector-Processor	❑ *Collects* raw sensor data ❑ *Processes* raw sensor data with one or more embedded science data processing algorithms ❑ Two or more measurement states selectable by the node ❑ *Transmits* raw and/or processed science data measurements and node state information	❑ LEO spacecraft with multi-spectral imager with on-board cloud mask algorithm to maximize the number of cloud-free scenes that are stored in its on-board SSR.

[45] Conceptual Study of Intelligent Archives of the Future; H.K. Ramapriyan, Gail McConaughy, Christopher Lynnes, Steve Kempler, Ken McDonald (NASA/GSFC), Bob Harberts, Larry Roelofs, and Paul Baker (Global Science and Technology, Inc.), August 23, 2002

Sensor Node Type	*General Characteristics*	*Sensor Sub-type*	*Representative Capabilities*	*Examples*
Reactor	❑ All of the properties of Collector Nodes AND… ❑ Collects and reacts to data and information from its sensor(s) or transmitted by another sensor, computing, or storage node	❑ Collector-Reactor	❑ *Collects* raw sensor data from its sensor(s) *and* from other nodes ❑ May have two or more measurement states selectable by the node *or* commanded by other nodes ❑ *Reacts* to data, information, & commands transmitted by other nodes (e.g., change from low rate to high rate measurement mode) ❑ *Transmits* raw science data measurements and node state information	❑ River gauge reports water level (*w*) measurements at time (*t*) intervals ❑ *One or more node*s in the sensor web detect a *dw/dt* condition and requests a Collector-Reactor node to change its data collection rate
		❑ Reactor-Processor	❑ *Collects* raw sensor data from its sensor(s) or from other nodes ❑ Has a science data processing algorithm ❑ May also have two or more measurement states selectable by the node ❑ *Transmits raw and/or processed science data* measurements in reaction to other node data measurement requests.	❑ GOES-R spacecraft (a *Reactor-Processor Node*) is commanded to initiate a rapid scan high-resolution mesoscale imaging mode over forecast model-sensitive regions and with selected sensor bands

Table 7. Proposed taxonomy: Sensor Web nodes and their characteristics.

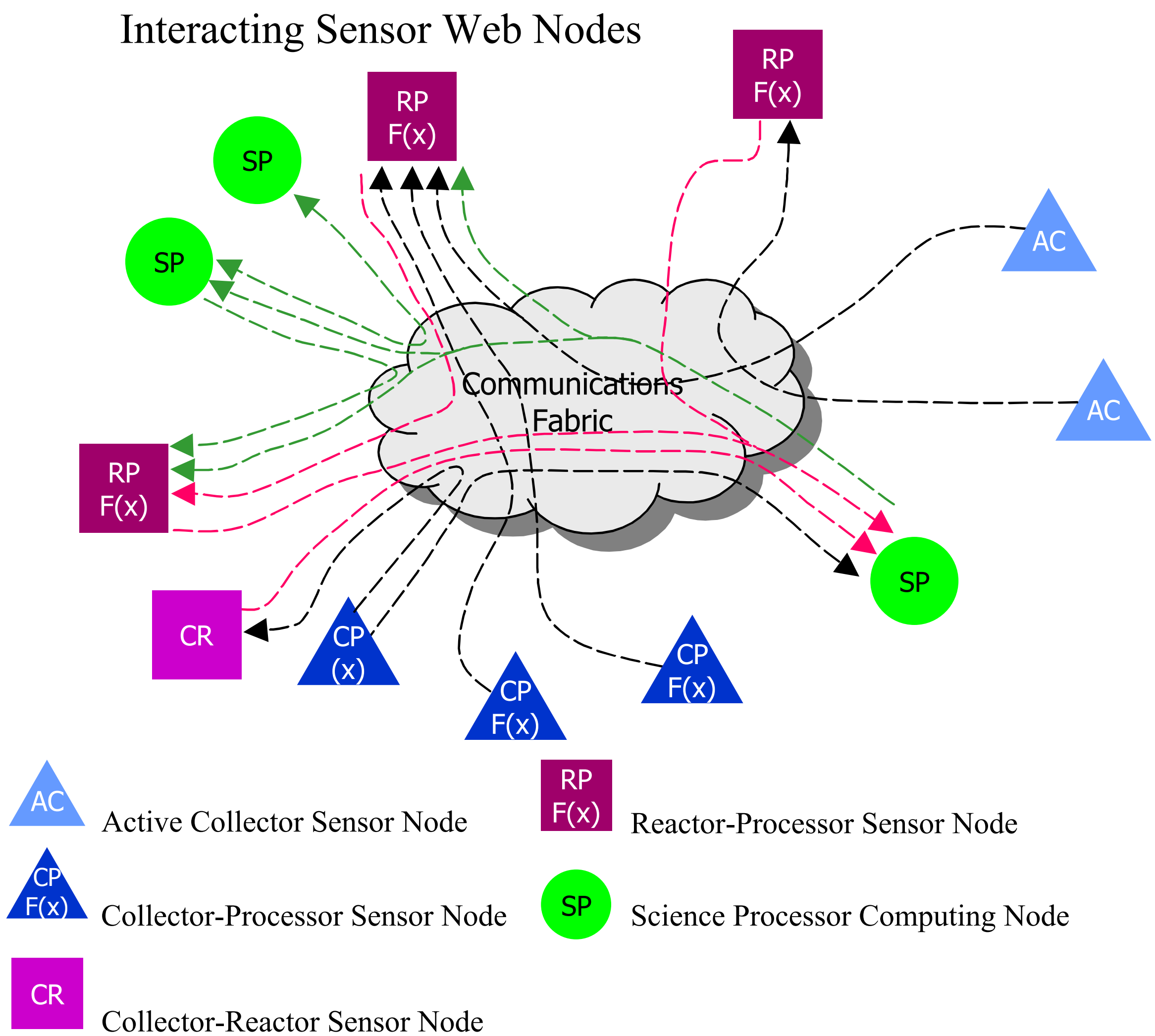

Figure 12. A seamless powerful space-space and space-ground communications fabric fully enables the Sensor Web

The dynamic observation *strategies* that can be used by a sensor web are intimately related to the *dynamic measurement capabilities* of its constituent sensor nodes. The majority of today's sensor nodes (e.g., radiosondes, LEO satellites, *in situ* weather stations) are for the most part "***Collector" nodes***. Many of these instruments are "ON" all of the time: typically, they neither possess multiple measurement modes and only a very few perform local science data processing on the measurement data. *There will continue to be a preponderance of "Collector" type sensor nodes and only a limited number of "Reactor" type nodes available in 2015. This will significantly constrain the weather observing system's ability to take full advantage of sensor web dynamic measurement techniques.* The inability of many sensor nodes to exhibit "*Reactor*" node behavior requires a concomitantly greater need for the human-in-the-loop to support planning and scheduling processes, and to implement node command generation procedures and command distribution (e.g., spacecraft uplink). *A robust communications infrastructure and concomitant set of protocols and event messaging procedures is lacking for the sensor assets that we currently have at our disposal, even those that can behave as reactor nodes, to support the notion of automated sensor node to sensor node cueing (or tasking) to initiate a change in the sensor node's measurement state or to invoke a new local science data processing algorithm.*

Today, "anywhere", "anytime" communications with space-based nodes is frequently not possible since access to on-orbit nodes (in particular, LEO meteorological satellites) relies upon only periodic availability of communications link access locations and times (i.e., bent-pipe communications satellite links via TDRS if it is supported by the spacecraft's C&DH system, and/or limited access to ground stations). As a result, the operations concept for most LEO meteorological satellites is to "store-and-forward" their measurement data, which may have "aged" by as much as 90 minutes from the time measurements were collected. For the 2015-era, the proposed NPOESS SafetyNet worldwide communications access points will, however, significantly contribute to the reduction of sensor data delivery latency by means of 15 globally distributed, unattended ground receiving stations and the use of wideband commercial fiber optic links [46]. The combination of terrestrial links and worldwide ground stations promises to provide communications with the NPOESS spacecraft during approximately 55% of each nominal 100 minute orbit: "77 percent of the environmental data records will be delivered to the Centrals[47] in less than 15 minutes from the time phenomena are observed, and 95 percent will be delivered in less than 28 minutes".

Some progress is also being made to demonstrate spacecraft "*Reactor*" node capabilities and the benefits of using a sensor web event detection, event notification, and reactive measurement observing strategies. Three experiments currently in progress, or soon to be performed, are described below. They are representative of the types of sensor web interactions that a 2015 implementation of the 2025 weather architecture should provide.

In one experiment, EO-1's on-board computer has been uploaded with new software to perform cloud detection using sensor data collected by its Hyperion (hyperspectral) instrument. The benefit of performing this processing is improved utilization and efficiency of its on board solid state recorder capacity since only those images that meet the criteria for relatively cloud free images will be stored for subsequent downlink. In a second experiment, sensor web event detection and notification is being assessed using two of NASA's morning constellation spacecraft. Selected bands from the MODIS multi-spectral instrument on the Terra spacecraft are processed (on board) in near real time to detect potential fires. EO-1 is then commanded to point its Hyperion instrument to suspect fire locations to collect hyperspectral measurements. If required, EO-1 is commanded to perform an attitude maneuver to point Hyperion from its nominal nadir viewing geometry to correctly position the fire within its field of view. Maximizing useful science return from Hyperion, which otherwise would require allocating large amounts of on-board storage and the need for a wideband communications downlink, is a distinct benefit of using this coordinated observing strategy between these two spacecraft. Another example of using the sensor web process of event detection, event notification, reconfiguration, and response is a candidate experiment to use MODIS data from Terra or Aqua to determine the locations of cloud free measurement regions for use by Aura's pointable Tropospheric Emission Spectrometer (TES) instrument. This is significant because TES, a Fourier Transform IR interferometer, will not return useful measurements if it

46 http://www.st.northropgrumman.com/mediacenter/SiteFiles/docs/NPOESSSafetyNetFactSheet.pdf

47 NOAA/NESDIS, USAF Weather Central, Fleet Numerical Meteorology and Oceanography Center, and the Naval Oceanographic Office

collects data in regions that are cloud contaminated. This form of coordinated measurement behavior will maximize useful TES science data return. Since TES measurements will be used to better understand tropospheric ozone (O_3), the use of regional atmospheric chemistry models to forecast O_3 precursors, such as nitrogen oxides and carbon monoxide, can provide additional criteria to determine where within these cloud free regions TES should point to in order to collect useful measurements. Should this experiment be conducted, the latter would further demonstrate the sensor web concept of predictive-model-driven measurement techniques.

In the last two examples a real-time space-based communications infrastructure does not exist to permit direct spacecraft-to-spacecraft event notification or "cueing". Instead, bent pipe communications via the ground segment is used. In the 2015 timeframe a robust space-based TCA-like communications infrastructure may be highly desirable to dramatically improve system response time for transient atmospheric conditions or for rapidly evolving meteorological phenomena. However, other communications fabric alternatives may be considered.

Observing System

The observing system consists of sensor assets or nodes that are located in space, within the atmosphere, and on or below the surface "skin" of the Earth. The latter may be on or below the land or water. It is possible for the observing system to have computing or storage nodes, however, for the purpose of this study we have assumed that they are not elements of the 2015 observing system. Representative examples of observing system assets include, but are not limited to, the following types:

Space-based Assets	*Atmospheric-based Assets*	*Surface/Subsurface Assets*
❑ LEO, MEO, GEO orbiting spacecraft and their instrument suites ❑ Spacecraft at special purpose orbital vantage points – L1, L2	❑ Radiosondes ❑ Long duration balloons ❑ Commercial aircraft ❑ UAVs	❑ Fixed weather stations ❑ Moored, drifting buoys ❑ Autonomous surface or underwater vessels ❑ Doppler radar

Table 8

Appendix B identifies and characterizes specific sensor assets that are expected to become available and comprise the 2015 observing system.

As described previously in this section, "*Collectors*" or *Reactors*" comprise the observing system's sensor nodes. The majority of sensor nodes expected to be available and in use for the 2015 observing system will be "*Collectors*" – as is the case today. A few exceptions will exist such as the planned GOES-R Advanced Baseline Imager (ABI), Hyperspectral Environmental Sounder (HES), and Aura's pointable TES instrument. GOES-R, from its unique GEO viewing vantage point, will support "*Reactor*" node properties by having the ability to change temporal and/or spatial measurement modes. And TES, as has been noted, will also have the capacity to demonstrate *Reactor* behavior since it will be able to point its instrument to targeted regions of interest. The degree of dynamic behavior of the 2015 observing system will, however, be derived principally from new MDAS capabilities and its interrelationship with the few observing system nodes that will have some capacity to change their measurement states. *MDAS dynamics will be realized by having the ability to change its current schedule-driven, global forecast model production to an event driven (and perhaps Mesoscale or regional) model when conditions warrant.* MDAS nodes may exhibit sensor web behavior by having the capability to dynamically change its grid scale from a global coverage, coarse grid resolution, to a smaller regional scale, fine mesh grid resolution concomitant with the scale of the phenomenon of interest. For example, dynamic grid sizing for targeted regions can be utilized for hurricane forecast tracking.

In 2015 it is expected that each of the observing system assets will continue to be associated (logically, physically, politically) with each organization that procures, deploys, “owns”, operates, and maintains them. NOAA and NASA are representative domestic US organizations, and NASDA (Japan) and EUMETSAT (Europe) are representative examples of international meteorological organizations that utilize a wide variety of *in situ* and remote sensing assets. This distinction between domestic vs. international organizational “ownership”, and between, for example, NASA and NOAA is an important factor to consider when designing a sensor web-based observing system. The development and implementation of standard mechanisms for recording and reporting data measurements, exchanging information with other nodes, performing asset command and control as well as planning and scheduling will be critical to ensure that a future sensor web-based weather forecast system can perform as a seamlessly integrated whole.

As sensor nodes aggregate over time, command and control complexity, and concomitant operations costs will tend to increase. To constrain costs, routine operations will need to be simplified to improve the system’s response time when performing targeted observations. It is envisioned that the observing system will require a goal-oriented command and control infrastructure. A representative goal may be to “collect and downlink measurements of cloud free regions”. In this example, the observing system will automatically translate this high level goal into an ordered series of valid command sequences unique to each sensor node. “Where” this goal translation takes place, on the ground, in the space segment, or perhaps in both locations, must be readily and easily accommodated by the architecture and will depend in part upon available technologies and asset-specific performance capabilities. The dynamics of the 2015 observing system requires a similarly dynamic, reactive capability to (re)plan and schedule observing system resources. Planning and scheduling performance requirements will depend upon many factors such as: the dynamic characteristics of the phenomenon being observed; the location of assets and the time that will be required for them to be in a the proper position to make measurements; and the availability of other assets with which to make coordinated, time synchronized measurements. In some instances the planning and scheduling may be localized and performed by the assets themselves using peer-to-peer communications protocols to coordinate their measurement techniques. In other instances, a centralized solution may be required. One of the factors that will influence the implementation of a decentralized versus centralized planning and scheduling system will be the availability of a ubiquitous communications fabric. If such an “anywhere, anytime” communications infrastructure were available, with sufficient bandwidth, then the complex planning and scheduling algorithms may be performed by very capable, high performance terrestrial-based computing systems rather than the assets’ typically lower performance, embedded processor counterparts. A single, all-encompassing planning and scheduling system is not likely to exist. Instead, many interoperable planning and scheduling systems must coexist. In 2015, new planning and scheduling systems developed to meet the needs of the sensor web architecture “subnets”, as well as legacy planning and scheduling systems still in use, must be able to seamlessly interact. If coordinated observing strategies are to be realized, planning and scheduling systems must be able to exchange and readily translate each other's format and interpret the content of each others commands. This degree of seamless interoperability does not presently exist. Instead of mandating a particular solution, a middleware approach using XML constructs may be the best approach to achieve the required interoperability.

8. Investment Recommendations

Phase II Investment Recommendations

This section identifies investments by NASA in those areas deemed critical to instantiate, by the year 2015, key functions of the 2025 sensor web-based weather forecast modeling system architecture. These investments will necessitate advances in hardware (notably space-based hardware), information technologies (that facilitate seamless information exchange), and communications mediums and protocol technologies. Some of these may require two or perhaps three decades to mature before they can be "operationally" deployed to comprehensively satisfy all functional and performance requirements and to ensure a sufficiently robust operations concept. Other technologies will evolve rapidly and independently, without the need for extraordinary unilateral NASA investments, since broader efforts by industry, academia and the Federal Government are gathering momentum in key areas, notably terrestrial-based grid computing, dense wavelength division multiplexed (DWDM) wideband fiber optic terrestrial communications, and sophisticated information exchange standards which are being driven largely by the increasingly competitive needs of electronic commerce and newly emerging real time, network centric defense program initiatives. Much of the related underlying basic research is sponsored by NSF as "cyber infrastructure". As significant as science, technology and engineering challenges are, progress toward meeting the challenges presented in the Phase I and Phase II weather forecasting architecture studies also depends critically on large-scale coordination among organizations and agencies.

The most significant challenge to developing a weather forecasting solution are developing the large scale deep infrastructure on which almost al of the more advanced proposed forecast system functionality depends. These are fundamentally in the areas of:

a. Communication Technology & Infrastructure
b. Interoperability
c. On-board Computing and Processing
d. Technologies and Operational Infrastructure
e. Decision Support Tools

Communication Technology & Infrastructure

The 2025 architecture presupposes the existence of a ubiquitous "anywhere", "anytime" communications fabric and data grid. Ideally such a fabric would be characterized as permitting the exchange of information including, but by no means limited to, the following representative examples: raw and/or processed sensor measurements; asset (i.e., "node") state or event detection notification messages; system-wide reconfiguration requests; updated MDAS model output data; and updated lists of targeted observation requests. The communications fabric and data grid will be required to provide connectivity for assets on the surface, in the atmosphere, and in space. Such a "network-centric" infrastructure will fundamentally alter our present view of computing: by 2015 "the network will become the computer".

It is not unreasonable to presume that, driven by an insatiable, ever-increasing demand for high bandwidth, web-based multimedia communications, the terrestrial communications infrastructure may, by 2015, be able to provide many of the required communications capabilities. As such, it is envisioned that it could serve as an effective stepping stone towards fulfilling 2025 Weather System architectural functional and performance needs to facilitate communications among *terrestrial-based* sensor, computing, and storage nodes (i.e., assets). Similarly, wireless technologies are expected to have significantly matured and, by 2015, a wide variety of mediums and robust communications protocols and services should be widely available to accommodate communications among atmospheric assets, and between atmospheric assets and ground-based assets. However, the remaining and perhaps most significant challenge to NASA will be to create a robust, highly interconnected, and interoperable (i.e., with the ground and atmospheric assets) next generation space network.

A robust space network that can provide ubiquitous (i.e., "anywhere", "anytime") narrowband and wideband spacecraft-to-spacecraft connectivity[48] for all 2015 weather observing system spacecraft, and between the observing system spacecraft and other 2015 weather forecast system components (e.g., MDAS, NOAA Forecast Operations, Weather Data User Communities, External Coordination System, other member surface- and atmospheric-based assets) is presently lacking, and such a system may not be widely available (at least on the civilian side) in that timeframe. Another important consideration is that two key space-based observing system components circa 2015 will be NOAA's GOES-R and NPOESS: the latter is well into the mission formulation phase and it is unlikely that modifications to the spacecraft bus, C&DH, communications packages, and other system elements will be accommodated at this time. GOES-R, by virtue of being a geosynchronous spacecraft, has the unique characteristic of having the potential for 100% duty cycle communications connectivity with ground assets. As a consequence, and since it is somewhat earlier in the mission formulation phase, it may therefore be a potential candidate for use in trial Sensor Web event detection and notification "experiments" during those times when operational forecasting and environmental monitoring needs are not significantly impacted. *We recommend that NASA and NOAA consider the use of GOES-R to periodically conduct such experiments (when permitted within operational constraints) to validate Sensor Web event detection, notification, reaction, and reconfiguration concepts for potential infusion into future operational GOES-class missions in the "post GOES-R era": i.e., circa 2025.*

Two current efforts to develop the next generation global space network are the NASA-led TDRSS Follow-on and the DoD-led Transformational Communications Architecture (TCA).

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48 Spacecraft-to-spacecraft communications services can be provided: (i) as a "direct point to point" connection-oriented protocol link between communicating pairs of spacecraft; (ii) as a "bent pipe point-to-point" connection oriented service via an intermediary communications spacecraft as is presently provided by TDRSS; and (iii) using "indirect" connectionless oriented communications paths via "packet routers in space". The latter concept, as with its terrestrial Internetworking Protocol (IP) counterparts, offer distinct architectural advantages for a Sensor Web.

We view that a network centric weather forecast system characterized by a robust communications infrastructure is the most necessary (but not sufficient) infrastructure requirement, and should be among the highest priorities in terms of technology investment strategies. NASA should examine its support and participation in TCA activities, or at least draw lessons from their strategies, and technology development efforts.

The joint DoD and NASA TCA (or perhaps a "TCA-like" architecture), that is specifically tailored to meet the needs of the weather forecast system of 2015, and eventually 2025, has significant potential to provide the core communications services to facilitate real time command and control and information interchanges between: (i) individual spacecraft and groups of formation flying missions; (ii) atmospheric assets such as radiosondes, dropsondes, ACARS, UAVs, and ultra long duration balloons; and (iii) stationary (e.g., Doppler radar, ASOS weather stations, moored buoys) and mobile (drifting buoys, autonomous surface- or underwater vessels) sensor assets. The TCA is attractive for the following reasons: (i) It is intended to support 24x7 military operations world-wide and therefore it will be a robust multi-layered system with built-in redundancies so important to operational weather forecasting; and (ii) It is designed specifically to support global, seamless, real-time, two-way and fully integrated terrestrial, airborne and space communications.

We recommend that NASA continue directly participate in, or continue to be cognizant of, TCA studies and technology development efforts. NASA must also consider how to incorporate, perhaps as part of all future spacecraft buses, a standard communications module interface that ensures that all NASA spacecraft (circa 2015 and beyond) have a "built-in" infrastructure that permits the exchange (i.e., send and receive) of event notification and other similar "e-mail-like" or "instant messenger-like" messages from other terrestrial-, atmospheric-, and/or space-based assets. Such a capability will permit future spacecraft C&DH systems to have the capacity to use this "actionable information" from other Sensor Web nodes to modify their spacecraft instrument measurement techniques and observation strategies in real or near-real time.

In anticipation of future space mission needs, NASA is developing requirements, and conducting pre-formulation studies, for a follow-on to the present day TDRSS: with a targeted on-orbit date circa 2012 for the first of the next generation TDRSS spacecraft. *Although the Sensor Web is not characterized a "mission" per se in the traditional NASA view, we strongly recommend however that the Sensor Web concept of operations for the 2025 Weather Architecture should be viewed by NASA as another form of "mission" and that Sensor Web Ops Concepts and communications protocol requirements (i.e., mediums, connectivity and routing needs, up/downlink bandwidth, messaging services, etc) should be actively solicited, evaluated, and incorporated by the TDRSS Follow-on pre-formulation study team members.*

For example, some of the characteristics of the Sensor Web concept, as described by this Phase II report, would impose certain functional capabilities upon a Follow-on TDRSS including, but not necessarily limited to the following:

- Provide a "router in space" which would facilitate real time, demand access to on-orbit assets to support ops concepts such as real and near-real time targeting requests from other ground- atmospheric-, or space-based Sensor Web assets;
- Support point-to-point and point-to-multipoint connectivity (e.g., IPv6 "broadcast" and "multicast" functions) to all or selected "clusters" or groups of assets (e.g., all *in situ* ocean-atmosphere monitoring assets currently located within the Caribbean);

- Ensure interoperability between terrestrial internet communications protocols (e.g., IPv6) and on-orbit assets to facilitate a common, widely available, and preferably commercial-based, communications infrastructure. Such an approach, if deemed feasible has the potential to reduce implementation risk, promote interoperability, and drive down ground systems costs by not imposing custom communications hardware solutions on the science data user community;
- Increased uplink bandwidth, and a concomitant increase in uplink duty cycle availability, to accommodate new "standard" operational uses (other than routine command string uploads) such as: upload new or updated science processing algorithms/code to on-orbit assets; upload forward model transform files and instrument calibration coefficient files; upload cloud mask data or other science data whose algorithms are deemed to be too compute intensive to be performed by the spacecraft itself.

We recommend that an assessment be performed of the potential benefits of a TCA-like solution versus a candidate Follow-on TDRSS with respect to the needs and applications described in this study. The 2015 architecture needs may require capabilities beyond the scope of the TCA and TDRSS studies.

Interoperability

The eventual emergence of consensus or de facto protocols and standards is part of the evolution that characterizes almost every relevant modern technology infrastructure. Evolving to consensus standards takes many years, even decades. In the short term and medium term, for many of the technologies discussed in this section, significant investments in software-based interoperability ("glueware", "middleware") solutions will be required. Even though it represents an additional layer of overhead, it is necessary in the absence of universal standards. Strategies for achieving interoperability may draw from the experience of the e-commerce community, which was greatly challenged to provide the "glue" to integrate diverse, legacy systems.

A key to success of a global observing system, or at least a globally accessible and addressable observing system is uniformity of protocols. However, interoperability issues are as much sociological and political as they are technological, and some consideration should be given to development of collaborative environments that ease difficulties of communicating across cultures. We identified a number of areas where interagency and international standards for interoperability are especially needed.

- Standards for addressing and commanding observing systems (from space-based to ground-based).
- Standards for interoperability between planning and scheduling systems that will facilitate seamless integration of international and interagency owned and operated satellite assets into a virtual global weather observing system.
- Standards for representing, communicating and storing geophysical data and metadata of every type.

Addressable Observing Systems

Targeting, a key capability of the weather forecasting architecture, is useful as we intended, only if the observing systems and sensors themselves are addressable remotely, and furthermore that those assets have an ability to respond in a useful way, and to communicate results back in near real-time, courtesy of some TCA-like infrastructure. In the context of our overall architecture, the observing system resources should be addressable by the observing system itself, by the modeling system and by humans within some common framework provided and enforced at the External Control System and/or Command and Control level.

There *are* current efforts within NASA to develop standard message sets and to integrate the best COTS solutions for commanding spacecraft. The GEMSEC Program [49] [GSFC Mission Services Evolution Center) is developing a standards and component based mission operations architecture to coordinate ground and flight data systems development and services at NASA/GSFC. It will provide standardized interfaces and middleware that will enable plug-and-play modularity and re-use of vendor- and project-specific flight operations software for spacecraft monitoring, flight dynamics, notification alerts, etc. These efforts are step in the right direction from the perspective of this weather forecast infrastructure study. Spacecraft command and control and science payload ops concepts are inextricably intertwined. GMSEC's scope should address the needs to standardize traditional spacecraft command and control functions, as well as the science payload needs and the potential for dynamic, reactive, reconfigurable, and collaborative Sensor Web science measurement techniques and related Sensor Web ops concepts.

Observing Asset Planning and Scheduling

NASA should consider investing in activities and tools that enable virtual (if not actual) interoperability for planning and scheduling of coordinated measurements across agencies/nations. It is likely that these organizations will possess one (or more) spacecraft-mission-dependent planning and scheduling systems. Yet, to facilitate and realize the possibility of coordinated observations (the ultimate aim of the Earth Summit Initiatives) will require that information from disparate P&S systems be exchanged. Interoperability via middleware or some other TBD methods will need to be investigated.

Standards to facilitate information exchange from various sources

There are community efforts underway to establish standards and protocols for weather and other earth science observations [50]. For example, ISO, ANSI and the American Society for Testing and

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49 Presentation by Danford Smith (NASA/GSFC) at 2003 Ground System Architectures Workshop (GSAW2003), March 4-6, 2003, Manhattan Beach, California.

50 http://stromboli.nsstc.uah.edu/SensorML/
http://aria.arizona.edu/research/metadata/metadatalinks.html
http://gcmd.gsfc.nasa.gov/Aboutus/standards

Materials (ASTM) are developing standard for meteorological in situ instrumentation performance and calibration. NASA should at least investigate these activities for NASA relevance, and possibly engage them with regard to compatibility of space and terrestrial observing. It is important that representations of space-based and terrestrially based observing be consistent. In addition, organizational efforts are needed to develop measurement system metadata standards that take into account the full range of interests of the non-NASA communities.

The forecasting system architecture calls for model derived information to be conveyed to specific assets as contextual or first guess information. Thus, a system is needed by which such model information is to be represented and translated into forms that information processing systems and communications links can readily accommodate. If the model-derived information is to be used directly (e.g., on-board the spacecraft), then traditional communications, command, and control functions and operational procedures will be impacted. For example, forward link (i.e., uplink) operations will have to be modified to allocate time to create and schedule an uplink for the transformed or un-transformed model data, and additional communication uplink bandwidth capacity may have to be accommodated. Thought needs to be given to this aspect of technique, protocol and process development.

On-board Computing and Processing

Based on general historical experience, space-based on-board computer processing power may be assumed to be 10% that of ground-based processing but still more expensive per computation than ground-based computing, owing to the cost of hardening electronics against the harsh space environment and the cost of deploying to space. Where space-based systems are concerned, much of the on-board space processing would be supporting image processing involving pattern recognition, and feature extraction, analysis and interpretation in time and space domains (See Figure 3 Sensor Web). On-board computing would also need to support geophysical retrievals, and local generation of geolocation and other metadata. On-board satellite retrievals and analysis would potentially require the ability to store or upload on demand ancillary databases, processing algorithms & parameters.

In order to coordinate and share responsibilities for supporting opportunistic change detection and follow-up among spacecraft, it may be necessary to store (on-board) and communicate geo-registered image products among spacecraft and space to ground. A spacecraft receiving images from another will need to transform that image to its own viewing geometry using universal image/ mapping / geographical reference frameworks and protocols.

Terrestrial observing assets will generally be used to provide point measurements, and they are not as likely to involve as intensive computations as would be needed to support large format image processing and analysis. Thus, demands for local computing on terrestrially-based remote observing assets will not be as severe, and in any case would be more tractable.

Decision Support Tools

For building a system described in this report the development path needs to differentiate between automation and autonomy. At the highest level of functionality the proposed system emphasizes enabling autonomous operation as much as possible. This is a long-term goal. Trained human analysts in weather forecast offices are able to integrate disparate information from weather forecast models and observations to identify meteorologically significant features (such as seeing patterns in a set of ensemble runs that suggest an East Coast winter storm is likely in 3 - 5 days). At present, these processes are largely manual. The proposed architecture includes decisions tools that would automate these processes. In order for the decision tools to be confidently used in the place of human beings, they must be at least as reliable as trained human analysts performing the same operation -- otherwise, the human will always be in the loop. Significant investment is required to develop decisions tools that are as reliable, or more reliable than expert human analysts. This will become more important as the amount of data from models and observations increases to levels anticipated in 2015 and beyond.

Apart from the longer range autonomous system objectives, in the medium term, while humans are part of the system, the practical focus should be on automation of routine analysis that involves gleaning from myriad observations and model simulations, patterns and structures that might escape a human analyst either because of the sheer volume of data to be analyzed or because of the subtlety of the signature. Visualization tools and techniques may be quite useful, but some incipient meteorological developments or patterns may not recognizable except through sophisticated mathematical / statistical techniques.

Some emphasis needs to be given to development of tools that can intelligently and objectively evaluate forecast models and data, and to infrastructure and decision frameworks to enable model based ensemble analysis, targeting and forecast validation in an operational framework. Specifically, techniques and tools should be developed that pro-actively help the forecaster in assessing results of various models relative to one another, and all the models relative to recent or real-time observations. Typically, a forecaster may have three or four have models at his disposal and must determine which of them is performing best with regard to the his particular forecast objective. Which model is performing best may change over time, and we believe tools and techniques may be developed to objectively assess short-term histories and trends in the relative performances of these models, and to continuously provide these analyses to the forecaster. Similarly, automated change and trend detection techniques may alert the forecaster to potentially significant changes in the observational data, or alert the forecaster to possible quality issues with that data (perhaps resulting in a forecaster requesting new confirming observations).

Beyond this, the clear trend in numerical weather model prediction (both medium and short range) is toward ensemble-based forecasting, involving dozens of model runs which must be assessed using statistical / mathematical techniques. Not only are ensembles critical for certain types of targeted observing operations, but they also contain information about the probabilities of alternative model future states. As a means for collapsing the number of model solutions a forecaster must deal with to a tractable level, it may be possible to enable the forecaster to view representative forecasts drawn from a few of the dominant clusters within the ensemble set. Based on this the forecaster can examine these forecasts in light of recent observations, perhaps applying the same tools referred to in the previous paragraph involving comparison of several discrete model predictions. This is an example of what might be done under the heading of automation tools that synthesize information for better human-decision making. The same methodologies that enable objective model-based targeted, if combined with logistical analysis tools can also benefit subjective targeting decisions by forecasters, as intended by targeted observing loop #3 in the architecture.

NOAA's current operational forecast system reflects a decade-long investment in automation, but focused mostly on automation in accessing and displaying meteorological information (e.g. AWIPS). We suggest investment in automating burdensome aspects of the decision-making analysis. Advances in Human Computer Interaction emphasizing decision automation and decision support may be brought to bear in a forecast operations environment. We also suggest that there is a legitimate role for NASA to invest R&D aimed at advanced technologies (not just satellite technologies) that would enable highly integrated operational frameworks and in support of operational forecasting agencies. This should be done jointly with the interest and support of the operational community.

Technologies and Operational Infrastructure

An intrinsic property of the 2025 weather architecture requires a closed loop interaction between the (i) data assimilation and numerical forecast processes and (ii) the observations (i.e., measurements) made by weather system observing system assets. Currently, model forecast results are interpreted by humans. Any resultant observational requests (e.g., an NWS request to NESDIS to place a GOES I-M series spacecraft into a rapid scan (GOES I-M) or GOES-R series Mesoscale imaging mode circa 2012) are developed by, and initiated through human-in-the-loop processes and procedures. To fully realize and implement the 2025 architecture, this process will have to become more automated and incrementally proven to be reliable by both the weather forecast community and spacecraft command and control organizations.

Enabling Targeted Observing

The ability to successfully carry out special targeting observing depends on rapid communication to and from observing assets and the ability to quickly reconfigure observing at both the platform and instrument level to meet needs of a dynamically evolving mission. It assumes that observing assets, either individually and collectively can be caused to operate in more than one mode (e.g., spatially, temporally, and spectrally).

Current large observing system assets such as LandSat or POES, operate in ways that are for the most part fixed-mode, limited designs shaped by the operational needs, cost, infrastructure and technologies of the day. From a system operations perspective these systems are custom designed, very expensive, and can only be operated by specially trained personnel. Thus, access to these systems is tightly controlled. The process of modifying any aspect of operations configuration to accommodate special requests typically requires weeks of advanced notice and bureaucratic review.

At the asset level, the ability to point instruments (space) to region of interest by slewing, articulated sensors/ mirrors, or even orbital maneuverability may support targeting. Simpler instruments are both cheaper and less prone to failure. But from a research investment perspective, NASA might solicit concept demonstrations of sensors and platforms that support flexible multiple-mission dependent modes that can be commanded remotely or triggered as a result of self-determined criteria. An ultimate aim is full dynamic reconfigurability.

Reconfigurability can be as much software-enabled as hardware-enabled. For example, a hyperspectral sensor, supported by sufficient on-board processing, might be instructed to alter the channel re-combinations it processes and communicates depending on the parameters (e.g ozone, water vapor, Carbon Monoxide) of interest. Or, an onboard geophysical retrieval package may include optional algorithms and parameters that it may implement if prompted. New algorithms themselves should be able to be uploaded as needed.

Another aspect of dynamic reconfigurability that applies well to terrestrial assets is remote command initiation or “Launch on Demand” capability. Simple examples are forward-deployed automated radiosondes, aircraft-based dropsondes, drift balloons or UAV’s. The technologies are not new; but to be useful would require that two-way communication be supported at the asset, first to receive a signal to launch, and second to communicate back processed measurement in near real-time perhaps through a link to satellite or airborne link (commercial aircraft or UAV). A challenge would be to downsize the commware and power so that even the smallest of in situ sensors could engage the communications network. Particularly impacted would be synthesis of data from mesonet observation systems and ASOS (Automated Surface Observing System) that can provide observations at fine spatial and temporal resolution over regional and local domains. The real-time aspect is valuable in connection with shorter model data assimilation windows, and provide input on a time-scale to be useful for certain weather prediction models running in a rapid update mode.

Observing System Technology

For the most part, thinking about advanced remote sensing techniques and technologies are well in hand by NASA. Because the time from new concept development, through deployment and operational duty is as long as two decades, senor systems in active development today, and their close derivatives may be expected to be operational even until 2025. However, during this time, there are several holy grails of remote sensing that will continue to challenge us because of inherent technical difficulties and cost. These challenges are mainly related to an inability to retrieve free tropospheric winds from space and to make measurements in clouds (including temperature moisture and winds). There is reason to continue and even accelerate research on a a geo-stationary microwave sounder, and a very high resolution LEO microwave sounder, and to continue development of radio occultation methods and infrastructure for measuring temperature and moisture profiles globally employing both orbiting and ground-based receivers. Because of the importance of wind information suggested by OSSE’s, it is reasonable to continue research on a space-based wind Lidar. Success in engineering a low cost deployable space-based Lidar depends on technology breakthroughs. There is really nothing new in these recommendations. However we want to reiterate, as described in the Phase I study report, that the whole issue of making direct surface pressure and pressure profile measurements from space-based laser should be re-considered, since the technique was a definitively proven and aircraft-prototyped over a decade ago (but apparently overlooked).

NASA tends to focus its investments in space-based technologies, but real-time commanding and access to *in situ* observing assets is also a critical component of our proposed architecture. There is a need to build small ruggedized *in situ* sensors, processors and transponders that can be addressed, interrogated, and can transmit their data via a combination of terrestrial and space-links. It is likely that miniaturization and innovations intended for space applications (because of the need for low weight and efficient power management) may prove desirable for terrestrial application. MEMS technologies and recently emerging nanotechnologies (e.g., carbon nanotube-based *in situ* biochemical sensors) will offer yet additional opportunities to deploy hundreds or thousands of sensors to collect *in situ* measurements of various chemical species (e.g., NO2, CO, CO2, etc) to supplement/complement space-based remotely sensed measurements.

Development Pathways & Demonstration Steps

The responsibility for public weather forecasting lies with the US National Weather Service under NOAA and the Department of Commerce. Both the U.S. Navy and Air Force operate very large scale forecast organizations that provide forecasts that support global military operations. Increasingly, there is coordination among these agencies including shared use of model products, and increasingly development of common meteorological satellite systems. NPOESS (NASA, NOAA, DoD) and GIFTS (NASA, USN) are two examples. There is also growing overlap between military uses and civilian research using un-manned aerial vehicles (UAVs).

New generation weather prediction models are being designed around the same dynamic numerical core codes (NASA and NCAR) with standardized modular physics interfaces (Earth System Modeling Framework) to provide new levels of interoperability among NWP centers and models, including models that will serve the needs of both research and operational forecasting (WRF). NASA, NOAA and others are collaborating in mathematical approaches to data assimilation and observation targeting. Although missions of NASA, NOAA and DoD differ in substantial ways, the tools and infrastructure required are the same (analogous to the way that scientist and engineers have different approaches to problem solving, but draw on the same mathematical and physics knowledge base).

After NSF, NASA has the largest atmospheric research budget of the civilian agencies. While NASA does not have a mandate to engage in operational weather forecasting, it has equivalent expertise (although applied differently), a mandate, and significantly more funding (than NOAA) and devote to lower TRL atmospheric science related technology R&D. Just as NASA has official responsibility for developing the advanced satellite systems that NOAA eventually operates, we think that NASA can make important contributions by investing in other advanced technologies and capabilities, perhaps even some of those envisioned in this report that will benefit NOAA the future. This is consistent with NASA's strategic view of its role as engaging in R&D that supports operationally oriented government agencies. But this is a role that can only be productive with the knowledge, participation and full support of the operational agencies.

A number of new science initiatives and trends are consistent with the vision of this report. For example, research programs like the proposed THORpex will engage operational weather agencies, research agencies (including NASA) and academic researchers internationally in basic research to assess ultimate viability of many of the same concepts in this report, from advanced integrated observing systems to targeted observing. We of course recommend that NASA leverage every opportunity to work in concert within THORpex, not only scientifically, but potentially as a venue to actually prototype and component technologies and functionalities in ways that could ultimately enable the two-way interactive forecast system. Observing and participating in THORpex may reveal opportunities for automating operational decision-making processes.

NOAA/NESDIS is spearheading another highly significant initiative (Global Earth Summit) intended to facilitate the eventual development of a truly interoperable global observing system [51] for weather forecasting and climate. The scope of our vision was somewhat broader than, but easily accommodates those initiatives.

Building such as system as described in this report is beyond current capabilities. The challenges are as much related to the evolution of organizational systems as they are to technological advances. And by far, the greatest of these challenges are in software system engineering. Reaching a decision whether or not to consider building a system to accomplish certain operational weather forecasting goals must start with small, then larger demonstrations of key component functionalities and benefits. Many advanced component capabilities required to execute an advanced two-way interactive weather prediction system will have to be demonstrated in stages. The first step would typically involve ground-based simulation prototyping using information from simulated or actual observing assets. Such demonstrations, (for example to show how real-time image data would be shared among spacecraft and acted on in a collective sense) if successful, might advance to small functioning prototypes against real data and small subsets of real applications. One might explore use of de-commissioned but still operable space assets to carry out technology demonstrations of model observing feedbacks or other more complex functions of the architecture.

Examples of useful research projects that could lend themselves well to ground-based development and simulation are autonomous event detection and reaction, Geographic Information System capabilities, autonomous geo-location and image analysis in space, and development of event and pattern detection utilities using image processing and statistical analysis of model output and remote sensing data. These are just a few of dozens of simple system functionalities that will have to be developed capabilities.

Future field research programs such as THORpex also provide leveraged opportunities to prototype and demonstrate new technology capabilities and use strategies, for example, quasi-operational testing of model based targeting.

NASA and ESTO already are sponsoring relevant research at NASA GSFC, Ames and JPL involving real-time onboard data processing, automated coordinated constellation mission planning, and automated observation scheduling. We suggest that in future research

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51 http://www. earthobservationsummit.gov/framework_discussioin_paper.html

announcements, some of these activities might be focused specifically to look at the at the problem and needs of weather forecasting as described in this report.

NASA should consider linking with NSF's Dynamic Data Driven Application Systems activities, perhaps offering to jointly sponsor a workshop on observing and modeling feedback systems.

Appendix A
Analysis of Current Practice and Trends in Weather Forecasting Operations and Infrastructure

Numerical Weather Prediction Models

Probabilistic forecasts based on ensemble techniques will be trending toward increased number of ensemble members and spatial resolution for both global / medium range (7-16 days) and regional / short range (3-5 days) forecasts (see tables A-1, A-2, A-3). The current state of the art (2003) for medium range global ensemble forecasts by ECMWF consists of 50 members run at 80 km horizontal spatial resolution (table A-1). NCEP currently produces 15 member short-range ensemble forecasts at 48km resolution. Projected plans through 2012 for NCEP are to perform probabilistic forecasting using increased spatial resolutions and ensemble members for all predictive scales as evident in the projected product suites (table A-2, A-3).

Organization	Members	Resolution (km)
ECMF (Global)	51	80*
NWS (Global)	25	104
CMC (Global)	17	205
NOGAPS (Global)	10	205
NCEP SREF (Regional)	15	48

Source: NOAA/NWS/NCEP Ensemble Training Page:
http://www.hpc.ncep.noaa.gov/ensemble/training and Changes to the ECMWF Operational Forecast System No. 89*. http://badc.nerc.ac.uk/data/ecmwf-op/model_changes.html

Table A-1. *Operational NWP Ensembles (2002-2003)*

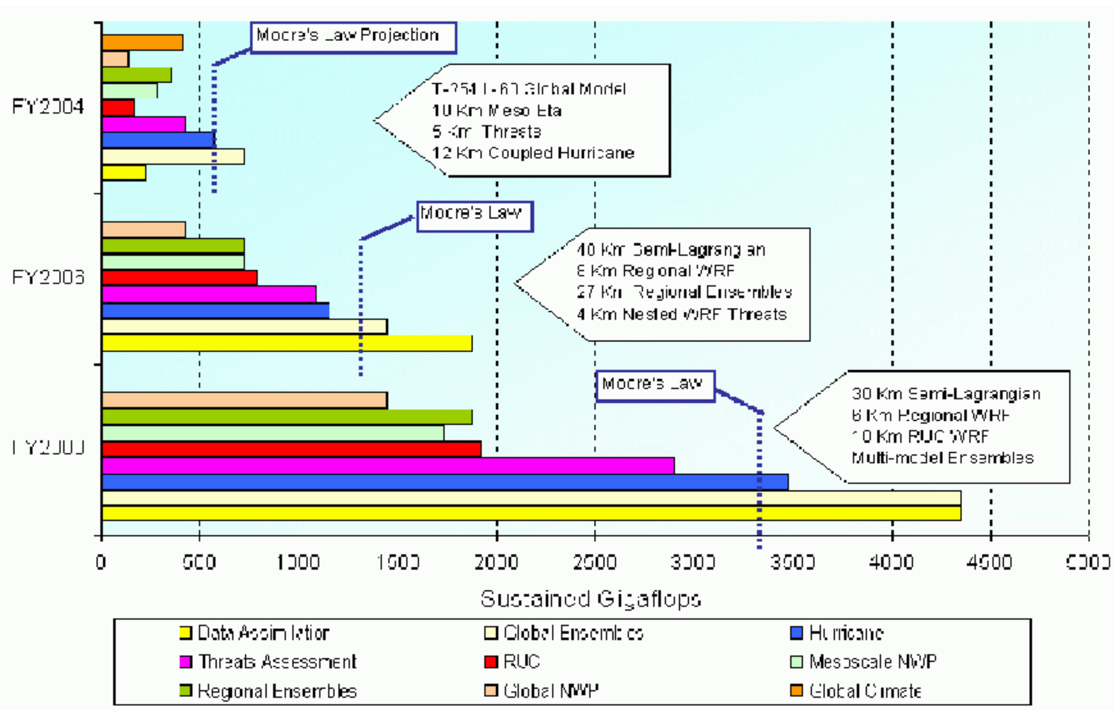
Date	Global Ensemble	Short Range Ensemble
2002	10 members, 100km (AVN)	15 members, 48km
2004	25 members, 95km (GFS)	15 members, 28km
2005	30 members, 90km (GFS)	20 members, 20km
2006	50 members, 90km	20 members, 18km (WRF)
2008	50 members, 80km	20 members, 16km (WRF)
2009	50 members, 80km	20 members, 14km (WRF)
2010	50 members, 70km	25 members, 12km (WRF)

Source: NCEP Ensemble Products. from Geoff Dimego Mesoscale Modeling Branch Where We've been and Where We're Going. NCEP Product Suite Reviews Dec. 11-12, 2002.

Table A-2. *NCEP Ensemble Products*

Based purely on reviews of planning documents we may expect that not only the resolution and number of members for ensemble products will increase, but also for multiple models to be included as members. Plans for short-range ensembles (SREF) for regional forecasts by 2010-2012 are for 12km resolution; however, this trend may be constrained by Moore's law considerations (see figure A-1).

NWP models operated in deterministic mode compared to ensemble mode will be capable of running at higher spatial resolutions (table A-3) and with more detailed physical representation of moist/cloud/precipitation processes. All NWP models (global and regional) will continue steady trends towards higher spatial resolution (table A-4).



Source: NOAA/NCEP/NCO Computing System Acquisitions: Draft Statement of Need for the Acquisition of Central Computing (Feb. 2001).

Figure A-1. *NCEP Workload Projection and Computer Resource Requirements .*

The increase in spatial resolution is indicated in NCEP projected model upgrade plans for regional and local forecasting in 2012 time frame. NWP models are also becoming increasing complex as reflected by the UK Meteorological Office plans to move global as well as regional models to non-hydrostatic, semi-implicit, semi-Lagrangian numerical schemes during the 2003-2005 time frame. Advances toward "earth simulation" models that couple ocean, atmosphere and land surface boundaries are reflected by NCEP plans to implement a 30km global coupled ocean atmosphere model by the 2007-2010 time frame [1]. The increase in model complexity, coupling and the need to run models as different spatial scales (global, regional or local) and in different (ensemble, rapid

[1] Source: NCEP Ensemble Products. from Geoff Dimego Mesoscale Modeling Branch Where We've been and Where We're Going. NCEP Product Suite Reviews Dec. 11-12, 2002.

update cycle) has necessitated the need for unification of models under common framework such as the Weather Research and Forecasting (WRF) model [2] and the Unified Model of the UK Met. Office [3]. A global version of the same model can then be utilized to generate the boundary conditions for regional or local models. Finally, as the increased observations from future satellite and in-situ observing systems become available, a trend toward operating some models on a rapid data assimilation and update cycle as frequently every two hours (table A-2).

	2002-2005	**2005-2010**	**2010-2012**
Probabilistic	GFS 95 km	GFS 90 km	Multi-model 70 km
	SREF 48 km	SREF 18 km	SREF 12 km
Global	GFS 55 km (3-384 hr)	GFS 45 km (1-384 hr)	Coupled 30 km
(4x/day)			
Regional (North Am.)	Eta 12 km (3-84hr)	WRF 8 km (1-84 hr)	WRF 4 km (1-96 hr)
(4x/day)			
Regional Rapid Update	RUC 20 km (3-48 hr)	RRW 11km (2-48 hr)	RRW 8 km (1-48 hr)
(8x/day)			(12x/day)
High Resolution	NMM 8 km (3-48 hr)	WRF 6 km (2-48 hr)	WRF 2 km (1-48hr)
(1x/day)			

Source: NCEP Projected Numerical Model Upgrades. Adapted from Jeff McQueen Science and Technology Infusion Plan, NCEP Product Suite Review, Dec. 11, 2002.

Table A-3. *NCEP Projected Numerical Model Upgrades*

Data Assimilation

Improvements in the accuracy of weather forecasts due to anticipated advances in NWP modeling and increased availability of satellite and in-situ based observations will depend greatly on corresponding advances in data assimilation and adaptive observing strategies [4]. Data assimilation is complex by nature in that complicated non-linear interactions and spatial/temporal scale dependencies of physical processes are being modeled during an assimilation cycle. Recognition of this is reflected by the major investments made by the NWP community in field

[2] Michalakes, J., S. Chen, J. Dudhia, L. Hart, J. Klemp, J. Middlecoff, and W. Skamarock (2001): "Development of a Next Generation Regional Weather Research and Forecast Model" in *Developments in Teracomputing*: Proceedings of the Ninth ECMWF Workshop on the Use of High Performance Computing in Meteorology. Eds. Walter Zwieflhofer and Norbert Kreitz. World Scientific, Singapore. pp. 269-276.
[3] Unified Model: http://www.met-office.gov.uk/research/nwp/numerical/unified_model/unified_model.html
[4] A Vision for the National Weather Service: Road Map for the Future (1999) http://www.nap.edu/openbook/0309063795/html/5.html,copyright 1999,2000 The National Academy of Sciences

programs such as FASTEX, NORPEX, PACJET, Winter Storm Reconnaissance (WSR) and THORPEX [5], and in planned Observing Systems Experiments (OSEs) and Observing System Simulation Experiments (OSSEs) [6]. Such programs and experiments are designed to answer questions regarding the quantitative impact of new observation systems, additional observations and data assimilation techniques on weather forecast accuracy.

Even now operational forecast centers are moving toward 3D-variational (3Dvar) and simplified 4D-variational (4Dvar) data assimilation techniques for global and regional predictive scales. 4Dvar techniques show promise for providing a more representative state of the earth/ocean/atmosphere, particularly in non-data intensive environments. However, in data intensive environments the advantages of 4Dvar over 3Dvar are less clear. There appears to be no consensus about the superiority of 4Dvar techniques over 3Dvar techniques in a data intensive environment. Recent trends point towards first implementing operational 3Dvar based data assimilation and then transitioning slowly where feasible to 4Dvar [7]. This trend is evident for global and regional forecasts. At high resolution (< 1 km) and nowcasting predictive scales, data assimilation may be based on one or a combination of optimal interpolation (OI), 3Dvar, 3Dvar+nudging, or 4Dvar techniques.

Another trend is toward assimilation of new types of data that have recently become available such as GPS occultation soundings, doppler radar winds & precipitation rates, lightning data, aircraft (AMDAR/ACARS) winds, cloud imagery, cloud motion winds, surface mesonet and profiler networks data, GPM satellite rain rates, and satellite soundings (Tables 4 and 5).

Date	Global Prediction Model	Global Data Assimilation	Regional Prediction Model	Regional Data Assimilation
2002	T254 / L64	3Dvar, AMSU-B, QuickScat	MesoEta 12 km	12 km, 3Dvar radar radial velocity
2004	T254 / L64	Gridpoint version, AIRS, GOES imagery	MesoEta 10 km	10km hrly update, improved background covar.
2005	45km+improved microphysics	3D background covar., cloud analysis	NMM 9 km	9 km AIRS, GOES imagery to 2mb
2006	40km / L80	Absorp/scat in rad trans.	WRF 8 km	8km WRF 4DDA

[5] The Use of Targeted Observations in Operational Numerical Weather Forecasting. Winter Storm Reconnaissance Program, Hua-Lu Pan, Zoltan Toth, I. Szunyogh, NOAA/NCEP EMC
http://sgi62.wwb.noaa.gov:8080/ens/target/wsr.html

[6] Review of Global OSEs and OSSEs, Implementation/Coordination Team on Integrated Observing systems, 2nd session, WMO, Geneva, 14-18 October 2002.

[7] Satellite Data Assimilation and its Future Plan in Japan Meteorological Agency, Yoshihiko Tahara, Numerical Predication Division, Japan Meteorological Agency, GMP Planning Workshop, May 17 2001 UMUC Conference Center, College Park, MD USA.
http//:gpm.gsfc.nasa.gov/documents./GPM_Planning_Workshop/tahara_japan_perspective.pdf.

2008	40km / L80	Aerosols in radiative transfer, GIFTS	WRF 7 km	7km absorption, scattering in radiative transfer
2009	40km / L80	NPP, integrated SST analysis	WRF 6 km	6 km aerosols in rad. transfer, reflectivity
2010	35km / L100	Advanced 4DDA, NPOES,IASI, air quality	WRF 5km	5km, NPP, advanced 4DDA, NPOES, IASI & air quality

Source: Adapted from Mesoscale Modeling Branch, Where We've Been and Where We're Going. Geoff DiMego, NCEP Product Suite Review, Dec. 11 2002.

Table A-4. *NCEP Projected Data Assimilation for Global and Regional NWP*

2015 Numerical Weather Prediction Models

Based on the current state of NWP modeling, the recent advancements and trends, a reasonable estimate of the numerical model product suite for the 2015 time frame may be provided. (Table A-5) reflects the trends identified toward common modeling infrastructures (Unified models) that enable the same model to be run in an ensemble or deterministic mode, and at different spatial scales and temporal modes.

The forecast products will be available more frequently, especially for short term forecast products, in addition to being available at higher spatial resolutions. It should be noted that although a data assimilation and forecast model run cycle may be as great as 6 hours, intermediate products are available at 1-3 hourly resolution out to the targeted extent of the forecast period. It should be noted that Table A-5 represents a simplified categorization of the actual kinds, numbers and of modes of operation that models that will likely be run at a given forecast center in the 2015 timeframe. In general, NWP models will be run in either an ensemble or deterministic mode. Models run in a deterministic mode will be able to provide products at high spatial and temporal resolution and incorporate as much physical realism such as coupling between atmosphere, land and ocean surfaces as the state of the art allows. Models run in an ensemble mode will be able to provide a forecast and the associated confidence for that forecast. It should also be noted that very high resolution mesoscale models for very short term weather predictions will most likely be run at local Weather Forecast Offices (WFOs) due to the advantages of being able to incorporate detailed local terrain and unique local observation systems such as "surface mesonets".

Model Class	Range (days)	Res.	Data Assimilation	Ensemble Members	Fcst Cycle	Fcst Prod. Avail.
Global Ensemble	long (7-16)	50km	*3d/4d var: *Sat. snd, UAV, AMDAR, SfcObs, RaObs	75-100	6 hr	1-3 hr
Global Ensemble	med. (3-6)	20km	*3d/4d *Sat.snd, UAV, AMDAR, SfcObs, RaObs	50	6hr	1-3 hr
Global Coupled (WRF, deterministic)	med-long	20-30km	*3d/4d Var, *Sat.snd, UAV, AMDAR, SfcObs, RaObs, NDVI	N/A	N/A	N/A
Regional Short Range Ensemble (SREF)	short (0-3)	10km	*3d/4d *sat snd, Radar, UAV, ACARS, SfcObs, RaObs	20-30	6hr	1-3 hr
Regional Short Range (WRF, deterministic)	short (0-3)	4-5km	*3d/4d *sat snd, Radar, Sfc. Meso, UAV, ACARS, Sfc Obs, RaObs	N/A	6hr	1-3hr
Regional Rapid Refresh (WRF/RRW)	very short (0-18hrs)	8km	*3dvar *sat snd, Radar, Sfc. Meso., UAV, ACARS, SfcObs, RaObs, lightning	N/A	2 hr	<=1 hr
Local Mesoscale (high res., state/county)	very short (0-12hr)	1-5km scalable	*3d *sat snd, Radar, Sfc. Meso., UAV, ACARS, SfcObs, RaObs,lightning	N/A	on demand	<=1hr
Huricane (WRF)	short-med. (0-7)	5km	*3dvar *sat snd, Radar, UAV, ACARS, SfcObs, RaObs	25-30	variable	1-3hr

Source : Adapted from NOAA/NCEP Product Review Dec. 11-12, 2002. DiMego, & Projected NWP Model Upgrades (McQueen)

***Table A-5**. Projected 2015 NCEP Product Suite*

2015 Data Assimilation

Data assimilation in the 2015 time frame is projected to occur on a more frequent basis and based on a mainly on 3 dimensional or 4 dimensional variational analysis techniques. Four-dimensional variational techniques will be utilized for larger spatial scales and 3d variational or nudging techniques at smaller spatial scales.

Scale	Assimilated Observations	Frequency	Technique
Global	Balloon soundings, surface, buoy, ASOS, GPS, UAVs, GIFTS, IASI, NPOES,AMSU-B, Quickscat, AIRS, GPM, COSMIC, ACARS/AMDAR	6 hr	4dVar/3dVar
Regional (continental & sub-continental)	Balloon soundings, surface, surface mesonet, buoy, radar, lightning, ASOS, ACARS/AMDAR, GPS, UAVs, GIFTS, IASI, NPOES, AMSU-B, AIRS, GPM, COSMIC	1-3 hr	3d/4d Var
Local (states, counties, cities)	Balloon soundings, surface, surface mesonet, buoy, radar, lightning, ASOS, ACARS/AMDAR, GPS, UAVs, GIFTS, IASI, NPOES, AMSU-B, AIRS, GPM, COSMIC	< 1hr	nudging or 3d Var.

Source: Adapted from NCEP product reviews, WMO & JMA documents

Table A-6. Projected 2015 U.S. Assimilated Data for NWP by Predictive Scale

In addition to the planned operational satellite observations, it is expected that available radar data, lightning data, surface based profilers, surface mesonets and ACARS/AMDAR reports and GPS data will be assimilated operationally. Global assimilation cycles are still listed as taking place on a 6hrly basis as shown in Table A-6 mainly due to the limitation of standard balloon based synoptic sounding network although the possibility exists to conduct assimilation cycles on 1-3 hourly basis incorporating all available satellite data. However, no plans for shifting global forecast data assimilation cycles to a 1-3 hour basis were found. It is highly likely that the more frequent 1-3hour data assimilation cycles will be performed for regional and local data assimilation and analysis to support short and very short-term forecasts for those scales. The more frequent or "rapid" data assimilation cycles are expected to incorporate observation systems that are capable of recording and reporting observations on an hourly or sub-hourly basis such as radar, lightning, GPS occultation soundings, ACARS/AMDAR, automated profiling and surface mesonet networks as well as conventional satellite and synoptic data.

Adaptive Observations

The concept that the forecast for a predicted weather event can be improved by performing additional observations in specific regions and for specific times most sensitive to/for growth of errors (**adaptive or targeted observations**) has progressed to an operational program with in a decade [8]. The concept was tested in early field programs (FASTEX. NORPEX, CALJET, PACJET) during 1996-1999. The Winter Storm Reconnaissance field program (WSR) was established in 1999 and became a fully operational NWS program in 2001 resulting in improvement of 70-90% of forecast cases and a 10-30% average RMS error reduction [9]. Adaptive observations are currently used by NWS to support forecast operations for U.S. land-falling winter storms.

Currently, the operational use of adaptive observations is limited to use of aircraft dropsondes. Significant weather events identified in medium range forecasts are considered as candidates for performing adaptive observations. Cases are selected based on probability and potential societal impact. Sensitivity analyses are performed to identify regions and times most sensitive to error growth. The determination of optimal flight tracks, decision, final decision and scheduling are performed by the NCEP/NCO standard duty meteorologist.

Because proper aviation planning flight requests have to be issued 24 hours in advance of take-off, flight planning usually takes place 36-48 hours in advance of the actual flights. For general planning purposes, the flight facilities also require a general outlook for the second day (i. e., whether a flight is expected or not). To prepare such an outlook, sensitivity calculations need to be run 60-72 hours before flight time. Operational procedures associated with identification of significant forecast events, performing sensitivity analysis, and prioritizing targeting of observing assets are also likely to evolve to more automated procedures over that of current methods.

The considerable expense associated with the use of manned aircraft has stimulated interest in performing cost / benefit and societal impact studies, and in developing new and better adaptive observing strategies. New strategies will most likely evolve from “THe Observing-system Research and predictability experiment” (THORpex) a proposed major 10-year international research

[8] Adaptive Observations at NCEP: Past Present and Future: Zoltan Toth, Istvan Szunyogh, Craig Bishop, Sharan Majumdar, Rebecca Morss5, Jon Moskaitis6, David Reynolds, David Weinbrenner8, David Michaud8, Naomi Surgi, Marty Ralph, Jack Parrish, Jon Talbot, John Pavone1, and Stephen Lord . Contribution to the Symposium on Obseravations, Data Assimilation, and Probabilistic Prediction. January 13-17 2002, Orlando Florida, American Meteorological Society.

[9] Ibid.

program [10]. THORpex embodies and would aim to demonstrate many of the concepts included in the Phase I study, especially as regards model-based targeted observing, globally coordinated observing, and use of satellite observing systems. As a result of these efforts, the use of remotely sensed satellite data in performing global targeted observation strategies will therefore be expected to increase.

Adaptive Observations 2015

The procedures associated for identification of forecasted significant (high impact) weather events, performing sensitivity analysis for identification of sensitivity regions and times are expected to be automated by the 2015 time frame. Scheduling of aircraft resources, UAVs or other observing asset resources are still projected to be performed manually. Operational strategies by 2015 will begin to incorporate some of the results of the THORpex program. Operational use of targeted observations are likely to be an extension of the current WSR model to include increased use of satellite data and broadening of operations to include Tropical Cyclones forecasting.

Forecast Operations

Advanced WFO workstations with capabilities beyond standard AWIPS systems will allow support of modernized forecast operations such as data ingest of satellite, regional and local data sources, scientific visualization of weather information, automated product generation, adaptive observation sensitivity analysis, hydro-meteorological applications, and product dissemination. Forecast operation systems currently being developed have the following components[11]:

- National and local data feeds;
- Mesoscale Analysis and Prediction System (MAPS) Surface Assimilation System (MSAS) and its attendant Quality Control and Monitoring System (QCMS);
- Local Analysis and Prediction System (LAPS), providing high-resolution analyses and short-range forecasts;
- Interactive display system (forecaster workstation), for data access and manipulation;
- Interactive Forecast Preparation System (IFPS),
- 3-d visualization, for viewing model grids (LAPS and NCEP);
- Hydrology applications developed at the NWS Office of Hydrology; and
- FSL-built dissemination system, providing data to local governments and emergency operations staffs.

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[10] Program Overview: The Observing System Research and Predictability Experiment THORpex, Melvyn Shapiro and Alan Thorpe, September 2002. http://www.angler.larc.nasa.gov/thorpex/docs/thorpex_plan13.pdf

[11] WFO-Advanced: An AWIPS-like Prototype Forecaster Workstation. Preprints, Twelfth International Conference on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology, 28 January - 2 February 1996, Atlanta, GA, 190-193. A. E. MacDonald and Joseph S. Wakefield

Also, WFO-Advanced Overview Forecast Systems Laboratory April 2001 http://www-sdd.fsl.noaa.gov/~jwake/WFO-A-intro.html .

Trends toward use of digital forecast products and databases, increased automation, performing scientific visualization and performing meso and local scale numerical prediction at regional and local WFOs are expected to continue and keep pace with technological advances in high performance workstations. The results will be evident in terms of increased spatial resolution, frequency and quality of short term forecast and nowcast weather forecast products produced by the regional forecast offices. Additionally, the digital forecast product paradigm is expected to result in increased variety and availability of specialized weather forecast products produced by the user community.

Assumed 2015 Forecast Operations

Forecast operations in the 2015 time frame will largely shaped/constrained by production schedules and numerical guidance products produced by the National centers (NCEP). Figure A-2 represents a simplified 2015 forecast production cycle. The operations at the regional and local WFO's are likely to incorporate the recent developments and trends described in section

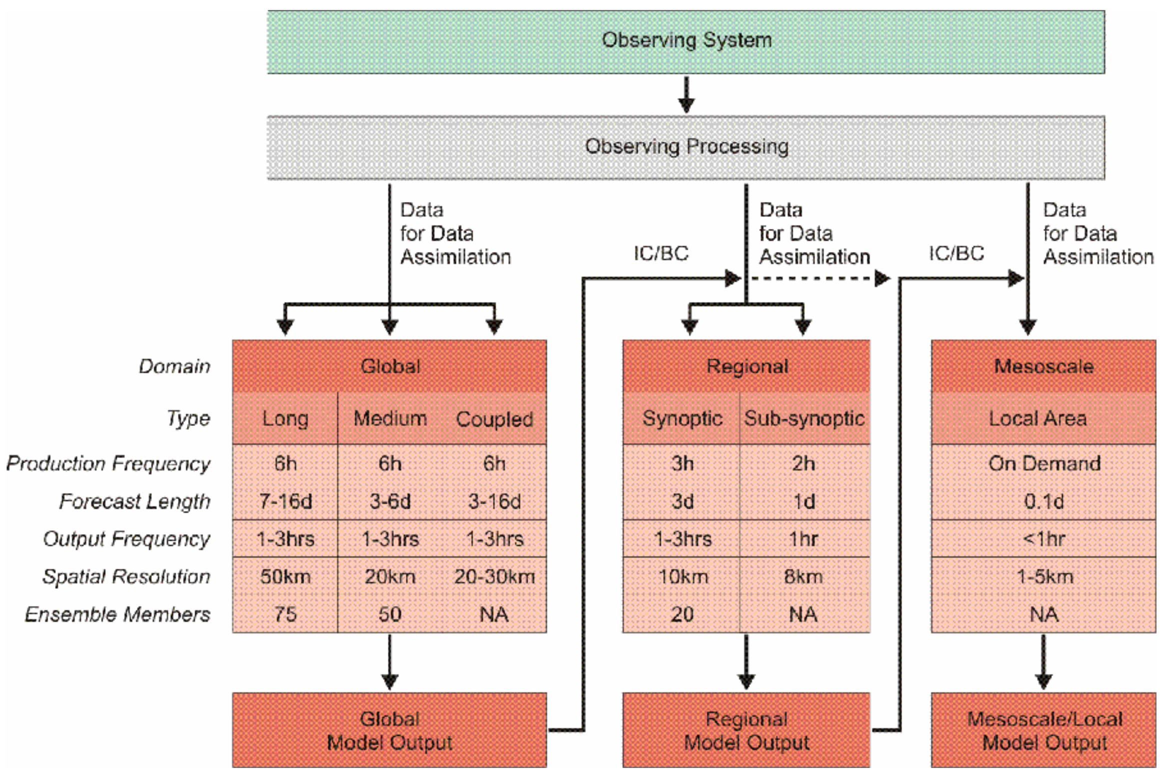

Figure A-2 *Assumed 2015 Forecast Model Operation*

Very short term Mesocale models are likely to be run at the local WFO sites while regional and larger predictive scales will most certainly continue to be run at the National Centers.

The National Digital Forecast Data Base and Interactive Forecast Processing Systems (IFPS) will be fully operational by 2015 allowing more automated distribution of warnings and standard forecast products in addition to providing more consistency and quality between forecast products issued by WFOs across the US. On going research at FSL and NRL related to Artificially Intelligent/Expert systems will be expected to yield dividends in terms of tools to support forecasting of hazards such as heavy precipitation, flash floods, severe orographic winds, icing, turbulence, convection and severe storm/tornado and issue the associated short term forecasts and warnings.

Appendix B
Assumed 2015 Observing Assets

The space- and ground-based observing assets and capabilities anticipated to be available in the 2015 time frame were characterized to constrain the scenario exercise. Table B-1 shows the upper atmosphere observing assets available in 2015. These assets, which include radiosondes, aircraft-mounted sensors and limited use of targeted drop-sondes are in current use in 2003. But, by 2015 all U.S. radiosondes, and most radiosondes internationally, will likely be GPS-equipped which will provide better accuracy of radiosonde derived winds. This improvement in wind velocity accuracy will support increased use of aircraft-based and dropsonde measurements. Recent field programs demonstrating the value of directed observations have encouraged development of methods for assimilating opportunistic measurements. We therefore expect progress will be made toward planning and implementing a more flexible upper air network that is able to more easily support non-synoptic data collections.

Table B-1 Assumed Atmospheric Assets-2015 Timeframe

Assets	Description	Geophysical Parameters	Spatial Characteristics	Temporal Characteristics
NWS Conventional Radiosondes[1]	Balloon borne instrument launched from ground	Air temperature, relative humidity, atmospheric pressure, geophysical height	102 sites scattered through the US	Twice daily (00 and 12 UTC)
NWS Radiosonde Replacement with GPS[2]	Balloon borne instruments with GPS	Air temperature, relative humidity, atmospheric pressure, geophysical height; precise locations using GPS	102 sites scattered through the US	Twice daily (00 and 12 UTC
Commercial Aircraft (ACARS)[3]	Sensors mounted on aircraft	Latitude, longitude, altitude, time, temp. wind direction and speed	Approx. 500 aircraft; 50K observations per day	Processed at FSL every 10 minutes
GPS Dropsondes[4]	Instruments dropped from aircraft	Pressure, temperature humidity ,wind ?	Targets of opportunity	Data sent to aircraft every 0.5 seconds

[1]http://www.ofcm.noaa.gov/fmh3/ text/rawinson.htm
[2] http://205.156.54.206/rrs/
[3] http://acweb.fsl.noaa.gov/
[4] http://www.atd.ucar.edu/rtf/sonde/gpsDropfacilities/dropsonde.htm

More than 50,000 winds and temperature observations are made daily by commercial aircraft using the Aircraft Communications Addressing and Reporting System (ACARS). This number is expected to increase. Although more than 90 percent of the data from these reports are at commercial jet cruise levels (near 9 km), these winds have been shown to yield improvements in short term model wind and temperature predictions [1,2]. ACARS coverage over North America is already extensive,

1 Automated Meteorological Reports from Commercial Aircraft. William R. Moninger, R. Mamrosh and P. Pauley. 2003: Bull. Amer. Meteor. Soc. vol 82. no. 2, 203-216.

while other nations are developing or have developed similar systems. The ability of ACARS to provide accurate humidity observations is expected to greatly improve in the next decade. Many observations could be greatly expanded with ACARS-type packages fitted to general aviation craft. Targeted dropsonde releases from commercial aircraft have been considered and the GPS dropsonde program may evolve to become more operational.

It is envisioned that the federal, states, county, and local governments, and segments of the private sector will all become better coordinated and generally yield better four-dimensional analyses. This will lead to improved very short term forecasts and warnings.

Table B-2 presents the ground assets assumed available in the year 2015. These include the NWS Automated Surface Observing System (ASOS), the National Data Buoy Center (NDBC) moored buoys, the extensive NWS operated hydrological network and radar profilers operated by NOAA and NDBC. The core of the nation's current surface observing network consists of approximately 2500 stations equipped with an Automated Surface Observing System (ASOS). These stations are supplemented by several thousand stations in the Cooperative Observer Network. The Cooperative Observer Network provides the basic data for defining the climate of the United States and for monitoring climate change. Reports from this network also provide important information for mesoscale flood forecasting [3]. These stations could be upgraded to provide automated text measuring and reporting. Together with the various state-operated [4] and other special-function networks, a combination of these sites would form a network of about 10,000 stations. There may also be major developments in special-purpose surface-observing networks operated by public or private sector entities. The Oklahoma Mesonet is one example. Many state highway departments operate observing networks to facilitate traffic flow and road-clearing operations. Airports, urban centers, and power generation facilities also operate special networks. As the value of specific weather and environmental data increases, the number and variety of these networks will also increase. In addition one may expect the hydrological network to become denser and more automated during the next decade as people continue to build homes near flood prone areas.

Both cost reduction and incremental improvements in reliability as well as accuracy of surface observations may occur. Significant advances are likely in the capability of microprocessors to process measurements of the meteorological, hydrological, and other physical quantities in varied and flexible formats. Microprocessors can calculate derived statistical measures, such as the maximum, minimum, average, and standard deviation of selected phenomena over a standard time interval, as well as rates of change and other derived indicators. Microprocessors can also facilitate the transmission of observational data for incorporation into the NWS database. Improvements in automated sensing of present weather (e.g., clouds and precipitation) are also likely.

For surface observations on the oceans, drifting and moored buoys and ships of opportunity could carry instruments to observe the standard quantities. Underwater instrument systems on these

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2 Benjamin, S.G., K.A. Brewster, R.L. Bratamer, B.F. Jewett, T.W. Schatter, T.L. Smith, and P.A. Stamus. 1991. An isentropic 3-hourly data assimilation system using ACARS aircraft observations. Mon. Wea. Rev. 119: 888-906.

3 Program Overview: The Observing System Research and Predictability Experiment THORpex, Melvyn Shapiro and Alan Thorpe, September, 2002. http://www.angler.larc.nasa.gov/thorpex/docs/thorpex_plan13.pdf

4 Brock, F.V., K.C. Crawford, R.L. Klliott, G.W. Cuperis, S.J. Stadler, L. Ilolanson, and M.D. Eilts. 1995. The Oklahoma Mesonet: a technical overview. Journal of Atmospheric and Oceanic Technology 12:5-19.

platforms could use thermistor strings and radio positioning techniques to measure ocean temperarare, salinity, and current velocity at several levels, down to several kilometers below the surface. To determine winds with great accuracy and high resolution for any location on the ocean, surface wind observations from these stations (or surface wind data from satellite scatterometer sensors) could be combined with high-resolution predictions of boundary layers from improved global weather prediction models.

Table B-2 Assumed Surface Based Assets-2015 Timeframe

Asset	Description	Geophysical Parameters	Spatial Characteristics	Temporal Characteristics
National Data Buoy Center[1]	Moored buoys	Wind speed, air temp, sea temp, sea level pressure	Atlantic and Pacific coasts	Hourly
NOAA Profilers[2]	Radar	Vertical profiles of horizontal wind speed and direction	Surface to troposphere measurements	Minutes
NDBC Profiler Surface Observing System[3]	Doppler Radar	Upper air wind speed in 250M increments between .5 and 16.3 km	In 16 states	Collected and forwarded every 6 minutes
Automated Surface Observing System (ASOS)[4]		Sky condition: cloud height and amount (clear, scattered, broken, overcast) up to 12,000 feet * Visibility (to at least 10 statute miles) * Basic present weather information: type and intensity for rain, snow, and freezing rain * Obstructions to vision: fog, haze * Pressure: sea-level pressure, altimeter setting * Ambient temperature, dew point temperature * Wind: direction, speed and character (gusts, squalls) * Precipitation accumulation * Variable cloud height, variable visibility, precipitation beginning/ending times, rapid pressure changes, pressure change tendency,	2500 sites	Every 5-15 minutes
Hydrological Network[5]	River Gauges	1.River ,stream flow conditions 2.Soil Moisture Conditions 3.Snow Condidtions	Throughout U.S.	Minutes to hourly

[1] http://www.ndbc.noaa.gov/index.shtml
[2] http://www.profiler.noaa.gov/jsp/index.jsp
[3] http://www.ndbc.noaa.gov/psos.shtml
[4] http://205.156.54.206/ost/asostech.html
[5] http://www.nws.noaa.gov/oh/hic/

Major improvements in surface-based remote sensors for upper-air observations should take place in the coming years. Current technologies include Doppler radars, such as the WSR-88D (commonly called NEXRAD) and wind profilers microwave radiometers, acoustic sounders, and various lidar (light-wave-length radar) systems. These technologies provide profiles or path-integrated values of humidity, temperature, and wind, as well as quantitative measures of other weather variables, such as cloud liquid water. New concepts for inferring path-integrated moisture using existing Doppler radars may prove to be operationally feasible [5]. One of the candidate modifications proposed for NEXRAD radar is polarimetry [6], a technique that uses the differential reflectivity between two signals polarized at right angles to measure the mass-weighted mean size of drops of precipitation [7,8].

In the future, it may be possible to equip emergency response vehicles and aircraft with simple Doppler radars. These mobile radars will be able to get closer to suspicious storms than a fixed-site radar can. The higher resolution of the velocity structure would make these observations more reliable and increase confidence in the tornado warning system. This concept has already been demonstrated with advanced experimental airborne Doppler radar [9] and with truck-borne "Doppler on wheels" [10]. Doppler radars have not yet been exploited to their full potential. Methods are being investigated to determine the full wind vector with a single radar [11]. The resulting wind fields could be used to reconstruct the temperature and pressure fields that drive the motion of the air. These derived fields could then be assimilated into storm-scale numerical models to predict the evolution of storms [12].

Table B-3 shows major satellite assets expected to be available in 2015. For the United States the two most important new operational satellites will be NPOESS and the GOES-R. NPOESS will carry a very large suite of instruments – please see table. GOES-R will have more flexible operations concept that will allow routine changes in image scanning modes, both routinely scheduled and ad hoc. Two other important satellites listed in Table B-3 – the European satellite Metosat Second Generation (MSG) and the Indian satellite – METSAT will add to global observing needs, and to some extent move us in the direction of increased coordination.

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5 Fabry, F., C. Frush, I. Zawadzki, and A. Kilambi. 1997. On the extraction of near-surface index of refraction using radar phase measurements from ground targets. Journal of Atmospheric and Oceanic Technology 14: 978-987.

6 Bringi and Hendry, 1990

7 Polger, P.D., B.S. Goldsmith, R.C. Przywarty, and J.R. Bocchicri. 1994. National Weather Service warning performance based on the WSR-88D. Bulletin of the American Meteorological Society 75: 203-214.

8 Bieringer, P., and P.S. Ray. 1995. A comparison of tornado warning lead times with and without NEXRAD Doppler radar. Weather and Forecasting 11(1): 47-52.

9 Hildebrand, P.H., W.-C. Lee, A. Walther, C. Frush, M. Randall, E. Lowe, R. Neitzel, R. Parstins, J. Testud, F. Baudin, and A. LeCornec. 1995. The ELDORA/ASTRAIA .airl~)me Doppler radar: High resolution observations from TOGA CARE. Bulletin of thc American Meteorological Society 77: 213-232.

10 Wurman, J., J. Straka, E. Rasmussen, M.Randall, and A. Zahrai. 1997. Design and deployment of a portable pencil-beam, pulsed 3-cm Doppler radar. Journal of Atmospheric and Oceanic Technology 14:1502-1512.

11 Wilson, J.W., and D.L. Megenhardt. 1997. Thunderstorm initiation, organization and lifetime associated with Florida boundary layer convergence lines. Monthly Weather Review 125: 1507-1525.

12 Sun and Crook, 1998

Only a combination of geostationary and polar-orbiting satellites can provide the spatial and temporal coverage required to measure the atmosphere and Earth system for weather and climate. Geostationary satellites provide images at high horizontal and temporal resolution, of clouds and total water vapor in tropical and middle latitudes but not over Polar Regions. Although some progress has been made in deriving vertical soundings of temperature and water vapor from geostationary satellites using infrared and microwave channels, the soundings have relatively low vertical resolution. Polar orbiters provide observations for all latitudes and longitudes, including Polar Regions, several times a day. Radiometric temperature and water vapor soundings derived from polar orbiters have better vertical resolution than the soundings from geostationary satellites. However, the vertical resolution of radiometrically-derived soundings from both geostationary and polar-orbiting satellites is not high enough for accurate initialization of NWP models.

The most valuable products from GOES satellites are cloud and water vapor images. The highest NWS priority for improving these products is frequent, high-quality, full-disk imaging to support its forecast and warning operations. GOES satellites also provide some useful information on the horizontal and vertical distribution of temperature and water vapor, as well as some useful information on winds based on rapidly sequenced images of cloud and water vapor features. However, complementary low Earth orbit (LEO) satellites are needed to provide the most important observations for improving NWS model forecasts: wind observations from laser systems and temperature and water vapor soundings with higher vertical resolution and greater accuracy, which could be obtained with the radio occultation technique (discussed more below). Current soundings do not adequately resolve important structures in the atmosphere, such as the tropopause and upper-level fronts. They are also generally limited to clear or partially clear regions of the atmosphere and have to be calibrated on a regular basis. In contrast, soundings derived by the radio occultation technique on polar orbiters have lower horizontal but higher vertical resolution than radiometric soundings. Radio occultation soundings are not affected by clouds, precipitation, or aerosols and are self-calibrating. Specifically, atmospheric profiling may be obtained through limb scanning of the atmosphere during the occultation of the signals from the GPS satellites as received by polar-orbiting LEO satellites [13]. The measurements relate directly to the refractivity of the atmosphere and, therefore, to electron densities in the ionosphere and temperature and moisture in the stratosphere and troposphere. Thus, radiometric and radio occultation sounding methods are synergistic, as are geostationary and polar-orbiting satellites. A combined system would provide high-resolution global coverage, spatially and temporally, of cloud images, temperatures, and water vapor.

13 Melbourne, W., E. Davis, C. Duncan, O. Hajj, K. Hardy, E. Kursinski, T. Meehan, L. Young, and T. Yunck. 1994. The Application of Space-Borne GPS to Atmospheric Limb Sounding and Global Change Monitoring. JPL Publication 94-18. Pasadena, Calif.: Jet Propulsion Laboratory, National Aeronautics and Space Administration.

Table B-3 Assumed Space Based Assets -2015 Timeframe

Assets/Launch	Orbit	Ops concept	Instruments	Measure-ments
GOES-R Series Launch 2012 10 Year Life	**2 on-orbit operational spacecraft:** GOES-E at 750W, GOES-W at 1350 W **1 on-orbit spare:** at 1050 W.	a. 1 Full Disk image produced every 15 minutes b. 1 CONUS sector produced every 5 minutes c. 1 Mesoscale product produced every 30 seconds d. All products are produced concurrently: therefore, every 15 minute interval produces 1 FD + 3 CONUS + 30 Mesoscale products	1.Advanced Baseline Imager (ABI) 2.Hyperspectral Environmental Sounder (HES)	1. 0.64 mm visible clouds, snow, ice 2. 1.6 mm daytime cloud/snow/ice discrimination 3. 3.9mm fog, low cloud discrimination, daytime reflectivity 4. 6.15 mm upper tropospheric winds 5.7 mm mid-tropospheric water vapor
Meteosat Second Generation (MSG) Launch: 8/28/2002 (MSG-1); ~2004 (MSG-2); ~2009 (MSG-3); TBD (MSG-4) Mission life~7 years	**Orbit: Geosynchronous:** 1 on-orbit operational s/c at 00 and 1 on-orbit back-up at 00	MSG is a spin stabilized S/C (100rpm)	Spinning Enhanced Advanced Visible and IR Imager (SEVIRI)	1.Derived wind vectors (from clouds) 2.Cloud analysis (coverage, height, type) 3. Tropospheric humidity 4. High resolution precipitation index 4.Cloud top height images 5.Clear sky radiances 6..Global air mass stability 7. Total ozone product

NPOESS	Orbit – polar orbiter	Many instruments. Joint effort between DOC/ DoD, NASA and NOAA	1.VIIRS Visible/Infrared Imager/Radiometer Suite 2.CrIS Crosstrack Infrared Sounder. 3. CMIS Conical Microwave Imager/Sounder. 4.GPSOS Global Positioning System Occultation Sensor 5. OMPS Ozone Mapping and Profiler Suite 6. SESS Space Environment Sensor Suite. 7. APS Aerosol Polarimeter Sensor.	Data products too numerous to list – from all disciplines – land, oceans, atmosphere, space environment, climate. See – http://www.ipo.noa.gov/observing_sensors-txt.html
GPM	Core satellite • Non-sun-synchronous orbit ~ 65° inclination ~400 km altitude Constellation satellites • Sun-synch & non-sun-synch orbits 600-900 km	Core satellite • TRMM-like spacecraft (NASA) • H2-A rocket launch (NASDA) Constellation satellite • Revisit time 3-hour goal at ~90% of time altitudes	Core Satellite • Dual frequency radar (NASDA) Ku-Ka Bands (13.6-35 GHz) ~ 4 km horizontal resolution ~250 m vertical resolution • Multi-frequency radiometer (NASA) 10.7, 19, 22, 37, 85, (150/183 ?) GHz V&H Constellation Satellites • Pre-existing operational-experimental & dedicated satellites with PMW radiometers	Data products still being defined. Assume TRMM-like data products (e.g. precipitation related)

The linkage of NPOESS with European polar-orbiting satellites, called METOP (* note – Meteosat is geosynchronous), in the near future will be an important step toward the creation of an integrated global observing system comprising the geostationary and polar-orbiting satellites of many nations. If NOAA assigns appropriate priority to this program, an integrated system is likely to be operational before 2025. Full exploitation of the synergism between geostationary and polar-orbiting satellites will provide the full spatial and temporal coverage for monitoring and predicting changes in the land-ocean-atmosphere system on both short (weather) and long (climate) time scales.

Together these satellites can provide the data to address NWS' priorities for better forecasts and warnings, as well as the scientific priorities of NASA and NOAA. Future generations of environmental satellites will benefit from a number of synergies: from a partnership among nations leading to a global observing system; from combinations of measurements from instruments on a single satellite or on multiple satellites; from advanced analytical systems that can combine satellite, radar, and other related in-situ observations to produce refined, accurate values for standard meteorological quantities; and from numerical models that can assimilate data and interact with the observing systems.

The TRMM satellite, which was launched in November 1997, illustrates the coming of age of radar as a space-based environmental observing system. TRMM carries the first meteorological radar in space, along with a multi-channel microwave imager, a visible and infrared (IR) radiometer, an Earth radiation budget sensor (the Clouds and Earth's Radiant Energy System [CERES]), and a lightning imaging sensor. The purpose of TRMM is to estimate precipitation in the tropical regions of the world. TRMM observations can distinguish between convective and stratiform rainfall and provide mean vertical profiles of latent heating and evaporative cooling. The Global Precipitation Mission (GPM), to be launched at the end of the decade, will also possess radars as sensors.

Greatly improved atmospheric temperature and humidity soundings are expected from the Advanced Infrared Sounder (AIRS), and the Advanced Microwave Sounding unit (AMSU), flying aboard AQUA, which was launched in April 2002. AIRS alone is expected to provide radiative fluxes and profiles of temperature and moisture that are substantially more accurate than current measurements. Present NPOESS plans call for the flight of a high-resolution sounder with capabilities similar to the AIRS sounder on NOAA N', the polar-orbiting satellite that will follow L, M, and N, around 2010.

Finally heat fluxes are important forcing factors in the development of intense cyclonic storms. NPOESS plans to fly a conical microwave imager sounder about 2010, which will use both a high-resolution sounder and a multi-channel microwave instrument to estimate ocean surface winds and determine ocean heat fluxes. Research satellites of the European Space Agency, such as the European Remote Sensing satellites ERS-1 and ERS-2, which are already in flight, the forthcoming environmental satellite ENVISAT, and the Canadian radar satellite RADARSAT could also provide useful data.

Appendix C
Case Study Weather Scenario Analysis: January 16- 21, 2001

Introduction

The analysis contained in this section looks at the 2015 Weather Forecast System acting against the Blizzard of 2000 super-scenario, using a scenario description format. The description highlights what are believed to be the more critical or interesting activities of the forecast system.

Before discussing the super-scenario, it is important to discuss the models and production cycle of the 2015 Weather Forecast System. Fig. C-1 provides information on the suite of weather forecast models anticipated to be available in the 2015 timeframe. Like today, they consist of three major classes: global, regional, and mesoscale forecast models. The major distinction between these classes is the horizontal domain of the forecasts:

- global- entire globe
- regional- continental-sized region (can vary size)
- mesoscale- small region within a continental-sized region (e.g., 1000 km x 1000 km)

For convenience in the discussions below, the forecast length of the models is used to further break down these classes into sub-classes as follows:

- long range (LR)- 7 to 16 days
- medium range (MR)- 3 to 6 day
- short range (SR)- up to 3 days
- very short range (VSR)- up to 1 day

The quantitative information contained within the central cells of each major block in Fig. C-1 further defines the forecast product. It contains the following information:

- forecast production frequency: how often the model is run
- forecast length: the range of time over which forecasts are provided
- product output frequency: frequency of output products within the forecast range
- spatial resolution: horizontal spatial resolution of the forecast models
- number of ensemble members: number of variants of the model that are executed each time the model class and sub-class are run.

Within a class and sub-class, there may be more than one physical model used to generate the forecast type. In addition, a given physical model may have a variety of execution options that will make the forecasts unique (e.g., different options for modeling convective processes). A given physical model may be initialized with variations on a baseline set of initial conditions, also leading to unique forecasts. The members of an ensemble might result from any one or a combination of these variants.

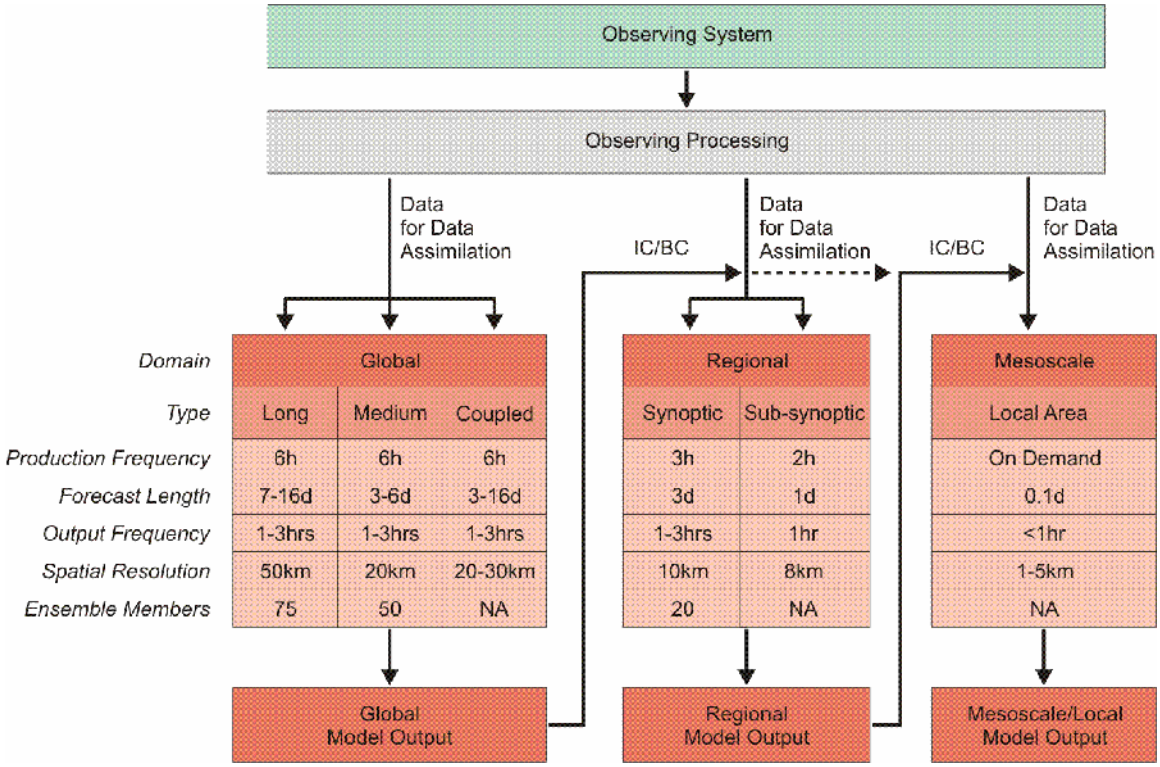

Figure C-1. 2015 Forecast Production Cycle

Fig. C-2 depicts the weather forecast models and observing system production schedule for a "typical day" in 2015. Each data type is provided a numeric label (see the legend) and its individual production schedule is shown on the graph. Table C-6 provides more information on the products.

Table C-1. 2015 Weather Forecasting System Regularly Scheduled Observation and Weather Forecast Products

	Data Types and Label	Description	Collection/ Processing Frequency	Processing Time	Comment on Processing Time
Ground-based	1: Sfc Obs/ ASOS	Surface observation and ASOS networks	Every 5 - 15 minutes	NA	Data available to Forecast System almost immediately
	2: Radar	Radar network	6 minutes	NA	Data available to Forecast System almost immediately
	3: Profilers	Wind profiler network	6 minutes	NA	Data available to Forecast System almost immediately
In-situ	4: Rawinsonde	Rawinsonde network	12 hours	NA	Data available to Forecast System almost immediately
Geostationary Satellite	11: GOES-R Imagery	GOES-R imagery data	5 min (CONUS Sector, Mesoscale 30 seconds)	NA	Imagery data available to downstream processing almost immediately
	10: GOES-R Imager EDR	Environmental Data Record (EDR) products resulting from processing imagery data to a form useable by NWP models.	See above	15 min	Imagery Processed to EDRS and available to Forecast System in 15 minutes
	13: GOES-R Sounder	GOES-R ABI imagery data	1 hr	NA	Imagery data available to downstream processing almost immediately
	12: GOES-R Sounder EDR	Environmental Data Record (EDR) products resulting from processing imagery data to a form useable by NWP models.	See above	30 min	ABI imagery Processed to EDRS and available to Forecast System in 30 minutes
Polar	15: GPM Data Collection	Collection of data from GPM Mission.	3 hrs	NA	Imagery data available to downstream processing almost immediately

	Data Types and Label	Description	Collection/ Processing Frequency	Processing Time	Comment on Processing Time
	14: GPM EDR	GPM (EDR) products resulting from processing of the GPM data	3 hrs	30 min	Imagery Processed to EDRS and available to Forecast System in 30minutes
	21,23,25: PMD-EUS/CUS/WUS Eq. Crossing	Polar PM orbiters equatorial crossing time for descending pass nearest eastern US (EUS), central (CUS), and Western US (CUS)	~100 min	NA	Imagery data for quarter orbit processed to L1 and available to downstream processing almost immediately
	20,22,24: PMD-EUS/CUS/WUS EDR	EDR products	~100 min	30 minutes	Produce EDRs from L1 for quarter orbit and available to Forecast System
	21,23,25: PMA-EUS/CUS/WUS Eq. Crossing	Polar PM orbiters equatorial crossing time for ascending pass nearest EUS, CUS, and WUS	~100 min	NA	Imagery data for quarter orbit processed to L1 and available to downstream processing almost immediately
	20,22,24: PMA-EUS/CUS/WUS EDR	EDR products	~100 min	30 minutes	Produce EDRs from L1 for quarter orbit and available to Forecast System
	27,29,31: AMA-EUS/CUS/WUS Eq. Crossing	Polar AM orbiters equatorial crossing time for ascending pass nearest EUS, CUS, and WUS	~100 min	NA	Imagery data for quarter orbit processed to L1 and available to downstream processing almost immediately
	26,28,30: AMA-EUS/CUS/WUS EDR	EDR products	~100 min	30 minutes	Produce EDRs from L1 for quarter orbit and available to Forecast System
	27,29,31: AMD-EUS/CUS/WUS Eq. Crossing	Polar AM orbiters equatorial crossing time for descending pass nearest EUS, CUS, and WUS	~100 min	NA	Imagery data for quarter orbit processed to L1 and available to downstream processing almost immediately
	26,28,30: AMD-EUS/CUS/WUS EDR	EDR products	~100 min	30 minutes	Produce EDRs from L1 for quarter orbit and available to Forecast System

	Data Types and Label	Description	Collection/ Processing Frequency	Processing Time	Comment on Processing Time
Forecast Models	41: Global Long: Analysis VT	Global long-range forecasts, analysis valid time	6 hrs	NA	This is the valid time of the initial analysis
	40: Global Long: Forecasts Available	Global long-range forecasts available	6 hrs	90 minutes	Assume it takes 90 minutes to produce full forecast product suite and available in archive
	43: Global Med: Analysis VT	Global medium-range forecasts, analysis valid time	6 hrs	NA	This is the valid time of the initial analysis
	42: Global Med: Forecasts Available	Global long-range forecasts available	6 hrs	90 minutes	Assume it takes 90 minutes to produce full forecast product suite and available in archive
	51: Regional Short Ensemble: Analysis VT	Regional short range ensemble forecasts, analysis valid time	3 hrs	NA	This is the valid time of the initial analysis
	50: Regional Short Ensemble : Forecasts Available	Regional short range ensemble forecasts available	3 hrs	60 minutes	Assume it takes 60 minutes to produce full forecast product suite and available in archive
	53: Regional Short Deterministic: Analysis VT	Regional short range deterministic forecasts, analysis valid time	6 hrs	NA	This is the valid time of the initial analysis
	52: Regional Short Deterministic: Forecasts Available	Regional short range deterministic forecasts available	6 hrs	60 minutes	Assume it takes 60 minutes to produce full forecast product suite and available in archive
	55: Regional Very Short Deterministic: Analysis VT	Regional very short range deterministic forecasts, analysis valid time	2 hrs	NA	This is the valid time of the initial analysis
	54: Regional Very Short Deterministic: Forecasts Available	Regional very short range deterministic forecasts available	2 hrs	15 minutes	Assume it takes 15 minutes to produce full forecast product suite and available in archive

	Data Types and Label	Description	Collection/ Processing Frequency	Processing Time	Comment on Processing Time
	61: Meso Very Short Deterministic: Analysis VT	Mesoscale very short range deterministic forecasts, analysis valid time	1 hrs	NA	This is the valid time of the initial analysis
	60: Meso Very Short Deterministic: Forecasts Available	Mesoscale very short range deterministic forecasts available	1 hrs	15 minutes	Assume it takes 15 minutes to produce full forecast product suite and available in archive

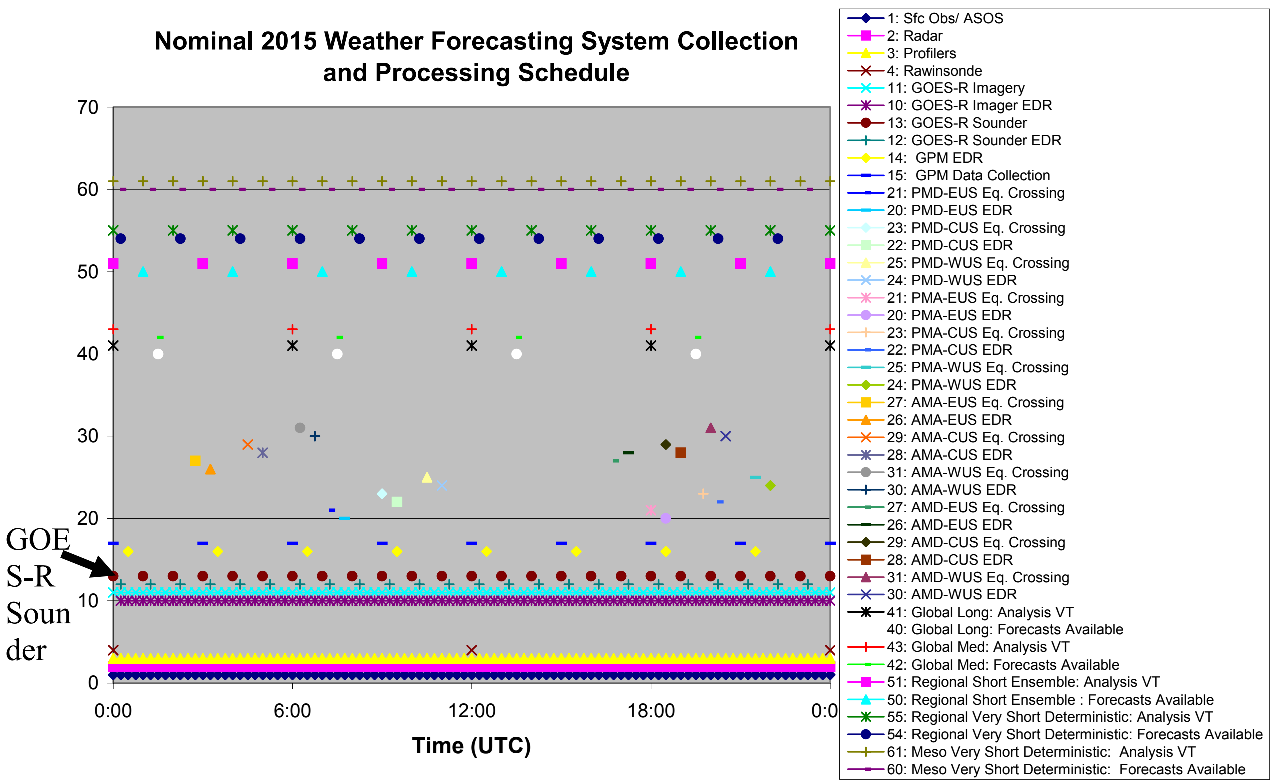

Figure C-2. Notional 2015 weather forecasting system collection and processing schedule

In Table C-1, the collection/processing frequency column indicates, depending on the product, how often data is collected, how frequently processing of data to an Environmental Data Record (EDR) occurs, how frequently a forecast model is run, or how frequently forecast model products are available. It is assumed that once data are processed they are available to the rest of the system.

Collected data are processed to a physically meaningful product called an EDR. Depending on the type of data, this is depicted as a one- or two-step process. All ground-based observations (see Table C-1) are assumed collected and processed to an EDR level almost immediately; therefore, the collection and processing are depicted as one entry in the graphic for each time the data are collected/and processed. Similarly, in situ measurements such as rawinsonde measurements (as well as irregular measurements from aircraft and dropsondes which are not shown) are assumed to be available to the system immediately. On the other hand, the collection and processing of satellite date is shown as a two-step process. It is assumed the data are collected at a certain frequency and at representative times, and that it takes some time to process the data to an EDR-level. The processing time is the time difference between the collection at the "representative time" and the time that the corresponding EDR product is available to the forecast system.

For example, GOES_R sounder data (Data Label 13) are collected every hour. These collections are plotted with a solid red circle along the y=13 axis in Fig. C-2. The corresponding GOES-R EDR data (Data Label 12) are available 15 minutes later, the availability times of the products are shown by the "+" symbol plotted along the y=12 axis in the figure.

Data from two types of polar orbiter data are shown: GPM and NPOESS. GPM data are shown as available every three hours globally. The NPOESS data are shown for AM and PM ascending (AMA and PMA) and descending (AMD and PMD) orbits over the Eastern US (EUS), Central US (CUS), and Western US (WUS). Because the local revisit times of NPOESS are not daily, the equatorial time of the nearest orbit to the EUS, CUS, and WUS changes every day.

The schedules for the Weather Forecast models are also shown in Fig. C-2.

The Super-Scenario

T-72 hours. It is 12 UTC January 22 2015, and a synoptic pattern eerily similar to the Blizzard of 2000 develops.....

For the past several days, the Weather Forecast System has been tracking a named event, 2015N004 (the fourth event of 2015), which is now exiting the Canadian Maritimes. Apart from this system, the weather conditions over the contiguous US are relatively tranquil at 12 UTC on January 22 2015 (Fig. C-3). As part of their routine operations the Weather Prediction System generates ensemble runs of their Global Medium Range (GMR) Forecast Models every six hours out to six days. Automated statistical models take the ensemble results, process them, and identify potential significant weather events, including east coast winter storms. Several ensemble members from the GMR forecasts generated on 20 and 21 January have shown the potential for another significant east coast winter storm on 25 January, and the models have flagged the event to the MDAS system. Although the ability to accurately identify, track, and forecast east coast storms has increased dramatically over the preceding 10 years, as of 2015 the 4- and 5-day forecasts are generally not used to invoke operational targeted observing to improve east coast forecasts. This is because the 2015 Weather Forecast System can quickly allocate resources to collect data that will improve forecasts; no longer are lead times of several days required. However, the National Weather Service and other research organizations sometimes conduct targeted observing in research mode, in a continuing effort to improve the accuracy of medium- and long-range forecasts.

Since the medium-range forecasts have been consistent in identifying a potential east coast storm, the Weather Forecast System was put into “alert mode” 24-hours ago, which means that operators were made aware of a potential upcoming event. In particular, those components of the Weather Forecast System which require long lead times, such as aircraft operations, are required to prepare for a potential operation within 24-hours of an alert.

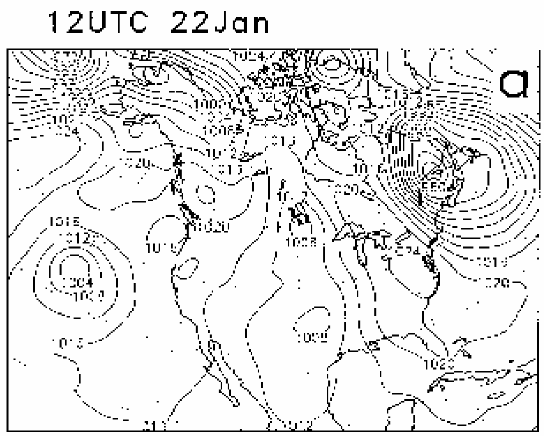

Figure C-3. Surface Analysis for 12 UTC 22 January 2015 (Figure extracted from Ref. 1)

T-70 hours. 14 UTC January 22 2015.

The MDAS automated analysis of ensemble runs from 12 UTC 22 January again flags a significant east coast event on 25 January. The automated analysis indicates a high probability of the event, based upon agreement among ensemble members from the 12 UTC 22 January runs, correlation with runs on prior days, and past performance of the models. With a high probability east coast event only 3-days away, MDAS operations formally names and tracks this event as 2015N005 (fifth event of 2015). Formally named events are continuously tracked until they no longer meet “event criteria”, such as being a serious threat to human activities. In this case, the major threat is heavy snowfall along the US east coast.

T-69 hours. 15 UTC January 22 2015.

MDAS Operations decides to invoke a sensitivity analyses (SA) based upon the results of the Regional Short Range (RSR) Forecast Ensemble runs produced at 12 UTC January 22. The SA quantifies the sensitivity of forecasts to the initial state of the atmosphere from which the forecasts are generated. In the case of event 2015N005, the 12 UTC 22 January SA shows the sensitivity of forecasts valid 12 UTC 25 January over the US east coast region to the specified initial conditions valid at 12 UTC 22 January. The SA shows the parameters (e.g., temperature, winds, humidity) and their location (latitude, longitude, and altitude) that have the most impact on the forecast, as well as the magnitude of the impact. Parameters and regions with high impact are candidates for targeted observing.

T-68 hours. 16 UTC January 22 2015.

The SA conducted using the forecasts for 12 UTC 22 January (Fig. C-4) shows geographically widespread sensitivity among several atmospheric variables and at many levels of the atmosphere. Automated utilities within MDAS take this information and develop a vertically integrated sensitivity product (Fig., C-5), which narrows down the regions of sensitivity. Experience gained over the past ten years shows that the integrated product can be used to focus targeted observing; however, both the integrated and individual SA products are still used to identify targeted observing opportunities. Targeted Observing Decision Aids (TODAs) take the SA products, together with information on the collection schedules of observing assets and develop products that identify where, when and what observations are required to improve forecasts. Although automatically generated, these products are reviewed by MDAS Operations personnel, who have the final say in determining the targeted observation nomination list (TONL) that is forwarded by MDAS to the Observing System through the Communications Infrastructure. The TONL includes the observing asset, the time and location of collections, and the required kind of data that needs to be collected. Automated utilities within the Observing System can determine the viability of most requests through application of automated rule-based algorithms, but occasionally requests are forwarded to the External Coordination System (ECS) for adjudication, especially if assets under control of non-US entities are involved.

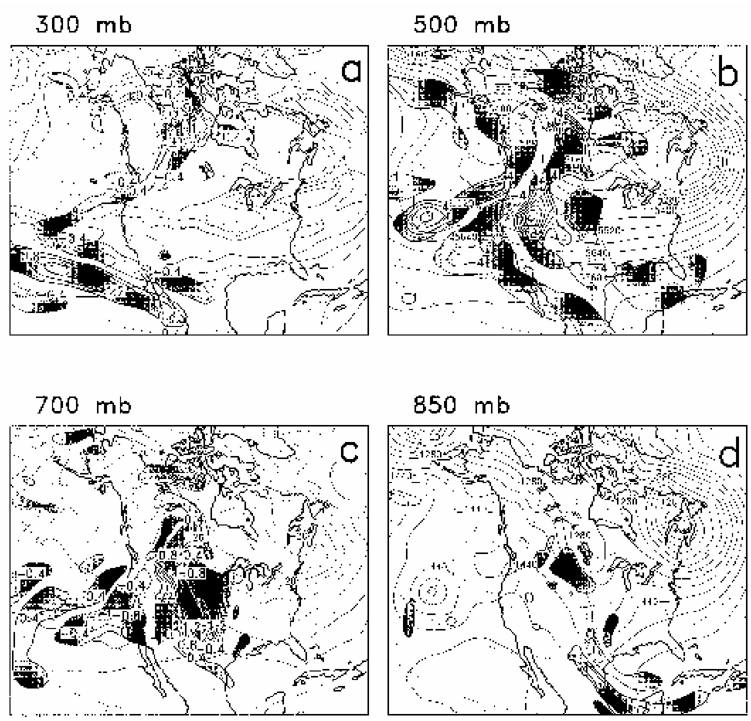

Figure C-4. Results of SA showing widespread sensitivity of forecasts to initial conditions. The figure shows the differences (shaded) between optimal and control initial conditions, valid at 12 UTC 22 January. (a) 300mb total wind speed; (b) 500mb height; (c) 700mb temperature; (d) 850mb vorticity. The background contours are (a) 300mb wind velocity; (b) 500mb height; (c) 700mb temperature; and (d) 850mb height. (Figure extracted from Ref. 1)

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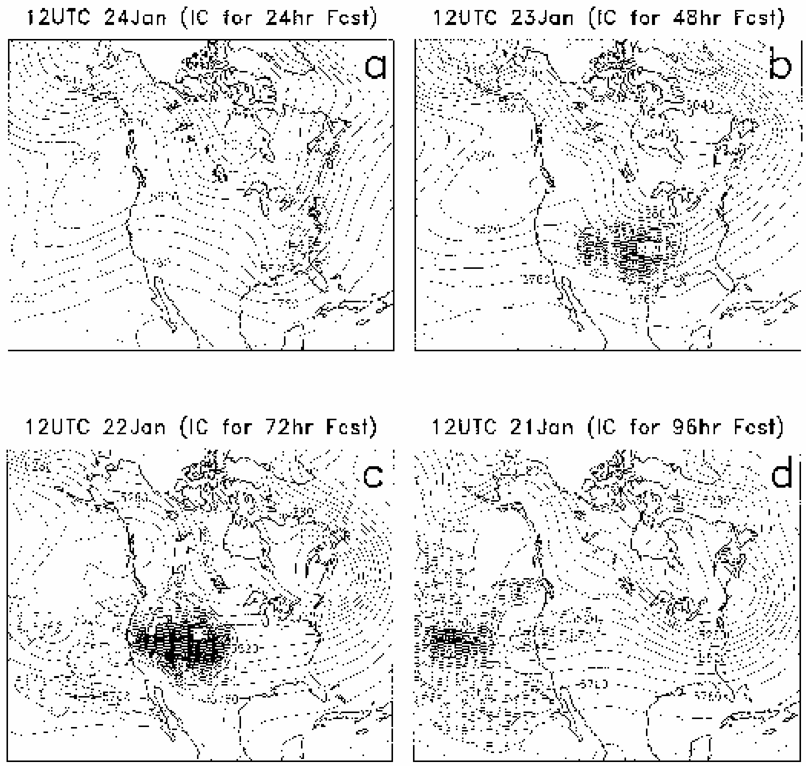

FIG. 7. Vertically integrated sensitivity (S) of forecast error at 1200 UTC 25 Jan 2000 in the region 25°–55°N, 50°–100°W to initial conditions at (a) 1200 UTC 24 Jan, (b) 23 Jan, (c) 22 Jan, and (d) 21 Jan 2000. Here, S is shaded, with a contour interval of 1.0 J kg^{-1}. The 500-hPa height is shown as solid contours (interval = 60 m).

Figure C-5. Vertically integrated sensitivity product (shaded) overlaid on 500mb height contours. (Figure extracted from Ref. 1)

The TODAs are designed to maximize the spatial and temporal overlap of measurements from multiple sensors, in order to obtain as complete a picture of the atmospheric state as possible within narrow time windows. In 2015, this means that the TODAs seek to schedule coincident collections from satellite (e.g., NPOESS, GOES-R, GPM), in-situ (e.g., rawinsondes, dropsondes, aircraft) and ground-based (e.g., surface observations, profilers) platforms. Advantages of coincident collections include:

- Accurate first guess profiles from rawinsondes and dropsondes for NPOESS, GOES-R, and GPM retrieval algorithms. This effectively spreads the quality of the in-situ measurements to the denser, but sometimes less accurate satellite measurements. This procedure improves the quality of satellite retrievals, especially in regions of extensive cloud cover.
- Widespread, high-quality measurements for data assimilation to improve the definition of the initial state of the atmosphere.

Based on the SA and the observing system schedule, the TODAs "recommend" intermediate launch of rawinsondes at 20 UTC 22 January over land areas in the region of highest sensitivity.

This schedule deviates from the routine 0 UTC and 12 UTC rawinsonde launch schedule, but this is allowed in 2015. The recommended geographical region includes the western US, southwestern Canada, and Northern Mexico (Fig. C-6). The TODAs also recommend aircraft collections. The TODAs show that more accurate measurements of wind speed, temperature, and the height of standard and significant pressure levels are needed off the US West Coast where rawinsonde measurements are not practical. The TODAs recommend the flight pattern and timing for aircraft measurements using dropsondes to "sound" the atmosphere. The recommended flight pattern is depicted in Figure C-7.

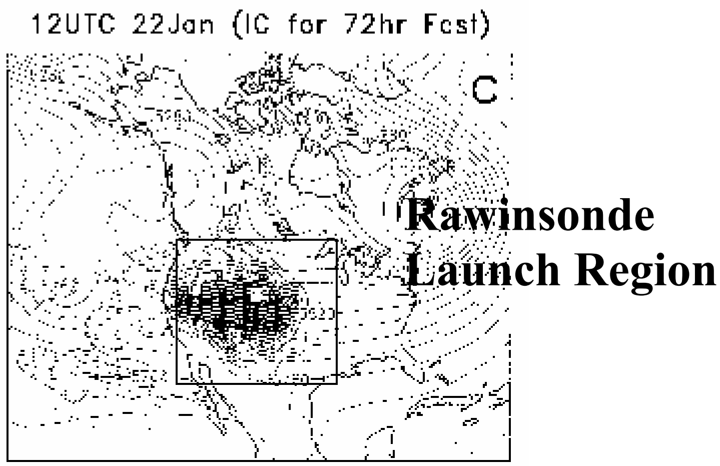

Figure C-6. Rawinsonde launch zone.

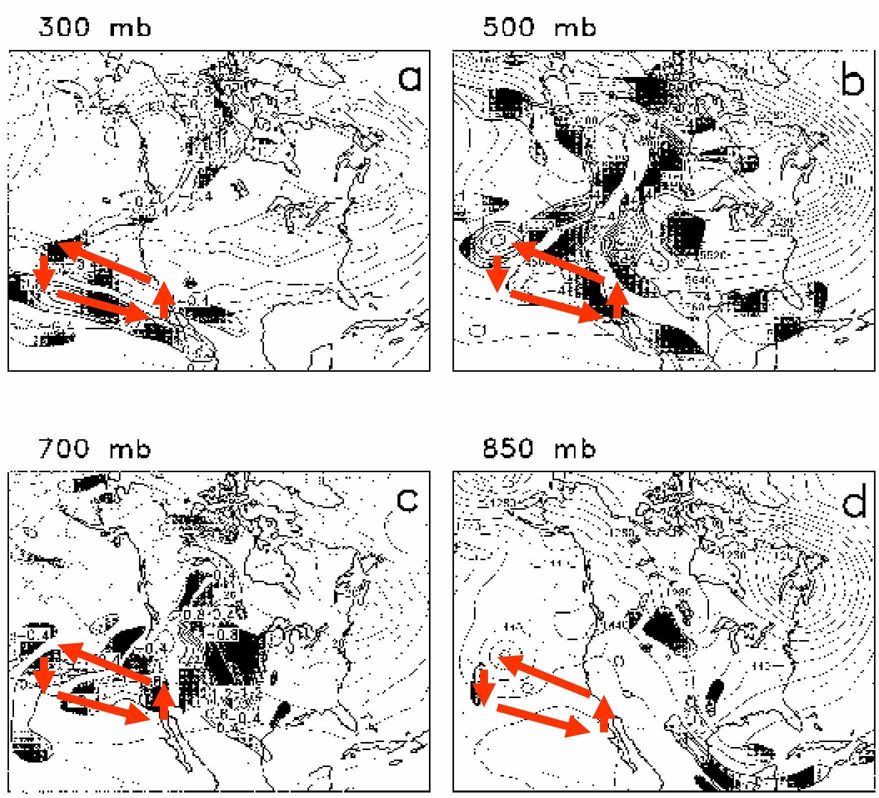

Figure C-7. Aircraft flight pattern for dropsondes.

Although rawinsondes and dropsondes provide the most accurate measurements of temperature, moisture, and wind data, their geographical distribution is limited relative to the coverage of meteorological satellites. In an effort to capture a more complete picture of the atmospheric state in the sensitive regions, the TODAs schedule GOES-R mesoscale regions (Figure C-8) to be set up over two zones to cover the aircraft and rawinsonde measurement areas. Both imagery and sounding products will be collected over these regions. In addition, the TODAs have scheduled the rawinsonde and aircraft collections to be at approximately the same time as the NPOESS-PM satellite overpass (see Figure C-9), so that the in-situ measurements can best support the NPOESS retrieval algorithms.

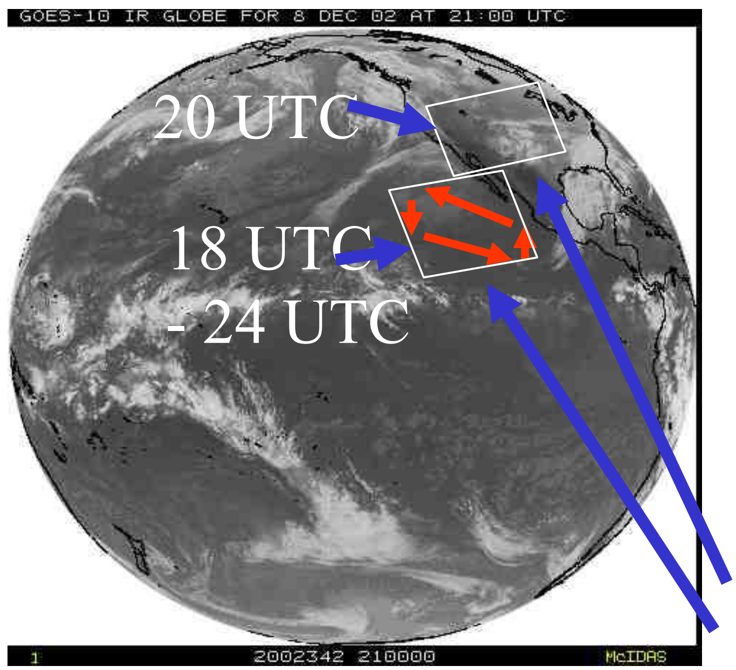

Figure 4-8. GOES-R mesoscale regions.

Figure C-8. GOES-R mesoscale regions.

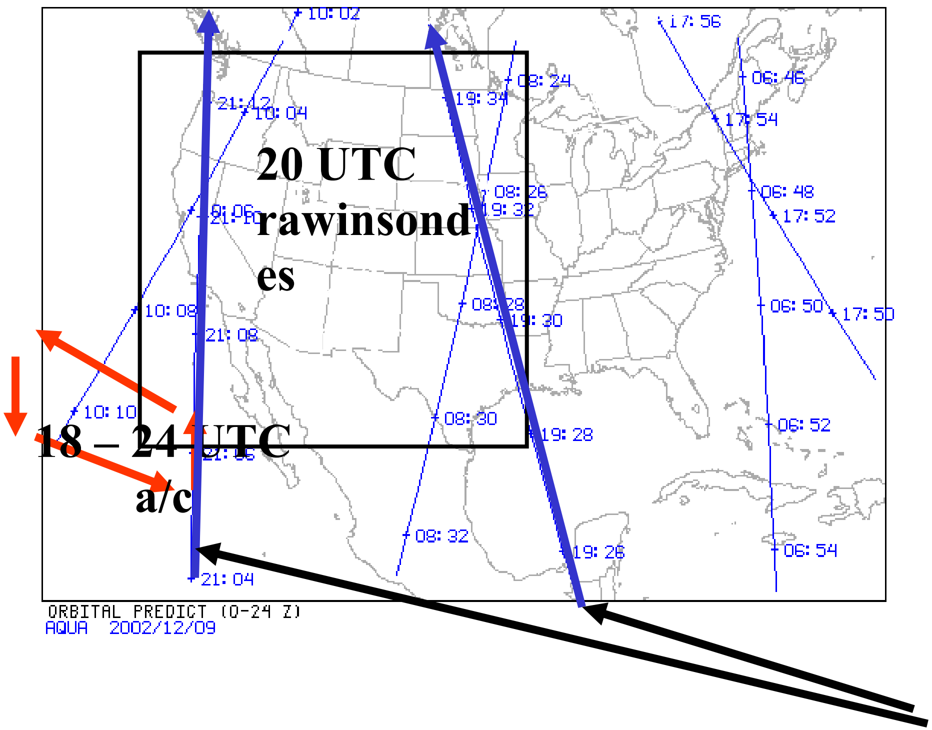

Figure C-9. NPOESS-PM overpasses near the time of the intermediate rawinsonde launches.

T-67 hours. 17 UTC January 22 2015

After reviewing the TODA-recommended TONL, personnel within MDAS Operations decide to "go with it", and the list is formatted for distribution to the Observing System. The formatted TONL is accepted by the Observing system, and operational schedules are appropriately modified. For the satellites, this means that the collection schedules are modified and transmitted up to the spacecrafts. For the ground-based observing system, e.g. the rawinsonde network, messages are automatically generated and distributed to the impacted observing sites. Since the recommended targeted observation region for rawinsondes extends beyond US borders, the rawinsonde portion of the TONL is automatically forwarded from the Observing System to the ECS to coordinate with foreign organizations; personnel within the ECS coordinate with Mexico and Canada to schedule rawinsondes in those countries as well.

T-59 hours. 01 UTC January 23 2015.

As the impending winter storm event nears to within 3-days, more attention is given to the Regional Short Range (RSR) forecast products. The 3-hourly MDAS data assimilations between 18 UTC 22 January and 00 UTC 23 January have included the targeted observations. In the data assimilation process, the forecasts from a previous run of the RSR forecast models are used in conjunction with recent observations to produce initial guess fields for the next RSR forecast. The RSR forecast ensemble runs initiated at 00 UTC 23 January have benefited from the assimilations of the target observation data, yielding a high quality initial state. As a result, the ensemble members available at 01 UTC are in much better agreement than they were for earlier runs. There remains, however, a strong suggestion of an east coast storm on 25 January and event 2015N005 continues to meet "event criteria". MDAS Operations, based upon automated guidance from the MDAS system, schedules another SA for 12 UTC 23 January. Meanwhile, the Weather Forecast System continues routine operation.

Note: Research showed (see Table C-5) that inaccurate initial conditions led to inaccurate medium-range forecasts for the Blizzard of 2000. The 3-5 day forecasts preceding the Blizzard of 2000 did not indicate a significant east coast storm. The 2015 system identifies the possibility of a significant east coast storm early, and then focuses the observing system on collecting the right kind of data to improve the medium range forecasts.

T-48 hours. 12 UCT January 23 2015

It is still two days prior to the anticipated east coast storm and the surface low associated with the system has not yet formed (Fig C-10). However, at high levels in the atmosphere (250 mb) the disturbance that will eventually lead the development of the surface low has progressed steadily from the Western Pacific several days ago to a position at about 105W at 12 UTC January 23. During the course of the past few days the disturbance has been moving at a rate of about 30 m sec-1, compared with the propagation speed of synoptic-scale ridges and troughs, which are propagating at a phase velocity of approximately 5 to 10 m sec-1. The region of maximum sensitivity travels at the speed of the disturbance and so it moves very quickly with time. The MDAS provides analysis and forecast products, such as shown in Fig C-11, to track the progress of upper level disturbances associated with named events based upon past analyses and future forecasts. The centroids of the disturbance location are marked with "x"s in the figure and are determined as a by-product of sensitivity analyses and by signature detection on prior analyses and forecast fields. *Comparisons between forecasted and observed disturbance and trough and ridge locations are used to determine the quality of the forecasts and can be used to identify which of several models is providing the most accurate forecasts.*

According to its normal schedule, the MDAS kicks of the 12 UTC RSR ensemble runs. MDAS Operations schedules a SA immediately following the runs to identify targeted observation opportunities.

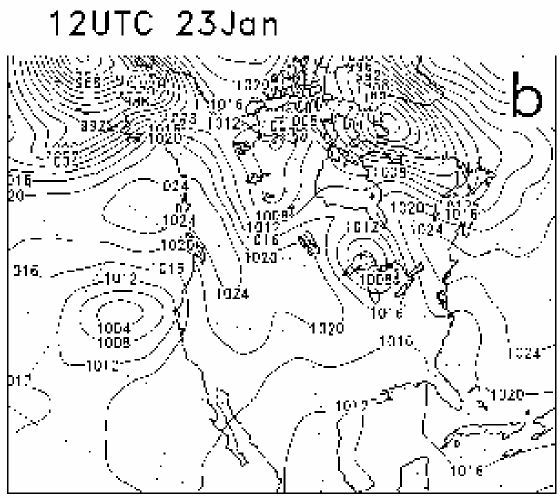

Figure C-10. Surface analysis valid 12 UTC January 23 2015. (Figure extracted from Ref. 1)

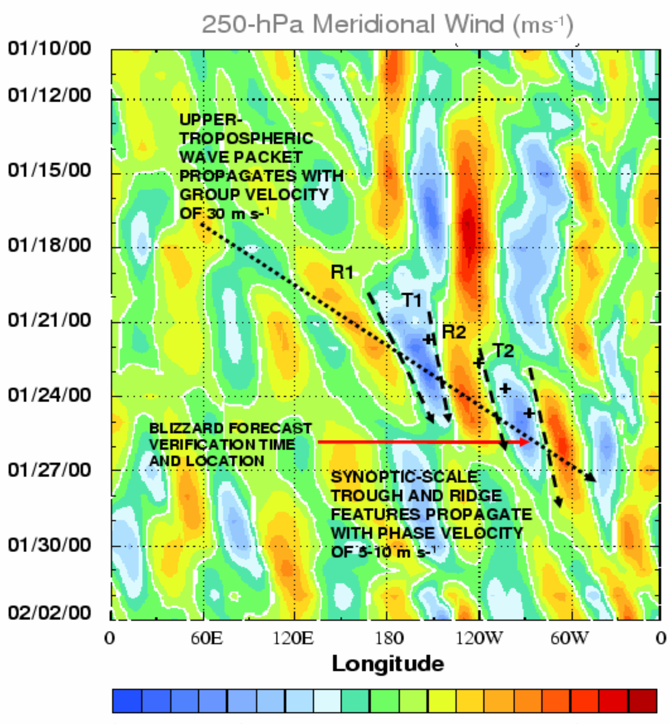

Figure C-11. Hovmöller diagram associated with event 2015N005. The diagram shows a time versus longitude analysis of the 250 mb meridional wind anomaly averaged over the 25° to 45° latitude band. In the figure, "R" denotes ridge and "T" denotes trough. The "+" symbol shows the position of the upper level disturbance, based upon maximum vertically integrated sensitivity from SA and signature detection algorithms applied both to analyses and forecast fields. (Figure extracted from Ref. 1)

MDAS contains a Model Performance Tracking product that can be used by forecasters to determine what models and parameters track best. For a tracked event, the parameters include the following: Upper-Level Disturbance Track, Surface-Level Storm Track, Sea Level Pressure, and Precipitation. MDAS provides these products in graphical and tabular form for distribution to Forecast Operations so that they can tailor their forecasts according to model performance.

T-47 hours. 13 UCT January 23 2015

The completed forecast models and SA show that the region of maximum sensitivity has moved rapidly eastward over the past 24-hours (Fig. C-12). Furthermore, the region of sensitivity is geographically more compact. Again, the TODAs identify where, when, and what observations are required to improve the forecasts. The TODA products are reviewed by MDAS Operations.

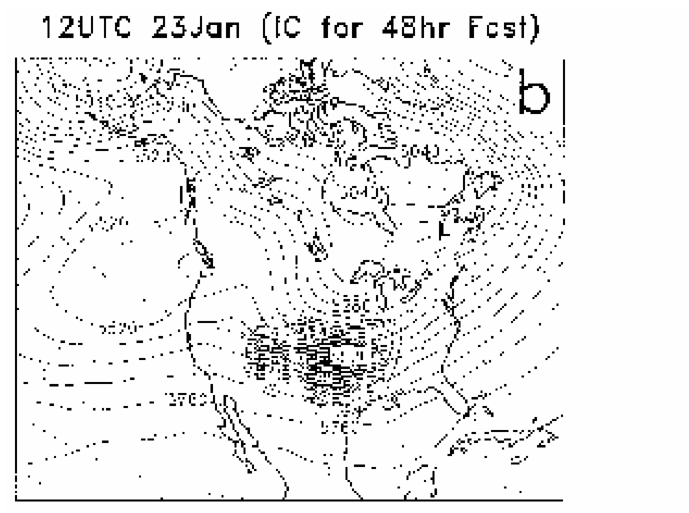

Figure C-12. Vertically integrated sensitivity product 12 UTC 23 January based on the initial conditions for the 48-hour forecast for the Eastern US. (Figure extracted from Ref. 1)

T-46 hours. 14 UTC January 23 2015

As for the previous day, the TODAs suggest intermediate rawinsonde launches, but this time for 16 UTC, as well as collaborative satellite collections. However, due the compact nature of the sensitivity fields over land areas, no special aircraft measurements are suggested by the TODAs. MDAS Operations ok’s rawinsonde launches over much of the US at 18 UTC (Fig. C-13).

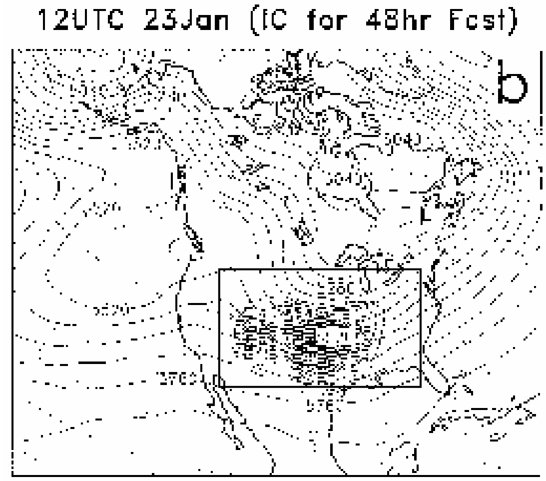

Figure C-13 Rawinsonde launch zone for 18 UTC 23 January

GOES-R Mesoscale Regions are set up over two zones to cover the rawinsonde measurement area to maximize the space-time coincidence of the calibration data set (Fig. C-14)

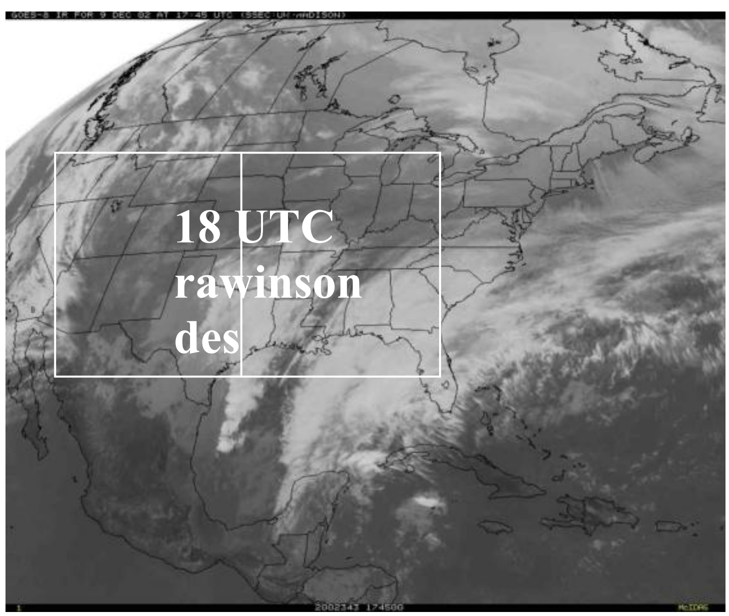

Figure C-14. GOES-R mesoscale regions.

The NPOESS AM (Fig. C-15) descending and the NPOESS PM ascending nodes have the preferred orbits for the majority of the rawinsonde coverage area. Because the polar orbiter data collections are constrained to sun synchronous orbits with inflexible overpass times, time coincidence with in-situ measurements is more difficult.

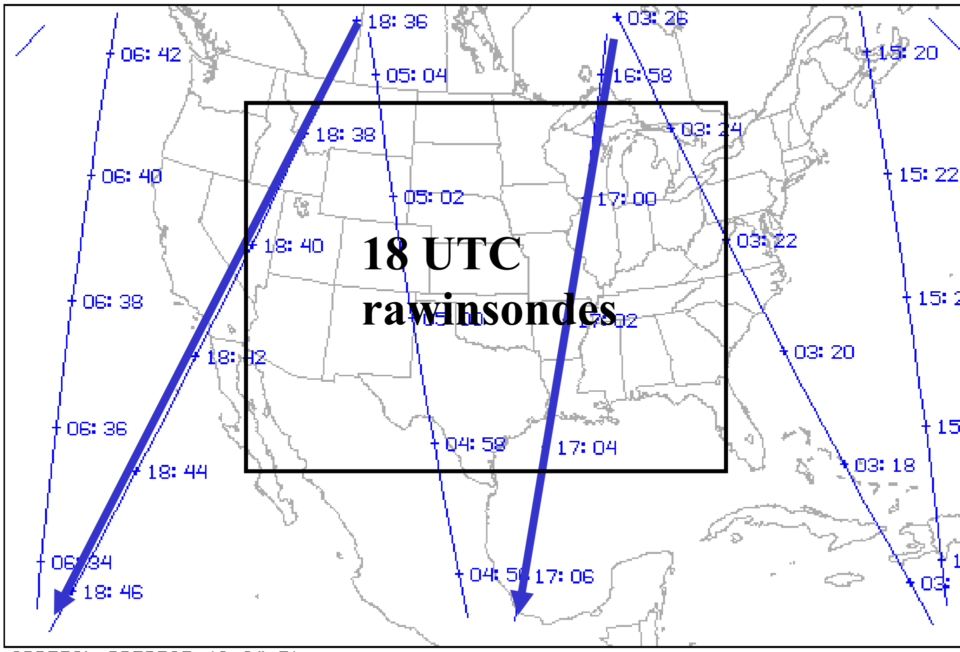

Figure C-15. NPOESS-AM overpasses near the time of the intermediate rawinsonde launches

T-41 hours. 19 UTC January 23 2015

The 18 UTC run of the RSR forecast models have assimilated the rawinsonde, GOES-R, and NPOESS-AM and -PM data and the ensemble elements show an even tighter solution set compared to earlier runs. The forecast track and intensity are in good agreement among the ensemble members. Nevertheless, the threat of a significant east coast storm on 25 January remains clear. Upon reviewing the model forecasts, Forecast Operations reaffirms with field offices the threat of a significant East Coast Storm.

T-36 hours. 00 UTC January 24 2015

The surface low associated with Event 2015N005 is beginning to form in the western portion of the Gulf of Mexico. A light precipitation shield also forms. Automated tools within the MDAS system generate and distribute graphical products and simple statistics that allow comparison between the observed and predicted positions of the low at this time, for all models and ensemble members. In addition, the position, type and intensity of the observed precipitation shield are compared with predictions. Precipitation observations from radars, ground observations, and GPM are used in the comparisons. These data are used in data assimilations. The MDAS utilities will automatically use this information to refine the model parameterizations that are used in future runs. In this case, a particular convective precipitation parameterization scheme has provided superior forecasts, and in future runs more ensemble members will use this parameterization, along with other variants on the baseline initial conditions and model, to produce forecasts. This process will continue to be used throughout the duration of the event to further refine forecasts.

MDAS Operations also initiates execution of Mesoscale Very Short Range (MVSR) forecasts for the area downstream of the projected track of the low. The mesoscale forecasts are produced on nested grids at increasing spatial resolution. The innermost grid has the highest spatial resolution, and covers about a 1000 x 1000 km area at 5-km spatial resolution. These MVSR forecasts will henceforth be generated hourly, and the nested grids will be re-located along the storm track.

Forecast Operations issues winter weather watches and advisories as appropriate all along the eastern US coast.

Note: In 2015, forecasters, government personnel, and the public are more confident in the forecasts than they were in 2000. One issue with the forecast for the Blizzard of 2000 was a busted forecast for the previous east coast storm. This led forecasters to be wary of the model guidance, which at first showed the storm staying well offshore, and then tracking closer to the shoreline in later runs. The 2015 system rapidly adjusts the initial conditions that are specified to the models, so that forecasts trend well with observations during the entire evolution of the event. This leads to more accurate long-, medium-, short-, and very short-range forecasts.

T-34 HOURS. 02 UTC JANUARY 24 2015

MDAS Operations and Forecast Operations have reviewed the RSR and MVSR products from the 00 UTC runs and have determined that the rawinsonde launch schedule should be altered from every twelve hours to every six hours for the region east of the Mississippi river. There are two reasons for this. First, the more frequent observations should improve forecasts. Second, the data from these observations will be used to confirm model predictions. As a matter of protocol, Forecasts Operations has the responsibility to format the appropriate request and forward it to the observing system. The request asks that rawinsonde launches commence at 06 UTC January 24 and continue every six hours through at least 00 UTC January 26.

T-24 hours. 12 UTC January 24 2015

The surface low has moved to the eastern Gulf of Mexico, along the west central coast of Florida, and is beginning to intensity rapidly (Fig. C-16). The precipitation shield (Fig. C-17) shows an expanding region of precipitation extending from the Florida panhandle into North Carolina. This band shows convective precipitation, particularly in Georgia extending into South Carolina. A second band extends from North Central Florida to the North Carolina coastal waters, just off the east coast. This band is along a coastal front, dividing warm moist air south and east of the front, and cold air north and west of the front. The actual track and position of the low is consistent with both the regional and mesoscale forecasts. Forecast Operations issues winter weather advisories and warnings as appropriate along the Eastern US Coast. Based upon the forecast track, the major east coast cities will be impacted by heavy snow during the next 24-hours.

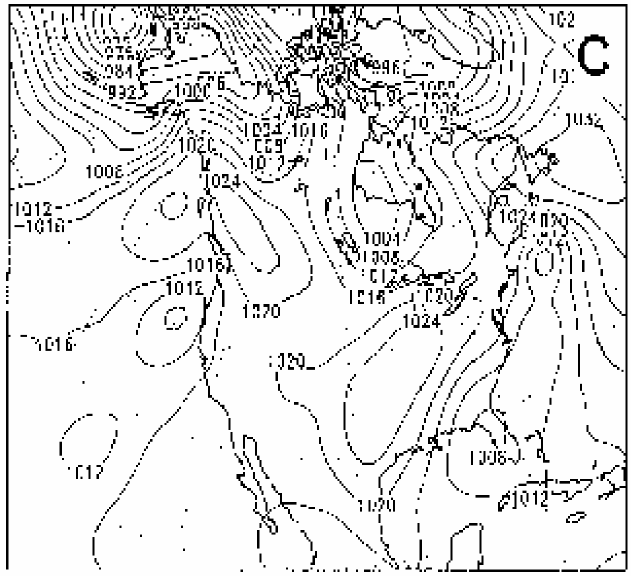

Figure C-16. Surface analysis for 12 UTC January 24 2015 showing developing storm in the eastern Gulf of Mexico. (Figure extracted from Ref. 1)

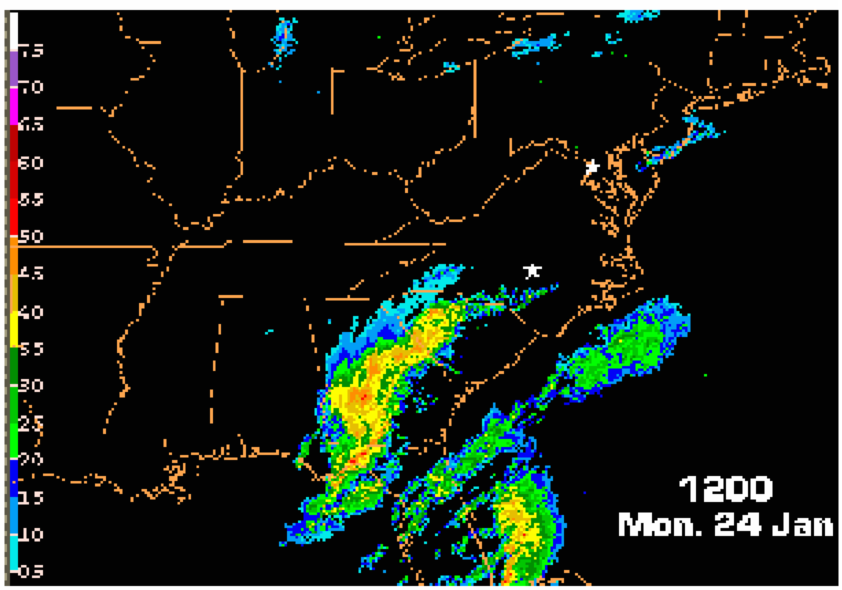

Figure C-17. Composite radar imagery for 12 UTC January 24 2015. (extracted from Ref. 2)

T-23 hours. 13 UTC January 24 2015

Using graphical products automatically generated by the MDAS system, MDAS Operations and Forecast Operations have noted that the 12 UTC wind observations from rawinsondes and cloud drift wind measurements from GOES-R are conflicting with model predictions in the southeastern

> Note: The rejection of rawinsonde data by the operational models in January 2000 was one of the leading candidates for explaining the forecast failures associated with the Blizzard of 2000. The January 24, 12 UTC operational Eta model assimilation rejected the Peachtree City, GA sounding and de-weighted the sounding from Greensboro, North Carolina (see Fig. C-18). As a result, the 250 mb wind speed used to initialize the model was too weak and the direction was in error in these areas. The correct wind information would have supported a forecast of more widespread convective precipitation in Georgia and South Carolina, with the heavier precipitation taking a more inland track than was forecasted. Subsequent research suggested that including the rejected soundings would have improved the details of the precipitation forecasts, but the forecast intensity and position of the surface low may not have been greatly influenced. Nevertheless, the precipitation forecast was one of the major issues with the

US, particularly in northern Georgia. The graphical products available on their workstations have flagged the regions of significant differences. Indeed, the RSR and MVRS assimilations initiated at 12 UTC have de-weighted these observations in favor of the prior forecasts, since the observations are inconsistent with the forecasted wind fields for that time. This conflict has led MDAS to automatically issue a warning to MDAS Operations and Forecast Operations with a suggested remedial action to conduct 3-hourly rawinsonde launches in the southeastern US and to more heavily weigh in the assimilations wind measurements from commercial aircraft in the southeastern US. Coincidentally, MDAS Operations and Forecast Operations personnel have noted that the most recent forecasts of precipitation have tended to show the heaviest band of precipitation shifted slightly east of the observed band obtained from radar and GPM measurements.

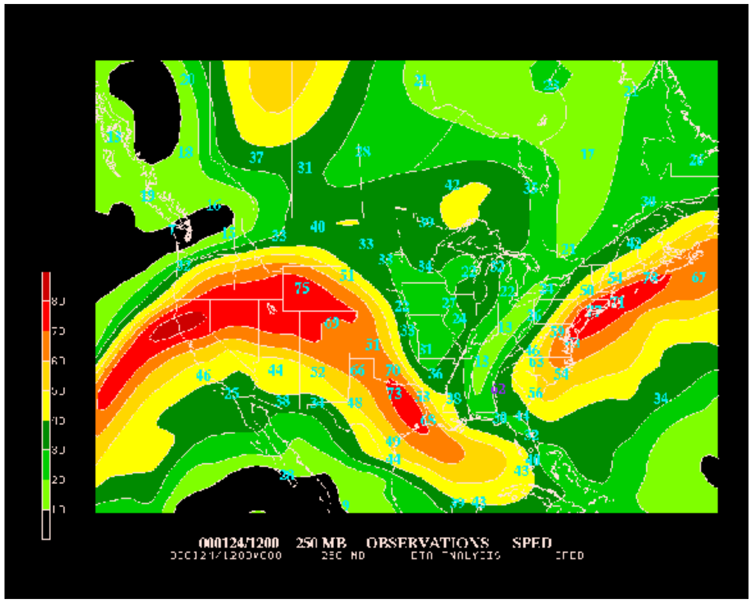

Figure C-18. The 12 UTC 24 January 2000, 250 mb wind speed analysis used to initialize the operational Eta model. The rejected Peachtree City, GA data is in purple. (Figure from Ref. 2)

T-18 hours. 18 UTC January 24 2015

The operational forecast models have assimilated the additional atmospheric measurements from rawinsondes and aircraft and the precipitation forecasts and location and intensity of the surface low are in good agreement. In the last six hours, the precipitation shield has rapidly expanded (see Fig. C-19).

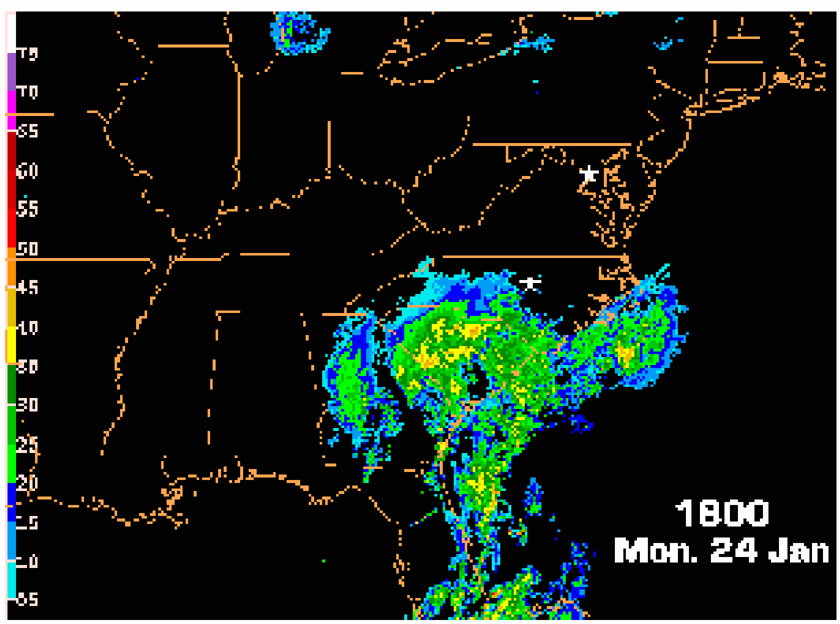

Figure C-19. The 18 UTC 24 January 2015, composite radar analysis. (Figure extracted from Ref. 2)

Note: In January 2000, the forecasts generated from the 18 UTC 24 January runs were the first to indicate moderate snowfall in the Washington DC area, despite the imposing precipitation shield evident from radar moving in from the southeast. In fact, the precipitation amounts forecasted for Washington DC did not reach winter warning criteria until the 00 UTC 25 January run. In January 2000, the forecast track and position of the precipitation shield was shifted steadily westward from one run to the next (see Fig. B-20). All forecasters could do was watch and wait as the models slowly adjusted to the obvious reality. By contrast, the 2015 system has built-in checks of forecasts against observations, more frequent and rapid data assimilation and forecast generation, and mechanisms in place to collect more data as needed to rapidly improve forecasts.

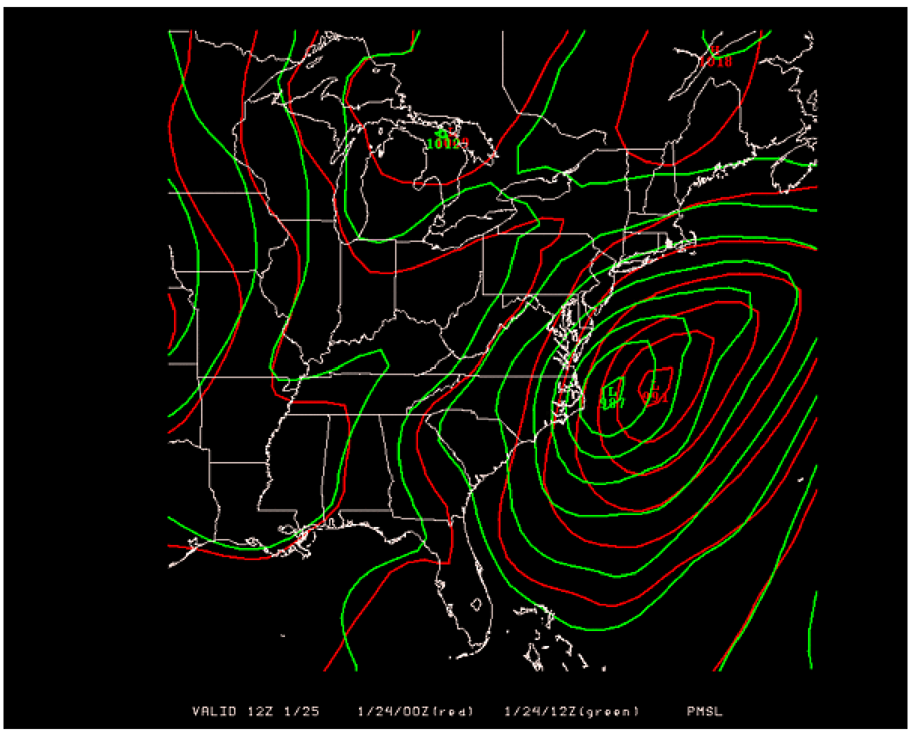

Figure C-20. Consecutive forecasts of storm position from the operational Eta model in January 2000. Forecasts are valid at 12 UTC 15 January 2000 and are from the 00 UTC (red) and 12 UTC (green) 24 January 2000 model runs. Note the progression of the storm center towards the west with time. (Figure extracted from Ref. 3)

T-12 hours. 00 UTC January 25 2015

The MVSR model is the primary forecast tool used by forecasters within 12 to 24 hours of an event. The MVSR nested grids continue to follow the track of the storm (see Fig. C-21). Its forecasts are being carefully examined for precipitation type and amounts along the eastern seaboard. The mesoscale precipitation forecasts are beginning to show banding structures and orographic effects. These features will be carefully monitored because the corresponding regions will be susceptible to especially heavy precipitation amounts. The 00 UTC radar imagery continues to show a widespread region of heavy precipitation (see Fig. C-22).

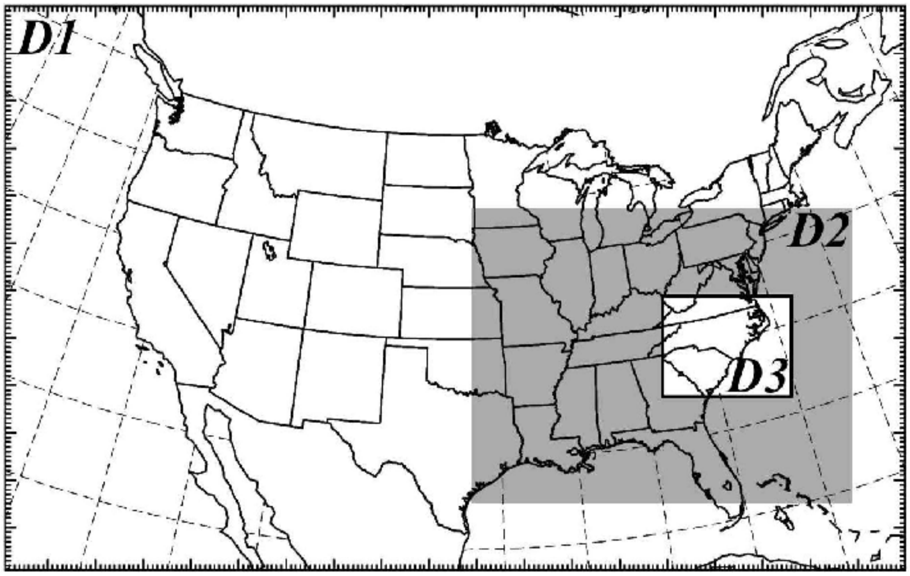

Figure C-21. MVSR model nested grid configuration for the winter storm. Note that the inner-most grid is centered near the storm position. (Figure extracted from Ref. 4)

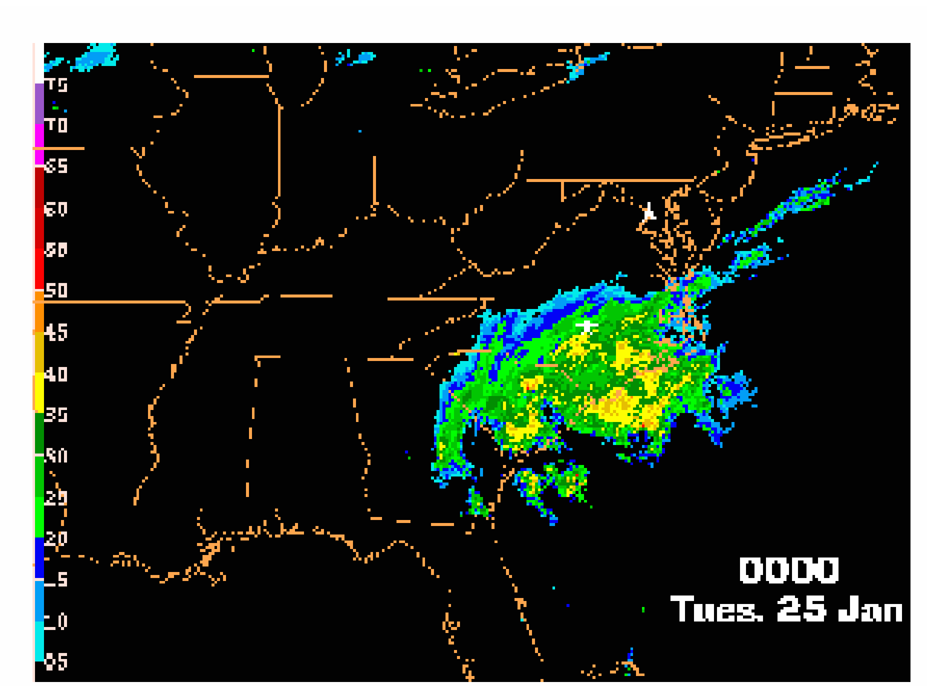

Figure C-22. The 00 UTC 25 January 2015 composite radar analysis. (extracted from Ref. 2)

T-06 hours. 06 UTC January 25 2015

The MVSR precipitation and storm intensity forecasts are now in good agreement with observations. Because of the rapid intensification of the system, the MDAS TODAs recommend that the region of more frequent (3-hourly) rawinsonde launches be spread further north into the Mid-Atlantic States and the northeast. In addition, aircraft measurements obtained from the intense air traffic in these areas will be more heavily weighted in the assimilations. Forecast Operations and MDAS Operations concur with the MDAS TODAs recommendations. Forecasts Operations alerts rawinsonde launch stations through the Observing System and MDAS Operations adjusts assimilations to more heavily weight aircraft observations in these areas. Meanwhile, the precipitation pattern continues to spread northeastward (Fig. C-23). It is now heavily snowing in Washington DC, and the heavy snow is spreading into the Philadelphia, PA area.

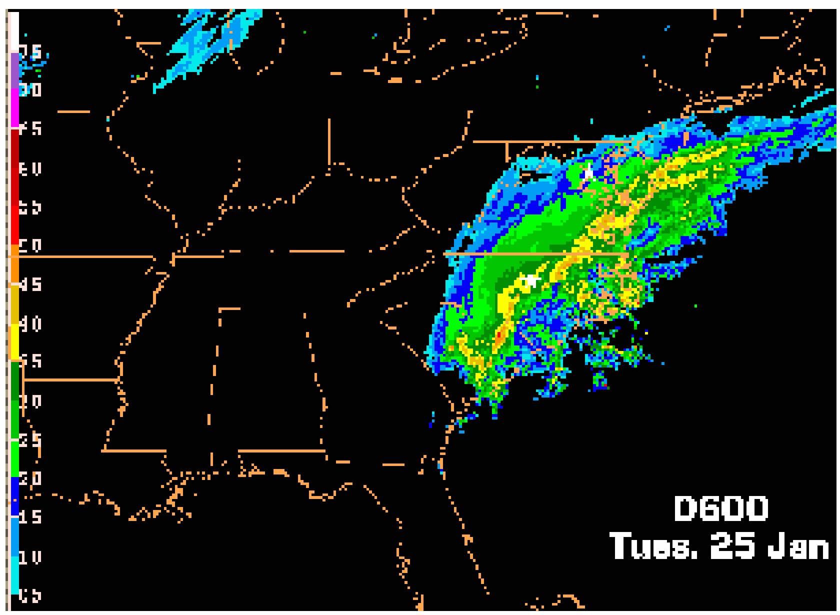

Figure C-23. The 06 UTC 25 January 2015 composite radar analysis. (extracted from Ref. 2)

> Note: Unlike the Blizzard of 2000, the municipalities and residents of the mid-Atlantic region have not been caught be surprise by this snowstorm. The rapid assimilation of new data and more frequent executions of the forecast models have led to excellent forecasts of storm track and precipitation intensity and type.

T-0 hours. 12 UTC January 25 2015

It is now snowing heavily from the Washington DC area into the southern northeast US. Thanks to the continued influx of new data into the assimilation system, the storm forecast continues to be excellent. The precipitation banding that is evident in the radar imagery (Fig. C-24) has been forecast by the mesoscale forecast model (MVSR model) and has led to refined precipitation forecasts in the affected areas. These band structures are producing snowfall rates at 3 to 4 inches per hour and ultimately lead to very heavy and in some cases record snowfall totals (Fig. C-25).

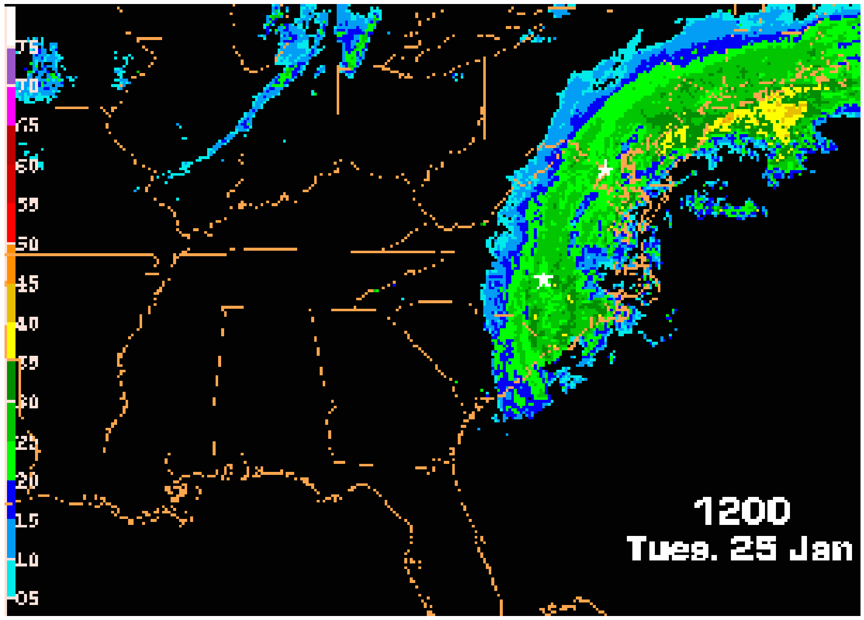

Figure C-24. The 12 UTC 25 January 2015 composite radar analysis. (extracted from Ref. 2)

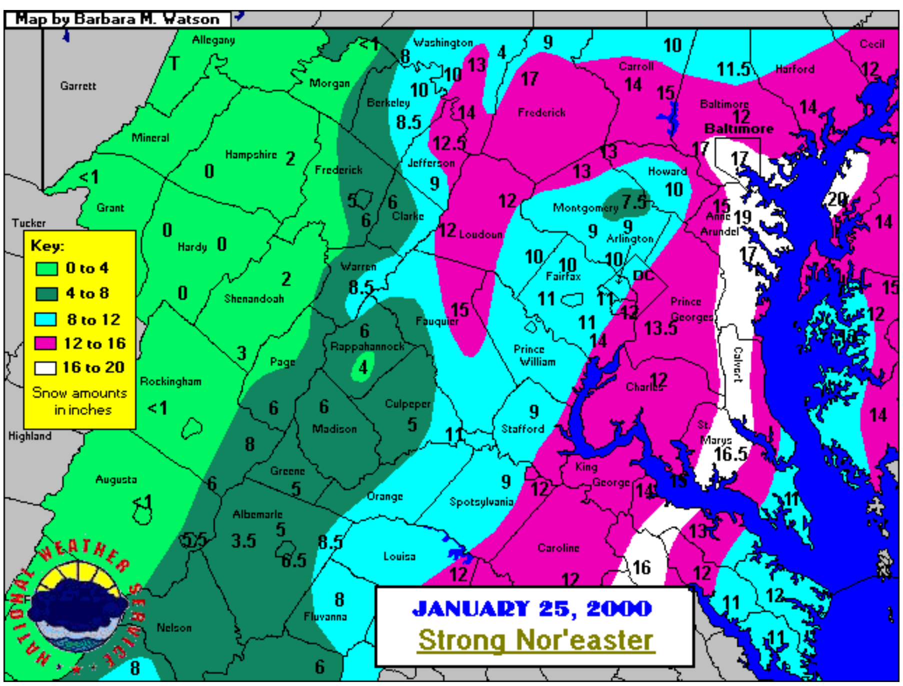

Figure C-25. Snowfall totals from the Blizzard of 2000. (Figure extracted from Ref.3)

Epilogue. The Blizzard of 2000 was considered one of the major failures of the operational forecast system at the time. The heavy snowfall in the Mid-Atlantic States, including Washington DC, was not forecast until the late stages of the storm and the residents of the region were caught by surprise. As described here, the proposed 2015 system takes steps in the early stages (several days in advance of the storm) as well in the later stages (during the last 24-hours) to ensure that the forecasts are accurate and in sync with observations. It accomplishes this by having a proactive feedback loop between the MDAS and Observational systems that is enabled by a robust communications infrastructure, as well as a much more frequent data assimilation and forecast cycle.

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