Appendix 4: Summaries of Presentations at 2009 ADI Workshop

Arctic Ocean Reanalysis

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Dmitri Nechaev (*University of Southern Mississippi*)
Gleb Panteleev (*International Arctic Research Center*)
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This is a NSF project #ARC-0628836: "Collaborative Research: Toward reanalysis of the Arctic Climate System - sea ice and ocean reconstruction with data assimilation".

An Integrative Data Assimilation for the Arctic System (IDAAS) has been recommended for development by SEARCH in 2005. While existing operational reanalyses assimilate only atmospheric measurements, an IDAAS activity would include non-atmospheric components: sea ice, oceanic, terrestrial geophysical and biogeochemical parameters and human dimensions data. Atmospheric reanalysis products play a major role in the arctic system studies and are used to force sea ice, ocean and terrestrial models, and to analyze the climate system's variability and to explain and understand the interrelationships of the system's components and the causes of their change.

Motivated by this success and the major goals and recommendations of SEARCH, we work to develop an integrated set of assimilation procedures for the ice–ocean system that is able to provide gridded data sets that are physically consistent and constrained to the observations of sea ice and ocean parameters.

In order to reach project goals we have developed an approach based on employing of two models. Model "A" uses a conventional Four Dimensional Variational (4D-VAR) technique. It does not have sea ice but uses all needed information from model "B" which is a regional coupled ice-ocean model. The B model is forced by atmospheric reanalysis fields and corrects its forcing based on data obtained from model "A".

Model "A" is a *Semi-Implicit Ocean Model (SIOM)* was designed specifically for the implementation of 4D-Var methods into regional models controlled by currents at the open boundaries and by surface fluxes and is a modification of the Madec *et al.*, [1999] model. The SIOM 4D-Var data assimilation system has been implemented successfully for the reconstruction of the summer circulation in the Barents, Bering and Kara seas (Panteleev *et al.*, 2006a,b,c), and for the variational hindcast of the circulation in the Tsushima Strait (Nechaev *et al.*, 2005).

Model "B" is *Pan-Arctic Ice-Ocean Modeling and Assimilation System (PIOMAS)* was developed at the Polar Science Center, University of Washington. This is a coupled parallel ocean and sea ice model capable of assimilating sea ice concentration and velocity data. PIOMAS is configured to cover the region north of 43°N. The model grid is based on a generalized orthogonal curvilinear coordinate system with the northern grid pole displaced into Greenland. This allows the model to have good resolution in the connections between the Arctic

Ocean and the Atlantic Ocean. The model is one-way nested to a Global Ice-Ocean Modeling and Assimilation System which consists of similar sea ice and ocean models. Output from this model will be specified along the southern boundaries of POIMAS (43°N) as open boundary conditions.

Based on this approach we plan to reconstruct sea ice and ocean monthly fields for three distinct periods, each representing a different state of the arctic climate:

- The first period is 1972-1978 (7 years) when the Arctic was relatively cold and there is a large quantity of hydrographic data available
- The second is 1989-1996 (7 years) when large changes begin in the Arctic Ocean circulation, in its hydrographic structure and in sea ice conditions
- The third is 2001-present when substantial amounts of open water begin to appear in the late summer.

In this project, we have completed reanalysis of the Chukchi Sea conditions for 1990-1991. This test allowed us to investigate our algorithms and technologies described above. Also we have completed reanalysis of climatic conditions for two periods: 1972-1978 and 1989-1996. The results of this project in combination with simulations of the coupled ice-ocean AOMIP regional and global models can be used to conduct OSSEs in order to design the sea ice and ocean observing network.

SEACOOS Program – Lessons Learned

Harvey Seim (*Department of Marine Sciences, University of North Carolina)*

The Southeast Coastal Ocean Observing System (SEACOOS, www.seacoos.org) can be considered a pilot implementation of a regional (i.e. a part of the US coastline) coastal ocean observing system. It operated from 2002 to 2008 at which point it was folded into an expanded, operational program (SECOORA, www.secoora.org). The SEACOOS program was a collaboration of (largely) institutional programs that had expertise in an area relevant to ocean observing, such that in aggregate, the program had expertise in all the necessary fields. In it's last year SEACOOS undertook a program review and documentation and published a special volume in the Marine Technology Society Journal (MTS Journal, 42:3, Fall 2008; see also http://seacoos.org/documents/mts-journal) that focused on lessons learned during the program. The presentation was derived in large part from the special volume.

SEACOOS strove to understand the necessary elements and structure of a COOS as envisioned by the Integrated Ocean Observing System (IOOS, www.ioos.gov). The regional systems within IOOS are responsible for governance and setting priorities, which requires engagement of a large number of diverse stakeholders, and for technical execution of the observing system. SEACOOS focused on the latter component, and defined 4 major components to the observing system: an observing component (that collects observations), a modeling and analysis component, a data management component, and an outreach and education component. Activities in these components were distributed geographically and were coordinated through a program management office. The distributed nature of the program made communications difficult and a well-staffed program office was identified as the best mechanism to ensure coordination among all funded participants. Planning activities were vital to promoting common goals and objectives and a shared vision for implementation and strategy.

Meaningful stakeholder engagement proved to be a challenge. The breadth of issues that can be addressed by an observing system translates into a host of potential stakeholders. Because of limited resources and the long lead times required for implementation of observing systems care must be exercised up front in defining an initial set of priorities and a realistic timeline for addressing the priorities. Doing so permits one to identify a subset of stakeholders to actively engage and to develop a strategy for managing expectations across the stakeholder base. It was found that stakeholders want to engage early and often and have a say in how the observing system is structured and operates. Attention to coordinating product development and user engagement can avoid stakeholder burnout from lack of progress in their area of interest.

The observing component must utilize a variety of tools. There is considerable pressure to provide (in the SEACOOS case, real-time) sustained observations, and the cost of doing so, in terms of personnel and project funds, was found to be the biggest single expense. As the number of observing assets and scope of topics being addressed increases the resource demand increases rapidly. Realism about availability of support systems (ships, communications, power systems), personnel availability and the need for spares is important when developing an implementation plan and in the budgeting process. Both factor into managing expectations, for the project team as well as for stakeholders.

Data management was considered the least understood aspect of the observing system when SEACOOS began. Significant progress in creating and operating a distributed information system was accomplished but it consumed roughly 30% of the SEACOOS budget (it is worth noting that the program was highly leveraged, with 1-2 times as much funding coming from other sources to support elements of the system, so that if all costs were considered, data management would be 10-20% of the total budget). A team of technical staff from the participating institutions developed a pragmatic strategy for data sharing and distribution. The strategy relied on adopting or developing standards that could be implemented using open-source technology in a way that did not interfere with existing (legacy) data management practices. For SEACOOS a by-variable approach to growing the content of the data management system worked well. Care in implementation is important to maintain flexibility in the face of rapidly changing technology and possible changes in priorities for the observing system as a whole.

For AON, it is important to recognize the implications of being stakeholder-driven, or even stakeholder-aware. SEACOOS ultimately could not succeed as a regional component of IOOS because it’s governance system was not inclusive of stakeholders. Addressing stakeholder needs is not a topic to be taken lightly; it may be wise to envision a long-term strategy in which the observing system begins as a science-driven enterprise but that seeks to transition to a more inclusive and societally-relevant enterprise as it matures.

SEACOOS found system design to be a balance between scientific understanding, model guidance and practical constraints. Each of these inputs have strengths and weaknesses that must be considered in the design process. Being realistic about time frames of achieving a given level of functionality is critically important. The planning process should result in a clear statement of objectives and the build-out timeline and must be undertaken as a group effort to ensure buy-in of all the participants. Do not under-estimate the importance of the data management/information management system, it will ultimately be the way in which the benefit of the observing system is realized.

The Long Term Ecological Research Network

John Vande Castle (*LTER Network Office, Department of Biology, University of New Mexico)*

John Vande Castle gave a presentation about the history of the Long Term Ecological Research (LTER) Network, a program of the National Science Foundation which started in 1980. The LTER Network comprises 26 research sites, selected for the excellence of the research conducted at each site as well as the potential of the site for long-term studies. The LTER Network now comprises 26 research sites plus a central Network Office.

When the program started it was unique in long-term dedication of Federal funds for basic research, with 6 year awards, anticipated renewals and a multi-decadal planning horizon. The Network was built on existing infrastructure (e.g., USFS; USDA; TNC; NWR) and is a model of a bottom-up research program with a largely autonomous site-based science focus. The Network's first decadal review in 1990 focused on expansion of sites and the Network as a whole while the second decadal review lead to a focus on Network level science and an emphasis on data and information management.

In 2007 work towards a LTER Decadal Strategic Plan resulted in the publication of a document titled "Integrative Science for Society and the Environment" which provides a framework for full integration of social and ecological sciences within the LTER program. This effort promises to fundamentally change the function of the future LTER program from being a Network of individual sites, to a functional integrative Network focusing on cross-site multidisciplinary science.

A current focus of the LTER Network is to increase the pace of research and data synthesis across the Network in a framework of new research and governance initiatives. This is being accomplished through regular meetings of the full LTER Science Council, the governing body of the LTER Network formed by all lead principal investigators of LTER sties as well as Triennial LTER All Scientists Meetings, individual LTER working groups and other LTER Network planning efforts. More information can be found on the LTER Website at www.lternet.edu.

The Present Arctic Observing Network: Gaps, Needs, Priorities

John Walsh (*International Arctic Research Center, University of Alaska Fairbanks*)

SEARCH Understanding Change Panel: J. Walsh, M. Berman, J. Overland, A. Proshutinsky, M. Serreze, J. Shimel, K. Arrigo, J. Randerson

The SEARCH Understanding Change Panel (UCP) was charged in mid-2009 with making a preliminary assessment of the present Arctic Observing Network (AON) in terms of gaps and needs, as well as priorities for addressing the identified gaps. In keeping with the panel's primary function in SEARCH, assessment was driven by considerations of present impediments to improved understanding of Arctic change. The identification of recently emergent (post-2005) science issues was included among the panel's charge. The panel drew upon existing documents, including the SEARCH Implementation Plan (ARCUS, 2005), the 2008 Workshop Report on Arctic Observation Integration, and the draft Science Plan of the International Study of Arctic Change (ISAC). The panel submitted its draft report in early November, 2009. While the panel represented a diversity of research subfields and sought input from colleagues, the panel's report is by not intended to be comprehensive; rather, it is a viewed as a starting point for more rigorous and complete assessments of the AON in the context of the driving science questions.

The panel's assessment of needs was organized into several spheres: (1) marine changes, (2) atmospheric changes, (3) terrestrial changes, (4) Arctic-global connections, and (5) the integration of information and knowledge networks. There is inevitably some overlap among the gaps and needs of these spheres, and there are some topics that fell between the spheres. Nevertheless, we follow this organizational framework in the following summary.

Gaps in the marine sphere were highlighted through the present difficulty in answering several fundamental questions concerning Arctic change: For example, are changes in Arctic marine mammal and fish distributions outside their ranges of natural variability? The recent need to inform decisions on species status (endangered, threatened, etc.) has pointed to our incomplete information on polar bears, seals, walrus and other marine mammals. Management of fisheries (e.g., pollock) also requires information on populations. In addition to quantitative information on distributions and their variations, there is a need for marine ecosystem information to enable explanations of variations and changes of the populations. A second example of a driving science question is: What is happening with Arctic sea ice? The answer to this question requires ocean observations that capture the subsurface drivers of sea ice changes, enabling an evaluation of the relative importance of atmospheric and oceanic forcing of sea ice. A major obstacle at this time is the general lack of coordination of ocean observations and field programs in the Arctic. A more systematic science-driven approach to Arctic Ocean observations is needed. A third example is: Are carbon pathways in the Arctic undergoing consequential changes? Systematic Arctic ocean measurements, especially in the shelf seas, are needed to answer this question, which has taken on added importance in the past few years as ocean acidification has emerged as a threat to marine ecosystems.

In the Arctic atmosphere, a key question that has gained prominence since the 2005 Implementation Plan is: What are the roles of black carbon and other aerosols in Arctic change? It is not known whether aerosols are contributing to the larger observational trends than are simulated by models, nor whether Arctic trends have been affected by “solar brightening” that may involve aerosols and/or clouds. There is a need for systematic monitoring of aerosols in the atmosphere and in snow.

In the terrestrial sphere, a key question is: What are the drivers of recent changes such as the increases of river discharge, wildfires and vegetative “greenness”? Potentially important roles of evaoptranspiration and snow (water equivalent) are largely unknown because these variables have not been monitored adequately to enable evaluation of their changes in the context of the broader Arctic system.

With regard to Arctic-global connections, a key question is: How is the Arctic contributing to global sea level rise? The answer requires a determination of the relative roles of Greenland and smaller glaciers/ice caps in discharging fresh water. The poor sampling network for glacier mass balance is a hindrance in this regard. A second important question is: How are mid-latitude climate and the global heat budget influenced by the loss of Arctic ice? The corresponding observational need is for a measurement system to quantify and track the atmosphere’s gain of heat (and moisture) from the Arctic surface.

The panel reiterated the long-recognized need for integration of community-industry observing networks and/or ecological knowledge cooperatives. Such integration should encompass industry, local communities, agencies and other information sources. A specific example is Arctic marine shipping activity, for which there is no centralized base of information accessible to researchers and other users.

Finally, the UCP report notes that other gaps and needs were mentioned in its deliberations, although these needs are not highlighted above in association with key science driving questions. The other gaps with observational needs are the Arctic upper atmosphere, surface albedo in the Arctic, atmospheric water vapor (in which changes can lead to high-leverage feedbacks to warming), and a high-resolution (~5 meter) panarctic Digital Elevation Map that would allow resolution of topographic slopes at scales relevant to hydrology, vegetation and permafrost.

Arctic Atmospheric Reanalysis

Keith M. Hines (*Polar Meteorology Group, Byrd Polar Research Center, Ohio State University*)

The presentation on Arctic atmospheric reanalysis is focuses on the Arctic System Reanalysis (ASR, http://polarmet.osu.edu/PolarMet/ASR.html) project. The ASR is an IPY project through NSF support and a SEARCH project through NOAA start-up funding. Reanalysis and data assimilation can be viewed as an optimal blend of modeling and observations. The chief deliverable for the ASR is a high-resolution description in space (10-km) and time (3 h) of the atmosphere-sea ice-land surface system of the Arctic. The atmosphere and land surface behavior are modeled with the Polar WRF mesoscale atmospheric model and the Noah land surface model, respectively. Atmospheric data assimilation is performed with WRF-3DVar. Ocean conditions, including sea ice thickness, albedo and snow cover are specified with a high degree of realism, with input from remote sensing and a new sea ice age dataset. The initial ASR will cover the EOS years 2000-2010. The institutions collaborating on the project are the Ohio State University's Byrd Polar Research Center, the WRF-Var group at NCAR, along with the Universities of Colorado and Illinois. The NCAR Research Applications Laboratory also contributes Noah LSM optimization for the Arctic and high-resolution land data assimilation. The ASR reconstructs the Arctic system's state, thereby serving as a state-of-the-art synthesis tool for assessing Arctic climate variability and monitoring Arctic change. As such, it responds directly to needs identified in the Implementation Plan for SEARCH. Gridded fields from the ASR, such as temperature, radiation and winds, can serve as drivers for coupled ice-ocean, land surface and other models.

The ASR is relevant for the AON as it ingests historical data streams along with measurements of the physical components. Obviously, the ASR needs data for input, quality control and verification. It is important to the have multiple sources of data readily available and in user-friendly format. Importantly, the ASR can serve as a vehicle for evaluating the relative and collective importance of Arctic data. Observing System Experiments (OSEs) and Observing System Simulation Experiments (OSSEs) can be conducted with the ASR's data assimilation procedures for the atmosphere and land surface. A wide variety of data are being incorporated into the ASR including, for example, in-situ land sites, ship reports, aircraft reports, buoys and rawinsondes, along with many remote sensing fields, especially from polar-orbiting satellites. Experiments can be used to guide the development of the AON through identifying observational needs and avoiding redundancies where possible. For example optimal siting of comprehensive and expensive systems could be explored. OSSEs can provide quantitative information on the value of new observation types in the Arctic. For example optimal dropsonde sampling can be evaluated. The ASR is currently conducting a prototype data assimilation for summer 2007 to fall 2008. Thus the components are already in place for conducting numerical experiments contributing to the optimizing of the Arctic Observing Network.

Transition from Research to Operations: Lessons from NOAA's TAO Array

Michael J. McPhaden (*Pacific Marine Environmental Laboratory, NOAA*)

This presentation describes the transition of NOAA's Tropical Atmosphere Ocean (TAO) array from research to operations. TAO was developed over a 10-year period (1985-94) as part of the international Tropical Atmosphere Global Ocean (TOGA) program under leadership of the NOAA's Pacific Marine Environmental Laboratory (PMEL). The purpose of the array was to provide data in real-time for improved detection, understanding, and prediction of El Nino and the Southern Oscillation (ENSO).

PMEL's management of the TAO array provided excellent service to both the research and operational forecasting communities on an ongoing basis as determined by an international review in 2001. Nonetheless, in 2002, the then new Administrator of NOAA mandated the transfer of TAO management responsibility from PMEL to NOAA's National Data Buoy Center (NDBC), which is a part of NOAA's National Weather Service responsible for operational maintenance of coastal and marine weather buoys. The premise was that TAO was effectively operational and it should therefore be maintained by an operational branch of NOAA rather than by a research lab. In principle, this transfer of management responsibility was supposed to ensure that TAO operations would be more cost-effective and stably supported over the long term.

The transition was mandated to take place over a 3-year period from 2005 to 2007. The transition however is still underway and the National Weather Service now estimates it will not be complete until 2015. In the meantime, operating costs have gone up much faster than inflation and array performance in terms of data return has declined. Fundamentally, the TAO transition has failed to achieve its planned objectives because NOAA Headquarters formulated its decision based on the unfounded expectation that transferring the system from PMEL to NDBC would be cheap and easy, despite advice to the contrary. As a result, the transition effort was not properly funded, did not take adequately take into account the complexity of the technology that needed to be transferred, and did not seriously consider proposed alternative management strategies that would have been more economical, efficient, and rapid to implement.

Climate is a long term problem, so the observations that underpin our ability to assess the state of the climate system and predict its future evolution require long term institutional support. Though past experience provides no simple formulas for how to successfully sustain ocean observational efforts for climate over decades, we can state as a guiding principle that the research community should be an active participant in the management of these observing systems because new discoveries constantly shape measurement requirements. Another key principle is that climate observations should be managed within the context of an end-to-end system that includes data collection, dynamic modeling, forecasting, and the provision of climate information and services to society. The recently proposed establishment of an international framework for climate services may thus provide a new approach to sustain climate observing systems in the oceans for the 21st century, in addition to other approaches that may prove to be viable for particular observing system components.

Ecosystem Services

Terry Chapin (*Institute of Arctic Biology, University of Alaska Fairbanks*)

Ecosystem services are the benefits that society derives from ecosystems. These include **supporting services**, which are the fundamental ecological processes that sustain ecosystem functioning, **provisioning services** (or **ecosystem goods**), which are products of ecosystems that are directly harvested by society; **regulating services** that influence society through interactions among ecosystems in a landscape; and **cultural services**, which are non-material benefits that are important to society's well-being. Ecosystem services are a potentially useful construct for AON because they provide an explicit bridge between the biophysical environment and the needs of society at local to global scales. Regulating services, for example, include albedo and carbon storage that determine how arctic change influences the global climate system and therefore the well-being of society globally. Caribou or seals are provisioning services that meet important nutritional needs of arctic indigenous people as well as providing important cultural ties to the land and sea.

Ecosystem services provide several opportunities to inform and improve AON project design. First, they identify the parameters that are of particular concern to society, both globally and locally. Second, they provide a framework for dialogue with stakeholders about (1) which arctic changes are of particular concern (communication from stakeholders to scientists) and (2) the information about arctic change that is of particular interest and importance to stakeholders. In this way, ecosystem services identify the topics and provide a venue for science-stakeholder dialogue. In addition, ecosystem services open the door to potential engagement of stakeholders in the design and implementation of AON. Indigenous residents, for example, are keen observers of their environment because they depend on this knowledge for their survival. They have generally been the first group of observers to describe incipient changes that have widespread scientific importance, including changes in animal abundances, thickness of river ice, river discharge, wetland drying, river channel geomorphology, and riparian disturbance. This opens the door to innovative opportunities for citizen science in which indigenous residents of the arctic identify incipient trends that can be both an integral component of AON and inform the evolution of its design, as new patterns of change emerge.

Observing System Simulation Experiments and Biophysical Process Studies Related to the Predictability of Land-Ocean Interactions

Villy Kourafalou (*University of Miami/RSMAS*)

The topographic complexity of the Arctic Ocean and marginal seas has great implications on land-sea interactions. One should distinguish among:

(a) the "local" problem, which dominates on the shelf areas and controls the initial development of the river plumes; and

(b) the "global" problem, which involves both shelf and deep regions and controls the transport and fate of the riverine low salinity waters and associated nutrients and sediments.

In order to properly address the development and evolution of river plumes on the Arctic shelves and the subsequent offshore removal of riverine waters and materials toward the Arctic interior, the AON should resolve circulation and transport on the shelf, as well as shelf break processes, such as boundary currents, fronts and eddies. Processes that are particular to the Arctic, such as the sudden flood of riverine waters after the winter ice blocking and the difference in cross-marginal transport for the wide vs. the narrow Arctic shelves should also be considered. This would require targeted theoretical and modeling studies to better understand the dynamics that control the major pathways of riverine waters and the exchanges with the Arctic interior and with the adjacent basins in the Pacific and Atlantic oceans.

A relevant example of interaction between a major river and a basin interior was presented. The Mississippi River influences not only the adjacent shelf areas, but also the Gulf of Mexico interior and even remote areas, through advection of riverine waters along the large scale Gulf Stream system. This example was used to elucidate that the predictability of Mississippi pathways is connected to the predictability of the northward extension of the Loop Current (LC) in the Gulf of Mexico, which is a complex process that involves the proper representation of the associated eddy field. Observing System Simulation Experiments (OSSEs) have been employed to determine an optimal observing system to provide data suitable to assimilate in regional models. The methodology follows the guidelines from the OSSE workshop in Miami (2008, organized by NOAA/AOML and UM/RSMAS, see OSSE procedure bullets on the AON workshop presentation by V. Kourafalou).

As an OSSE methodology highlight, an ensemble of simulations for the study of model errors and observation array design were presented. The performed non-assimilative "nature run" is the regional Gulf of Mexico Hybrid Coordinate Ocean Model (GoM-HYCOM; http://coastalmodleing.rsmas.miami.edu). The LC was shown to progressively extend toward the northern Gulf, and eventually shed warm, massive eddies that drift westward, in satisfactory agreement with observations in terms of dynamics and hydrography. The mechanisms by which the LC develops and sheds an eddy are an active research topic. The transport and the vorticity of the incoming flow, through the Yucatan Channel, seem to play an important role in the LC dynamics (Ezer et al., 2003, Candela et al., 2002, Oey, 2003). Therefore, the simulated LC should be highly sensitive to the boundary conditions feeding the GoM model. Consequently, a 40 member ensemble of simulations was performed to study the sensitivity of the model to incoming flows through the boundaries. Based on Monte-Carlo methods, this ensemble was generated by randomly perturbing the incoming currents along the boundaries, adding a random linear combination of pre-calculated Empirical Orthogonal Functions (EOFs) of these currents during the study period. This allows stressing or relaxing patterns that are already present in the forcing field, thus leading to realistically perturbed forcing. Statistics from this ensemble provide a proxy for the model error statistics associated to uncertainties in the boundary currents, as in the Ensemble Kalman Filter (Evensen, 1994). The results showed that inside the GoM, the model ensemble standard deviation first grows at the edge of the LC, especially on the locations of cyclonic eddies that surround it. Then the overall error growth tends to slow in amplitude, in association with a spreading of errors patches, still surrounding the LC and the associated eddy. This is related to the difference among simulations in eddy shedding (some do not even shed any eddies), illustrating the non-linear dynamics of the LC. In addition, the ensemble study supports the hypothesis that the variability in LC ring shedding is closely associated to the eddy field around the mean current, suggesting that observations should monitor their development and evolution.

The ensemble of simulations also provides a way of studying the performances of various simulated observations networks, using the Representer Spectra Matrix technique (Le Hénaff et al., 2009). This method is based on the normalization of the model error covariance by the prescribed observation error covariance of the considered network. An eigenvalue decomposition of the resulting matrix determines the number of “detected” eigenmodes, defined as those whose eigenvalues are larger than one. It is then possible to evaluate the relative performances of several networks by comparing the number of modes detected by each network, but also to evaluate the qualitative impact of those modes through the study of the corresponding eigenvectors. In that respect, the modal representers provide a projection in the model space of the detected modes. This part of the analysis is essential in determining the relevance of the eigenvalues hierarchy. For example, it is useful for discarding spurious modes. It also allows determining the typical scales associated with the detected mode, thus checking if the processes expected to be measured by the network are identified. Depending on the end-user expectations, this analysis may favor one of the considered networks.

In the context of OSSEs, the ensemble statistics provide a model error covariance matrix that can be used in the assimilation process, or at least referred to. Moreover the use of the RMS technique allows reducing the number of networks to actually test, by discarding obviously less favorable ones and optimizing the design of the array. Therefore, this method can be highly valuable in the process of the AON observation array design assessment.

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Satellite Remote Sensing and the AON

Walt Meier (*National Snow and Ice Data Center, University of Colorado*)

Satellite remote sensing will be a key complement to the Arctic Observing Network. Satellite sensors have distinct advantages over in situ systems. First and foremost, they can acquire data over a broad region at regular intervals. Once successfully launched and turned on in orbit, sensors generally provide reliable data for several years without concerns about weather or other factors. They can accumulate a far more spatially dense data stream over many years. Over several years, through a series of sensor, a long-term, consistent climate record can be built up.

However, satellite-borne sensors also have distinct limitations. First, the spatial resolution is relatively low – on the order of 100s of meters to 10s of kilometers. Thus small-scale details, such as melt pond charactistics, cannot be determined except in a spatially-averaged sense. Acquisition of data requires a region to be within the sensors field of view (swath width), which at best generally occurs a few times a day (even in the high polar regions where polar orbiters can achieve numerous overlaps) and may be able to image a region only once per several days (e.g., at lower levels and/or for sensors with narrower swath widths).

Many cryospheric features can be discriminated in wide range of the electromagnetic spectrum. This potentially allows multiple sensor types to be used to obtain combined information. However, the relevant physical quantities are normally not directly observed by the sensors, but rather must be inverted from electromagnetic energy (e.g., radiance, brightness temperature). There can be substantial ambiguity in the observed EM energy and there may not be a unique inversion to the desired physical parameter. There is also uncertainty in remotely sensed fields due to spatial resolution, temporal sampling, algorithm parameterizations, surface/sub-surface/atmosphere effects on the retrieved energy.

One of the most notable Arctic satellite remote sensing products is sea ice extent and concentration fields derived from passive microwave imagery. There is now a continuous, consistent 31+ year record of sea ice cover and the observed decline is one the iconic indicators of warming. However, over the years several algorithms have been developed. Each has differing advantages and limitations, but to date, none has proven to be clearly superior and there are dedicated user groups for several of the algorithm products. This results in potentially inconsistent values when intercomparing products. Passive microwave imagery is also useful for snow water equivalent, soil moisture, sea ice age via Lagrangian motion tracking.

Visible and infrared imagery provide a wealth of information on sea ice, snow extent, glaciers/ice sheets, vegetation, sea surface temperature, primary productivity, clouds, and other atmospheric parameters. Visible channels are limited by winter darkness and, for surface features, clouds. Infrared channels are also limited by clouds for surface features; also during summer, surface types can be difficult to distinguish due to near-freezing temperatures through much of the Arctic.

Scatterometry, active microwave imaging, can yield valuable information on sea ice type, sea ice motion, melt state of ice, as well as ocean winds. Synthetic aperture radar can provide high resolute, all-sky, imagery of sea ice and other surface features. However, coverage is limited, data access can be expensive, and the data is complex and can be difficult to interpret.

A key question that needs to be answered by an Arctic Observing Network is the ice mass balance, both on land and in the ocean. However, these observations are difficult to get from surface and near-surface instruments because such broad spatial coverage is required. However, new sensors have been launched in the last several years that have significantly improved estimates. These include polar-orbiting altimeters than derived ice sheet thickness and sea ice freeboard, and gravity observers that observe the bulk water mass budget for ice sheets and hydrological cycles.

Such satellite-borne remote sensing instruments can complement in situ measurements by filling in gaps in spatial coverage, integrating from point measurements to large-scale model grid cells. This is important because key Arctic processes happen at all scales. Linking these disparate types scales of observations is not trivial and will require the development of sophisticated data fusion/assimilation methods.

<u>List of selected Arctic remote sensing resources</u>

<u>Passive microwave sea ice, snow water equivalent, soil moisture:</u>
Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR)
DMSP Special Sensor Microwave/Imager (SSM/I)
NASA Earth Observing System Advanced Microwave Scanning Radiometer (AMSR-E)
National Snow and Ice Data Center (http://nsidc.org)

<u>Active microwave scatterometer sea ice type, winds:</u>
NASA QuickScat Seawinds
NASA Jet Propulsion Lab (http://winds.jpl.nasa.gov)

<u>Visible/infrared imagery:</u>
NOAA Advanced Very High Resolution Radiometer (AVHRR)
NASA Moderate Resolution Imaging Spectroradiometer (MODIS)
National Snow and Ice Data Center (http://nsidc.org)

<u>Altimeter:</u>
NASA Ice, Cloud, Land Elevation Satellite (ICESat)
National Snow and Ice Data Center (http://nsidc.org)

<u>Gravity:</u>
NASA Gravity Recovery and Climate Experiment (GRACE)
NASA Jet Propulsion Lab (http://grace.jpl.nasa.gov/)

The Argo Float Program - A case study for an observing system

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The Argo float program is one of the flagship components of the ocean observing system. The way that this program was set up, the international collaboration, and its management, data access, and strong connection with end users all serve as excellent prototypes for the Arctic Observing Network. The scientific objectives for Argo were formulated by US Scientists in 1998 and a strong partnership with senior NOAA administrators was forged to articulate and promote it.

From the outset, this was an international program with only 50% of the resources provided by US funding. It also was closely linked to other global, satellite observing system, particularly the JASON and GLACE missions. Clearly stated short-term goals, 300 global floats and a focus on seasonal to inter-annual variability on 1000 km scales were also critical to the successful implementation of this program. Close collaboration between the Argo community and the forward and inverse modeling community has significantly improved the data quality and identified systematic errors, although, at times, at the expense of incorrect interpretations of the climate signal.

International coordination is carried out through an international steering team and an international information center. Territorial concerns were addressed, but not completely eliminated, through an IOC-UNESCO (Intergovernmental Oceanographic Commission – United Nations Education, Scientific and Cultural Organization) resolution.

The data is available in real-time over the GTS system and from global data acquisition centers at a very modest fraction of the overall cost of the program. The data distribution system takes advantage of the existing climate data systems and resources developed under the Global Ocean Data Assimilation Experiment. Delayed mode quality control is carried out by float providers using agreed-upon, best-practice methods.

The success of the Argo float program can be attributed to the continued, dedicated commitment of an international group of oceanographers who guide the program based on the clear scientific objectives of the program.

Adjoint data assimilation and quantitative network design

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The coupled sea-ice ocean model NAOSIM (North Atlantic/Arctic Ocean Sea Ice-ocean Model) has been used frequently for studies of the sea ice and ocean in the North Atlantic and Arctic Ocean. NAOSIM was developed at the Alfred Wegener Institute.

Within the EU-FP6-project DAMOCLES the variational data assimilation system NAOSIMDAS has been built around NAOSIM. NAOSIMDAS is still in a test phase. Currently, a version with about 50km horizontal resolution and with 20 unevenly spaced vertical levels is employed. The Model domain consists of the North Atlantic north of about 50N and the Arctic Ocean. A time step of 30 min is used for the sea ice model and the ocean model. Daily NCEP reanalysis forcing is used in the presented results. In forthcoming assimilations NCEP forcing will be replaced, either by the Japanese atmospherics reanalysis (JRA25) or by ERA interim, a new reanalysis of the European Center for Medium-range Weather Forecast.

Automated differentiation (AD) is explained briefly. A numerical model is a (rather complex) concatenation of code statements defined by elementary functions (+,/,**,sin, exp, etc.). Input to the model is a (very large) vector of model parameters, and initial and boundary conditions. Output is some target quantity of relevance. In the case of data assimilation the target quantity is a cost function (observation-model misfit), but is can be any quantity which can be calculated in the model. For a sensitivity study of the September 2007 sea ice conditions the target quantity was chosen to be the seaice area at the last two weeks of September 2007 (Kauker et al, 2009). Because the model consists of a concatenation of elementary functions the derivative of y with respect to m can be done automatically.

The automated differentiation tool TAF is used for the generation of the tangent linear and the adjoint code. For the tangent linear code the chain rule is applied in forward direction and consists of a concatenation of the local Jacobian of the elementary functions. The costs to calculate the derivative depends on the length of the input vector m. If one applies the chain rule in reverse direction (adjoint) the costs of the evaluation of the gradient are independent to the length of the input vector (but depends on the length of the target quantity which is normally very low dimensional). The reversal of the control flow complicates the coding dramatically.

In a variational data assimilation system a cost function is minimized by variating the initial and boundary conditions, and the model parameters (control vector). The cost function has two parts: the observation-model misfit and a prior term which describes the deviation of the control vector from it's a priori values. Both expressions are weighted by a matrix of uncertainties of the observation and the control vector, respectively. The uncertainties have to be deduced carefully.

Efficient minimization algorithms use the cost function and the gradient of th cost function in an iterative procedure. Typically the prior value is used as starting point of the iteration. The gradient is helpful as it always points uphill. The adjoint is used to provide the gradient efficiently. Smart gradient algorithms use an approximation of the Hessian.

Variational assimilation systems provides a model trajectory (a model history of model fields) that is consistent with the model dynamics and the available observational data streams (can be unevenly distributed in space and time).

The performance of NAOSIMDAS is presented by two test application: the Sea Ice Outlook 2009 and a two years assimilation of IPY data.

For the Sea Ice Outlook 2009 two sets of outlook have been prepared. One is performed in the same manner than last year and one uses with NAOSIMDAS optimized initial states (see http://www.arcus.org/search/seaiceoutlook June, July, and August reports). Assimilated data are ocean temperature and salinity from the WODB05, ITPs (WHOI web site), Argo floats (CORIOLIS web site) plus additional T and S from recent Arctic cruises, ice concentration and ice drift (April and May) from OSI-SAF, and EM-Bird ice thickness from the Polar 5 expedition (AWI) along the Canadian/Alaskan 'coast'. For the August ensemble outlook (initialized at July 11th) without optimized initial state ('free run') we got an ensemble mean prediction (most likely value) of 5.02 million km2. However we applied a bias correction of 0.60 million km2. This bias correction was calculated by comparing the September 2007 and 2008 modeled September sea-ice extend with the values estimated by NSIDC. Especially north of the Laptev Sea the model tends to underestimate the ice conditions. Accordingly, the uncorrected value for the free run is 4.42 million km2. The corresponding value for the ensemble forecast with an optimized initial state is 4.72 million km2. The 'observed' value for 2009 was 5.36 million km2, i.e. both forecasts underrate, although the observed value lies within one standard deviation (0.39 million km2) uncertainty in case of the free run. Slide 10 shows the difference of the mean July ice thickness for the free run (left) and the optimized run (right). The optimized run shows larger ice thickness north of the Laptev Sea and less ice in the Beaufort Sea. This is archived myvariating mainly the wind stress (not shown) and the initial ice thickness and snow thickness

A two years assimilation of IPY data from 2006 to 2008. Especially in September it can be seen that the ice edge follows much closer the observation.

Optimal Network design. Assume you have minimized some costfunction. After some algebra it can be shown that the uncertainties on a (future) target quantity depends on the (inverse of) the second order derivative of the costfunction (approximation of parameter uncertainties) and a linearizion of the model. This can be used for optimal network design.

Example for optimal network design: CCDAS is a variational data assimilation system around the terrestrial biosphere model (BETHY) that diagnoses carbon dioxide fluxes from vegetation index fields coupled to an atmospheric transport model TM2(3). Target quantities are the net primary production (NPP) and the net ecosystem production (NEP).

The design of a very simple network which consist only of two flask measurements at Mauna Loa and at the South Pole (network 1).

For network 2 a flask measurement in the Nordic Sea is added.

All uncertainties of the target quantities (NPP and NEP) are reduced for network 2, i.e. network 2 is favorable for all sectors (Europe, Russia, Brazil).

Conclusions: We think that quantitative network design as sketched here is feasible and can be used in the Arctic. However, quantitative network design depends on the model employed. Sea iceocean models for which an adjoint exist are NAOSIM and MITGCM. These models are candidates for optimal network design studies. Optimal (or quantitative) network design has to operated jointly by observers and modelers.

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NEON Overview and Observing System Simulation Experiments

Dave Schimel (*National Ecological Observatory Network*)

NEON's mission is to improve understanding and forecasting of ecological change at continental scales. To achieve this end, NEON has been designed as a continental-scale platform for researchers interested in understanding and forecasting the impacts on ecology of climate change, land use change, and invasive species (Figure A1). NEON's open access approach to its data and information products will enable scientists, educators, planners, and decision makers to map, understand, and predict primary effects of humans on the natural world and effectively address critical ecological questions and issues.

Continental-Scale Design

NEON's continental sampling design is based on domains, partitioning the continent defined by a statistical analysis using national data sets for ecoclimatic variables. The statistical design is based upon algorithms for multivariate geographic clustering (MGC) (Hargrove and Hoffman, 1999, 2004). In MGC, clusters are formed so that each cluster contains roughly the same fraction of the total ecoclimatic variance, and so that the centroids of the clusters lie roughly equally far apart in ecoclimatic space. Thus, selecting one core site per domain allows NEON to sample within the ecoclimatic variability of the U.S. in a roughly uniform way. These sites will form a long-term baseline of observation in minimally managed, wildland systems. They also are primary locations for studies of climate impacts and reference sites for studies of other causes of change and stressors. Additional sites, called relocatable sites, probe aspects of continental scale ecology through comparisons of managed relocatable and unmanaged core sites, gradients of site along transport flowpaths and other question-driven studies.

Analysis

NEON is an observing system, but investments at this scale must be guided by quantitative analysis and careful evaluation of tradeoffs. Ecological forecasting, modeling, and analysis activities are central to the NEON process. The science vision that led to NEON's conception involved advancing the field's ability to quantitatively predict, not just to develop retroactive explanations (NRC, 2003). Aspects of ecological forecasting such as forecasts for invasive species and forecasting the biological carbon budget illustrate two potential applications of NEON information. Data collected through NEON and used for analysis and forecasts could contribute to an estimate of the U.S. biological carbon budget, and the attribution of fluxes to specific ecological mechanisms.

NEON and non-NEON data provide both detailed site-based process information and spatial measures of pattern and process. These data will be integrated into a land surface model that incorporates both biophysical and biological processes integrated with observations over time using data assimilation schemes such as the ensemble Kalman filter or ensemble Kalman smoother. This approach will produce estimates of ecosystem-atmosphere fluxes of CO2 that can be compared at regional scales to similar estimates deduced from atmospheric concentration gradients using a system such as NOAA's CarbonTracker.

Modeling and forecasting are important ways of learning about the behavior of complex systems, when the system behavior depends on the exact state of the system. In such a system, the outcome of an experiment, for example, will depend on when that experiment is done. Even a model developed over a single forecast cycle explores a small subregion of the possible outcomes, whereas models that are developed iteratively through repeated updating can characterize a much larger region of the solution space, complementing experiments. Iterative/cyclic forecasting can reveal patterns of error that are not evident in a single forecast cycle. Sequential evaluation of the model against data, along with careful consideration and modeling of the error structure, can detect when these changes are large enough to affect the model's prediction and will provide insight into processes that only become significant at longer time scales (Sacks et al., 2007). This forecasting process should also guide the design and future manipulative experiments. Ecological forecasting requires a research strategy including long-term observations and experiments, such as NEON provides through a 10-year aquatic experiment. A single dedicated researcher may generate a few time series suitable for long-term forecasting studies, but these will inevitably fall short of enabling forecasting at the continental scale.

The advent of continental-scale research will lead to changes in ecological science itself, including its related infrastructure, culture, and training. NEON provides data and infrastructure for decadal and continental-scale science, and will join an emerging global network of environmental observatories. Together, these facilities will provide information on the causes and consequences of environmental change.

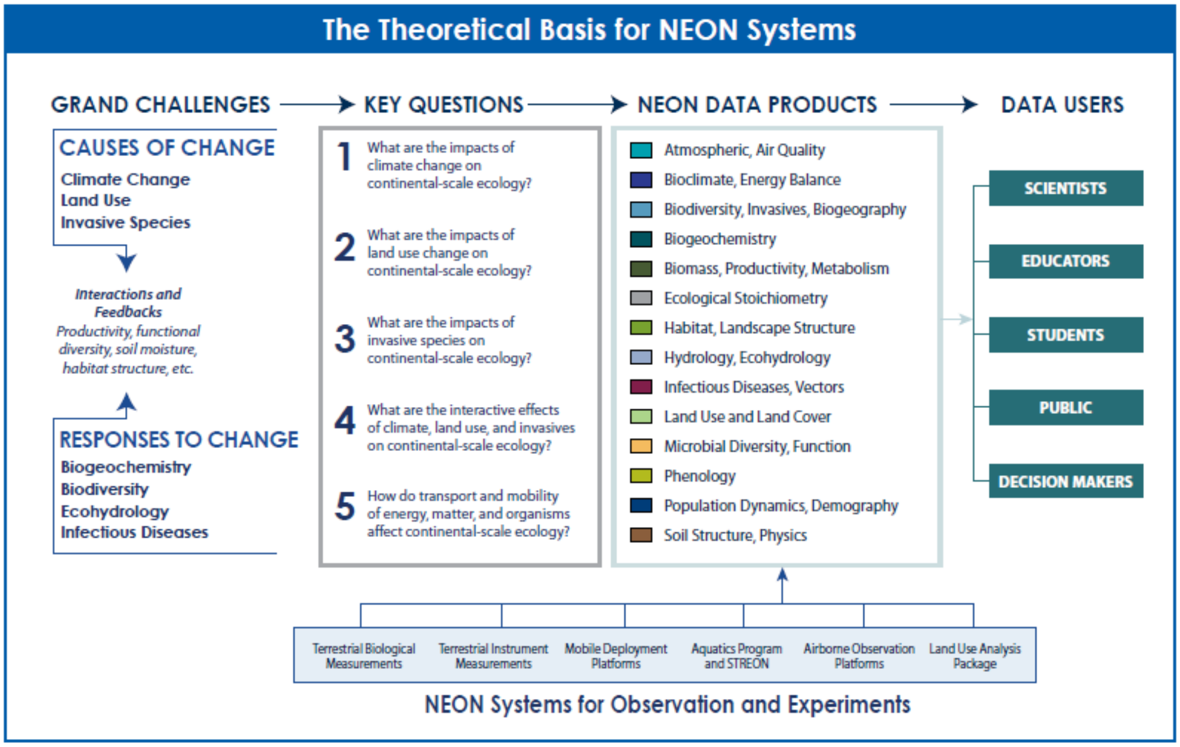

Figure A1. How the Grand Challenges translate into the five key questions and then into the data products and the required NEON systems for observation (Source: NEON 2011 Science Strategy)

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Overview of outcomes from Ocean Observing 2009 conference and white papers

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The 2009 Arctic Observing Network meeting focused on issues surrounding network design and optimization using: (i) plenary talks that drew examples of network design both from the Arctic and mid-latitude science communities, (ii) working groups tasked to review design issues and develop recommendations, and (iii) plenary discussions.

SEARCH science and implementation plans identify and prioritize questions. However, in the short period between the release of these foundation documents and the initial build-out of the AON, Arctic environmental change and advances in scientific understanding of the Arctic system have revealed additional high-priority issues. Examples of issues that were not prominent during the initial formulation of SEARCH plans include ocean acidification, ocean-ice sheet dynamics and rapid changes in sea ice extent. This emphasizes the need for an agile AON design that is capable of continually evolving in response to advances in understanding, changes in the Arctic environment and the availability of new observational technologies.

AON design and optimization efforts inherently depend on the specific science questions, goals and data needs of the network's end-users. The broad diversity of goals makes AON optimization challenging. For example, the network could be designed and optimized around quantifying Arctic change, around improving model forecast accuracy and hindcast fidelity, or around stakeholder needs for specific data products. Each of these goals implies different design specifications and performance metrics, and could drive divergent design choices. Ultimately, any design and optimization effort must begin with a careful articulation of network goals and the specification of quantitative performance targets, around which design decisions can then be made.

Readiness for undertaking formal design efforts varies widely across the disciplinary components of the existing AON. Currently, AON design rests with PI groups who employ a mix of results from previous observation, expectations from theory and existing understanding to prioritize measurements and define sampling schemes. For some disciplines, numerical models can provide quantitative assessment of measurement priorities and array designs, but such assessments are only as reliable as the models upon which they are based. Closely specifying the what/how/where/when of network elements will likely not be as productive as developing broader design specifications (i.e. the ability to quantify variables to within prescribed uncertainties). Other disciplines are still wrestling with defining key science questions, and will require additional time and research before meaningful design and optimization efforts will be possible. There exists a wide range of possible approaches to network design and optimization. Given the diversity of science and approaches, the AON will benefit most from adopting a wide range of design techniques.

Speakers provided an overview of critical lessons extracted from the build-out of other large observing networks, including the International Arctic Buoy program and the ARGO float array. Common themes from these endeavors were:

- Tightly focused networks tend to be the most successful. This presents a challenge for the AON, which spans many disciplines and questions, and argues for identification and maintenance of a limited number of critical observations what would form the core network.

- International collaboration will be required to build and sustain a network of the AON's envisioned scope.
- Provision and stakeholder acceptance of useful data products may be needed to help justify support and stabilize funding streams.
- The AON may need to work with the funding agencies to explore alternative funding models that are more suited to building and supporting a long-term, highly integrated network.
- The AON community will need mechanisms, such as SEARCH, for providing advice to the funding agencies.
- Individual (personal) contacts can be critical to network success. There does not appear to be a way to design this out, and it may not even be desirable to do so. Large, complex systems have an inherent social dimension that cannot be neglected.
- Patience will be needed. 'Easier' cases of network design and implementation can require 10+ years, and 20+ years would not be unreasonable for a task as complex as the AON.

Adaptive Observatory Network Design

Sandy Andelman *(Conservation International)*

Three of the eight grand challenges to the environment (NRC, 2001) are addressed by the Tropical Ecology Assessment and Monitoring Network (TEAM): 1) Biological diversity and Ecosystem Services; 2) Climate variability; and 3) Land-use dynamics. Current climatic conditions in the tropics and sub-tropics are projected to disappear entirely by 2100 and be replaced with either climatic conditions from another region, or in some cases, climatic conditions entirely outside of the climate envelope observed over the previous century (Williams et al. 2007). At the same time, the Intergovernmental Panel on Climate Change found that of 30,000 data sets with a 20-year time series of a biological variable (e.g., a species) and a climate-related variable (e.g., temperature) in the same place, only 15 – not 15,000 – come from the tropics. Thus, our knowledge base for understanding the ecological implications of climate change in the tropics is severely constrained. TEAM is a network designed to address this knowledge gap through standardized monitoring of climate, land cover change, tree and liana biodiversity, carbon stocks and vertebrate biodiversity. TEAM is not an ad hoc collection of sites. Rather it is a Network by design, with sites distributed in proportion to the major continental tropical forest blocks, and systematically spanning key gradients (e.g., latitude, current climate, projected future climate and socioeconomic settings). The TEAM Network currently comprises 16 sites, distributed in humid tropical forests in Latin America, Africa, and Asia.

After pilot projects using seven protocols at five sites, we used a cost-benefit analysis to determine the most efficient investment of resources and allocation to different measurements. We calculated the average annual cost per site relative to the informational value of monitoring different biological indicators (e.g. leaf litter, birds, terrestrial vertebrates), with regard to answering the key underlying questions that motivate TEAM. This resulted in the selection of five core in situ protocols (climate, bird biodiversity, mammal biodiversity, tree and liana biodiversity and carbon stocks). In addition, land cover/land use change is monitored using remote sensing.

Monitoring biodiversity at a plot-level (1 hectare) integrates the effects of human influences at landscape scales. To scale up, in-situ plot level measurements can be integrated with LiDAR and hyperspectral data at landscape scales (200 – 500 km^2), LiDAR, hyperspectral and SAR data at regional scales (1000 – 10,000 km^2) and then up to continental scales. Each protocol (e.g., above ground biomass, from which we derive estimates of above-ground carbon stocks) is managed through workflows that specify the entire process from field data collection, to application of algorithms to yield calculations of biomass.

An expanding suite of metrics for ecosystem services also are being used to monitor ecosystem health and livelihoods, and guide management and policy decisions. The TEAM Network functions as an early warning system for biodiversity change, using a strategically selected, standardized suite of field measurements of climate, tropical biodiversity and ecosystem services (Figure 1).

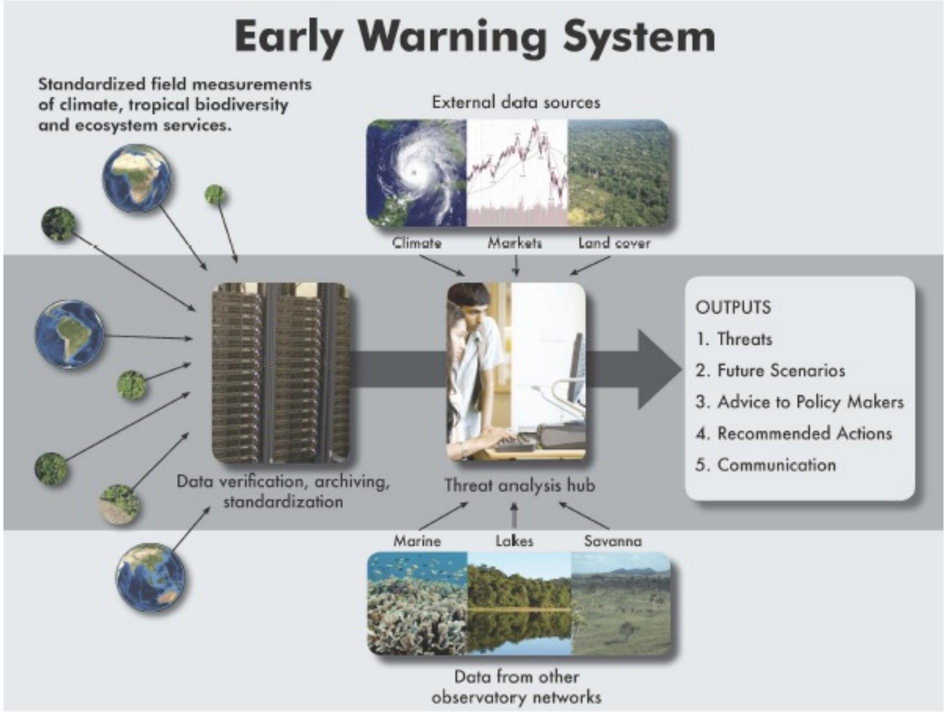

Figure A2. Schematic of an early warning system using data from observatory networks

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