

NASA APPLIED SCIENCE

*Ecological Forecasting Project on
An Agent-Based Interface to Terrestrial Ecological Forecasting*

***Terrestrial Observation Prediction System (TOPS)
Final Benchmark Report***
(v. 2.1)
9/3/10

Earth Science for Society
*Accelerating the realization of economic
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TOPS-NPS Team

Ramakrishna Nemani, NASA Ames Research Center–*PI & Team Leader*

TOPS

Forrest Melton, Applications development
Petr Votava, Software development management
Andy Michaelis, Climate component and security development
Sam Hiatt, TOPS Data Gateway Developer
Wanlin Pang, QSS Group, AI planning and scheduling

National Park Service

John Gross, Inventory & Monitoring Program, NPS Ft. Collins
Linda Mutch, SIEN I&M Coordinator
Bill Kuhn, GIS, Project Point of Contact
Andi Heard, Inventory and Monitoring
Meryl Rose, Inventory and Monitoring
Lisa Acree, Park Botanist
Kent Van Wagendonk, GIS/Fire

Component Models and Tools

Michael White, Utah State University, modeling & integration into TOPS
Christina Tague, San Diego State University, RHESSys model development

1 Purpose

1.1 Document Purpose

This document describes the results achieved by the project titled “*An Agent-Based Interface to Terrestrial Ecological Forecasting*”, and benchmarks the impacts of the project on the National Park Service (NPS) Inventory & Monitoring (I&M) Program for decision support. The primary objective of this project was to extend the capabilities of the Terrestrial Observation and Prediction System (TOPS)[1,2] to support decision making related to protected area management, and to integrate these capabilities to provide an enhanced monitoring and management capability for NPS. This report describes major advances and improvements made to TOPS to facilitate use by NPS, and identifies how these advances supported achievement of project objectives and deliverables.

1.2 Project Goals & Objectives

The overall goal of this project was to create a flexible, ecological nowcasting and forecasting system with applications for ecosystem monitoring and protected area management. This goal has been achieved, and the system developed combines multiple distributed data sources and models to provide near-real-time answers to questions about the state of ecological conditions and provide additional information to aid protected managers in decision-making. By providing a framework for ecological forecasting as well as the post-processing of model and data visualization and access, TOPS facilitates rapid data exploration and utilization of data from NASA satellites and ecosystem models.

As described in the project plan[3], additional overall objectives of the project included the following items. Descriptions of project accomplishments supporting each objective and sub-objective are described in Section 2.2 of this report.

1. Develop software for automated production of monitoring and forecasting data and information products to assist the National Park Service (NPS) Sierra Nevada (SIEN) Inventory & Monitoring (I&M) network in management of U.S. National Parks including Yosemite National Park and Sequoia-Kings Canyon National Park.
2. Extend TOPS software for automated production and delivery of climate and satellite data to be used by the SERVIR project.
3. Extend the current TOPS modeling framework to implement RHESSys, BIOME-BGC and other models as needed to improve high-resolution modeling and to aid in scenario evaluation of forecasting of potential impacts of management decisions within the NPS.
4. Provide access to the data produced by the system in multiple ways, including FTP, WMS, and browser-based data access.

1.3 Project History

As described in Section 1.4 of the project plan[3], this project underwent a significant modification to the scope and deliverables associated with the project, which were contained in the original proposal and revised work plan. The reason for this correction was due to the departure of the project's PI, Keith Golden, who played a crucial role in the AI technology development. The 2006 project plan[3] provided an amendment to the original work plan and an updated project scope.

The departure of the original project PI also resulted in one significant oversight during the project hand-off to the new project PI, Rama Nemani. The project began in FY04, and it was believed that the initial funding for the project was provided in FY04. The project budget provided to the new PI and Co-Is by the original PI listed funding in FY04-FY08. However, unbeknownst to other project team members, the REASoN program sent funds to the original PI's division in late FY03, in addition to early FY04. The FY03 funding was spent by the original PI's division management, and this information was not communicated to the current project team. Despite multiple references to FY08 activities, and inclusion of a budget for FY08 in the revised project plan submitted in June 2006, this oversight was not caught until early FY08. This had a significant impact on activities planned for FY08, including final transition of system capabilities to NPS.

Fortunately, the project team members were successful in proposing a related activity with NPS through the NASA 2005 ROSES DECISIONS solicitation that allowed the project team members to continue work with NPS and successfully achieve major project objectives through the following project. However, funding provided for the effort by the Applied Sciences program through the DECISIONS award[4] was only 10% of the budget for FY08 included in the 2006 REASoN revised project plan. As such, some elements of the project were postponed as noted in the following sections. The DECISIONS project was originally titled "Ecological Condition of US National Parks: Enhancing Decision Support Through Monitoring, Analysis, and Forecasting", and is presently known within NPS as the NASA-NPS Park Analysis of Landscapes and Monitoring Support (PALMS) project.

2 Project Accomplishments

2.1 Project Tasks and Deliverables

This section provides a brief overview of project achievements that contributed to the successful completion of deliverables identified in the project plan. This section is organized around the specific WBS elements described in the project plan.

The project Evaluation Report described the baseline status of the NPS I&M program and its use of data from NASA satellites and ecosystem models. This report was developed in cooperation with collaborators from Yosemite National Park and NPS headquarters.

WBS 4.0 NPS Coordination Management

Regular communication with NPS was held throughout the project, and included conference calls on at least a quarterly basis, and meetings with NPS collaborators at NPS facilities at least three times per year. In addition, key NPS collaborators also spent time at NASA Ames learning about TOPS and potential applications of NASA satellite data.

WBS 5.0 NPS Data Requirements

In collaboration with NPS, data requirements were formalized, and requirements for data formats and metadata were described in the Evaluation Report[5] and the revised project plan. These requirements included specific format requirements and constraints on data storage capacity at NPS facilities. In addition, as the project progressed, TOPS data products were mapped to specific I&M monitoring objectives.

WBS 6.0 NPS Service Requirements

TOPS was implemented for the Sierra Nevada Network (SIEN). Satellite observations (MODIS MOD10, MOD11, MOD13 and MOD15) were continuously processed for the SIEN greater park ecosystem boundaries. In addition, TOPS was applied to calculate anomalies in FPAR and EVI to identify and map anomalies in vegetation condition. Data products were delivered to NPS personnel via the TOPS Data Gateway described in Section 2.3.4, providing a near real-time capability for monitoring and anomaly detection, with a lag time of 8-16 days, depending on the compositing period for the data product.

WBS 7.0 AI Technology Integration

A series of enhancements to TOPS were implemented to provide a robust capability for sustained, automated data acquisition and temporal composition of satellite and model-derived datasets (see Section 2.3 for details).

WBS 8.0 Remote Sensing and Climate Integration

A capability was added to TOPS for retrieval and processing of MODIS Direct Broadcast (DB) data. TOPS was applied to retrieve DB from EDC and OSU to provide RGB imagery for SIEN parks within hours of satellite overpass. However, this capability became redundant with the imagery available from the MODIS Rapid Response project, and the data feed was adjusted to retrieve 250m color composite imagery from the MODIS Rapid Response ftp server. This data, however, is composited with other TOPS data products and distributed to NPS via the TOPS data gateway. GOES data feeds were also integrated into TOPS, however, distribution of the data products via the data gateway was deferred until the NPS NPCLime project identified the key climate indicators to be used by the NPS I&M project.

WBS 9.0 TOPS core system redesign/refactoring

A series of extensive modifications was made to the TOPS core system and is described in Section 2.3. This effort resulted in the extensive expansion of the Java Distributed Application Framework, integration of the IMAGEbot Planner, and the development of FlexTOPS, a

streamlined version of the TOPS core components that is designed to facilitate rapid deployment of TOPS for new regions. These capabilities have been successfully applied for other parks and I&M networks under the NASA-NPS DECISIONS project[6].

WBS 10.0 Climate Module Development/Enhancement

Under this project, multiple improvements were made to the Surface Observation and Gridding System, the primary TOPS data processing component for interpolating meteorological surfaces. Key improvements included the ability to support multiple interpolation algorithms for precipitation (two additional algorithms added), improvements to the algorithms to increase computational efficiency, and modifications to the algorithms and SOGS configuration to support complete parallelization of the interpolation system, reducing processing time by more than 90% with sufficient compute resources.

WBS 11.0 QA/QC

Extensive improvements were made to the TOPS QA/QC framework under this project. Key improvements included development of completely automated cross-validation for the temperature and precipitation surfaces to quantify errors in the surfaces generated for each region on a daily time step. In addition, a series of modules were implemented to provide for more rigorous filtering of MODIS-derived inputs to TOPS based on MODIS cloud cover and QA flags, which proved critical for the development of accurate anomaly products in mountainous and tropical regions. Finally, additional modules were developed in TOPS to streamline comparison of TOPS outputs against observational data from Fluxnet sites for use in validation and accuracy characterization of TOPS modeled products, such as gross and net primary productivity and evapotranspiration.

WBS 12.0 TOPS/NPS System Integration

As described in the Evaluation Report[5], initial assessment of compute resources available to the SIEN NPS network included less than 1 terabyte of on-line storage and a single data server available to support all NPS tasks in the SIEN I&M network. NPS compute resources have expanded considerably since that time, but the decision was made early in the project to focus the integration effort on the development of tools to focus primarily on web-based delivery and visualization of NASA data products via TOPS. In addition, by implementing algorithms to support calculation of key summary metrics for NPS (e.g., measures of anomalies and long term trends), TOPS was applied to enhance the value of NASA data products for NPS by reducing the additional processing required by NPS personnel for operational use of NASA data products. An on-line, web-based data visualization and query system was developed for the SIEN network to support review, query, and retrieval of NASA data products by NPS. Integration with other NPS I&M networks has continued under the NASA-NPS PALMS project led by Andy Hansen[4], and includes development of data products for the Greater Regional Yellowstone Network (GRYN), Rocky Mountain Network (ROMO), and the Eastern Rivers and Mountain Network (ERMN).

WBS 13.0 Subsystem Integration

As described in Section 2.3, through this project we have developed the Data Processing Action Description Language (DPADL) to facilitate integration of the IMAGEbot planner with other separate modules within TOPS, including JDAF, SOGS, and the QA/QC modules. The power of the IMAGEbot planner, combined with the flexibility of the JDAF framework provides us with a

system that is much more robust, flexible and efficient. It can be quickly tailored to support a range of users and applications, ranging from global long-term monitoring of environmental change, to near-real-time analysis of extreme events such as floods, fires, and droughts.

14.0 Documentation

The NPS I&M program is based upon clearly defined monitoring protocols, which included detailed, step-by-step standard operating procedures (SOPs). As such, SOPs describing the generation of TOPS data products and procedures for applying data from TOPS to support I&M objectives were drafted. Review and revision of these SOPs by NPS personnel is ongoing, and the process of finalizing the SOPs and incorporating them into NPS I&M monitoring protocols will be completed under the NASA-NPS PALMS project. As part of the final system, the protocols will be available through the data gateway and will be directly linked with the data products and data access tools.

WBS 15.0 Field Tests/Demonstration

Demonstrations of the TOPS data gateway have been conducted at Yosemite National Park, Sequoia National Park, and at NPS I&M headquarters. Feedback from NPS obtained during these demonstrations was used to redesign the data gateway to focus on dashboard-style summaries, and the completion of the field testing is occurring under the DECISIONS project.

WBS 16.0 Testing and Validation

The full end-to-end system was completed in December 2007 and was run operationally for a period of three months under this project, demonstrating successful development of the end-to-end data processing framework from ingestion of climate and satellite inputs, to production of TOPS outputs, including measures of climate, hydrologic, and ecosystem conditions, and distribution of the data via web services and a web browser-based interface. Due to the funding issues described in Section 1.3, additional testing planned for the final year of the project was canceled, and was instead conducted under the NASA-NPS PALMS project.

WBS 17.0 Security

The TOPS Data Gateway relies on multiple open source platforms and required an extensive security audit. In addition, the data gateway was designed to provide an optional password and user management interface.

WBS 18.0 SERVIR Project Integration

As part of this project, satellite and climate data products from TOPS were compiled for Mesoamerica and the Caribbean and integrated into the SERVIR-Viz platform. Demonstration and training was provided to SERVIR users and two SERVIR workshops[7,8] held in Panama in 2007, and the Dominican Republic in 2008. TOPS data products for the SERVIR-Viz platform were produced and distributed via SERVIR-Viz through 2009, and continue to be available on demand.

WBS 19.0 Final Demonstration

The final demonstration to the SIEN network was conducted on November 15, 2007[9]. In addition, additional enhancements to TOPS for NPS were presented to an NPS-wide audience on

March 2-6, 2009 at the George Wright Society meeting, a primary science and technology conference for NPS. Results and user feedback from the demonstration were compiled and submitted as part of the NASA-NPS PALMS project second year report.

2.2 Fulfillment of Project Objectives

The project fully met the stated project objectives, and examples of successful achievement of specific project objectives are included below.

Objective 1: Develop software for automated production of monitoring and forecasting data and information products to assist the National Park Service (NPS) Sierra Nevada (SIEN) Inventory & Monitoring (I&M) network in management of U.S. National Parks including Yosemite National Park and Sequoia-Kings Canyon National Park.

- a. Production of data sets to support real-time monitoring of ecosystem conditions was provided for Yosemite and Sequoia-Kings Canyon at moderate resolutions (500m – 1000m). Datasets produced for the SIEN I&M network included solar radiation, air temperature, humidity, rainfall; and satellite and model-derived data on ecosystem variables including soil moisture, vegetation productivity, and phenological stage.
- b. Demonstrated TOPS capabilities for forecasting for a suite of parameters related to ecosystem function (snow pack, soil water content, evapotranspiration, stream flow, and net primary productivity) for the Merced watershed, for the period from 1950-2100.
- c. Processing of historic climate and satellite data for the SIEN I&M network from 1982 to present, including AVHRR and Landsat data.
- d. Implementation of a system for detection of anomalies from long-term normals for satellite- and model-derived measures environmental variables, to assist in identification of indicators of ecosystem change or potential threats to the park.

Objective 2: Extend TOPS software for automated production and delivery of climate and satellite data to be used by the SERVIR project.

- a. Provided a suite of TOPS datasets for Mesoamerica to the SERVIR project for distribution via SERVIR-Viz, including measures of meteorological conditions (temperature, precipitation, vapor pressure deficit, solar radiation), vegetation state (NDVI, EVI), photosynthetic activity (FPAR), canopy structure (LAI), and vegetation productivity (GPP and NPP).
- b. Presentation of these datasets to the SERVIR user community at two separate SERVIR training workshops[8,9].

Objective 3: Extend the current TOPS modeling framework to implement the RHESSys, BIOME-BGC and other models to improve high-resolution modeling and to aid in scenario evaluation of forecasting of potential impacts of management decisions within the NPS.

- a. Implemented RHESSys within TOPS and conducted a series of hydrologic modeling runs to evaluate future climate impacts on the hydrology of the Merced watershed. Presented initial results to SIEN NPS staff.

Objective 4: Extend TOPS to provide access to the data produced by the system via multiple mechanisms:

- a. Developed a user-friendly web interface to the TOPS data holdings that included expansion of the existing data browsing tools contained within the TOPS website to allow browsing of the full data archive, data subsetting, data query, and data retrieval.
- b. Implemented of a Web Map Server (WMS) and Web Coverage Server (WCS) to support visualization using the NASA WorldWind and/or Google Earth applications.
- c. Automated the integration of data products from TOPS into the NPS and into SERVIR systems by:
 - i. Automating the extraction of regional subsets of data (e.g., Yosemite National Park plus a buffer zone) from existing data archives using shapefiles provided by NPS and SERVIR collaborators; and
 - ii. Implemented tools to automate the conversion of data from binary to GIS compatible formats (e.g., GeoTIFF) and converted existing TOPS metadata structures into formats compatible with the NPS Vital Signs Inventory & Monitoring (I&M) system database templates.

Publications and Presentations: Results and progress from this project were also communicated via multiple publications and presentations. The full list is provided in Section 5.

2.3 Extensions to the TOPS Framework

The section provides an overview of the major improvements made to TOPS under this project.

2.3.1 IMAGEbot Planner and Scheduler

Development of the IMAGEbot AI Planner and Scheduler was largely completed by the original PI, Keith Golden, prior to his departure from NASA Ames in 2006. Additional work completed by the project team led to the successful integration of the IMAGEbot planning engine with the TOPS JDAF framework. Within IMAGEbot, the domain libraries provide the descriptions of file formats and data-processing operations associated with particular application domains, written in DPADL. To support productions of the datasets described in Section 3.2 for NPS, new domain libraries and JDAF interfaces were developed using DPADL. Since many data formats and data-processing programs are widely used across different problem domains, and the description/interface for any given format or program need only be written once, the development of a large domain library also simplifies the task of applying TOPS and the integrated IMAGEbot/JDAF framework to new application domains.

2.3.2 JDAF: Java Distributed Application Framework

Through this project, we extended the JDAF framework to support access to all databases, processing components and models that are part of the TOPS system. Additionally, we improved

the automation of model and data integration by developing a standard interface between the JDAF framework and several external components. We fully integrated both the Biome-BGC and high-resolution RHESSys modeling framework, and the climate gridding system (SOGS) into the components accessible by JDAF. The interface developed has also supported integration of multiple other carbon cycle and ecosystem models under other projects.

2.3.3 SOGS: Surface Observation and Gridding System

Extensions to SOGS as part of this project included completion of fully automated spatial autocorrelation and theoretical variogram modeling modules. We also extended the I/O capabilities of the SOGS system to include bzip, GeoTIFF, HDF5, and shapefiles for both input and output. To improve some of our output data streams, we added GOES satellite data, which allowed us to provide better estimates of the meteorological variables to NPS, particularly for precipitation. We improved our radiation algorithm and conducted several reprocessing campaigns to improve our historic data holdings for the SIEN NPS network, with accuracy benefits for both nowcasts and forecasts. Finally, in order to take advantage of the processing power of the supercomputing resources at NASA Ames in the future, we parallelized the SOGS code so that we can improve both temporal and spatial resolution of our historic runs. Finally, we re-designed parts of our database system for meteorological station data to improve performance and developed additional APIs to this database.

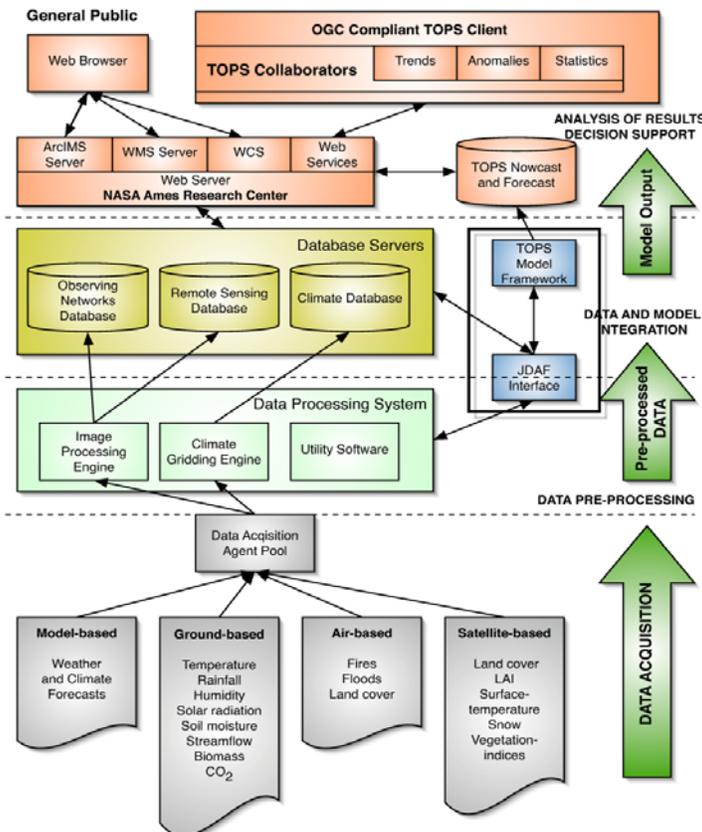


Figure 1. Integrated TOPS architecture produced by the project

2.3.4 TOPS Data Gateway User Interface

Through this project, significant advancements were made in the TOPS data access interface, and a TOPS Data Gateway was developed to provide capabilities for data visualization and query for NPS users. TOPS regularly produces large amounts of gridded environmental datasets that are valuable for monitoring current and past ecosystem conditions. However, the large volume of data generated presented challenges related to data access and visualization for NPS. In order to provide simplified access to TOPS data, we developed the TOPS Data Gateway which provides web services that expose TOPS products to external applications as well as a browser-based interface that presents interactive maps and charts derived from TOPS data. Now, only a web browser is needed to access and visualize current and past ecosystem conditions.

In planning the development of the Data Gateway it was desirable to build a system supporting open standards in order to improve interoperability of each of the system parts. The Open Geospatial Consortium (OGC) has developed a set of standards that define data models and communication protocols for working with geospatial data. By setting up a client-server architecture that supports OGC protocols we were able to build a system that can easily be extended or used with other data clients supporting these open standards.

In addition to supporting open standards, our data server is built on a free and open source software stack that implements the OGC Web Map Service (WMS) and Web Coverage Service (WCS) interfaces that provide the map image tiles and data used in web mapping clients. The server uses software from the Constellation and GeoServer projects, both based on the GeoTools GIS toolkit, a Java library which implements OGC standards as they are published to provide a collection of standards-based programming tools for working with geospatial data.

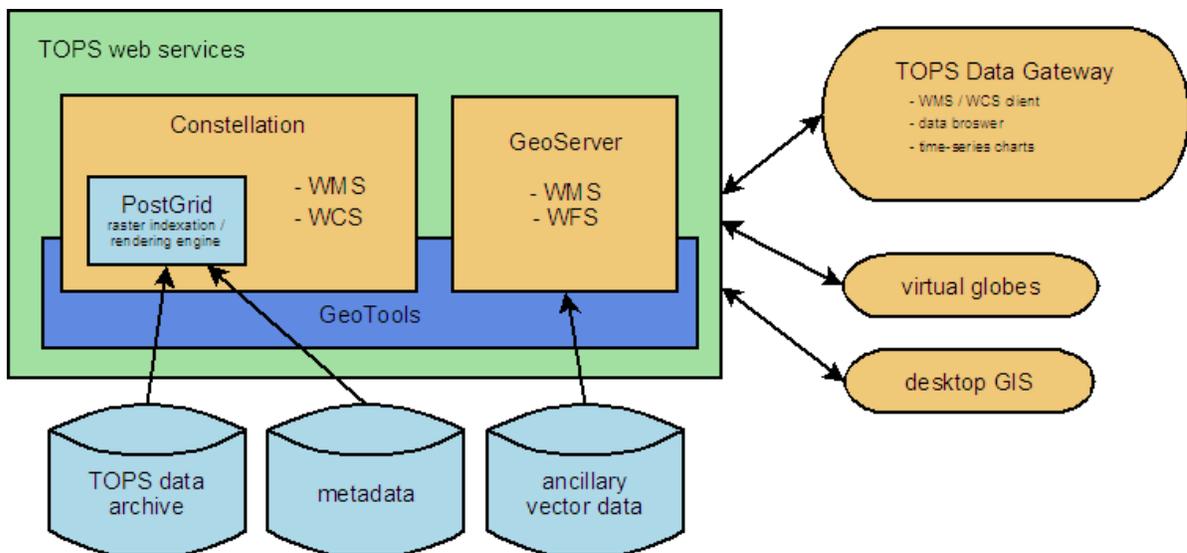


Figure 2. Architecture of the TOPS Data Gateway

GeoServer provides the WMS used to serve ancillary vector layers such as cities, roads, states, park boundaries, etc. GeoServer reads data stored in a database or in ESRI shapefiles and can produce map tiles based on default or custom styling definitions. However, like most existing GIS software, GeoServer assumes raster coverage data is two-dimensional (x,y), neglecting support for the temporal dimension of dynamic coverage data, like that produced by TOPS. The Constellation geospatial data services infrastructure is designed to work with multidimensional raster data, making it suitable for use with TOPS. We leveraged components from Constellation, such as the PostGrid raster indexation engine, to provide a WMS/WCS interface to TOPS products.

PostGrid was initially developed as part of a project for analysis of four-dimensional (x,y,z,t) oceanographic data. It defines a PostgreSQL database schema for indexing the spatio-temporal context of raster data, and manages the metadata necessary for interpreting pixel values. PostGrid uses the information stored in the database to ingest the raw binary data from TOPS, assembling a multidimensional data structure that can be interpreted by GeoTools. GeoTools, in turn, performs the necessary image manipulation tasks such as raster coloring, scaling, subsetting, or reprojection, using Sun Microsystem's open source Java Advanced Imaging library.

Our standardized web services expose TOPS data to a range of potential clients, from web mapping applications to virtual globes and desktop GIS packages. Software supporting OGC protocols may request map layers from TOPS, or request actual raster data for use in numeric analysis. In order to provide NPS personnel with a custom interface to TOPS data, we built an Ajax web application derived from the kaMap Javascript toolkit. Through this interactive web application, users can easily visualize current or historic park conditions and directly query the map for parameter values at any particular point. Users can also visualize temporal trends by requesting time-series plots to view the parameter's behavior over a specified period of time. This ability to examine a parameter's behavior in both space and time helps provide a much better understanding of the landscape dynamics.

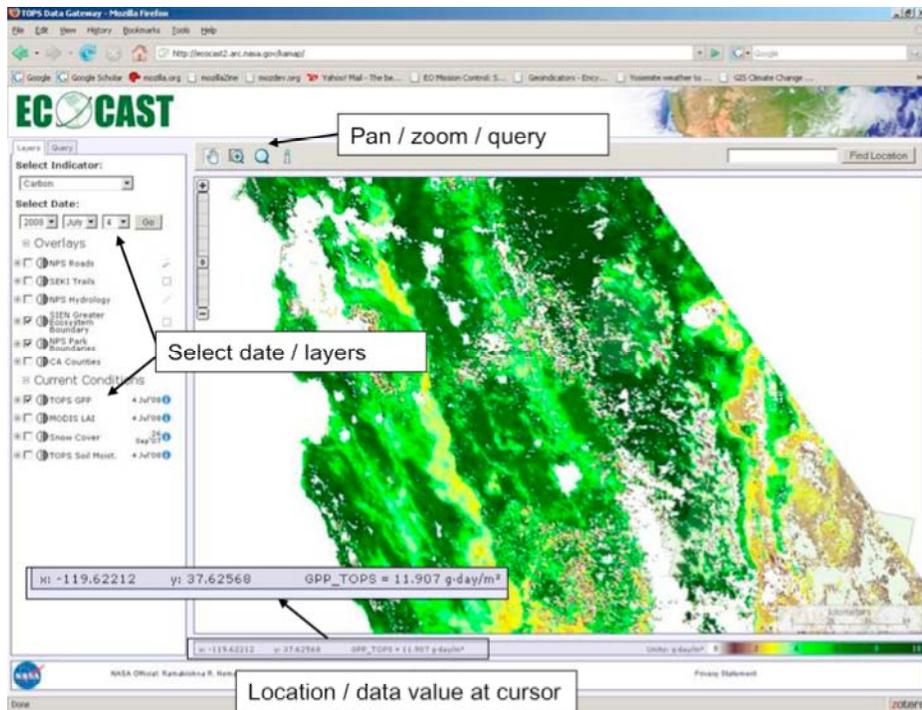


Figure 4. TOPS Data Gateway showing primary tools and features.

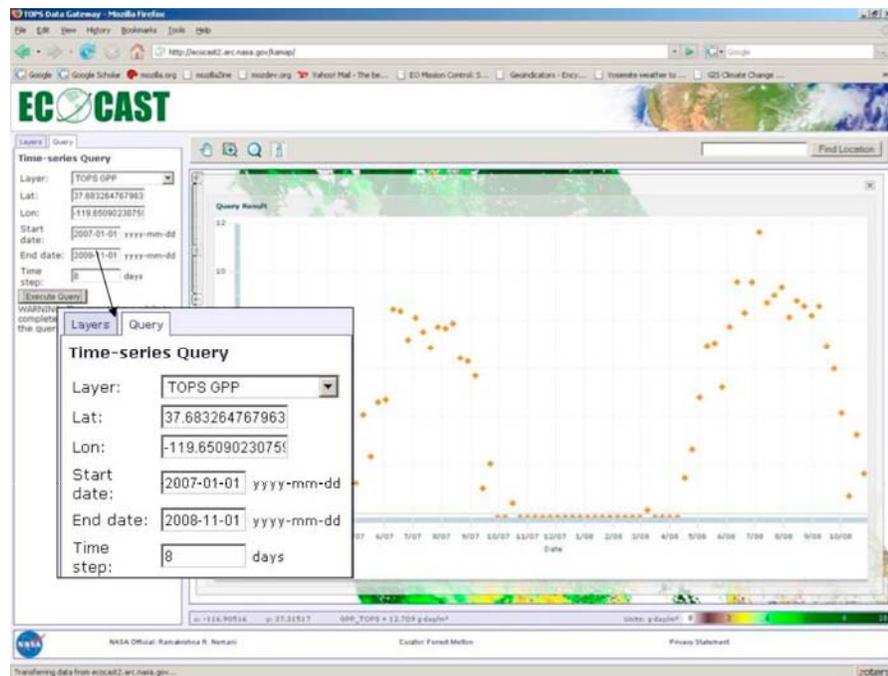


Figure 5. TOPS Data Gateway time series query tool.

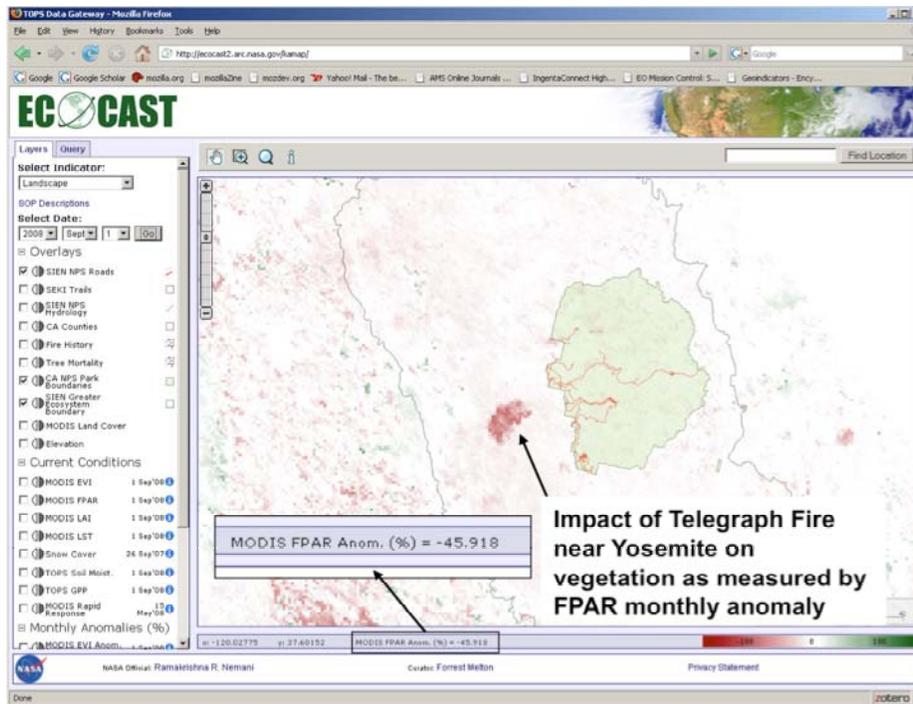


Figure 6. TOPS Data Gateway anomaly query tool.

3 Project Benchmarking

3.1 Baseline Status of Decision Support System

Overview

Monitoring and understanding the condition of ecosystem and natural resources in national parks is fundamental to the National Park Service's ability to manage park resources. To address the need for a comprehensive data system for compiling monitoring data and information, the NPS has developed the Vital Signs Inventory & Monitoring (I&M) Program to provide a framework for collecting and archiving data pertaining to park vital signs. The NPS I&M program is described in detail in the NPS Vital Sign Inventory and Monitoring Program plan (<http://science.nature.nps.gov/im/monitor/>). The baseline status of the NPS I&M program is fully described in the Evaluation Report[5] and is summarized below.

Park vital signs addressed in the I&M program include physical, chemical, and biological elements and processes of park ecosystems that represent the overall health or condition of the park, known or hypothesized effects of stressors, or elements that have important human values. Monitoring data help to define the normal limits of natural variation in park resources and provide a basis for understanding observed changes and possible management connections. Understanding the dynamic nature of park ecosystems and the consequences of human activities is essential for management decision-making aimed to maintain, enhance, or restore the ecological integrity of park ecosystems and to avoid, minimize, or mitigate ecological threats to these systems.

Under the I&M program, 270 park units have been organized into 32 networks that share funding and a core professional staff to conduct long-term ecological monitoring. Each network links parks that share similar geographic and natural resource characteristics to improve efficiency and reduce costs. Parks are encouraged to use or modify standard protocols and partner with existing programs wherever possible to allow comparability and synthesis of data at multiple scales, but the primary use of the data is at the park level for management decision-making and integration with park operations.

The long-term programmatic goals of the I&M Program are as follows:

- Establish natural resource inventory and monitoring as a standard practice throughout the National Park system that transcends traditional program, activity, and funding boundaries.
- Inventory the natural resources and park ecosystems under NPS stewardship to determine their nature and status.
- Monitor park ecosystems to better understand their dynamic nature and condition and to provide reference points for comparisons with other, altered environments.
- Integrate natural resource inventory and monitoring information into National Park Service planning, management, and decision-making.
- Share NPS accomplishments and information with other natural resource organizations and form partnerships for attaining common goals and objectives.

The NPS I&M program is focused on monitoring of vital signs selected to represent a range of environmental parameters that collectively characterize the condition of parks and park

ecosystems. Each I&M network selects the vital signs determined to be relevant to the ecosystems and cultural resources located within the network parks, though many vital signs, such as Land Cover and Use, are common across many I&M networks. Examples of vital signs selected by I&M networks are provided in Table 1.

Vital Signs Monitoring Framework		
Level 1 Category	Level 2 Category	Examples of Vital Signs Selected by I&M Networks
Air and Climate	Air Quality	Ozone, wet and dry deposition, visibility and particulate matter, air contaminants
	Weather and Climate	Weather and climate
Geology and Soils	Geomorphology	Glaciers, shoreline change, channel morphology, physical habitat index
	Subsurface Geologic Processes	Cave air quality, seismic activity
	Soil Quality	Biological soil crusts, soil structure and stability, soil cover, permafrost
Water	Hydrology	Groundwater dynamics, surface water dynamics, stream flow, lake and pond elevation, saltwater marsh water table
	Water Quality	Water chemistry, chloride flux, kettle pond acidification, nutrient loading and eutrophication, pollutant metals, aquatic macroinvertebrates
Biological Integrity	Invasive Species	Invasive/Exotic plants early detection, areal extent of established populations, exotic aquatic assemblages
	Infestations and Disease	Whitebark pine disease, forest insect/disease outbreaks
	Focal Species or Communities	Land birds, forest vegetation structure & composition, fish communities, intertidal communities, salt marsh vegetation, seagrass communities, wetland vegetation, riparian plant communities, prairie grassland communities, freshwater mussels, cave aquatic fauna, amphibians, white-tailed deer, caribou, wolves
	At-risk Biota	T&E plants, western prairie fringed orchid, northern spotted owl, western snowy plover, Ozark hellbender, Allegheny woodrat, Topeka shiner
Human use	Point-Source Human Effects	Contaminants, illegal roads and trails
	Non-point Source Human Effects	Estuarine nutrient inputs
	Consumptive Use	Fisheries harvest, poaching of native plants and animals
	Visitor and Recreation Use	Visitor usage
Landscapes (Ecosystem Pattern and Processes)	Fire and fuel dynamics	Fire occurrence and extent, fuel loading
	Landscape Dynamics	Land cover and use
	Soundscape	Soundscape
	Nutrient Dynamics	Nutrient cycling
	Productivity	Productivity, plant phenology

Table 1. I&M data framework and examples of vital signs.

Following selection and prioritization of vital signs, monitoring protocols are developed to describe a repeatable process for collecting, analyzing, and interpreting data to support monitoring of each vital sign. Each protocol, in turn, can be comprised of multiple Standard Operating Procedures (SOPs), which describe and document in detail the methods used by each component of the overall protocol. NPS I&M networks lead the development of the monitoring protocols and SOPs, and often work with collaborating scientists from universities and partner government agencies on the development of the SOPs.

3.2 Functional and Technical Needs Identified in the Evaluation Report

While the NPS I&M program Vital Signs Monitoring Framework (Table 1) and data management framework is designed to accommodate data from a wide variety of sources (including data from satellite sensors and ecosystem models), at the outset of this project, remote sensing and ecosystem modeling played a very limited role within the I&M program. High resolution aerial photography was utilized in the development of vegetation maps for individual parks, and NPS utilized maps of burned area polygons provided by the USFS Remote and derived from Landsat, SPOT, and other satellite data. Some parks were also utilizing data from the National Land Cover Database (NLCD) for use in evaluating land cover and land cover around parks, and a limited number of parks were evaluating remote sensing strategies for quantifying land cover and land use change within and around parks on a more frequent time interval than is provided by NLCD. Beyond these uses by NPS, within a few parks acquisition and utilization of remote sensing data was also performed for individual scientific studies, primarily for retrospective analysis for a single location or set of locations but this data was not used for routine monitoring and assessment.

The I&M program's emphasis on integration and coordination across programs and agencies, and the development of modern information systems and practices to build institutional knowledge and make the resulting information more available and useful, provided a key opportunity to integrate data from NASA satellites and ecosystem models into the NPS I&M program for use in operational support of monitoring of park ecosystems. A primary requirement for use of NASA data (or any data) in vital signs monitoring, was relevance to the five Goals of Vital Signs Monitoring, use by all 32 I&M network to guide the development and implementation of integrated natural resource monitoring:

- 1) Determine the status and trends in selected indicators of the condition of park ecosystems to allow managers to make better-informed decisions and to work more effectively with other agencies and individuals for the benefit of park resources.
- 2) Provide early warning of abnormal conditions of selected resources to help develop effective mitigation measures and reduce costs of management.
- 3) Provide data to better understand the dynamic nature and condition of park ecosystems and to provide reference points for comparisons with other altered environments.
- 4) Provide data to meet certain legal and Congressional mandates related to natural resource protection and visitor enjoyment.
- 5) Provide a means of measuring progress towards performance goals.

For most parks, vital signs monitoring is the primary means of measuring the status and trends in the condition of park natural resources, and in conjunction with qualitative resource assessments done by the parks, is used to report to the DOI strategic Land Health Goals. Periodic condition assessments using best available information and expert opinion can provide a rapid, qualitative "snapshot" of current resource conditions across an entire park or all resource categories, and may be used to demonstrate major changes in resource condition. Vital signs monitoring, in comparison, provides quantitative trend information with known confidence intervals for a subset of park resources or ecological processes, and is able to detect more subtle changes in resource condition and provide early warning of impending threats. However, for many parks, only a few selected resources can be monitored due to funding and logistical constraints.

Additionally, as part of the NPS efforts to improve park management through greater reliance on scientific knowledge, a primary purpose of the I&M program is to develop, organize, and make available natural resource data and to contribute to the Service's institutional knowledge by facilitating the transformation of data into information and knowledge through analysis, synthesis, and modeling. To help provide information needed at the park, network, regional, and national levels, the vital signs networks provide a system for scientific data collection, analysis, and reporting that is unprecedented in the NPS, and that directly contributes to the Department's strategy to "Improve information base, information management, and technical assistance".

While still limited, use of ecosystem models is more prevalent, and NPS scientists and university researchers working within U.S. National Parks use ecosystem models to study processes such as forest growth (e.g., Forest-BGC) and wildfire (e.g., WX), and NPS-wide efforts such as the Landfire Project (<http://www.landfire.gov/>) have implemented these models within multiple parks to facilitate integrated analysis and evaluation of management scenarios. However, routine utilization of ecosystem models to complement the continuous stream of observational data and provide forecasts and simulations of ecosystem conditions was not common within the NPS at the beginning of this project. Together, these characteristics led to the formulation of the following requirements for integration of data from TOPS into the NPS I&M protocols:

- Inclusion of meta-data for all data products in an MS Access compatible format;
- Delivery of all data in a GIS compatible format;
- Capability for automated retrieval and integration of data from NASA sources into the I&M framework.
- Data products to be spatially and temporally continuous for the regions and time periods of interest, whether retrospective analyses, near real-time monitoring, or forecasts.
- Data products for continuous monitoring to be provided reliably on regular intervals (daily, weekly, monthly, or annual).
- All data products will be evaluated, validated, and approved by NPS scientists and staff prior to integration with the I&M framework.

In addition, the emphasis of Vital Signs Monitoring Goals 1-3 on identification of trends, early detection of abnormal conditions, and monitoring to understand the dynamic nature and condition of park ecosystems resulted in an additional corresponding requirement for data products used to be summarized to provide measures of long-term trends and short-term changes.

An initial barrier to use of data from TOPS within NPS was the limited IT infrastructure available to most parks. Even the Sierra Nevada Network (SIEN), which includes Yosemite National Park and Sequoia-Kings Canyon National Park, had a total combined storage of only 1 terabyte for all data used by the NPS I&M network and very limited compute resources available for data processing and modeling. In addition, the remote location of many of the NPS I&M network offices was associated with limited bandwidth availability, constraining the ability of I&M staff to routinely ingest and process the large data volumes produced by many NASA remote sensing instruments and models. These constraints added a final requirement that data would initially be hosted by NASA, and would be accessible via a light-weight, browser-based interface that would provide both qualitative (e.g., imagery) and quantitative (e.g., data subsets, graphs) information to NPS users.

3.3 Current Status and Impacts of NASA Data on the NPS I&M System

3.3.1 Impacts to the NPS I&M Program

The primary impact of this project was to develop the data processing and distribution capabilities to utilize TOPS products in support of the NPS I&M program. The project resulted in substantial expansion of the capabilities provided by TOPS and demonstration of the capability for integrating data from TOPS into multiple NPS I&M vital signs monitoring protocols. In particular, this project developed capabilities that will facilitate use of NASA data in monitoring of phenology, carbon balance within park ecosystems, landscape dynamics, and climate patterns. Through the TOPS products listed in Table 2, the following products are now available to NPS personnel for monitoring park conditions in near-real time to facilitate assessment of current conditions and evaluation of long-term trends.

The project demonstrated the following specific impacts to the NPS I&M program. Additional details on the TOPS framework developed and its utility for NPS are provided in Nemani et al. (2008)[1].

- 1) Creation of an end-to-end system for automated processing of NASA data products for use by NPS in near-real time.** Through work completed under this project, we were able to implement a complete data processing, assimilation, and modeling framework that ingests data from NASA and NOAA satellites, surface observation networks, and ancillary datasets to produce a suite of data products targeted to support NPS I&M objectives. The development of this capability overcomes one of the primary barriers to use of NASA data by NPS for achievement of management and monitoring objectives. The system is capable of producing data products for NPS with a 1-day lag, operating models in near-real-time to produce estimates of current conditions and forecasts of future conditions, and provides tools for calculating multiple derived summary metrics for use in evaluation of current conditions in the context of past conditions and events.
- 2) Implementation of the TOPS Data Gateway to support visualization, query, and retrieval of data by NPS staff.** The formats and data volumes of NASA satellite data products have historically limited the access and use of NASA data products by NPS personnel. Implementation of the TOPS Data Gateway described in Section 2.3 addressed this barrier, and provided a light-weight interface for use in rapid evaluation of current conditions relative to past years, visualization and query of time series of TOPS data products, including climate surfaces, MODIS, AVHRR, and Landsat-derived satellite data products, and modeled ecological parameters, and retrieval of data sets for further processing or analysis. NPS staff were able to query anomaly maps and time series to investigate regions of interest and assess multiple measures of land surface conditions around regions showing evidence of change. Staff were also able to retrieve the TOPS data products in GIS compatible formats and access metadata that were compliant with NPS data standards.
- 3) While an operational capability for climate impact assessment was beyond the scope of work for this project, we did apply TOPS to demonstrate the potential for NASA satellite data**

products and models to support evaluation of climate change impacts on park hydrology through integration and application of the RHESSys and Biome-BGC model to evaluate climate impacts on the Merced watershed. A series of model runs were conducted to evaluate the potential impact of climate change scenarios on snow melt and runoff dynamics for the period from 1950-2100. This work was continued under the NASA-NPS PALMS project and expanded to address issues pertaining to impacts of climate change on vegetation productivity. Results from this work were presented to NPS and summarized in Nemani et al. (2008)[1].

- 4) This project led to a significant increase in the visibility of NASA products to NPS staff through on-line visualization tools and multiple presentations and discussion at Yosemite and Sequoia Kings Canyon National Parks, the NPS I&M headquarters, as well as at NPS-wide science conferences (see Section 5). These meetings and discussions have fostered additional collaborations and led to funded follow-on activities to more fully integrate TOPS products into the NPS I&M programs at multiple parks and networks.

TOPS Monitoring Products for the SIEN I&M Network		
Parameter	Spatial Resolution	Temporal Resolution
MODIS Direct Broadcast	250 m	Daily
FPAR	1 km	8-day
LAI	1 km	8-day
GPP / NPP	1 km	8-day
LST	1 km	8-day
Snowcover	500m	8-day
NDVI/EVI	1 km	16-day
Phenology	30 m to 1 km	8-day
Evapotranspiration	30 m to 1 km	8-day & daily
Soil Moisture	30 m to 1 km	Daily
Outflow	30 m to 1 km	Daily
Landcover	30 m to 250 m	Annual
Thermal Anomalies (Fire)	500 m	Daily
Temperature (Max / Min)	30 m to 1 km	Daily
Precipitation	30 m to 1 km	Daily
Vapor Pressure Deficit	30 m to 1 km	Daily
Solar Radiation	30 m to 1 km	Daily

Table 2. TOPS products developed for the NPS SIEN I&M Network

3.3.2 Impacts to the SERVIR Project

As a demonstration of the abilities provided by TOPS to support regional monitoring and management activities, TOPS was also applied to produce a suite of data products for Mesoamerica and the Caribbean. The products were provided to support routine monitoring of land surface conditions by a range of resource managers and government agencies via the SERVIR platform. A historical archive of data products were generated for the period from 2000 to 2009. Products were updated daily, and integrated with the SERVIR platform for distribution to the SERVIR user community. The data products developed for SERVIR included a subset of the data products developed for NPS, but were produced over a much larger geographic domain. The suite of data products included satellite and model-based measures of land surface and weather conditions (Table 3, Figure 7).

TOPS Monitoring Products for SERVIR		
Parameter	Spatial Resolution	Temporal Resolution
FPAR	1 km	8-day
LAI	1 km	8-day
GPP / NPP	1 km	8-day
LST	1 km	8-day
NDVI/EVI	1 km	16-day
Landcover	1km	Annual
Temperature (Max / Min)	1 km	Daily
Precipitation	1 km	Daily
Vapor Pressure Deficit	1 km	Daily
Solar Radiation	1 km	Daily

Table 3. TOPS products proposed for integration in the prototype system.

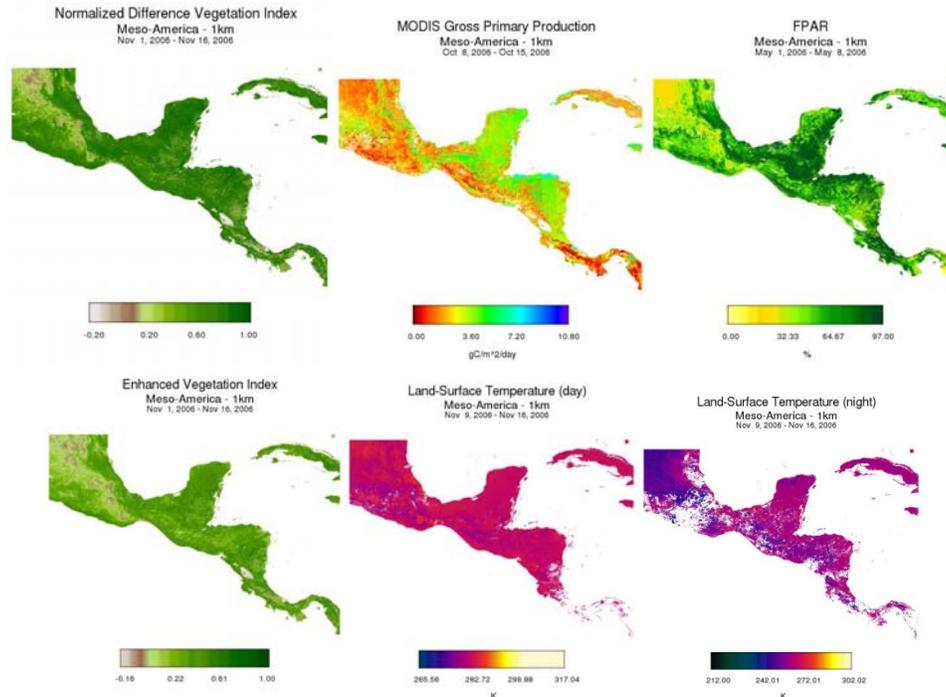


Figure 7. TOS data products for SERVIR-Viz.

3.4 Project Transfer

Completion of efforts to transfer components of the TOS framework to NPS were scheduled for the final year of the project. While the compute resources maintained by NPS have expanded since the start of the project, in meetings with NPS it was determined that support of a full implementation of the TOS modeling framework within NPS was not a viable option within the current NPS compute infrastructure. As such, the strategy developed focused on ongoing production and processing of datasets at NASA as part of core efforts related to ongoing research and applied science activities. Tools and interfaces for data retrieval and further processing were to be jointly developed by the TOS project team in collaboration with NPS I&M staff, facilitating full integration with NPS I&M processes and procedures. Due to miscommunications regarding the project funding as described in Section 1.3, completion of the planned transfer activities were not completed as part of this project. These activities have been supported by the NASA-NPS PALMS project and progress on these activities has been provided in the annual reports for the PALMS project.

3.5 Other Impacts and Benefits

In addition to fulfillment of project objectives specific to NPS, this project has also achieved a number of wider ranging impacts. The extensions to the TOS framework achieved under this project have developed a set of capabilities for operational ecological monitoring and forecasting with the ability to support a wide range of applications. As a direct result of improvements made through the REASoN supported project, TOS is currently being applied to support more than 20 ongoing R&A activities, including more than 10 NASA applied science activities, ranging

from crop yield forecasting to stream temperature forecasting for management of habitat for endangered salmonid species[10]. Capabilities developed through this project for monitoring of parks and protected areas continue to be applied through the NASA-NPS PALMS project (PI: A Hansen), the NASA Decision Support System for Monitoring, Reporting and Forecasting the Ecological Conditions of the Appalachian National Scenic Trail project (PI: YQ Wang), and the Development of RRSC Models for Use within the USFWS Strategic Habitat Conservation Framework project (PI: B Crabtree).

4 Lessons Learned

In the course of working closely with NPS collaborators on this REASoN project we learned a number of important lessons about successful implementation and transfer of NASA data products and technology resources to partner agencies. The advice and guidance provided by NPS collaborators on this project has been invaluable, and is incorporated in the items below.

- 1) Partnerships take time: The decision making structures, IT infrastructure, and organizational culture of government agencies varies widely and is a function of both their mission and institutional history. Less obvious is that understanding differences in organizational cultures and priorities can be a critical part of designing a successful strategy for integration and transfer of data products or technical resources. The process of developing a relatively complete understanding of potential partners is time consuming, and is often bypassed to focus on identification of specific data needs. For example, within this project, understanding that the history of NPS resource management was rooted in field-oriented biological and ecological studies was important in understanding concerns about use of data from satellites and ecosystem models. To overcome this concern, we had to design the system to facilitate comparison of NASA data products against related field data sets. Similarly, understanding factors such as the bandwidth and data storage constraints even in well funded parks were important factors in the design of the integration strategy.
- 2) Focusing on a single issue of concern to the partner can be beneficial: In the early stage of project with a new partner agency, it is tempting to focus on a broad range of potential problems identified by the user to attempt to maximize the impact of the project, and to mitigate against the potential failure of any single project component. In addition, it is common to avoid items which do not directly contribute to project objectives, even if the issue is of high concern to the partner. However, the ability to make rapid progress on a problem of particular concern to the partner can significantly increase partner engagement, accelerating the rate of overall progress in the long term and maximizing project impact. Within this project, completion of modeling runs to evaluate the potential climate change impacts on park ecosystems was important in engaging NPS partners. However, we initially avoided the use of Landsat data to address issues of concern to NPS pertaining to changes in the condition of high altitude meadows on the basis that it was not a capability that could be sustained long term (the current data policy of free data access was not in place at the time). In hindsight, focus on this problem would have been beneficial in strengthening the partnership in the early stages, even if unsustainable in the long-term. In the end, there are tradeoffs between focusing on an issue to engage a partner, and implementing a portfolio of

capabilities to “spread the risk”. Each project will have to balance these alternate strategies based on the requirements of the partner agency.

- 3) Data format and access limitations are significant barriers to use of NASA data products, but data volumes can be an equal barrier. Initial efforts to deliver data products to NPS focused on delivery of a complete archive in an easy to retrieve, GIS compatible format. However, this strategy was not successful due to the volume of data produced. To ensure that data products were accessible and useful to NPS, this project worked extensively to develop multiple data access and delivery channels, including browser-based and ArcGIS compatible distribution mechanisms.

5 Project Publications, Presentations, and Reports

Results from this project were also distributed via the following peer-reviewed publications, presentations, and reports.

Nemani, R, Hashimoto, H, Votava, P, Melton, F, Wang, W, Michaelis, A, Milesi, C, Hiatt, S, and White, M. 2008. Monitoring and forecasting ecosystem dynamics using the Terrestrial Observation and Prediction System (TOPS). *Remote Sensing of Environment* 113(7):1497-1509.

Nemani, R., Votava, P., Michaelis, A., White, M., Melton, F., Milesi, C., Golden, K. 2007. Terrestrial Observation and Prediction System (TOPS): Developing ecological nowcasts and forecasts by integrating surface, satellite and climate data with simulation models, in *Research and Economic Applications of Remote Sensing Data Products*. Aswathanarayana, U. and R. Balaji (eds.). American Geophysical Union.

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Hiatt, S.H., H. Hashimoto, F.S. Melton, A.R. Michaelis, C. Milesi, R.R. Nemani, W. Wang. 2008. Building Geospatial Web Services for Ecological Monitoring and Forecasting. *Eos Trans. AGU*, 89(53), Fall Meet. Suppl., Abstract IN31C-1151. American Geophysical Union 2008 Fall Meeting, San Francisco, CA.

Melton, F., et al. 2008. Monitoring and Modeling Environmental Conditions with the NASA Terrestrial Observation and Prediction System. *CAFTA-DR Workshop*, Dominican Republic, March 25-26, 2008.

- Melton, F., et al. 2007. Applications of the Terrestrial Observation & Prediction System. SERVIR Training Workshop, CATHALAC, Panama City, Panama, March 1, 2007.
- Melton, F., et al. 2007. Ecological Conditions of US National Parks: Enabling Decision Support Through Monitoring, Analysis, and Forecasting. Presentation to the NPS Sierra Nevada I&M Network. Nov. 15, 2007, Three Rivers, CA.
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- Nemani, R., et al. 2005. Evaluation Report for the Ecological Forecasting Project on An Agent-Based Interface to Terrestrial Ecological Forecasting. Submitted to the NASA Research, Education and Applications Solutions Network on December 30, 2005.

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