# Cold Land Processes
# Science, Technology, and Applications

## 9th Workshop of the NASA Cold Land Processes Working Group

**May 28-29, 2003**

**Boulder, Colorado**

## Agenda

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This will be the ninth in a series of open workshops focused on identifying and developing the science, technology, and applications infrastructure necessary to support improved understanding and prediction of water in cold land regions.

There are two major objectives for this workshop. The first is to provide a review of the status of all data collected during the 2002-2003 Cold Land Processes Field Experiment (CLPX) in order to facilitate planning for future research projects. The review will include a summary of the data that were collected, their current status and format, their potential for use in science investigations, and how they may be accessed. The review will be conducted by the experiment coordinators and instrument teams, and will provide important information for anyone considering submission of a research proposal that might involve CLPX datasets.

The second objective is to review and refine a new science plan and roadmap for Cold Land Processes (CLP) within NASA's Earth Science Enterprise. The CLP roadmap describes a series of planned science and technology development activities, <u>including future CLP field experiments</u>, that are necessary to advance understanding and prediction of cold regions water, weather and climate. Importantly, this includes efforts now underway to develop the science and technology framework to support a new measurement mission concept called the Cold Land Processes Pathfinder. This will be a science-driven mission to measure snow water equivalent and snow wetness from space. The centerpiece of this mission concept is a set of four overarching science questions related to winter precipitation, snowpack water storage, atmospheric and terrain controls on snow distribution, and snow-atmosphere interactions. Through previous workshops, these questions have evolved as the principal science drivers for improving our understanding and predictive capabilities. New measurements from the pathfinder mission will be expected to directly address these questions. Workshop participants will be asked to review, discuss and refine both the science questions and the CLP roadmap, and to identify specific research issues that will need to be addressed as we proceed in the future. This is an important opportunity help guide the direction of this exciting science and technology development effort.

**Wednesday, May 28**

8:30 - 8:45 Introductory Remarks

8:45 - 9:00 CLPX Overview and Study Areas (Don Cline)

Meteorological Data Collection

9:00 - 9:10 RUC2 and LAPS Analyses (Glen Liston)
9:10 - 9:20 Micromet - Main Towers (Gus Goodbody)
9:20 - 9:30 Micromet - Mini-Met (Paul Houser)
9:30 - 9:40 Micromet - LSOS (Janet Hardy)
9:40 - 9:50 Eddy Covariance - Rabbit Ears Systems (Paul Houser)
9:50 - 10:00 Eddy Covariance - North Park System (Larry Mahrt)

10:00 - 10:20 Break

Passive Microwave RS Data Collection

10:20 - 10:30 AMSR-E Satellite Data (Mary Jo Brodzik)
10:30 - 10:40 PSR Airborne Data (Boba Stankov)
10:40 - 10:50 U of M Ground-based Radiometers (Tony England)
10:50 - 11:00 GBMR Ground-based Radiometers (Richard Armstrong)

Active Microwave RS Data Collection

11:00 - 11:10 QuikSCAT and Radarsat Satellite Data (Kyle McDonald)
11:10 - 11:20 AIRSAR Airborne Data (Yunling Lou)
11:20 - 11:30 POLSCAT Airborne Data (Simon Yueh)
11:30 - 11:40 U of M Ground-based Radar (Kamal Sarabandi)
11:40 - 11:50 FMCW Ground-based Radar (HP Marshall)

11:50 - 1:00 Lunch

Optical RS Data Collection

1:00 - 1:10 MODIS Satellite Data (Terry Haran)
1:10 - 1:20 AVHRR Satellite Data (Don Cline)
1:20 - 1:30 Landsat Satellite Data (Bert Davis)
1:30 - 1:40 Hyperion Satellite, AVIRIS Airborne, and Ground Spectrometer Data (Tom Painter)
1:40 - 1:50 LIDAR and CIR Airborne Data (Bert Davis)

Other RS Data Collection

1:50 - 2:00 GAMMA Airborne Snow and Soil Moisture Data (Tom Carroll)
2:00 - 2:10 GPS Airborne Data (Dallas Masters)

In situ Snow and Soil Moisture Measurements

2:10 - 2:20 ISA Snow Surveys (Kelly Elder)
2:20 - 2:30 MSA Snow Surveys (Kelly Elder)
2:30 - 2:40 MSA Soil Moisture Data (Don Cline)
2:40 - 2:50 LSOS Snow Surveys (Janet Hardy)

2:50 - 3:10 Break

Data Management and Access

3:10 - 3:20 Entry and Quality Control of Field Data Sets (Mark Parsons)
3:20 - 3:30 Accessing CLPX Data (Mark Parsons)

Science and Research

3:30 - 3:50 NASA Earth Science and CLP Roadmaps (Jared Entin)
3:50 - 5:00 Discussion - How do we improve observation, understanding and prediction of water, weather, and climate in cold regions? How can CLPX data be effectively used for this goal? (Note: this brief discussion is a warm-up for tomorrow's discussion.)

**Thursday, May 29**

Cold Land Processes Technology

8:30 - 8:45 CLP and the NASA Earth Science Technology Office (ESTO) Technology Needs Assessment Database (Don Cline)
8:45 - 9:00 Evaluation of CLP Measurement Technologies - Active (Simon Yueh)
9:00 - 9:15 Evaluation of CLP Measurement Technologies - Passive (Ed Kim)

Cold Land Processes Pathfinder Mission (CLPP)

9:15 - 9:25 Overview (Don Cline)
9:25 - 9:40 Preliminary Engineering Development (Simon Yueh)
9:40 - 10:10 Measurement Objectives and Science Drivers (Bert Davis)

10:10 - 10:30 Break

10:30 - 2:00 Breakout Session: CLPP Science and Technology Development

Four to seven groups will break out and address one of the following areas. Each group will be asked to evaluate and refine the current science plan and roadmap for their respective area, in an effort to flesh out the science issues and determine science trade-offs with respect to major options under consideration for the parthfinder mission. Then the groups will be tasked to identify data gaps that will need to be filled in the next CLPX to address specific science questions in their area, and to suggest possible experimental plans that might be used to address these questions.

Group 1: Snowfall Precipitation and Estimation (PRECIP) (Daqing Yang)
Group 2: Snowpack Water Storage (STORAGE) (Kelly Elder)
Group 3: Controls on Snowpack Dynamics (CONTROLS) (Richard Kelly)
Group 4: Feedbacks on Weather and Climate (FEEDBACKS) (Glen Liston)

Optional Groups
Group 5: Microwave Algorithm Development (ALGORITHMS)
Group 6: Technology Development (TECHNOLOGY)
Group 7: Applications Development (APPLICATIONS)

Material for each of these areas will be distributed prior to the workshop.

2:00 - 4:30 Group Presentations and Discussion (20 min each)

4:30 - 5:00 Wrap-up

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# Logistics

Please see detailed logistics on the web at http://nsidc.org/events/clp2003

**Location**

The meeting will be held at the University of Colorado, in Room #123 of the Computer Building on CU's East Campus. See the above web site for directions.

**Lodging**

Rooms are being held at the Best Western Golden Buff Lodge for May 27 and 28. The rooms will be held under "CLPX Workshop/NSIDC" until May 16 at $79.00 plus tax.

1-800-999-2833
1-303-442-7450
1725 28th Street
Boulder, CO 80301
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## Appendix 1: NASA Earth Science Enterprise Research Strategy

The mission of NASA's Earth Science Enterprise (ESE) is to develop a scientific understanding of the Earth system and its response to changes, as well as to improve prediction capabilities for climate, weather, and natural hazards. Thus, the Earth science research program aims to gain deeper insight by describing how the components of the Earth system function, how they interact, and how they may evolve in the future. These interactions occur on a continuum of spatial and temporal scales ranging from short-term weather to long-term climate variations, and form local and regional to global scales. The challenge is to develop the ability to predict changes that will occur in the next decade to century, both naturally and in response to human activities.

In general, the Enterprise aims to provide scientific answers to five challenging scientific and societally relevant Earth system science questions:

- **Earth's natural variability:** How is the global Earth System changing?
- **Forcing factors:** What are the primary forcings of the Earth System?
- **Response to disturbances:** How does the Earth System respond to natural and human-induced changes?
- **Consequences:** What are the consequences of change in the Earth System for human civilization?
- **Prediction:** How well can we predict changes in the Earth System that will take place in the future?

In the ESE Research Strategy, there is a set of 23 subsidiary questions associated with these five main categories of questions (Table 1). Highlighted questions are closely associated with the focus of the Cold Land Processes Working Group.

**Table 1**
**ESE Key Research Questions**
**Overall: How is the Earth changing and what are the consequences for life on Earth?**

***How is the global Earth system changing? (Variability)***
- How are global precipitation, evaporation, and the cycling of water changing?
- How is the global ocean circulation varying on interannual, decadal, and longer time scales?
- How are global ecosystems changing?
- How is stratospheric ozone changing, as the abundance of ozone-destroying chemicals decreases and new substitutes increases?
- What changes are occurring in the mass of the Earth's ice cover?
- What are the motions of the Earth and the Earth's interior, and what information can be inferred about Earth's internal processes?

***What are the primary forcings of the Earth system? (Forcing)***
- What trends in atmospheric constituents and solar radiation are driving global climate?
- What changes are occurring in global land cover and land use, and what are their causes?
- How is the Earth's surface being transformed and how can such information be used to predict future changes?

***How does the Earth system respond to natural and human-induced changes? (Response)***

- What are the effects of clouds and surface hydrologic processes on Earth's climate?
- How do ecosystems respond to and affect global environmental change and the carbon cycle?
- How can climate variations induce changes in the global ocean circulation?
- How do stratospheric trace constituents respond to change in climate and atmospheric composition?
- How is global sea level affected by climate change?
- What are the effects of regional pollution on the global atmosphere, and the effects of global chemical and climate changes on regional air quality?

***What are the consequences of change in the Earth system for human civilization? (Consequences)***
- How are variations in local weather, precipitation and water resources related to global climate variation?
- What are the consequences of land cover and land use change for the sustainability of ecosystems and economic productivity?
- What are the consequences of climate and sea level changes and increased human activities on coastal regions?

***How well can we predict future changes in the Earth system? (Prediction)***
- How can weather forecast duration and reliability be improved by new space-based observations, data assimilation, and modeling?
- How well can transient climate variations be understood and predicted?
- How well can long-term climatic trends be assessed or predicted?
- How well can future atmospheric chemical impacts on ozone and climate be predicted?
- How well can cycling of carbon through the Earth system be modeled, and how reliable are predictions of future atmospheric concentrations of carbon dioxide and methane by these models?

The complete NASA ESE Research Strategy may be found at:

http://www.earth.nasa.gov/visions/researchstrat/Chap1_Research_Strategy.doc

## Appendix 2: Cold Land Processes Pathfinder Concept

**Instrument Concept**

- Combined Active/Passive imaging microwave system
- Both active and passive sensors are dual-frequency
- Breakthrough in passive resolution
- Dual-polarization
- Low incidence angle (~10 degrees off-nadir) for both active and passive

| Sensor | Sensor | Frequency | Wavelength | Resolution | Polarization |
|---|---|---|---|---|---|
| Active | SAR | 4-6 GHz (C-band) | 5-8 cm | 100-m | Dual |
| | SAR | 11-14 GHz (Ku-band) | 2-3 cm | 100-m | Dual |
| Passive | Radiometer | 18-19 GHz | 1.5 cm | 5-km | Dual |
| | Radiometer | 37-39 GHz | 0.8 cm | 2-km | Dual |

**Orbital Configuration**

- Narrow swath width (~30-km)
- Temporal repeat interval 3-9 days, depending on required spatial coverage and revisit time (Table 1, Figures 1-3).

| Latitude | Swath Separation 3-day Repeat (km) | Swath Separation 6-day Repeat (km) | Swath Separation 6-day Repeat (km) |
|---|---|---|---|
| 70 | 280 | 140 | 93 |
| 60 | 431 | 214 | 142 |
| 50 | 564 | 279 | 186 |
| 40 | 677 | 335 | 223 |

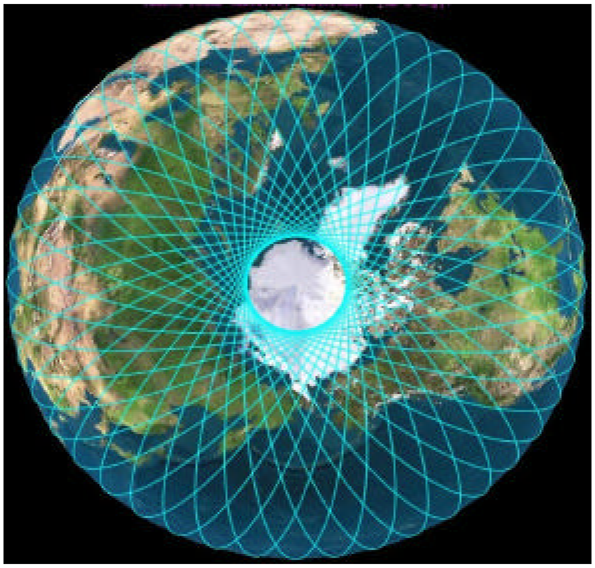

**Figure 1**. Orbital tracks for 3-day repeat interval are shown in blue. Each track would be revisited every 3-days in this exact-repeat configuration. The tracks are shown at their full 30-km swath width, therefore gaps between the tracks would never be imaged by the sensor. Exact longitudinal position of the track-set can be configured to optimize areas imaged by the sensor. For reference, this configuration would have 7 ascending and 7 descending tracks between San Francisco and New York.

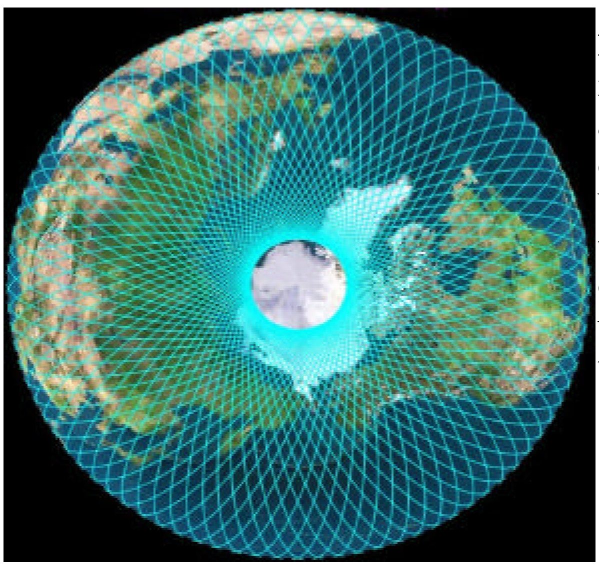

**Figure 2**. Orbital tracks for 6-day repeat interval are shown in blue. As above, the tracks are shown at their full 30-km swath width. The closer spacing of the orbital tracks is achieved by trading off the repeat interval. Individual tracks would not be revisited for 6-days in this configuration. For reference, this configuration would have 14 ascending and 14 descending tracks between San Francisco and New York.

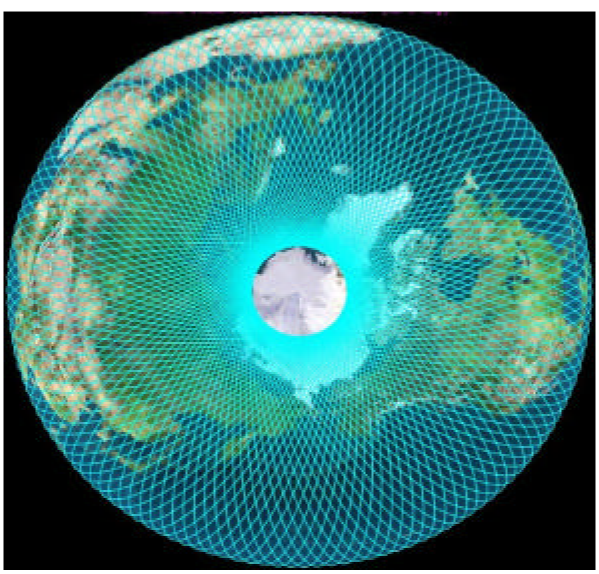

**Figure 3**. Oribital tracks for 9-day repeat interval are shown in blue. As above, the tracks are shown at their full 30-km swath width. Again, the closer spacing is achieved by trading off temporal resolution. Individual tracks would not be revisited for 9-days in this configuration. For reference, this configuration would have 21 ascending and 21 descending tracks between San Francisco and New York.

## BREAKOUT GROUP 1: SNOWFALL DISTRIBUTION (PRECIPITATION)

### MAJOR SCIENCE QUESTION:

**What is the frequency and distribution of global snowfall?**

- What is the intraseasonal and interannual frequency and distribution of snowfall?
- How many snowfall events contribute to the formation of snowpacks and the world's fresh water storage?

### ESE SCIENCE DRIVERS:

- *How are global precipitation, evaporation, and the cycling of water changing? (Variability)*

### PROBLEM STATEMENT:

Snowfall is a major component of the Earth's precipitation budget but is poorly measured. Although expected to be a sensitive indicator of climate variability and changing water cycle dynamics, we have little ability today to quantify fundamental characteristics of global snowfall (i.e. frequency and distribution). This first step must be addressed before we can understand how global precipitation (snowfall) and the cycling of water is changing.

- Although poorly measured, snowfall is the most common form of precipitation in many high-latitude and mountainous regions of the world. The frequency of snowfall events varies widely. In some regions, snowpacks develop from a high frequency of light-snowfall events. Elsewhere, fewer but larger events form the snowpack. In areas such as the western U.S., single storms often make the difference between well-below normal and well-above normal seasonal snowpacks. Understanding the frequency and distribution of winter precipitation is essential to understanding weather and climate variability.

- Most precipitation gages are designed for rainfall and do not capture snowfall effectively. Gage-undercatch of 25-50% is common, depending on wind conditions and the type of gage. Furthermore, gage networks are sparse in high-latitudes. Consequently, the distribution of winter precipitation is poorly known. Planned precipitation measurement missions will be unable to measure light snowfall anywhere and will not make any measurements at all in high-latitude areas.

### CLPP MEASUREMENT APPROACH:

Conceptually, frequent measurement of accumulated snow water equivalent (SWE) from a spaceborne sensor could reveal snowfall. Other snowpack mass exchange processes, such as sublimation and melt, would certainly affect the reliability of snowfall inferences drawn from changes in accumulated SWE, but the extent to which these affects would impact inference off snowfall from SWE change detection would depend largely on the frequency of repeat measurements. The effect of error characteristics of the remotely sensed SWE measurement on the ability to reliably infer snowfall also needs to be evaluated.

## BREAKOUT GROUP 1 QUESTIONS

1. Does the problem statement adequately capture the scientific thrust of the problem? If not, please comment and suggest modifications or additions.

2. For this conceptual approach to measuring snowfall by SWE change detection, the sensor and algorithms would ideally have high accuracy and precision to detect small changes in SWE associated with light snowfalls, and high temporal resolution to detect brief storms. However, realistically these characteristics are limited by a complex set of trade-offs involving algorithm capabilities, sensor technology, and cost, among other factors. In addressing the following questions, please consider whether the answers are fundamentally different for different time, space, and process scales, e.g. climate, weather, hydrologic response, etc.

- What are the limitations of this conceptual approach?
- How is the ability to address the science questions impacted by measurement repeat intervals of 3 days? 6 days? 9 days?
- The CLPP concept is an exploratory mission that would have a life of just 2-3 years. To what extent can the science questions be addressed in two years? Does this change significantly if the mission life is extended to 3-years?
- It is convenient to refer to remotely sensed SWE as "measured", but to be clear it is a quantity retrieved from microwave measurements using various algorithms, so it is really "modeled". The error characteristics of both the measurement (of microwave radiation) and the model (SWE algorithm) contribute to an overall accuracy and precision of the retrieved quantity. Inference of snowfall from SWE change detection depends on the overall accuracy and precision of the retrieved quantity. For example, a highly precise measurement with a consistent bias (low accuracy) might work well for snowfall inference. How would different levels of SWE accuracy and precision affect science objectives?
- Consider a hypothetical graph with one axis being temporal resolution and the other being measurement accuracy or precision. How does the ability to address the science questions fit into this graph, e.g. where in the 2D space does the ability to infer snowfall from SWE change detection usefully exist? Is this different for different objectives (i.e. climate, weather, hydrology, etc.)?
- Is spatial resolution of the measurement a major driver for this conceptual approach? Why or why not?
    - e.g. precipitation gages measure precip falling within a few square centimeters, while ground-based radars measure precipitation with resolution of a few square kilometers. Is there an "ideal" resolution for snowfall measurement? Does it depend on the purpose?

3. What research is needed to better understand the potential capabilities of the CLPP conceptual approach to winter precipitation measurement?

- Can the 1-, 2-, 4-, and 6-day repeat intervals of the ground and airborne active and passive microwave CLPX datasets be used to explore this approach?

4. Are there any field datasets not collected in CLPX that are necessary to conduct needed research and advance the capability to address the science objective?

## BREAKOUT GROUP 2: SNOWPACK WATER STORAGE (STORAGE)

### MAJOR SCIENCE QUESTIONS:

**How much of the global fresh water budget is stored seasonally as snow? How variable is this at different time and space scales?**

- What is the intraseasonal and interannual variability in the amount of fresh water stored in seasonal snowpacks (i.e. snow water equivalent, or SWE) at local, regional, continental and global scales?

### ESE SCIENCE DRIVERS:

- *How are global precipitation, evaporation, and the cycling of water changing? (Variability)*
- *How are variations in local weather, precipitation and water resources related to global climate variation? (Consequences)*

### PROBLEM STATEMENT:

The storage of large amounts of fresh water in seasonal snow covers is a major component of the global water cycle. A nearly 3-decade record of snow water equivalent (SWE) retrieved from passive microwave radiometry provides a baseline for monitoring changes in this important storage term. However, the error characteristics of these retrievals around the globe need to be better quantified before definitive understanding of the spatial and temporal variability of SWE is possible. Furthermore, this record has coarse spatial resolution (~25-km), prohibiting understanding of local-to-regional scale variability.

- This storage term is very dynamic, as the location and amount of water stored in seasonal snowpacks can change dramatically in a matter of days. On average, over 60% of the northern hemisphere land surface has snow cover in mid-winter, and over 30% of Earth's total land surface has seasonal snow.

- Our historical "baseline" for estimating this storage term is the 27-year passive microwave record of SMMR and SSM/I, now being carried forward by AMSR and eventually by NPOESS sensors. Due to limitations of coarse resolution radiometry, there is substantial uncertainty associated with historical baseline. Models are now beginning to provide estimates of snow water equivalent (SWE), but because of the high uncertainty of available observations these estimates remain largely unconstrained.

### CLPP MEASUREMENT APPROACH:

A new remote sensing measurement system for SWE needs to accomplish at least two things in this area. First, it needs to tie-in to the existing historical (and continuing) passive microwave record in some way, and enable improved understanding of its accuracy and precision. Second, it needs to break new ground by enabling improved understanding of the local-to-regional characteristics of snow water storage and their affects on weather and climate. Both issues are addressed by the combination of relatively high-resolution radiometry, the high-resolution radar, and the 30-km swath width that will “contain” entire traditional passive microwave footprints. This combination will create possibilities to evaluate sub-footprint scale characteristics of the coarse-resolution passive microwave sensors, possibly permitting calibration of the global algorithms.

## BREAKOUT GROUP 2 QUESTIONS

1. Does the problem statement adequately capture the scientific thrust of the problem? If not, please comment and suggest modifications or additions.

2. Overall, this question is concerned with fundamental issues of measurement and sampling. The ability to detect variation depends on the spatial and temporal scale of the variation, the spatial resolution and temporal frequency of the measurement, the accuracy and precision of the measurement, and on the sampling strategy used for the measurement.

- From the perspectives of climate, weather, and hydrology, what spatial and temporal scales of variation in snow water storage are most important for understanding different processes, and why?
- For different science objectives, what understanding is enabled by different spatial and temporal measurement resolutions?
    - For example, consider a range of spatial resolutions such as 50-m, 100-m, 250-m, 500-m, 1-km, and 5-km, and of temporal resolutions such as 3-days, 6-days, or 9-days. What questions can be answered with SWE measurements at one resolution but not another?
    - Are there “breakpoints” along a hypothetical curve where a large gain in understanding is enabled by reaching a particular spatial or temporal resolution?
- The CLPP concept is an exploratory mission that would have a life of just 2-3 years. To what extent can the science questions be addressed in two years? Does this change significantly if the mission life is extended to 3-years?
- Detection of variation requires measurements with error characteristics (i.e. accuracy and precision) substantially less than the degree of variation (e.g. < 0.5 Nyquist). For different science objectives (climate, weather, hydrology, etc.) and different scales (local, regional, continental, global), what accuracy and precision may be necessary to enable understanding of important variability?

3. Unlike many familiar remote sensing systems that provide global “wall-to-wall” imagery with spatially continuous and contiguous measurements covering the world, various constraints on a moderate-to-high resolution microwave sensor system have lead to a different sampling approach for the CLPP. In this approach, SWE would be measured at relatively high spatial resolution (on the order of 100-m for active, and 2 to 5 km for passive) along narrow swaths (~30-km). Swaths would be on the order of a couple of hundred kilometers apart, depending on latitude (the higher the latitude, the closer together the swaths get). See Appendix 2 for more details.

- How does the tradeoff between repeat interval and orbital track coverage affect the ability to detect and quantify spatial and temporal variability of snowpack water storage?

- Is understanding of different processes, or the ability to address different science objectives, enabled or disabled by the combinations of measurement repeat intervals and swath separations outlined in Appendix 2?
- Do these affects change if the CLPP measurements are considered together with existing coarse-resolution global-imaging microwave sensors, such as AMSR or QuickSCAT?

3. What research is needed to better understand the potential capabilities of the CLPP conceptual approach to quantify snow water storage and its variability?
   - Each of the three CLPX MSAs contains high-resolution airborne microwave remote sensing datasets (AIRSAR and PSR), and all three MSAs are contained within a larger domain of satellite microwave datasets (AMSR and QuickSCAT). Can these datasets, perhaps with land surface modeling, be used to test the ability to quantify snow water storage and its variability?

4. Are there any field datasets not collected in CLPX that are necessary to conduct needed research and advance the capability to address the science objective?

## BREAKOUT GROUP 3: CONTROLS ON SNOWPACK DYNAMICS (CONTROLS)

### MAJOR SCIENCE QUESTIONS:

**What governs the magnitude and variability of snow water storage and snow melt - atmospheric controls, or surface controls?**

- To what degree is the magnitude, spatial and temporal variability, and evolution of snow water equivalent and snow melt controlled by weather and climate? By surface topography and land cover?

### ESE SCIENCE DRIVERS:

- *How are global precipitation, evaporation, and the cycling of water changing? (Variability)*
- *What are the effects of clouds and 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)*

### PROBLEM STATEMENT:

Orographic precipitation, wind redistribution of snow on the ground, and forest canopy interception of snowfall are three examples of surface controls that have a significant affect on the formation and fate of snowfall. The magnitude and variability of snow water storage and snow mass and energy exchanges depends to varying degrees on such surface controls. The tools of choice for understanding the complex nature of these interactions are physically based, spatially distributed water, weather and climate models. However, representation of these effects is not yet well developed in most models, and understanding is limited as a result. Perhaps more importantly, few observations are available to evaluate these effects in model analyses. The very nature of the heterogeneity resulting from these surface controls often makes analysis of point observations of snow extremely difficult and of limited utility.

- The extent and distribution of the Earth's snow covers are controlled by complex interactions between moderate- to large-scale atmospheric phenomena and relatively small-scale terrain features of the land surface. While snowpack formation obviously begins with snowfall from the atmosphere, the distribution of snow on the ground is affected to a large extent by land surface characteristics and interactions with wind. In mountainous areas, snowfall itself is affected by topography. As a result of these interactions, snowpacks exhibit a high degree of spatial and temporal variability at scales from meters to a few kilometers, and from hours to days.

- Wind redistributes snow during and after snowfall, resulting in complex depositional patterns that are controlled by topography and vegetation as well as by the amount of snow available for redistribution. This dramatically changes both the mass and energy regimes of the snowpack by moving snow preferentially to different slopes, aspects, and land covers. Snow may be completely removed from some areas, exposing bare ground with markedly lower albedo. These changes influence subsequent energy exchanges with the atmosphere and snow melt, and in turn affect feedbacks to the atmosphere that change local, and possibly larger-scale weather.

## MEASUREMENT APPROACH:

The CLPP concept focuses on achieving high-resolution remote sensing observations of snow water equivalent (SWE) and snow wetness within limited swath coverage, to augment current and future global imaging systems that operate at much coarser resolution. High-resolution measurements are needed to evaluate models and develop a more complete understanding of the surface processes that contribute to significant variability in snowpack water storage and snow melt. Importantly, the resolution of the measurements must be commensurate with the resolution of the models. Continental and global land surface models are now coming on-line with resolution of 1-km, and hemispheric-scale weather prediction models have resolutions of 10-km now, and 5-km models are anticipated to come on-line soon. Thus remote sensing is needed at resolutions (ideally) of less than half of these model resolutions (e.g. 500-m or less for detailed land surface models, 5-km or less for weather and climate prediction models) to support model evaluation.

## BREAKOUT GROUP 3 QUESTIONS

1. Does the problem statement adequately capture the scientific thrust of the problem? If not, please comment and suggest modifications or additions.

2. Consider the effects of spatial and temporal resolution of SWE measurement on the ability to observe and understand processes related to orographic precipitation, wind redistribution of snow on the ground, and snow in forested areas. For this exercise, ignore the effects of spatial resolution on the accuracy of SWE measurement (e.g. mixed pixels).

- Does the ability to observe and understand these processes change significantly between resolutions of 50-m, 100-m, and 250-m? Between resolutions of 2-km and 5-km?
- Does it change significantly between temporal resolutions of 3-days, 6-days, and 9-days?
- The CLPP concept is an exploratory mission that would have a life of just 2-3 years. To what extent can the science questions be addressed in two years? Does this change significantly if the mission life is extended to 3-years?

2. Consider the effect of accuracy and precision of both SWE and snow wetness measurements on the ability to understand controls on the distribution of snow water storage and melt.

- How much measurement accuracy is needed to resolve the effects of different controls?

3. What research is needed to better understand the potential capabilities of the CLPP conceptual approach to understand controls on snow water storage and its variability?

- Can ground and airborne SWE measurements from the different landscapes in CLPX be used to develop and test a methodology for understanding these controls globally?

4. Are there any field datasets not collected in CLPX that are necessary to conduct needed research and advance the capability to address the science objective?

## BREAKOUT GROUP 4: FEEDBACKS ON WEATHER AND CLIMATE (FEEDBACKS)

### MAJOR SCIENCE QUESTIONS:

**How do snowpack characteristics control weather and climate?**

- At what spatial and temporal scales do the extent, variability, and evolution of snow water equivalent (SWE) and snow wetness affect weather and climate through controls on fluxes, storage, and transformations of water and energy?

- How significant are these effects, and what are the implications for improved prediction?

### ESE SCIENCE DRIVERS:

- *How are global precipitation, evaporation, and the cycling of water changing? (Variability)*
- *What are the effects of clouds and 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)*
- *How well can transient climate variations be understood and predicted? (Prediction)*
- *How well can long-term climatic trends be assessed or predicted? (Prediction)*

### PROBLEM STATEMENT:

Snow cover characteristics affect weather through several mechanisms. Many interactions between the snowpack and the atmosphere involve inherently processes that are most comprehensively understood at local or hillslope scales. Very little is known about the aggregate behavior of these local-scale processes, their variability, or their consequences at larger scales.

- Snow covers affect the atmosphere through their obvious and dramatic modification of the surface albedo, and by their less obvious but equally important affects on stability of the boundary layer, surface roughness, and sensible and latent energy and mass exchanges. The significant energy required to melt seasonal snow covers makes them an important energy sink in the global energy budget. As air masses advect over snow cover, their characteristics can be changed markedly depending on the characteristics of each. Thus snow covers exert a control on weather both locally and downstream.

- The nonlinear behavior of these cold land processes results in dramatic shifts in behavior that depends to a first order on snow water equivalent (i.e. mass of ice and water present) and snow wetness (i.e. amount of liquid water present, and an indication of temperature and melt state of the snowpack). These characteristics change constantly and often rapidly. Because these snow cover characteristics themselves are highly variable in space and time, the nonlinear processes they affect and the resultant affects on weather are also highly variable.

**MEASUREMENT APPROACH**:

The CLPP concept focuses on quantifying snow water equivalent (SWE) and snow wetness. These are considered to be the first-order snowpack properties that influence snow-atmosphere interactions. The high spatial resolution of the CLPP measurements will permit studies of how local-scale snowpack properties aggregate or "scale-up" to affect larger scale weather and climate. The temporal resolution needs to be addressed

**BREAKOUT GROUP 4 QUESTIONS**

1. Does the problem statement adequately capture the scientific thrust of the problem? If not, please comment and suggest modifications or additions.

2. Models describing snow-atmosphere energy exchanges are fundamental to this science question. In particular, this question requires modeling approaches that can reveal how snowpack properties influence weather at scales ranging from local to global. In this setting, CLPP data would most likely be used for model initialization, updating and validation, and most inferences about snowpack controls on weather and climate would be drawn from the models themselves.

- From the modeling perspective, what spatial and temporal resolutions for SWE and snow wetness measurements are needed for this purpose (consider that CLPP data would come on-line in the 8-10 year time frame).
    - How do these needs differ for different purposes (e.g. weather, climate, or different processes)?
- How is the ability to address the science questions impacted by measurement repeat intervals of 3 days? 6 days? 9 days?
- The CLPP concept is an exploratory mission that would have a life of just 2-3 years. To what extent can the science questions be addressed in two years? Does this change significantly if the mission life is extended to 3-years?
- What constraints does the sampling framework of the CLPP (30-km swaths separated by 100-700-km, with 3-6 day repeat intervals - see Appendix 2) pose for model initialization, updating and validation?

3. What research is needed to better understand the potential capabilities of the CLPP conceptual approach to understanding the effects of snow characteristics on weather and climate?

- Can the CLPX in situ, remote sensing, and modeling data sets be used to demonstrate a framework for understanding these effects globally using future CLPP data?

4. Are there any field datasets not collected in CLPX that are necessary to conduct needed research and advance the capability to address the science objective?