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RESTORATION OF NPOESS CLIMATE CAPABILITIES: CLIMATE DATA RECORDS

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ABSTRACT

The NPOESS Program was designed primarily to serve operational users who typically need near real time observations and products. Consequently, NPOESS does not provide reprocessing, data record gap filling, or assurance that its products are consistent with those of heritage missions. However, these characteristics are critical for climate science and applications since climate signatures are generally small compared to normal observation variability. In this article, we describe a joint NOAA, NASA and USGS program plan to develop climate data records (CDRs). The proposed program systematically evolves a candidate algorithm through a 6-level research and operational path to maturity, and includes ongoing algorithm maintenance and technology insertion. The proposed program is jointly managed by the responsible agencies, but its execution relies extensively on community expertise and resources. The CDRs resulting from this program would provide a comprehensive set of climate data and information records (CIRs) useful for spatio-temporal detection, analysis and prediction of environmental change, and for development of a complete and coherent environment for climate model execution.

1. INTRODUCTION

The NPOESS program was initiated in 1994 to merge the nation's military and civil meteorological programs. Although designed to provide operational products (e.g., for weather forecasting), the NPOESS member agencies (NASA, NOAA/Department of Commerce and the Department of Defense) expected NPOESS would extend the mature Earth Observing System (EOS) measurements and products (King et al., 2004) -- many of which address the nation's climate monitoring needs -- in an operational environment.

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As the NPOESS Program developed and as early EOS products began to emerge, it became increasingly clear that the climate community's geophysical product requirements differed from those of NPOESS. The NPOESS products are being developed primarily to serve users who typically need near real time information. In contrast, detecting climate change, understanding the associated shifts in climate processes, and projecting the impacts of these changes on the Earth system requires a comprehensive set of consistent measurements collected over decades. For example, the IPCC's Fourth Assessment (IPCC, 2007) outlined a series of pressing climate issues whose resolution involves analysis of long-term, self-consistent data, e.g.,

- The geographical distribution and time evolution of the radiative forcing due to changes in aerosols during the 20th century are not well characterized.
- Multi-decadal changes in daily temperature range (DTR) are not well understood, in part because of limited observations of changes in cloudiness and aerosols.
- Incomplete global data sets for extremes analysis and model uncertainties still restrict the regions and types of detection studies of extremes that can be performed.

The National Research Council (NRC, 2004) described the requisite Climate Data Records (CDRs) as "time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change." To provide such quality and consistency, NPOESS products would have to be defined, processed, and packaged similarly to their climate-quality EOS predecessors such that EOS-to-NPOESS product transition would be effectively seamless. Because this requirement was not part of the

NPOESS program formulation, it is unlikely that any NPOESS operational product will provide a seamless EOS-to-NPOESS transition for climate research and applications. Indeed, in many cases the EOS and NPOESS product definitions differ considerably despite their common names.

To address this shortcoming, NOAA, NASA and the USGS began drafting a program to address the CDR recommendations of the Climate Change Science Program (2006), Global Climate Observing System (WMO, 2003) and other organizations. The evolving program is built upon lessons learned from several prior CDR activities which, while oftentimes successful, were not comprehensive, systematic and sustained over time – defining characteristics of the proposed program. The proposed program also attempts to optimally leverage the mandates and competencies of the respective agencies to provide a pathway for reprocessing existing products and for evolving new experimental products into CDRs.

2. OPERATIONAL VS. CLIMATE PROCESSING

Operational satellite products are typically generated in near real time fashion because their data may contain potentially life-saving weather and hazard information. This low latency (fast delivery) processing is typically achieved at the expense of product sophistication and quality (Bates, 2004). Operational products usually incorporate instrument and algorithm knowledge available at the time of observation; however, experience has repeatedly demonstrated that this knowledge increases throughout a satellite mission. In fact, a better understanding of a mission's data may be realized much later when a more technologically advanced sensor is flown. Unfortunately, "forward-only" near real time products never benefit from later knowledge.

A CDR, in contrast, is generally a multi-decadal global record of a geophysical variable generated with data from many different satellite sensors (sometimes blended with in-situ data) using the best instrument and algorithm knowledge available (e.g., CCSP, 2006b and Figure 1). Because they incorporate the consensus knowledge of the satellite community, CDRs are rigorous, have random and time-dependent error estimates in accordance with accepted standards, and are scientifically defensible (Barkstrom et al., 2007). CDRs typically increase in value significantly as their record length increases, although cost and complexity typically also increase as input data from disparate observing systems are employed.

Given their retrospective incorporation of state-of-the-art knowledge and practices, CDRs provide the reference global data sets for the detection of climate change – the potential catalyst for policy decisions at state and national levels, and of accords and treaties at international levels. Indeed, without CDRs, current satellite data lack a historical context and fundamental earth changes can go unnoticed or falsely represented.

3. FOUNDATIONS OF PROPOSED CDR PROGRAM

The proposed CDR program will capitalize on lessons learned from heritage CDR activities (Bates, 2004). These include broad initiatives such as the NASA/NOAA Pathfinders (Ohring and Dodge, 1992), as well as many *ad hoc* CDR activities aimed to satisfy narrow research needs. An excellent review of these efforts is in NRC (2004). However, three cornerstones principals of the proposed program define its point of departure from the earlier activities. Specifically, the proposed program is:

1) Systematic in that it progressively develops CDRs through a consistent and well-defined set of maturity milestones.

2) Comprehensive in that it addresses the suite of CDRs identified in the CCSP and GCOS CDR lists, prioritized and adjusted over time by an expert advisory team (Barkstrom et al., 2007). Further, it will address all aspects for CDR development and stewardship, from algorithm development and (re-)processing to validation, archiving, and distribution (NRC, 2005).

3) Designed for sustained implementation, such that mature CDRs can be subjected to further improvements crafted through a parallel basic research program, or experimental products (e.g., newly sensed variables evolving from the decadal survey missions; NRC, 2007) can be entrained into the CDR pipeline.

4. EVOLUTION OF A CDR

Following Bates and Barkstrom (2006), the proposed program is based on the systematic progression of satellite algorithm and product through a series of maturation levels, culminating in the release of a scientifically irrefutable Level 6 CDR. To advance a step in the maturity matrix, a candidate CDR algorithm must satisfy the "exit criteria" in seven areas (see Table 1 for specifics):

- Sensor usage – the satellite sensors for which the candidate algorithm has been successfully adapted and proven credible
- Algorithm stability – the estimated likelihood and magnitude of theoretical changes required to provide research quality products
- Metadata and Quality Assurance – the completeness and conformance of these attributes to international standards

- Documentation – the completeness, stability and availability of a required set of documents

- Validation – the quantity, quality and diversity of independent quantitative assessments of product uncertainty (bias and precision)

- Public Release – the availability of algorithm source code and data sets

- Science and Applications – the extent to which a product has been used successfully in societal benefit areas (IWGEO, 2005), including climate studies.

In this approach, individual CDRs progress at their own pace based on the rate at which they mature. Indeed, given existing NASA, USGS and NOAA development programs (e.g., EOS), many algorithms have already achieved fairly high levels of maturity.

To estimate the processes, resources and schedule required to advance an algorithm through this matrix, we have developed a notional pathway. The path is best described as a spiral development between a research agency (most commonly NASA) and an operational agency (typically NOAA or USGS). The four key phases of the spiral development include:

1) Early Development. This phase is primarily addressed by research agencies and encompasses Maturity Levels 1- to 3. It includes initial algorithm development, pre-launch instrument characterization, post-launch characterization, and multiple iterations of test product generation, evaluation/validation, and improvement.

2) Transition and Maturation. This phase is coordinated by the operational agency, and encompasses Maturity Levels 4- to 6. It begins when the sponsoring research and operational agencies independently co-generate a product to demonstrate transition readiness. In this phase, an algorithm's applicability is extended to all relevant heritage sensor data (if not completed earlier). The phase includes additional validation, algorithm refinement, and reprocessing efforts, and culminates in the release, distribution, and archiving of an irrefutable Level 6 CDR.

3) Operations and Maintenance. This post-released phase provides funding to competitively selected algorithm experts to maintain a CDR algorithm in production. On-going maintenance is imperative to ensure the highest product quality through the unavoidable and continuous degradation of on-orbit sensors.

4) Technology Incubation and Insertion. This component, which operates in parallel rather than in series with the other phases, ensures continually state-of-the-art CDRs through the support of basic research and advanced algorithm development. In the coming decade, for example, this component would facilitate usage of data from new missions described in the NRC decadal survey report (NRC, 2007).

As part of this process, the agencies anticipate concurrent development and production of climate information records (CIRs), defined here as a time series derived from CDRs and related long-term measurements to provide specific information about an environmental phenomena of particular importance to science and society. CIRs are often designed to convey key aspects of complex environmental phenomena in a manner useful to a variety of applications of particular interest to specific user communities. Examples of CIRs include metrics of El Nino Occurrence/Persistence/Magnitude, Antarctic Ozone Hole Area and Magnitude, Drought Indices and Occurrence/Persistence/Magnitude, and Hurricane Intensity and Tracks. CIRs have demonstrated success in bridging the gap that sometimes occurs between systematic satellite products and societal benefits.

5. AGENCY ROLES AND RESPONSIBILITIES

By charter, NASA's focus is on utilizing space missions involving the latest technologies and the most current analytical techniques to advance climate science and our understanding of climate variability. NOAA's focus is on operational systems, both in space and on the Earth's surface, to provide sustained measurements of key climate variables over the periods of time necessary to resolve small persistent shifts that represent true climate change. By providing both innovative development and sustained production, the proposed program inherently requires participation of both NASA (or other research agencies, such as USGS) and NOAA.

A critical challenge to this approach is the transitioning of responsibility for a given CDR from the research to operational agency. Indeed, although technology transition from NASA to NOAA or USGS is called for often, its execution often encounters unexpected challenges. We have therefore tried to anticipate such challenges and devise approaches that reduce risk. For example, throughout the process, NOAA and/or USGS personnel participate in the NASA development of the draft algorithm and, later, NASA personnel continue to support NOAA personnel in the development of the mature CDR. Further, NASA shares its research data and technology with NOAA to facilitate a subsequent transition should it be appropriate. After transition, NOAA shares its operational data with NASA and NASA remains in a supportive role to further develop and maintain the algorithm. Just prior to transition, a specific

Research-to-Operations Transition Plan for a given algorithm is developed and agreed to by both agencies.

Throughout the process, the primary role of the respective agencies will be one of coordination and accountability. Indeed, the algorithm expertise required for development and maintenance of a top-quality CDR develops from specialized training over many years. A successful program must therefore support competencies where they already exist. We therefore anticipate many of the hands-on activities will occur outside of agency facilities (e.g., in universities).

6. MANAGEMENT AND OVERSIGHT

Following NRC (2004) recommendations, our proposed program specifies three groups responsible for coordinating and managing CDR evolution.

Each candidate CDR has a *CDR Working Group* that is comprised of several scientists responsible for the maturation of that particular CDR. The purpose of the CDR Working Group is to define the specific steps on the path of maturing the candidate algorithm to a draft CDR, assisting the transition to an operational system, and continuing to define the process of producing a mature CDR. They may also assist in the definition of CIRs associated with the CDR. This path is captured in a CDR Development Plan that is maintained by the CDR Working Group and updated annually. This plan contains a three-year projection of work associated with the CDR. Each year, a CDR Working Group forwards their updated CDR Development Plan to the CDR Science Advisory Board.

The *CDR Science Advisory Board* is comprised of 5-7 senior climate scientists. Its purpose is to provide science guidance to the maturation of the CDRs. This group meets annually to review, evaluate, and prioritize the CDR Development Plans provided by the individual CDR Working Groups. This group in particularly provides guidance on end-user needs and developments. Its CDR prioritization is critical to support subsequent budgetary decisions on the part of sponsoring agencies

The *CDR Steering Committee* is comprised of senior scientists and managers from NASA, NOAA and the USGS. The Committee coordinates agency budgetary inputs to provide an integrated approach to maturing CDRs. They use the three-year projections in all of the CDR Development Plans to make sure that the planned work does not oversubscribe the budget for the next year. These plans are also used to generate the budget submission for two years hence. This group is responsible for the overall coordination of the CDR process between agencies. It is intended to be a knowledgeable forum in which to maximize the cost-effectiveness of the combined agency investments.

7. INITIAL IMPLEMENTATION

To allow flexibility and to incorporate lessons learned, we have outlined a Pilot Program which begins with a single mature pathfinder product, developed under research agencies, that is ready to undergo transition. Thereafter, we initialize 1-2 new CDR starts per year, focusing first on Fundamental CDRs (i.e., Level 1 products; see NRC, 2004) and lowest-complexity Thematic CDRs (geophysical products) as appropriate given the NPOESS-era instrument launches. As the proposed program evolves and stabilizes, it will address more complex or sophisticated CDRs.

We anticipate that each CDR will provide unique challenges and will likely follow a unique path to maturity. Some candidate algorithms will never reach Level 6 maturation and further development will be halted. Similarly, some Level 6 CDRs in production may be subsumed by superior products, or cease to be cost effective, in which case a termination (sunsetting) provision will be invoked. The *CDR Science Advisory Board* will be responsible for periodically advising the agency on CDR priorities and relevance.

8. CONCLUSIONS

Because of their expert development, state-of-the-art accuracy, and long-term consistency, Climate Data Records have proven extremely valuable in facilitating climate change discovery, analysis and prediction (e.g., Nemani, 2003). NOAA, NASA and the USGS are designing a systematic, comprehensive and sustained CDR development and production program to ensure NPOESS-era measurements, and their predecessors, can help answer pressing climate questions and benefit society to the greatest extent. The proposed program accepts algorithms at various states of development, and outlines an orderly path towards irrefutable, Level 6 CDRs. The path specifies the complementary roles of research and operational agencies as a candidate algorithm undergoes early development, transitioning and maturation, and finally, sustained production and maintenance. A concurrent technology incubation and insertion component limits risk of CDR obsolescence. The agencies have outlined a Pilot Program strategy to thoughtfully initiate development and transitioning activities at a pace that allows evolution and adjustment. The wider scientific community will actively participate in program execution, both through competitively selected development, maintenance and stewardship activities and via program advisory boards. The proposed program is designed to be a non-duplicative, non-redundant complement to past and current efforts, as well as be timely and cost-effective.

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Table 1. CDR Maturity Level Definitions

Maturity	Sensor Use	Algorithm stability	Metadata & Quality Assurance (QA)	Documentation	Validation	Public Release	Science & Applications
1	Research Mission	Significant changes likely	Incomplete	Draft Algorithm Theoretical Basis Document (ATBD)	Minimal	Limited data availability to develop familiarity	Little or none
2	Research Mission	Some changes expected	Research grade (extensive)	ATBD Version 1+	Uncertainty estimated for select locations/times	Data available but of unknown accuracy; caveats required for use.	Limited or ongoing
3	Research Missions	Minimal changes expected	Research grade (extensive); Meets international standards	Public ATBD; Peer-reviewed algorithm and product descriptions	Uncertainty estimated over widely distribute times/location by multiple investigators; Differences understood.	Data available but of unknown accuracy; caveats required for use.	Provisionally used in applications and assessments demonstrating positive value.
4	Operational Mission	Minimal changes expected	Stable, Allows provenance tracking and reproducibility; Meets international standards	Public ATBD; Draft Operational Algorithm Description (OAD); Peer-reviewed algorithm and product descriptions	Uncertainty estimated over widely distribute times/location by multiple investigators; Differences understood.	Data available but of unknown accuracy; caveats required for use.	Provisionally used in applications and assessments demonstrating positive value.
5	All relevant research and operational missions; unified and coherent record demonstrated across different sensors	Stable and reproducible	Stable, Allows provenance tracking and reproducibility; Meeting international standards	Public ATBD, Operational Algorithm Description (OAD) and Validation Plan; Peer-reviewed algorithm, product and validation articles	Consistent uncertainties estimated over most environmental conditions by multiple investigators	Multi-mission record is publicly available with associated uncertainty estimate	Used in various published applications and assessments by different investigators
6	All relevant satellite missions; unified and coherent record over full series, considered scientifically irrefutable following extensive scrutiny	Stable and reproducible; homogeneous and published error budget	Stable, Allows provenance tracking and reproducibility; Meeting international standards	Product, algorithm, validation, processing and metadata described in peer-reviewed literature	Observation strategy designed to reveal systematic errors through independent cross-checks, open inspection, and continuous interrogation	Multi-mission record is publicly available from Long-Term archive	Used in various published applications and assessments by different investigators

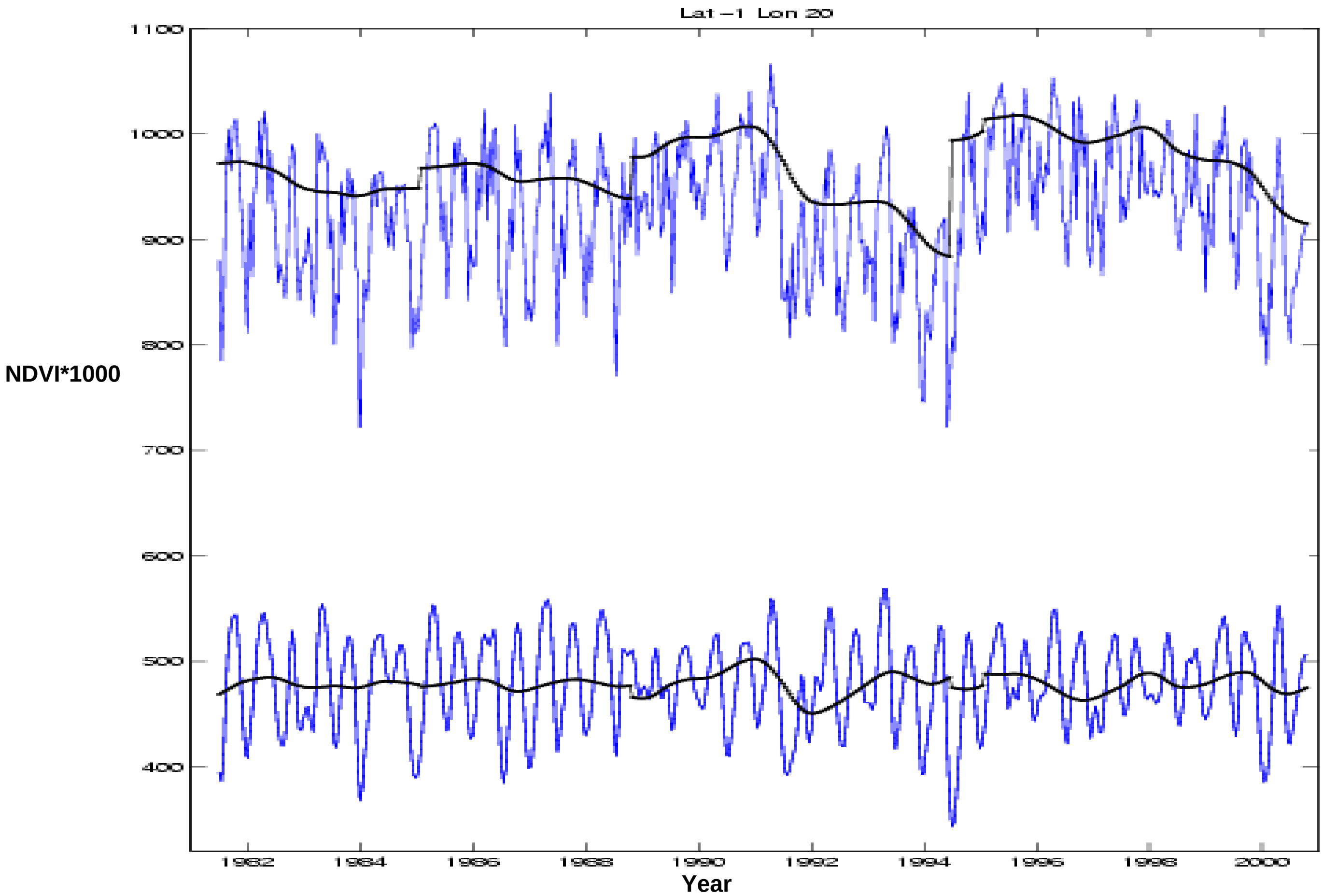

Figure 1. Operational Data Records (top lines) and Climate Data Records (bottom lines) of the Normalized Difference Vegetation Index (NDVI) near the equator, derived from the AVHRR sensors on a series of afternoon-overpass NOAA polar orbiting satellites (NOAA-6, -7, -9, -11, -9 (again), and -14; spanning 1981- to 2001). Plotted values are multiplied by 1000 for better clarity. Satellite orbital drift causes a change in the time of observation. The uncorrected operational product therefore shows erratic trends and variability due to observatory rather than environmental changes. The CDR is reprocessed with calibration and orbital corrections and provides a much improved record of environmental changes. Figure courtesy of the GIMMS Project, NASA/GSFC.