Decadal Study

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COLD-LAND PROCESSES PATHFINDER MISSION CONCEPT

Advanced Space-based Observation of Fresh Water Stored in Snow

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The Cold-Land Processes Pathfinder will be the first space-based mission optimized to measure fresh water stored in snow on land and on ice sheets.

The potential science, application and socioeconomic benefits are very high.

This unique high-resolution, high-frequency microwave mission concept addresses a high-priority need widely identified nationally and internationally and fills a major gap in the conceptual global water-cycle observing system.

It is a mature, community-driven concept ready for an exploratory mission and has strong potential for future transition to operations.

Acknowledgements

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Cold-Land Processes Pathfinder Concept: Fact Sheet

Observation Objective

- Fresh water stored in terrestrial snow covers (snow water equivalent)
- Also snow depth and wetness
- Focus on snow cover on land and ice sheets
- High-resolution global sampling
  - 100-m spatial, 3-15 day temporal
- Support research and operations

Measurement Approach

- Microwave remote sensing from space
  - Enabling: High-frequency (X-, Ku-band) Synthetic Aperture Radar (SAR)
  - Enhancing: High-frequency (K-, Ka-band) passive microwave radiometry
- Applicable heritage and experience from:
  - SIR-C/X-SAR, TOPEX, SeaWinds, QuikSCAT, POLSCAT, ERS, RadarSAT, SMMR, SSM/I, AMSR
- Medium-size mission ($200-500 M)

Benefit to Science and Operations

- Snow is a cross-cutting component of interdisciplinary Earth science.
- Advanced snow observations are formally required to improve operational water and weather applications.
- Adanced snow observations are necessary to understand the causes and extent of changes in variability in the water cycle to improve prediction.
- This Cold-Land Processes Pathfinder mission concept fills a major gap in the global water-cycle observing system.

Societal Needs and Benefits

- Snow is the principal source of fresh water for many regions of the Earth
- Improve fresh-water resources information for:
  - Drinking Water
  - Food Production
  - Energy Production
  - Transportation
  - Industry and Manufacturing
  - Recreation
- Improve flood, drought, avalanche, and debris-flow hazard forecasts and decision-support
- Improve local-to-global weather prediction
- Understand snow accumulation effects on ice-sheet mass-balance to improve assessment of sea-level rise

Relevant Panel Themes

- Water Resources and the Global Hydrologic Cycle
- Earth Science Applications and Societal Needs
- Climate Variability and Change
- Weather
- Land-use Change, Ecosystem Dynamics, and Biodiversity
- Human Health and Security
- Solid Earth Hazards, Resources, and Dynamics

High Priority

- Snow regimes are changing, but we lack sufficient observations to understand and predict these changes
- This is a unique mission – the combination of high-frequencies and high-resolution microwave measurements fills an important gap in current space-based observing systems.
- High synergy with other observing systems
  - CMIS, VIIRS, GPM, HYDROS, others
- Need is clearly identified by national and international studies and strategic plans:
  - GEOSS, US GEO, GCOS, IGOS, WMO/WCRP, IPCC, NASA, NOAA
- High readiness – technology is available, science and application infrastructure are prepared.
- High benefit-to-cost ratio – at least 10:1 over three year period, with potential benefits of $1.3B/year.
- Rapid realization of operational benefits.

Introduction

Fresh water stored in snow on land is an important component of the global water cycle. In many regions of the world it is vital to health and commerce. It is not adequately measured by current or planned observing systems. This paper proposes an approach to significantly advance space-based observation of terrestrial snow water storage and other snow properties, called the "Cold Land Processes Pathfinder" concept. Developed and refined over the past five years by an interdisciplinary and international working group[1], this concept is the result of a coordinated effort to identify the best approach to address contemporary science and operational requirements for snow observation.

Snow is a cross-cutting phenomenon that influences many facets of science and society. In the global water cycle, terrestrial snow is a dynamic fresh-water reservoir that stores precipitation and delays runoff. Snow properties influence surface water and energy fluxes and other processes important to weather and climate, biogeochemical fluxes, ecosystem dynamics, and even certain solid-earth hazards and dynamics. Snow is often the principal source of fresh water for drinking, food production, energy production, transportation, and recreation, especially in mountain regions and the surrounding lowlands. Snow can also be a significant hazard – snowmelt has been responsible for many of the most damaging floods in the United States[2]. Consequently, the advanced snow observing capabilities described in this paper will benefit a broad range of science and socioeconomic sectors.

Snow water storage is implicated in climate change hypotheses concerning redistribution and acceleration of the water cycle. Significant spatial and temporal changes in local, regional and global snow water storage are projected. Evidence of large-scale changes in snow regimes is accumulating, but historical and current snow observing systems are insufficient to understand and explain these changes, especially at local-to-regional scales[3]. Given the scientific and socioeconomic importance of snow water storage, now is an exceptionally important time to advance snow observation capabilities from local to global scales.

A Critical Gap in Water-cycle Observation

A high priority in the U.S. and internationally is to determine and understand the extent and causes of changes and variability in the water cycle in order to improve prediction[4]. Our conventional ground and airborne snow observing systems meet many specific local needs, but lack the consistency and coverage necessary for this larger purpose. Current and planned satellites do not have the necessary combination of frequencies and resolutions to measure snow water storage consistently across different environments or to observe the signatures of important terrestrial snow processes. Their capability is lowest in mountainous areas, where snow water storage is especially important, and in forests. Consistent with this priority, then, is the observation approach that leads to understanding the scale considerations.

Addressing this priority requires coordinated observations of each of the major fresh-water components of the water cycle. Augmentation of critical *in situ* observations with observations from space is critical to provide the high sampling density and coverage required. Several fresh-water components are observable from space, including precipitation, soil moisture (storage), ground water storage, snow water storage, and river discharge[5]. The first three of these are being addressed through the Global Precipitation Mission (GPM) for rainfall (but not snowfall), the Hydrospheric States Mission (HYDROS) for soil moisture, and the Gravity Recovery and Climate Experiment mission

[1] Since 2000 sixteen workshops have been conducted by the Cold Land Processes Working Group (CLPWG) to identify and develop the science, technology and applications infrastructure necessary to support a future mission for advanced observation of snow water storage. The working group is sponsored by NASA's Terrestrial Hydrology Program. Collectively the workshops represent national and international participation by over 250 individuals from more than 20 universities and research institutions and nine federal agencies.

[2] **Perry**, C., Significant floods of the 20th century – USGS measures a century of floods, *U.S. Geological Survey, Fact Sheet 024-00*, 2000; **O'Connor**,. J.E. and J.E. Costa, Large floods in the United States: Where they happen and why, *U.S. Geological Survey, Circular 1245, 13 p*., 2003.

[3] **Brown**, R., Northern hemisphere snow cover variability and change, 1915-1997, *J. Climate (13), 2339-2355,* 2000.

[4] This is articulated in several documents, including: **Hornberger**, G.M., J.D. Aber, J. Bahr, R.C. Bales, K. Beven, E. Foufoula-Georgiou, G. Katul, J.L. Kinter III, R.D. Koster, D.P. Lettenmaier, D. McKnight, K. Miller, K. Mitchell, J.O. Roads, B.R. Scanlon, and E. Smith, *A Plan for a New Science Initiative on the Global Water Cycle.* US Global Change Research Program, Washington, DC, 2001; **Mahoney**, J., Asrar, G., Leinen, M., Andrews, J., Glackin, M., Groat, C., Hohenstein, W., Lawson, L., Moore, M., Neale, P., Patrinos, A., Schafer, J., Slimak, M., and H. Watson, *Strategic plan for the U.S. Climate Change Science Program.* A report by the Climate Change Science Program and the Subcommittee on Global Change Research, Washington, D.C., 2003; **Watson**, R., et al*., IPCC Third Assessment Report: Climate Change 2001*, Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2001.

[5] **Hildebrand**, P., Establishing the global fresh water cycle sensor web, Symposium on Living with a Limited Water Supply, 85th Annual Meeting of the American Meteorological Society, San Diego, January, 2005.

(GRACE) for ground water. Snow water storage remains as a critical observation gap. The need for better space-based measurement of snow water storage has been widely articulated in numerous studies (see p. 5). A satellite mission optimized to measure snow water storage and cold season processes is a major recommendation of the International Global Observing Strategy for the water cycle[6]. The Cold Land Processes Pathfinder is a community-driven approach to fill this critical gap.

The CLP Pathfinder Concept

The overarching objectives of the Cold Land Processes Pathfinder mission concept are to enable a major leap-ahead in understanding snow process dynamics in the global water cycle and to forge a pathway to operations, initiating significantly enhanced global monitoring and prediction of snow properties for multiple water, weather, and climate applications. These objectives have driven development of the concept through consideration of current and anticipated science and application requirements and the capabilities of current and planned observing systems, both space-based and *in situ*. The resulting concept steps toward a larger vision for long-term integrated observation of the water cycle.

Observation Objectives

The primary variables to be measured are snow water equivalent (SWE) and snow depth on land and on ice sheets. The objective is to sample the water content and depth of terrestrial snow covers at moderately high spatial resolution (50-500 m) to observe local-scale variability related to terrestrial processes, with a 3-15 day repeat interval to resolve synoptic events, and with accuracy consistent with (currently unmet) operational requirements for snow depth and water equivalent, described by NPOESS and NOAA[7]. Secondary objectives include observation of snow depth on sea ice and other cryosphere variables, such as sea-ice extent, type and motion.

[6] **Lawford**, R., Herland, E., and K. Nakamura, *A Global Water Cycle Theme for the IGOS Partnership, Report of the Global Water Cycle Theme Team,* Integrated Global Observing Strategy, 2004.
[7] See the NOAA Observing System Architecture (NOSA) at www.nosa.noaa.gov for further details of operational snow observation requirements.

Measurement Requirements

Accuracy. There are two modes of measurement accuracy requirements for snow water equivalent. In areas where shallower snow packs are predominant, differences of a few centimeters can have important hydrologic consequences. In deeper snow areas, such as mountainous areas where SWE often exceeds 100 cm, less stringent information is required. This leads to a two-tiered accuracy requirement of 2 cm RMSE for SWE less than or equal to 20 cm, and 10% RMSE for SWE greater than 20 cm. The minimum detection threshold is 3 cm.

Coverage Domain. Observations are required over land areas above 30° latitude, and over ocean areas above 50° latitude, with specific exceptions for orbits over regions of interest at lower latitudes such as the Himalaya or the Sea of Okhotsk. As an exploratory pathfinder, global sampling is acceptable; complete observation coverage between orbital swaths is highly desirable but not required. Coverage beyond this domain is welcome and may benefit other observation needs and concepts, but is not strictly necessary for snow observations.

Resolution. Over the course of many meetings, the CLPWG has paid special attention to the spatial and temporal resolution requirements necessary to address key science questions. The trades become critical since these two variables are among the major drivers in mission design and cost. The consensus on spatial drivers includes: 1) resolve the signature of terrain- and microclimate-related snow processes to enable linking across process scales for improved understanding of variability and change, and 2) support emerging and future water, weather, and climate models by providing observations at similar resolutions. Consideration of the drivers leads to concluding the need to measure at sub-kilometer ground sampled distances.

To resolve important terrain-related processes, observations are required with spatial resolution on the order of 50-100 m to support the understanding necessary to link local-scale physical processes to the larger picture. This is the minimum baseline spatial-resolution requirement. It is not essential, however, to have this resolution everywhere all of the time. A second mode of operation with a moderate sub-kilometer spatial resolution would often be sufficient as long as 50-100 m observations were regularly available to provide a link to higher-resolution local and hillslope-scale processes.

The temporal drivers are to resolve intra-seasonal and synoptic-scale snow accumulation and ablation processes. To resolve intra-seasonal changes in snow accumulation and ablation, observations are required with temporal resolution on the order of 15 days. To resolve the effects of synoptic weather events, a shorter repeat interval of 3-6 days is needed. On-going trade-studies to further refine this requirement take into consideration rates of snow accumulation processes in different geographic areas and under different conditions, and recognize the need to avoid aliasing in temporal sampling.

Proposed Measurement Approach

The role of the pathfinder is to address contemporary science and application objectives, build experience, demonstrate capability, and catalyze further development towards a future operational capability. The CLPWG has conducted engineering studies to identify the most suitable measurement approach to address these goals. The result is an envelope of technical options centered on a baseline measurement approach which fundamentally meets the mission objectives. This envelope is structured around a medium-cost mission ($200-500 M). Within this envelope, several trade-offs are possible that will ultimately define the mission and are governed to a large extent by the overall mission budget.

Active Microwave Sensor. The enabling sensor for the pathfinder concept is high-frequency synthetic aperture radar. Microwave sensors are best suited for the measurement objectives, and synthetic-aperture radar is needed to attain the targeted spatial resolution. The optimal frequency range with the necessary sensitivity to volumetric snowpack properties is 8-18 GHz (X- and Ku-bands; 2-4 cm wavelengths). The theoretical and empirical basis for this is from radar experience over the past 25 years from numerous modeling and field studies, large-scale experiments including SIR-C/X SAR, TOPEX, and CLPX, and from spaceborne sensors including SeaWinds, QuikSCAT, ERS-1, ERS-2 and RadarSAT[8]. Co- and cross-polarization measurement at two frequencies within this frequency range is the preferred approach to observing SWE and snow depth.

Passive Microwave Sensor. The pathfinder concept can be significantly enhanced by coincident measurements from an improved-resolution passive microwave radiometer sensor to augment the high-resolution radar observations. Active and passive microwave sensors have different sensitivities to the same snowpack properties, so provide complementary information. Also, the legacy long-term record of remotely sensed snow water equivalent information has been derived from low-resolution passive microwave measurements in the 18-40 GHz range (K- and Ka-bands; 1-2 cm wavelengths). Improved moderate-resolution passive microwave measurements could help support the high-resolution radar measurements, help make linkages across process scales, and help relate the new pathfinder observations to the long-term record.

Baseline Mission Concept. Near the center of the options-cost envelope (approximately $300 M), the fundamental baseline mission concept is a two-frequency synthetic aperture radar at 10 and 17 GHz (X- and Ku-band) with VV- and VH-polarization, combined with a two-frequency radiometer at 19 and 37 GHz (K- and Ka-bands) with H-polarization. In this concept, costs are reduced by using the same antenna for both the radar and radiometer, maintaining a simple deployment strategy for the antenna and solar panels, and by eliminating scanning mechanisms needed for wide-swath systems (Figure 1).

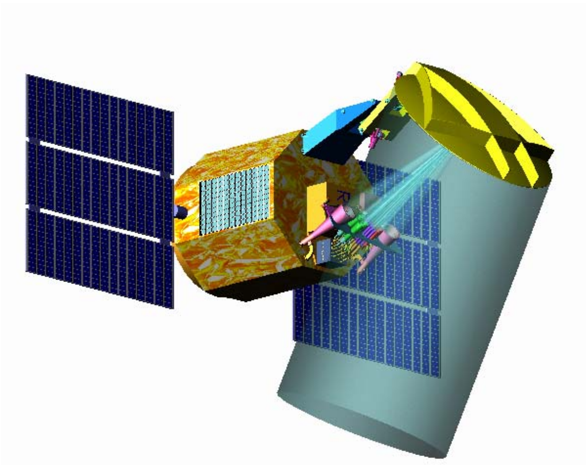

Figure 1. The baseline Cold Land Processes Pathfinder mission concept, showing a 2-m pushbroom reflector antenna with offset radar and radiometer feeds.

In this non-scanning configuration with a 510-km altitude sun-synchronous orbit, 30° incidence angle, and 100-W peak transmit power, the spatial resolution of the radar would be 100-m with a swath width of about 40

[8] There are numerous examples, including: **Ulaby**, F., Stiles, W., and M. Abdelrazik, Snowcover influence on backscattering from terrain, *IEEE Trans. Geosci. Remote Sens. 22(2)*, 126-133, 1984; **Rott**, H., and T. Nagler, Capabilities of ERS-1 SAR for snow and glacier monitoring in Alpine areas, *Proc. 2nd ERS-1 Symp.,* ESA SP-361, 965-970, 1994; **Long**, D., and M. Drinkwater, Cryosphere applications of NSCAT data, *IEEE Trans Geosci. Remote Sens. 37(3)*, 1671-1984, 1999; **Shi**, J., and J. Dozier, Estimation of snow water equivalence using SIR-C/X-SAR, Part 1: Inferring snow density and subsurface properties, *IEEE Trans. Geosci. Remote Sens., 38(6)*, 2465-2474, 2000; **Nghiem**, S., and W. Tsai, Global snow cover monitoring with spaceborne Ku-band scatterometer, *IEEE Trans. On Geosci. Remote Sens., 39(10),* 2118-2134, 2001; **Steffen**, K., Nghiem, S., Huff, R., and G. Neumann, The melt anomaly of 2002 on the Greenland Ice Sheet from active and passive microwave satellite observations, *Geophysical Research Letters (31),* L20402, 2004; **Cline**, D., Yueh, S., Nghiem, S., and K. McDonald, Ku-band radar response to terrestrial snow properties, *American Geophysical Union Fall Meeting,* 2004.

km. The spatial resolution of the 19-GHz radiometer would be 7-km with a 45-km swath width. At 37-GHz, the spatial resolution would be 4-km with a 40-km swath width. Within the range of 3-9 day exact-repeat orbits, the baseline concept provides global sampling but the swaths would not provide full global coverage. Full coverage at higher latitudes is achieved at repeat intervals longer than 9 days.

The technology risks of this concept are low. The single shared pushbroom antenna will use low-cost, mature lightweight composite reflector technology flown on the SSM/I, QuikSCAT, WindSat and future CMIS missions. The radar and radiometer electronics technologies also have high heritage from current and past space missions. All of the technology necessary for this concept is readily available.

The science benefits of this baseline concept are high. It meets the principal objectives for the exploratory pathfinder mission. This concept would provide frequent and consistent global samples of snow water equivalent at high resolution to address science objectives, build experience, demonstrate capability, and catalyze further development towards a future operational capability. This concept integrates well with other observing systems; some important strengths of this concept include:

- Relationships between these observations and conventional *in situ* snow observations (e.g. snow courses, etc.) would be more easily established because the spatial scale of the sampling (i.e. support in the geostatistical sense) is similar. This is particularly valuable for linking historical records at individual sites to new remote sensing observations, and is also beneficial for mission calibration and validation.
- These observations would complement high- to moderate-resolution observations of snow cover extent from optical sensors like the Moderate Resolution Imaging Spectrometer (MODIS) and its NPOESS follow-on, the Visible/Infrared Imaging Spectrometer (VIIRS). The addition of commensurate snow water storage and snow depth observations to optical observations of snow cover and albedo approaches a gestalt snow observing capability.
- These observations would complement past, current and planned low-resolution snow observations from passive microwave sensors including the AMSR-E on Aqua and its NPOESS follow-on, CMIS (Table 1). The resolution of these sensors is too low to adequately observe snow water storage in mountainous areas[9]. This baseline concept addresses this important gap. Further, this concept addresses degradation of low-resolution sensing over forests. The opportunity to make measurements in forest openings (e.g. fire scars, fens, meadows) increases with finer resolution. This concept also provides a valuable diagnostic tool to better understand the long-term, low-resolution record and help calibrate and validate these observations.

Table 1. Spatial resolution (instantaneous field of view, IFOV) of past, current and future passive microwave sensors at frequencies used for snow depth and water equivalent observation.

		Resolution (IFOV)	
Sensor	**Epoch**	**18-19 GHz**	**36-37 GHz**
SMMR	1978-1987	54x35 km	28x18 km
SSM/I	1987-Present	69x43 km	37x29 km
AMSR	2003-Present	27x16 km	14x8 km
CMIS	2010	24x16 km	16x12 km
CLPP	2010+	7x7 km	4x4 km

The baseline concept would enable a major leap forward in understanding variability and change in the water cycle. It would enable observation of high-resolution signatures of terrain-related processes and would provide a clear link to larger scales. This concept is technically and scientifically mature. It has consistently been highly rated throughout multi-step science and technology reviews at both the Jet Propulsion Laboratory and at the NASA Goddard Space Flight Center.

Options and Trade-offs. The baseline concept and the resulting science and application benefits can be enhanced within the $200-500M cost envelope. Several configuration options and trade-offs are possible. For example, the addition of conical scanning capability would provide wider swaths and achieve full global coverage more rapidly, but at decreased resolution. In conical scanning mode, radar swath width would be approximately 400 km, providing full coverage at mid-to-high latitudes in a six-day repeat orbit. To maintain greater resolution, higher transmit power and data rate are required, which are also possible within the same cost envelope. Alternative antenna and platform architectures

[9] **Allison**, I., Barry, R., and B. Goodison, Climate and Cryosphere (CliC) Project Science and Coordination Plan, Version 1. WCRP-114, WMO/TD No. 1053, 2001.

have also been considered that can maintain resolution and increase the swath width to approximately 120 km without mechanical scanning (full coverage in 12-15 days). These and other trade-offs will ultimately define the mission and will be largely governed by the available budget.

A High Priority for Earth Science and Applications

The Cold Land Processes Pathfinder mission concept is a mature, community-driven approach to advance Earth science and applications and to provide a high benefit to society. All ten prioritization criteria for the NRC Decadal Study are well-met by this concept. Advanced observation of snow has been widely identified as a requirement and high priority in previous studies and has relevance to all seven Panel themes. It contributes to important contemporary science questions as well as to operational applications. It provides a direct linkage to traditional *in situ* and heritage remote sensing observations used for long-term monitoring of the Earth. It complements other current and planned observing systems. The concept is affordable – the benefit-to-cost ratio of this pathfinder approach is very high. The readiness level is high. The concept, especially with the scanning option, helps mitigate risk and provides redundancy for operational sensors. The concept fits well with other national and international plans. These criteria are discussed further in the following sections.

1. Identified in Previous Studies

GEOSS. Endorsed by 55 countries, the Global Earth Observing System of Systems (GEOSS) 10-year Implementation Plan[10] seeks to achieve comprehensive, coordinated and sustained observations of the Earth system. The GEOSS plan identifies observation of snow water equivalent as a priority in four themes where it is currently a significant observation gap:

- *Reducing loss of life and property from natural and human induced disasters.* SWE is identified as an observation gap for disaster mitigation – "now monitored with marginal accuracy, spatial and temporal resolution and timeliness". Disaster Observation Requirement #23 specifies the need for improved snow water content measurements.
- *Improving water resource management through better understanding of the water cycle.* SWE is a prominent requirement in this theme. Recommendations for snow water storage observations include:
  - "…space agencies should give priority to the development of effective sensors and missions for surface and subsurface water stores – including snow water equivalence…"
  - "6-Year Target: Facilitate, with space agencies and research communities, the development of effective sensors and missions for precipitation, surface and subsurface water stores – including snow water equivalence…"
  - "6-Year Target: Advocate continuous sensor development with improvement of accuracy and higher spatial-temporal resolutions, and with special attention to snow water equivalent and stream flow."
  - Water Observation Requirement #16 specifies needs for snow water equivalent, noting that currently these observations are only locally available or experimental.
- *Improving weather information, forecasts, and warnings.* SWE is identified as a weather observation gap, needed for warnings, nowcasts and short-term forecasts (Weather Observation Requirement #36). This is also articulated by the World Meteorological Organization (WMO) Global Observing System 2015 Vision document, which identifies SWE as one of the top five priorities for weather observations.
- *Architecture of a system of systems.* GEOSS places a high-priority on data and information products commonly required across diverse societal benefit areas. Snow is included in this category.

US GEO. The U.S. Group on Earth Observations (formerly the Interagency Working Group on Earth Observations – IWGEO) is a standing subcommittee reporting to the National Science and Technology Council Committee on Environment and Natural Resources. Seventeen federal agencies are represented in the US GEO. The US GEO plan is the US contribution to GEOSS. Seven of ten US GEO *Societal Benefit Technical Reports*[11] articulate the need for improved snow water equivalent observations or other needs addressed by CLPP's high-resolution, high-frequency radar/radiometer system, including:

[10] The GEOSS implementation plan is available at http://earthobservations.org.

[11] These reports are available from the US GEO at http://www.ssc.nasa.gov.

- *Protect and Monitor Water Resources.* Snow water equivalent is integral to this theme.
- *Improving Weather Forecasting.* SWE is identified as one of six critical parameters not adequately addressed by current or planned observing systems
- *Reducing Loss of Life and Property from Disasters.* SWE observations are required to mitigate damages from snowmelt flooding.
- *Support Sustainable Agriculture and Forestry, and Combat Land Degradation.* Better observations of water quantity and quality are needed to detect impacts of global change on both.
- *Understand, Assess, Predict, Mitigate, and Adapt to Climate Variability and Change.* SWE is identified as an essential climate variable to support the objective of closure of terrestrial water budgets.
- *Understanding the Effect of Environmental Factors on Human Health and Well-Being.* Observation of snow water storage is directly related to water quantity and indirectly to water quality. Also, the use of SAR to enhance existing efforts is identified.
- *Protect and Monitor our Ocean Resources.* The CLPP mission concept will provide "capacity-building measurements" – high-resolution observations of sea ice using active systems to support weather and climate, marine operations, natural hazards, and national security.

GCOS. The Global Climate Observing System[12] (GCOS) supports each of the GEOSS recommendations noted above, and identifies the additional theme of energy (improving management of energy resources), where improved snow observations are needed.

CliC. The Climate and Cryosphere Program (CliC), of the WMO World Climate Research Program (WCRP), articulates the need for high-quality snow measurements to evaluate and validate models and emphasizes that this need "cannot be overstated"[13].

IGOS. The Integrated Global Observing Strategy (IGOS) is a partnership of 14 international organizations that are concerned with global environmental change issues[14]. The CLPP concept is one of five priorities for satellite mission planning identified by the IGOS report on water-cycle observations[15]:

- "Drawing on experience with cold season satellite measurements and cold season field projects, plans [should] be developed for a satellite mission optimized to measure cold season processes and variables from space."

The need for SWE observations is also articulated in the IGOS Geohazards report[16], where it is considered as part of a "climate trigger" for ground instability and is identified as one of "most required ground instability hazard observations".

NASA. The need for a high-resolution radar mission to measure SWE emerged as the "EX-7 Mission" in NASA's Easton Report on recommended post-2002 missions.

NRC. The National Research Council's Report on Adequacy of Climate Observing Systems[17] identified snow water equivalent as a "high-impact observation" related to climate variability and change.

IPCC. The Intergovernmental Panel on Climate Change[18] (IPCC) recognizes that significant changes in snow cover have occurred in the last four decades and projects that storage of fresh water will decrease further in the future with widespread consequences. The IPCC report identifies a high-priority need to evaluate

[12] GCOS is an international joint undertaking of the WMO, the United Nations Education, Science and Cultural Organization (UNESCO), the United Nations Environment Program (UNEP), and the International Council for Science (ICSU).

[13] **Allison**, I., Barry, R., and B. Goodison, Climate and Cryosphere (CliC) Project Science and Coordination Plan, Version 1. WCRP-114, WMO/TD No. 1053, 2001.

[14] IGOS Partners include: Committee on Earth Observation Satellites (CEOS), Food and Agriculture Organization for the United Nations (FAO), Global Climate Observing System (GCOS), Global Ocean Observing System (GOOS), Global Observing System/Global Atmosphere Watch of WMO (GOS/GAW), Global Terrestrial Observing System (GTOS), International Council for Science (ICSU), International Geosphere-Biosphere Programme (IGBP), International Group of Funding Agencies for Global Change Research (IGFA), Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO), United Nations Environmental Programme (UNEP), United Nations Environment, Science and Cultural Organization (UNESCO), World Climate Research Program (WCRP), and the World Meteorological Organization (WMO).

[15] **Lawford**, R., Herland, E., and K. Nakamura, *A Global Water Cycle Theme for the IGOS Partnership, Report of the Global Water Cycle Theme Team,* Integrated Global Observing Strategy, 2004.

[16] **Marsh** S., et al., *IGOS Geohazards Theme Report, Report of the Geohazards Theme Team,* Integrated Global Observing Strategy, 2003.

[17] **Karl**, T., et al. *Adequacy of Climate Observing Systems, Panel on Climate Observing System Status*, National Research Council, National Academy Press, Wasington DC 1999.

[18] **Watson**, R., et al., *IPCC Third Assessment Report: Climate Change 2001,* Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2001.

threatened fresh-water resources. Also a high priority is quantification of mass-balance components of the Greenland ice sheet, including snow accumulation.

2. Contributes to More than One Theme

Snow is a cross-cutting component of interdisciplinary Earth science. By advancing snow observation capabilities, the Cold Land Processes Pathfinder concept makes a significant contribution to all seven NRC Decadal Study panel themes:

Water Resources and the Global Hydrologic Cycle. The CLPP mission will fill a critical gap in the water cycle observing system, needed to help close the water budget. It will enable discovery of unknown spatial and temporal variations in the global distribution of cold-season precipitation, water storage, and surface fluxes.

Earth Science Applications and Societal Needs. Snow is the principal source of fresh water for many regions of the Earth. The CLPP mission will support a wide array of decision support systems that depend on information about the distribution and magnitude of fresh water resources for drinking water, food production, energy production, transportation, industry and manufacturing, and recreation. By greatly increasing the snow water equivalent observation capability this mission will improve water supply, flood, drought[19], avalanche and debris-flow hazard forecasts and decision support, and improve local-to-global weather prediction. This mission will help understand snow accumulation effects on the mass-balance of ice-sheets to support and improve assessment of sea-level rise[20].

Climate Variability and Change. The CLPP mission will improve quantitative understanding of variability and change in snow accumulation and water storage from local-to-global scales, including the process linkages that relate local-scale snowpack processes to larger synoptic-scale processes. This will enable a leap ahead in our understanding of the local consequences of climate change, especially on water storage effects and on ice-sheet mass-balance.

[19] Advanced observation of snow water storage is directly relevant to several recommendations of the National Integrated Drought Information System (NIDIS; **Western Governor's Association**, *Creating a Drought Early Warning System for the 21st Century: The National Integrated Drought Information System*, Denver, CO, 2004).

[20] **Church**, J.A. and J.M. Gregory. *Climate Change 2001: The Scientific Basis, Chapter 11: Changes in Sea Level,* IPCC, Cambridge Press, 881p, 2001.

Weather. Snow covers seasonally up to 50 million km^2 in area (34% of total land area), affecting atmospheric circulation and climate from local to regional and global scales. The CLPP mission will provide necessary initial and boundary conditions for numerical weather prediction models to improve weather prediction.

Land-use Change, Ecosystem Dynamics, and Biodiversity. The CLPP mission will provide quantitative information needed to help understand the effects of snow on vegetation dynamics, soil moisture, soil freeze/thaw state, permafrost and biogeochemical fluxes.

Human Health and Security. Snow cover is a fresh-water resource vital to human health and security. This is not only true in high-latitude areas; snow is particularly important in many densely populated areas of North- and South America, Europe, the Middle East and Asia. Climate change seriously threatens the abundance of this fresh-water resource, calling for immediate action to improve the understanding of climatic effects on water balance and hydrological processes. The CLPP mission will provide critical new information about fresh water resources. The mission will help reduce loss of life and property from natural disasters (e.g. snowmelt floods and debris flows).

Solid-Earth Hazards, Resources, and Dynamics. The CLPP mission will help improve prediction of snowmelt-induced debris flows[21] and periglacial dam breaches in mountain catchments[22]. The mission will also improve understanding of crustal deformation beneath ice-sheets by quantifying snow accumulation processes in ice-sheet mass-balance dynamics.

[21] For example: **Rickenmann**, D., and M. Zimmerman, The 1987 debris flows in Switzerland: documentation and analysis, *Geomorphology, 8*, 175-189, 1993; **Bardou**, E., and R. Delaloyle, Effects of ground freezing and snow avalanche deposits on debris flows in alpine environments, *Natural Hazards and Earth System Sciences, 4,* 519-530, 2004.

[22] For example: **Haeberli**, W., Kaab., A., Muhll, D., and P. Teysseire, Prevention of outburst floods from periglacial lakes at Grubengletscher, Valais, Swiss Alps, *Journal of Glaciology, 47,* 111-122, 2001; **O'Connor**, J., Hardison, J., and J. Costa, Debris flows from failures of neoglacial-age moraine dams in the Three Sisters and Mount Jefferson Wilderness Areas, Oregon, *USGS Professional Paper 1606,* 2001; **Hugel**, C., Kaab, A., Haeberli, W., and B. Krummenacher, Regional-scale GIS models for assessment of hazards from glacier lake outbursts: evaluation and application in the Swiss Alps, *Natural Hazards and Earth System Sciences, 3,* 647-662, 2003.

3. Contributes to Important Scientific Questions Facing Earth Sciences

The cross-cutting role in many Earth science themes makes the CLPP mission concept particularly important. Advanced snow observations from CLPP will contribute to many important scientific questions and lead to new discoveries. Some important examples include:

How is the global water cycle changing? Snow-water storage regimes are sensitive to changes in temperature and precipitation. Significant spatial and temporal changes in snow accumulation and melt are projected in many climate-change hypotheses concerning redistribution and acceleration of the water cycle[23], but this is not well understood. Studies examining trends and variability have concluded that available empirical evidence is insufficient to fully answer the questions[24]. Distinction between natural variability and climate-change effects on snow water storage remains unclear and requires better understanding of the coupling between synoptic weather and climate patterns and local-scale terrain controls[25]. Consistent global, high-quality snow water equivalent observations provided by CLPP are necessary to help develop credible understanding of variability and change.

How do surface hydrologic processes affect Earth's climate? In addition to the well-known ice-albedo feedback effect on radiative energy exchanges, seasonal snow covers reduce air temperatures with subsequent reductions of 500-1000 mb atmospheric pressure thickness[26]. The latter tends to effect the steering of cyclonic activity and the planetary wave structure, which in turn modifies the occurrence of snowfall[27]. Snow water storage (i.e. mass of snow) is a key factor influencing the persistence (and therefore predictability) of these effects. Through better observation of snow water storage, these feedback effects can be better understood.

How are local variations in the water cycle related to global climate variation? Local variations in snow water storage are poorly resolved by current snow observing systems; *in situ* networks are typically too sparse for this purpose, and the resolution of space-based passive microwave sensors is insufficient. These variations are signatures of terrain-related processes affecting mass and energy exchanges between the surface and the atmosphere. CLPP will provide the resolution and coverage necessary to observe these variations and link them to larger regional and global climate variation.

How can new space-based observations reduce uncertainties in water and weather forecasting? Predictive water, weather, and climate models require observations of key state variables, including SWE, to evaluate model performance and uncertainties and to constrain the model through data assimilation. Today, land surface models are operating at resolutions on the order of 1-km at regional-to-global scales, and at even higher resolution at local scales. Numerical weather models are operating at scales of less than 10 km and resolution is increasing regularly. The CLPP concept will uniquely provide frequent SWE observations at scales commensurate with current and anticipated resolutions of these models, enabling more direct diagnostic evaluation of model process dynamics and regular updating through data assimilation.

How are ice sheets responding to climate variability and change? Changes in ice-sheet mass balance related to snow accumulation are being observed that were unknown only five years ago. Projections include decreased snow accumulation in Greenland and increased snow accumulation in Antarctica[28]. Processes involved in these changes, however, are not well understood. CLPP will provide observations of snow accumulation needed to better define processes involved in ice sheet mass balance and reduce uncertainty pertaining to the ice sheets of Greenland and Antarctica.

How does the carbon cycle respond to climate variability and change? About 14% of the global carbon reservoir is stored in the frozen soils of Arctic

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[23] For example, **Karl**, T., Groisman, P., Knight, H., and R. Heirn, Recent variations in snow cover and snow fall in North America and their relation to precipitation and temperature variations, *J. Climate (6),* 1327-1344, 1993; **Compagnucci**, R., da Cunha, L., Hanaki, K., Howe, C., Maihu, G., Shiklomonov, I., Stakhiv, E., and P. Doll, *Climate Change 2001: Impacts, Adaptation and Vulnerability, Chapter 4: Hydrology and Water Resources,* IPCC, Cambridge Press, 2001.

[24] **Brown**, R., Northern hemisphere snow cover variability and change, 1915-1997, *J. Climate (13), 2339-2355,* 2000.

[25] For example: **Cline**, D., Snow surface energy exchanges and snowmelt at a continental, midlatitude alpine site, *Water Resources Research (33)4*, 689-701, 1997.

[26] For example: **Lamb**, H., Two-way relationships between the snow cover or ice limit and 1000-500 mb thickness in the overlying atmosphere, *Quarterly J. Royal Met. Soc. (81),* 172-189, 1955.

[27] **Williams**, L., Ice-sheet initiation and climatic influence of expanded snow cover in Arctic Canada, *Quaternary Research (10),* 141-149, 1978; **Clark**, M. and M. Serreze, Effects of variations in east Asian snow cover on modulating atmospheric circulation over the North Pacific Ocean, *J. Climate (13),* 3700-3710, 2000.

[28] **Church**, J.A. and J.M. Gregory. *Climate Change 2001: The Scientific Basis, Chapter 11: Changes in Sea Level,* IPCC, Cambridge Press, 881p, 2001.

lands. Changes in snow accumulation (depth, extent, seasonality) have important consequences on the soil thermal regime, which in turn affects carbon fluxes from soil. CLPP will help support investigation of geographical and temporal distributions of the major pools and fluxes in the global carbon cycle. The radar data of CLPP will also be useful for monitoring wetland dynamics, another important influence on land-atmosphere carbon exchange.

How are oceans responding to climate variability and change? The CLPP mission will contribute to improved understanding of fresh-water input to oceans, especially in Arctic regions. The contribution of snowmelt runoff from gauged and ungauged rivers in response to climate variability and change needs to be better understood. Available observations allow order-of-magnitude estimation of the annual inflows and outflows of freshwater in the Arctic regions, but the accuracy is insufficient to quantify even relatively large inter-annual differences, let alone long-term climate trends[29].

4. Contributes to Applications or Policy-making (Operations, Applications, Societal Benefits)

Although CLPP is an exploratory pathfinder (research driven), the mission will contribute much-needed observations of fresh-water storage to specific operational applications that have widely recognized societal benefits and are required by binding legislation. The snow observations provided by this mission directly address requirements outlined by NOAA and also NPOESS that ultimately support numerical weather prediction models (e.g. the Weather Research and Forecast Model, WRF) and river and flood analysis and forecast models (e.g. National Snow Analyses[30], NSA; National Weather Service River Forecast System, NWSRFS). NOAA's Weather and Water Goal has explicit requirements for high-resolution remote observations of SWE to support weather and flood forecasting operations, as outlined in the NOAA Observing System Architecture[31] (NOSA). These applications are mandated by the Organic Act of 1890 (15 U.S.C. 313), the Inland Flood Forecasting and Warning System Act of 2002 (Public Law 107-253), and the Global Change Research Act of 1990 (Public Law 101-606). Use of these pathfinder observations in operational environments will demonstrate benefit and catalyze further development towards a future operational-class mission.

Similarly, observations from the CLPP mission will also contribute to numerous academic, governmental, and commercial applications and decision support systems, driven by non-binding authoritative guidance, recommendations, and policy, such as the Strategic Plan for U.S. Climate Change Science Program, GEOSS, strategic plans for both NASA and NOAA, and commercial and industrial weather and hydrology services.

The societal benefits of advanced snow water storage observations provided by CLPP will be considerable. Improved monitoring of freshwater resources will benefit economic development (e.g. water supply for commercial, industrial, recreational, and energy uses), human health (e.g. fresh drinking water and water supply for domestic use), and irrigation and food production activities. Better observation of snow water storage will benefit flood prediction and help reduce forecast uncertainties. CLPP observations of snow water storage and snow depth will directly support the National Integrated Drought Information System (NIDIS)[32]. Indirect benefits can be expected through improvements in weather prediction through better definition of initial and boundary conditions, exploiting the memory and predictability inherent in snow water storage to improve short- to long-term (days to weeks) prediction[33]. Other indirect benefits of improved snow water storage observations include estimation of antecedent moisture conditions for wildfire management planning.

5. Contributes to Long-term Monitoring of the Earth

The CLPP concept is aimed at bridging a critical gap between our two sources of long-term information of snow accumulation and water storage. The longest record

[29] **World Climate Research Program** (WCRP), Hydrologic cycle in the Arctic region. In: *ACSYS Implementation and Achievements* (revised draft), available from www.npolar.no/acsys/impplan/index.htm, 1999.
[30] The National Snow Analyses combine snow observations with high-resolution model information to provide daily synoptic snow condition products for the US. They are available at www.nohrsc.noaa.gov . See the Strategic Plan for the US Integrated Earth Observation System at http://iwgeo.ssc.nasa.gov/docs/EOCStrategic_Plan.pdf for more information about the role of the National Snow Analyses.
[31] The NOSA web site is www.nosa.noaa.gov.

[32] **Western Governor's Association**, *Creating a Drought Early Warning System for the 21st Century: The National Integrated Drought Information System*, Denver, CO, 2004.
[33] For more information see **Entekhabi**, D., et al., *Report of a Workshop on Predictability and Limits-to-Prediction in Hydrologic Systems*, Committee on Hydrologic Science, Water Science and Technology Board, National Research Council, 2002.

consists of *in situ* observations of snow depth and (to a lesser extent) water equivalent, measured in sparse networks of individual points or short transects (i.e. "snow courses"). These networks represent a valuable database for monitoring effects of climate variability and change over large regions, but lack the sampling density necessary to extend such analyses to smaller scales, and have significant gaps in coverage. A shorter record (27 years) is provided by space-based passive microwave observations, but the low spatial resolution of these sensors precludes observation of local scale processes and impacts the accuracy of resulting snow observations.

CLPP will contribute to the long-term *in situ* record by providing high-resolution observations closer in scale to *in situ* observations, with extensive and consistent global sampling. This will make it much easier to relate the satellite measurements to *in situ* observations, and will enable better understanding of how local *in situ* observations relate to larger scale variability. CLPP will contribute to the long-term passive microwave record by providing complementary information at sub-footprint scales, helping to "sharpen" contemporary low-resolution data sets and estimate local-scale variability in the long-term record.

6. Complements other Observational Systems

The objectives of the CLPP mission do not depend on any other satellite mission. There are several missions in orbit or planned, however, that are of complementary interest, which together with CLPP would enable or enhance the scientific gain and improve long-term benefits. Snow and ice observations at very coarse spatial resolution are or will be made by low-resolution radiometry (e.g. DMSP-SSM/I, EOS-AMSR, NPOESS-CMIS) and scatterometry (C-band ASCAT on the ESA MetOp satellite, and the Indian Oceansat-2 Ku-band Scatterometer). Data from these systems with CLPP can be used to study scaling issues, and the CLPP data can be used for calibration and validation of low resolution geophysical products from these sensors. CLPP's snow water storage observations will be highly complementary to systematic observations of soil moisture that will be made by the European SMOS mission using L-band radiometry and by the NASA Hydrospheric States (HYDROS) mission, which will combine radar and radiometer measurements at L-band. The CLPP mission will also complement SAR sensors operating at lower frequencies (e.g. European ASAR on ENVISAT and the Canadian Radarsat SAR, both operating at C-band, and the future Japanese PALSAR on ALOS and European TerraSAR-L, both operating at L-band). Signature research shows the complementarities of high-frequency backscatter data in particular for retrieving vegetation parameters and soil moisture. CLPP will be complementary to the German TerraSAR-X (X-band), not only because CLPP is a dual-frequency mission, but the mission objectives and strategies are quite different. CLPP is also highly complementary to the European CryoSat mission because it addresses different properties and processes of the cryosphere that so far have not been observed with sufficient detail.

7. Affordable (Cost/Benefit)

The CLPP mission concept is a medium-sized mission, with an estimated baseline cost of approximately $300M. Several options to significantly enhance the mission are possible within the medium-sized mission cost envelope of $200-500M.

The expected benefit-to-cost ratio of the CLPP mission (for the U.S.) is approximately 10:1 over a mission duration of three years ($1.3B per year). Snow has substantial economic effects, with both costs and benefits to society. According to a preliminary report to NOAA's Chief Economist on the value of snow information[34], snow itself has an aggregate positive impact of $50-400B per year in the U.S. Major economic benefits include snow water storage (up to $348B per year in western U.S.) and winter tourism (exceeds $8B per year in New England and the Rocky Mountains). Major economic costs include snow removal (exceeds $2B per year for U.S.), flooding from snowmelt (a single event, the Red River of the North flood in 1997, cost $4.3B), and road closures that cause lost retail trade, wages and tax revenue (exceeds $10B per day for closures in the eastern U.S.). These effects are significant in their size relative to other weather phenomena.

More relevant to the benefit of the CLPP mission is the value of improved snow information, which is less than the overall economic impact of snow but reflects the actual benefit of having better information about snow. Adams et al[34] conclude that improvements in the accuracy of snow metrics such as water content will have substantial economic payoffs to a broad range of economic sectors by improving individual and public decision making; they estimate a preliminary potential

[34] **Adams**, R., Houston, L., and R. Weiher, *The value of snow and snow information services*, preliminary report to NOAA Office of Program Planning and Integration, August 2004.

benefit associated with improved snow information for the U.S. alone of greater than $1.3B per year.

8. Degree of Readiness

The technology necessary for the baseline CLPP mission is readily available and low-risk. A substantial science and application infrastructure exists to use CLPP data and products as they become available. These include several Earth system modeling and analysis systems. With additional investment to support short-latency data acquisition (e.g. use of the NPOESS Safety Net[35] and investment in rapid data processing) CLPP data and products could be used for many operational water and weather prediction applications. Several related science activities help support CLPP. The Cold Land Processes Working Group is a large, international and interdisciplinary group of scientists and technologists with strong interests in this mission concept. The NASA Cold Land Processes Experiment[36] (CLPX) focused on data collection supporting advanced observation of snow water storage, process understanding, and model improvement. In conjunction with the International Polar Year (IPY), further experiments are planned for Alaska (to test snow algorithms and explore other applications) and for Canada (to conduct an end-to-end observation-to-modeling test-bed of the approach in collaboration with the HYDROS soil moisture mission).

9. Risk Mitigation and Strategic Redundancy

The high-resolution radar data from the CLPP mission provides an important backup of other critical systems. For example, CLPP data could replace RadarSAT data for operational sea ice monitoring by the National Ice Center[37]. CLPP could provide high-resolution near-shore ocean wind information, complementary to the low-resolution (25-km) winds from the NASA QuikSCAT Ku-band scatterometer and the ESA ASCAT on MetOp. Inclusion of increased-resolution radiometers on CLPP to enhance science benefit would also provide some redundancy and risk-reduction for the NPOESS CMIS sensor.

[35] Safety Net is an innovative data routing and retrieval architecture to ensure near-real time delivery of mission data from NPOESS satellites (www.ipo.noaa.gov).

[36] See http://nsidc.org/data/clpx for more information.

[37] The National Ice Center is a multi-agency operational center providing strategic and tactical sea- and lake-ice information to government, military and civil sectors (www.natice.noaa.gov).

10. Fits with other National and International Plans and Activities

National

Executive Office of the President. The ability to measure, monitor, and forecast the U.S. and global supplies of fresh water was recently identified as a high-priority concern of the White House[38]. Improved methods for tracking changes in snow water storage was specified as a first-order need to help define available water resources and fill knowledge gaps related to water availability and use, and radar was identified as a possible solution[39]. The CLPP mission concept directly addresses this priority.

US CCSP. The CLPP mission concept directly addresses Goals 1 and 3 of the U.S. Climate Change Science Program[40] by:

- helping to quantify the present spatial and temporal variability of the Earth's snow and ice across multiple scales,
- enabling improved interpretation and understanding of the historical remote sensing record of snow and ice variations,
- enabling improved representation of hydrologic and cryospheric processes in climate models,
- focusing observations on key regions and processes especially vulnerable to abrupt climate change, including snow water storage in the water cycle, Greenland snow accumulation, changes in snowmelt runoff, and the insulative role of snow on permafrost dynamics, and
- helping to reduce uncertainty in projections of how Earth's climate and related systems may change in the future.

[38] "Update on Research and Development Budget Priorities, Office of Management and Budget and Office of Science and Technology Policy". *Executive Office of the President, August 12, 2004.*

[39] "Science and Technology to Support Fresh Water Availability in the United States, Report of the National Science and Technology Council Committee on Environment and Natural Resources, Office of Science and Technology Policy, *Executive Office of the President, November 15, 2004.*

[40] **Mahoney**, J., Asrar, G., Leinen, M., Andrews, J., Glackin, M., Groat, C., Hohenstein, W., Lawson, L., Moore, M., Neale, P., Patrinos, A., Schafer, J., Slimak, M., and H. Watson, *Strategic plan for the U.S. Climate Change Science Program. A report by the Climate Change Science Program and the Subcommittee on Global Change Research*, Washington, D.C., 2003. Goal 1 is "Improve knowledge of the Earth's past and present climate and environment, including its natural variability, andimprove understanding of the causes of observed variability and change". Goal 3 is "Reduce uncertainty in projections of how the Earth's climate and related systems may change in the future".

NASA. The CLPP mission concept addresses five science questions posed by NASA's research strategy and roadmaps[41]:

- How are global precipitation, evaporation, and the cycling of water changing? (*Variability*)
- What changes are occurring in the mass of Earth's ice cover (*Variability*)
- What are the effects of surface hydrologic processes on Earth's climate? (*Response*)
- How are variations in local weather, precipitation, and water resources related to global climate variation? (*Consequences*)
- How can weather forecast duration and reliability be improved by new space-based observations, data assimilation and modeling? (*Prediction*).

NOAA. The CLPP concept supports seven performance objectives of NOAA's FY05-10 Strategic Plan[42]:

- increase lead time and accuracy for weather and water warnings and forecasts
- improve predictability of the onset, duration, and impact of hazardous and severe weather and water events
- reduce uncertainty associated with weather and water decision tools and assessments
- increase development, application, and transition of advanced science and technology to operations and services
- increase coordination of weather and water information and services with integration of local, regional and global observing systems
- describe and understand the state of the climate system through integrated observations, analysis and data stewardship
- reduce uncertainty in climate projections through timely information on the forcing and feedbacks contributing to changes in the Earth's climate.

CLPP is also relevant to NOAA's 5-Year research strategy[43]. An objective of the Climate Mission Goal is to understand the role of snow, especially at high latitudes, to enhance society's ability to plan and respond to climate variability and change. Objectives of the Weather and Water Mission Goal include improving NOAA's ability to monitor and predict the runoff from snowmelt and forecast snow levels, and leverage satellite instrumentation to observe precipitation, snow water content, and soil moisture to improve hydrologic forecasts.

Water Policy. CLPP complements the Western Governor's National Integrated Drought Information System[44]. Data from CLPP will provide much needed information on the availability of fresh water to support administration of water policy in the U.S. and internationally and to help formulate future water policy[45].

International

World Meteorological Organization. The CLPP concept supports long-term strategies and goals of the WMO[46] to improve and optimize global systems for observation of water resources (e.g. Strategy 6, Goal B). There are several relevant WMO programs and activities that either require, or would benefit from, advanced snow observing capabilities provided by the CLPP concept. Within the WMO World Weather Watch Program, the Global Observing System (GOS) specifies a need for advanced observation of water resources. The WMO World Climate Watch Program includes requirements for advanced snow observing capabilities noted previously within both GCOS and the World Climate Research Program – CliC Program. The Hydrology and Water Resources Program (HWRP) includes goals for large-scale assessment of fresh-water quantity, and the HWRP implementation of the World Hydrologic Cycle Observing System (WHYCOS) in Baltic, Himalayan and Arctic regions has specific needs for advanced snow observations.

European Space Agency. Two major scientific priorities of ESA's Living Planet Programme are Physical Climate and Geosphere/Biosphere[47]. Science and

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[41] "Exploring Our Home Planet: Earth Science Enterprise Strategic Plan" and subsequent roadmap updates at http://science.hq.nasa.gov/strategy/roadmaps. *National Aeronautics and Space Administration, 2000.*

[42] "New Priorities for the 21st Century: NOAA's Strategic Plan", *U.S. Department of Commerce, 2005.*

[43] "Research in NOAA: Towards Understanding and Predicting Earth's Environment, A Five-Year Plan: Fiscal Years 2005-2009", *U.S. Department of Commerce, 2005.*

[44] **Western Governor's Association**, *Creating a Drought Early Warning System for the 21st Century: The National Integrated Drought Information System*, Denver, CO, 2004.

[45] **Lane**, N.F., Bierbaum, R.M., and M.T. Anderson, Science and water policy for the United States: Science, policy and management, Lawford, R., Fort, D., Hartmann, H., and S. Eden (eds), *Water Resources Monograph 16*, American Geophysical Union, 207-222, 2003.

[46] Sixth WMO Long-term Plan, 2004-2011, *World Meteorological Organization, 2004.*

[47] The Science and Research Elements of ESA's Living Planet Programme, European Space Agency SP-1227, October 1998 (www.esa.int/esaLP).

research elements of both themes identify the need for improved knowledge of the spatial and temporal distribution of snow water storage. This specific need was reiterated in the Global Water Cycle Priority of the 2005 Call for Ideas for Earth Explorer Core Missions[48].

Summary

The Cold-Land Processes Pathfinder will be the first space-based mission optimized to measure fresh water stored in snow on land and on ice sheets. The potential science, application and socioeconomic benefits are very high. This unique high-resolution, high-frequency microwave mission concept addresses a high-priority need widely identified nationally and internationally, and fills a major gap in the conceptual global water-cycle observing system. It is a mature community-driven concept ready for an exploratory mission, and has strong potential for future transition to operations.

Acronyms

ALOS	Advanced Land Observing Satellite
AMSR	Advanced Microwave Scanning Radiometer (Japan)
AMSR-E	Advanced Microwave Scanning Radiometer for Earth Observing System (Japan)
ASAR	Advanced Synthetic Aperture Radar (Europe)
ASCAT	Advanced Scatterometer (Europe)
CEOS	Committee on Earth Observation Satellites
CliC	Climate in Cryosphere Program (WMO/WCRP)
CLPP	Cold Land Processes Pathfinder
CLPWG	Cold Land Processes Working Group
CLPX	Cold Land Processes Field Experiment
CMIS	Conical Scanning Microwave Imager/Sounder (U.S.)
CONUS	Conterminous United States
DMSP	Defense Meteorological Satellite Program
EOS	Earth Observing System
ERS	European Remote Sensing Satellite
ESA	European Space Agency
FAO	Food and Agriculture Organization of the United Nations
GAW	Global Atmosphere Watch (WMO)
GCOS	Global Climate Observing System (WMO, UNESCO, UNEP, ICSU)
GEOSS	Global Environmental Observing System of Systems
GOOS	Global Ocean Observing System
GOS	Global Observing System (WMO)
GPM	Global Precipitation Mapping Mission (U.S.)
GTOS	Global Terrestrial Observing System
HYDROS	Hydrospheric States Mission (U.S.)
HWRP	Hydrology and Water Resources Program (WMO)
ICSU	International Council for Science
IFOV	Instantaneous Field of View
IGBP	International Geosphere-Biosphere Program
IGFA	International Group of Funding Agencies for Global Change Research
IGOS	Integrated Global Observing System
IPCC	Intergovernmental Panel on Climate Change
IPY	International Polar Year
IWGEO	Interagency Working Group on Earth Observations
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NIDIS	National Integrated Drought Information System (U.S.)
NOAA	National Oceanic and Atmospheric Administration
NOSA	NOAA Observing System Architecture
NPOESS	National Polar Orbiting Environmental Satellite System
NRC	National Research Council
NSA	National Snow Analyses (www.nohrsc.noaa.gov)
NWSRFS	National Weather Service River Forecast System
PALSAR	Phased-Array type L-band Synthetic Aperture Radar (Japan)
POLSCAT	Polarimetric Scatterometer
RMSE	Root Mean Squared Error
SAR	Synthetic Aperture Radar
SIR-C/X	Shuttle Imaging Radar-C/X
SMMR	Scanning Multichannel Microwave Radiometer (U.S.)
SMOS	Soil Moisture and Ocean Salinity mission (Europe)
SSM/I	Special Sensor Microwave Imager (U.S.)
SWE	Snow Water Equivalent
TOPEX	Ocean Topography Experiment
VIIRS	Visible-Infrared Imaging Spectrometer (U.S.)
UNEP	United Nations Environment Program
UNESCO	United Nations Education, Science and Cultural Organization
WCRP	World Climate Research Program (WMO)
WHYCOS	World Hydrologic Cycle Observing System (WMO)
WMO	World Meteorological Organization
WRF	Weather Research and Forecast Model

[48] See www.esa.int/esaLP/earthexplorers.html