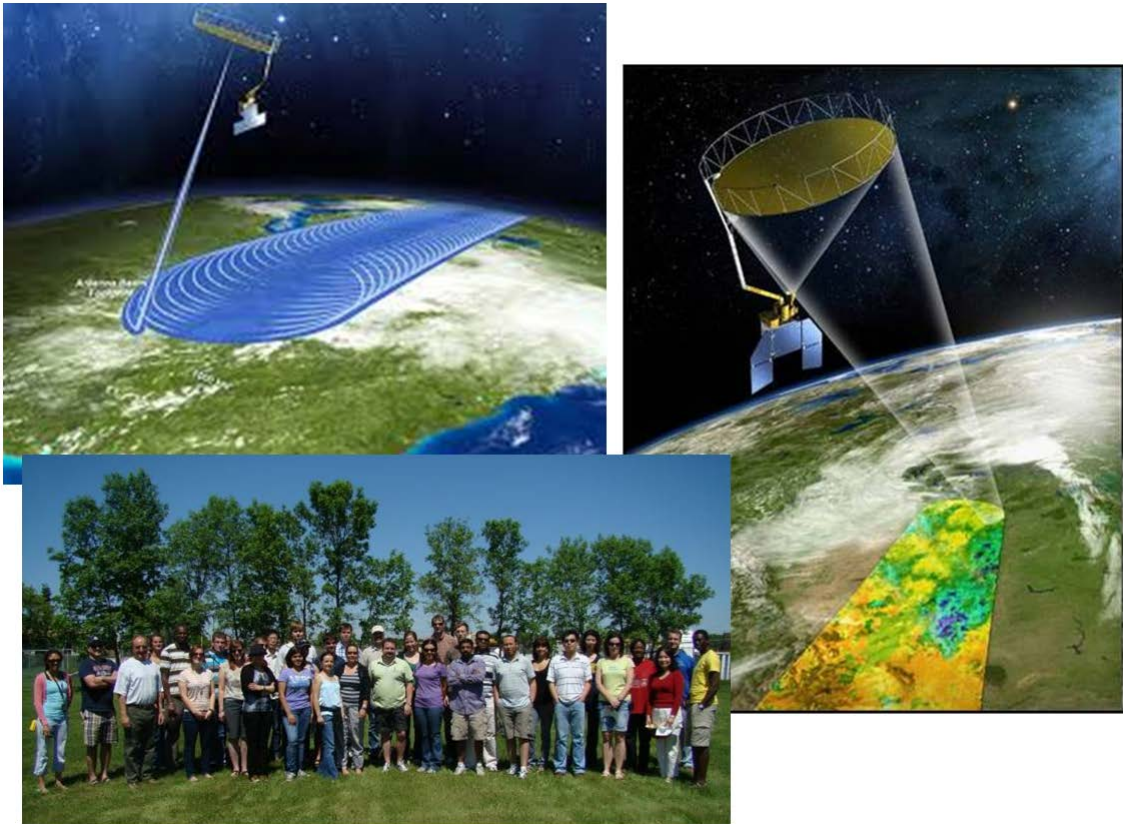


Canadian Science and Applications Plan for the Soil Moisture Active and Passive Mission



October 2013

Document Revision History

Revision	Date	Comments
1.0	20 Dec. 2010	Preliminary version presented to Environment Canada
2.0	22 Aug. 2011	First complete version of the Plan.
3.0	13 Nov. 2013	Updated version of the Plan (second phase of funding)
3.1	22 Jan. 2014	Modification to the budget section

Foreword (first version of the Plan)

In many respects, this plan for a Canadian contribution to NASA's SMAP mission is similar and is a natural extension to what was intended for Hydros, a mission that was selected in the early 2000s for Preliminary Analysis Phase in the context of NASA's ESSP program. The Hydros mission was dropped by NASA in 2005, just at the time when the Canadian Community was gathering to define its potential contribution, presented in a document called "Hydros Canadian Science and Applications Plan". A few aspects of this plan are still relevant for SMAP and appear with very little changes in the present document.

This is true for the inclusion of SMAP microwave remote sensing data (active and passive) into Environment Canada (EC)'s land data assimilation system, which has been the main driver for EC's involvement in this venture, and which at the end will provide Canada-wide near-surface and root-zone soil moisture products, in addition to improve operational environmental predictions (weather and hydrology). Other aspects of the Plan, however, have been greatly modified and/or augmented. The calibration-validation component, for instance, is now more extensive and more coordinated with US partners. Furthermore, new areas of research and development are now proposed for this Canadian contribution to SMAP. The possible combination of SMAP L-band data active and passive data with existing C-band active data from RADARSAT is an interesting example of this. Another example is the inclusion of a carbon modeling and assimilation component to the project, which establish links with climate applications that were not envisioned in the Canadian Hydros plan.

Foreword (updated version)

A few major goals were achieved during the first few years of the Canadian SMAP project. With support from the Canadian Space Agency (CSA), several research projects aimed at enhancing the impact of SMAP passive and active observations were initiated and funded for all the academic members of the Canadian Science Team. Research and development programs within two Government departments (Environment Canada, EC, and Agriculture and Agri-Food Canada, AAFC) have positioned SMAP as a crucial component of their upcoming operations. And two major field campaigns were conducted on Canadian soil for the calibration and validation (Cal-Val) of SMAP soil moisture products, involving large groups of Canadian and US scientists, from government and universities, including students, scientists, and professors. Without a doubt, the Canadian Science and Applications Plan for SMAP has played an important role in the elaboration and execution of all these activities.

Now, about a year before the expected launch of the SMAP satellite, there is a need to revisit this plan to make it more relevant for the second funding phase of the project, starting on April 1st 2014. As the reader will see, the section on Cal-Val has been greatly modified in this new version to include new field activities related to soil moisture, and more importantly to significantly increase Canada's contribution on the Cal-Val of SMAP freeze / thaw products. Other substantial modifications can be found in the Data, Products, and Outreach section as these aspects will become more important after launch.

Following the successful first few years of the Canadian SMAP project, it is with confidence that this new version of the Canadian Plan for SMAP is proposed to CSA and to the Canadian community. In collaboration with partners from the SMAP Science Team just recently established, the research and development activities proposed below will hopefully ensure that products resulting from or enhanced by the SMAP mission will optimally benefit Canada's society.

Stéphane Bélair

15 October 2013

Executive Summary

The Soil Moisture Active and Passive (SMAP) mission, initiated in February 2008 by the National Aeronautics and Space Administration (NASA), is now planned for launch in November 2014. Managed by the Jet Propulsion Laboratory (JPL) and NASA's Goddard Space Flight Center (GSFC), with a Science Definition Team Lead from the Massachusetts Institute of Technology (MIT), this mission will include a microwave radiometer and a radar, both operating at frequencies in the L-band range, and will provide a capability for global mapping of soil moisture and freeze/thaw (F/T) state with unprecedented accuracy, resolution, and coverage.

The main objectives of the Canadian scientific participation in SMAP are to *i*) contribute to the calibration and validation (Cal/Val) of SMAP soil moisture and F/T products by acquiring and processing experimental data over Canada, and *ii*) improve the representation of the energy, water, and carbon cycles in Canadian environmental analysis and prediction systems using SMAP soil moisture and F/T data.

The Canadian contribution to SMAP Cal/Val includes both pre-launch and post-launch activities. Pre-launch Cal/Val is focused on the validation of the means in place to fulfill the mission objectives, whereas post-launch Cal/Val is focused on validating that the science products meet their quantified requirements, and on improving the algorithms and quality of products over the mission life. As part of this Plan, several Canadian observational networks will be used as SMAP core validation sites for both soil moisture and F/T. A first field campaign called the Canadian Experiment for Soil Moisture in 2010 (CanEx-SM10) was conducted in Saskatchewan, in collaboration with the US SMAP Project. A second field campaign called SMAP Validation Experiment 2012 (SMAPVEX12) took place in Southern Manitoba. A post-launch campaign is also expected in 2016.

The research and development proposed in this plan regarding soil moisture retrieval essentially focus on the use of SMAP high-resolution active data to refine soil moisture retrievals and to be included in a high-resolution version of the Canadian Land Data Assimilation System (CaLDAS), currently being developed and tested for operational implementation at EC. More specifically, a synergistic approach including passive (Soil Moisture and Ocean Salinity - SMOS, SMAP) and active (Advanced Land Observing Satellite - ALOS, Advanced Synthetic Aperture Radar - ASAR-Envisat, RADARSAT-2, SMAP) remote sensing data will be developed. In all this research that will be done in Canada concerning soil moisture retrieval from SMAP and from other space-based instruments, emphasis will be placed on providing relevant data to inform on the best strategy to use in CaLDAS related to forward modeling.

Critical issues regarding F/T retrieval from space-based remote sensing will be examined as part of an effort of the Canadian SMAP team to include L-band active data from SMAP in their algorithms to retrieve the F/T state of the soil. As is the case for soil moisture retrieval, results and methods arising from this work will be used for forward

modeling in CaLDAS, and careful attention will be given to the specification of the uncertainty of the retrievals.

The main objective of the data assimilation component of this scientific plan is to produce high-resolution and accurate soil moisture and F/T state analyses based on the inclusion of both passive and active measurements from SMAP into CaLDAS. Several of the issues for achieving this have been examined in the context of other sensors (i.e., SMOS) and will continue to be investigated with SMAP. These include bias correction or renormalization of brightness temperatures, the impact of land water fractional coverage, and the specification of both first guess and observations uncertainty. Other issues, more specifically linked with SMAP high-resolution data, are related to the combination of SMAP active data (3 km resolution) with lower-resolution passive data from SMAP and SMOS radiometers (about 40 km resolution) and with screen-level observations (air temperature and humidity). Combination with high-resolution C-band data from RADARSAT-2 or from the upcoming RADARSAT Constellation Mission (RCM) will also be examined.

Because of the strong interconnections between the energy, water, and carbon global cycles, and because of the benefits that are expected by analyzing and representing processes associated with all three cycles in a single analysis and assimilation system, it is proposed as part of this Plan to include (or closely link) terrestrial ecosystem models into (with) CaLDAS in order to assimilate or analyze vegetation characteristics (LAI, canopy conductance) and produce estimates of CO₂ fluxes and of Net Ecosystem Exchange (*NEE*). Following these recent developments, it is thus proposed to include a carbon component to CaLDAS, in addition to the assimilation of surface temperatures, soil moisture, and terrestrial snow.

Accurate representation of soil moisture is of primary importance for several types of environmental prediction systems, and will be evaluated in the context of numerical weather prediction (NWP). Other studies related to hydrology and risk assessment for agriculture could (and may eventually) also be included.

Other aspects of this plan include the distribution and outreach to ensure Canadians (population, government, academia, industry) uses SMAP-related products to their full potential. Three approaches will be used for the distribution: numerical raw data, static maps from a web site, and geospatial products (e.g., web mapping service). Several activities will be organized as part of outreach.

The Canadian science team members are responsible for carrying out the scientific activities described in the Canadian SMAP Plan. This team is composed of a group of scientists that have successfully worked together in the context of previous research projects, field experiments, and science working groups. This group comprises scientists from both government and academic institutions, and from several regions of the country.

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List of Acronyms

2CA	Dual-Polarization Iterative Algorithm
AAFC	Agriculture and Agri-Food Canada
ABLE	Atmospheric Boundary Layer Experiments
AGDM	Agricultural Drought Monitoring Stations
AIEM	Advanced Integral Equation Model
AirMOSS	Airborne Microwave Observatory of Subcanopy and Subsurface
ALECTRA	Alaskan Ecological Transect
ALOS	Advanced Land Observing Satellite
AMSR-E	Advanced Microwave Scanning Radiometer for Earth Observation Systems
A/P	Active / Passive
ASAR	Advanced Synthetic Aperture Radar
ATBD	Algorithm Theoretical Basis Document
AWIFS	Advanced Wide Field Sensor
BERMS	Boreal Ecosystem Research and Monitoring Sites
BEPS	Boreal Ecosystem Productivity Simulator
Biome-BGC	Biome-BioGeoChemical Cycles model
CaLDAS	Canadian Land Data Assimilation System
CALM	Circumpolar Active Layer Monitoring
Cal/Val	Calibration and validation
CanEx-SM10	Canadian Experiment for Soil Moisture in 2010
CaPA	Canadian Precipitation Analysis
CASA	Carnegie-Ames-Stanford Approach
CBRN	Chemical, Biological, Radioactive, and Nuclear
CCC	Canadian Climate Centre
CDR	Critical Design Review
CDF	Cumulative Distribution Function
CEN	Center for Northern Studies
CEOS	Committee on Earth Observation Satellites
CFS	Canadian Forest Service
CGU	Canadian Geophysical Union
CIC	Canadian Ice Centre
CIFFC	Canadian Interagency Forest Fire Centre
CMEM	Community Microwave Emission Model
CMOS	Canadian Meteorological and Oceanographic Society
CRD	Climate Research Division (EC)
CRN	US Climate Reference Network
CRSS	Canadian Remote Sensing Symposium
CSA	Canadian Space Agency
CTEM	Canadian Terrestrial Ecosystem Model
C-TESSSEL	Tiled ECMWF Scheme for Surface Exchanges over Land
DMRT-ML	Dense Media Radiative Transfer – Multi-Layers
DND	Department of National Defense

DRDC	Defence Research Development Canada
EBCM	Method of Moments
EC	Environment Canada
ECMWF	European Centre for Medium-Range Weather Forecasts
EnKF	Ensemble Kalman Filter
FFRA	Federal Freshwater Research Agenda
FFST	Framework for Federal Science and Technology
F/T	Freeze / Thaw
FY	Fiscal Year
GCM	General Circulation Model
GCOS	Global Climate Observing System
GEO	Group on Earth Observations
GeoSens	Geospatial Cyberinfrastructure for Environmental Sensing
GEOSS	Global Earth Observation System of Systems
GEWEX	Global Energy and Water Cycle Experiment
GPP	Gross Primary Production
GRACE	Gravity Recovery and Climate Experiment
GRIP	Government Related Initiatives Program
GSC	Geological Survey of Canada
GSFC	Goddard Space Flight Center
GSWP	Global Soil Wetness Project
GTN-P	Global Terrestrial Network of Permafrost
HQP	Highly-Qualified Personnel
IEM	Integral Equation Model
IGOS-P	Integrated Global Observing Strategy Partnerships
IGWCO	Integrated Global Water Cycle Observation
INRS-ETE	Institut national de la recherche scientifique – Eau, terre, et environnement
IR	Infrared
IOC	In Orbit Check
ISMWG	International Soil Moisture Working Group
ISBA	Interactions between Surface, Biosphere, and Atmosphere
IPY	International Polar Year
JECAM	Joint Experiment on Crop Assessment and Monitoring
JERS	Japanese Earth Resources Satellite
JPL	Jet Propulsion Laboratory
LAI	Leaf Area Index
LPRM	Land Parameter Retrieval Model
LPVS	Land Products Validation Subgroup
MAFRI	Manitoba Agriculture, Food and Rural Initiatives
MIT	Massachusetts Institute of Technology
MODIS	Moderate Resolution Imaging Spectroradiometer
MRD	Meteorological Research Division
MSC	Meteorological Service of Canada
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Predictions

NDVI	Normalized Difference Vegetation Index
NEE	Net Ecosystem Exchange
NEP	Net Ecosystem Production
NPP	Net Primary Production
NRC	National Research Council
NRCan	Natural Resources Canada
NRCS	Natural Resources Conservation Service
NWP	Numerical Weather Prediction
NWRI	National Water Research Institute
PALS	Passive/Active L/S band sensor
PALSAR	Phased Array type L-band Synthetic Aperture Radar
PDR	Preliminary Design Review
PI	Principal Investigator
RCM	RADARSAT Constellation Mission
RFI	Radio-Frequency Interference
RISMA	Real-time In situ Soil Monitoring for Agriculture
RMS	Root-mean-square
RR	Dual-Polarization Reflectivity Ratio Algorithm
SAGES	Sustainable Agriculture Environment Systems
SAR	Synthetic Aperture Radar
SCA	Single-Channel Algorithm
SCAN	Soil Climate Analysis Network
SDT	Science Definition Team
SMAP	Soil Moisture Active and Passive mission
SMAPVEX12	SMAP Validation Experiment 2012
SMAPVEX16	SMAP Validation Experiment 2016
SMOS	Soil Moisture and Ocean Salinity
SNOTEL	SNOWpack TELEmetry Network
SOPFEU	Société de protection des forêts contre le feu
SPM	Small Perturbation Method
SPOT	Système Probatoire d'Observation de la Terre
SSA	Small Slope Approximation
SSM/I	Special Sensor Microwave Imager
UAVSAR	Uninhabited Aerial Vehicle Synthetic Aperture Radar
UHF	Ultra-High Frequency
USDA	United States Department of Agriculture
VIIRS	Visible Infrared Imager Radiometer Suite
VWC	Vegetation Water Content
WCCP	Water Cycle Community of Practice
WGCV	Working Group on Calibration and Validation
WMO	World Meteorological Organization
WMS	Web Mapping Service
WSSD	World Summit on Sustainable Development

1. The SMAP Mission

The Soil Moisture Active and Passive (SMAP) mission is one of four missions that has been recommended by the US National Research Council (NRC) Committee on Earth Science and Applications from Space for launch in the 2010-2013 time frame. A mission initiated by the National Aeronautics and Space Administration (NASA) as a start mission in February 2008, SMAP is now planned for launch in October 2014, about a year after the time frame established in NRC's Decadal study. Measurements from SMAP will play a crucial role in furthering our understanding of the Earth's water, energy, and carbon cycles. Managed by the Jet Propulsion Laboratory (JPL) and NASA's Goddard Space Flight Center (GSFC), with a Science Definition Team Lead from the Massachusetts Institute of Technology (MIT), this mission has been selected in March 2010 to proceed to Phase B (Definition Phase) at NASA, it has proceeded to Phase C (Design and Build) in July 2012, and is now in Phase D (Integration) since May 2013.

SMAP will provide a capability for global mapping of soil moisture and freeze / thaw (F/T) state with unprecedented accuracy, resolution, and coverage. The specific objectives of SMAP are to acquire space-based hydrosphere state measurements over a three-year period to:

- understand processes that link the terrestrial water, energy, and carbon cycles;
- estimate global water and energy fluxes at the land surface;
- quantify net carbon fluxes in boreal landscapes;
- enhance weather and climate forecast skill; and
- develop improved flood prediction and drought monitoring capabilities.

As alluded to in the last two items, observations from SMAP will be of crucial importance in future systems that will observe and predict natural hazards related to extreme weather, climate change, floods, and droughts. SMAP measurements will also provide key information related to the carbon cycle and in particular in regard to the so-called "missing carbon link".

The SMAP mission will include a microwave radiometer and a radar, both operating at frequencies in the L-band range. At such wavelengths (~ 20 cm), the electromagnetic signal is sensitive to moisture in a thin surface soil layer (2-10 cm, in optimal conditions depending mainly on the soil water content). This sensitivity to soil moisture is reduced in regions with dense vegetation due to the attenuating effect of liquid water contained in the leaves and trunks of the vegetation. The radiometer will provide brightness temperatures at the 1.41-GHz frequency, which is protected by international regulation for passive services. At this frequency, interference from radio frequencies should be limited, although this is not always the case as is currently being observed by the European Space Agency (ESA)'s Soil Moisture and Ocean Salinity (SMOS) mission. Radiometric observations from SMAP will provide accurate measurements of soil moisture through moderate vegetation of up to approximately 5 kg m⁻² water content,

which corresponds to mature crop fields. The radar, on the other hand, will measure surface backscatter at the 1.26-GHz frequency, with greater horizontal resolution than the radiometer but with less accuracy and more sensitivity to vegetation water content and soil roughness.

Because of its radar capability, SMAP will provide high-resolution global mapping of the surface F/T state. In the absence of large rainfall events that have the potential to alter landscape dielectric properties on short time scales, it is valid to assume that F/T state transitions mostly control rapid changes that are observed in radar backscatter measurements. A change detection methodology is thus currently favored to retrieve the landscape F/T state at high spatial resolutions.

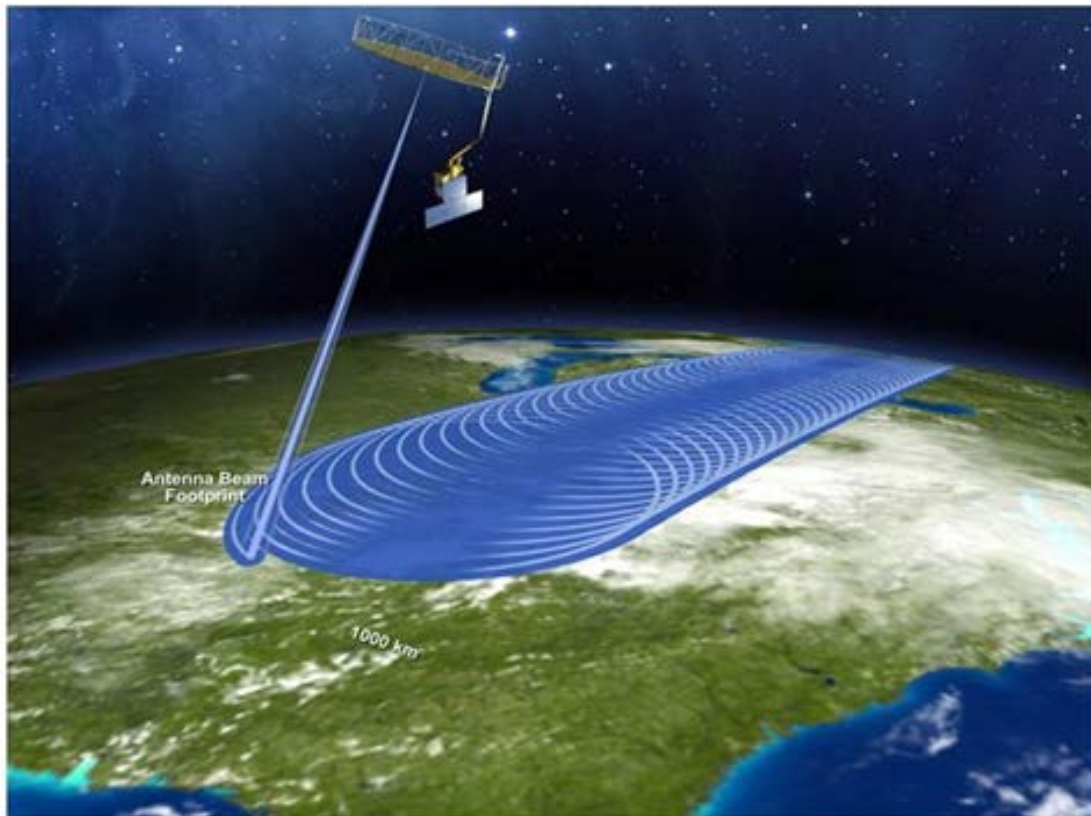


Fig. 1.1. Schematic of SMAP's orbit and conical data acquisition.

SMAP will operate on a near-polar, sun-synchronous orbit approximately 680 km above the Earth surface, with a 6AM/6PM Equator crossing and an 8-day repeat ground-track. The swath width will be on the order of 1000 km, which will provide global coverage every 3 days at the Equator, and every 1-2 days at mid and high latitudes (see Fig. 1.1 for a schematic). The 6-m diameter deployable mesh antenna with 40° incidence angle will ensure a 40-km footprint for the radiometer and 30-km real aperture footprint for the radar. Range and Doppler discrimination combined with further processing will be used to obtain a 1-3 km spatial resolution for radar measurements, in a synthetic aperture radar (SAR) mode. Passive and active observations will be combined by processing and by

data assimilation algorithms to produce accurate soil moisture estimates at an intermediate horizontal resolution of 10 km. More details about the SMAP instruments, mission requirements, and data products are given in the Appendices.

More details about the mission are provided in the following appendices:

- A. SMAP Scientific Measurements Requirements
- B. SMAP Satellite and Instrument Specifications
- C. SMAP Data Acquisition Strategy
- D. SMAP Data Products
- E. Top-level science schedule

In contrast with its predecessor mission Hydros, SMAP is a NASA directed mission, with no direct contribution from Canada on satellite or instrument development and/or construction. In spite of this, and because of the strong interest expressed by the Canadian scientific and operational communities for this mission (as was also the case for the Hydros mission), the Canadian Space Agency (CSA) has agreed to partner with Environment Canada (EC) to develop this Canadian Science and Applications Plan for SMAP. This involvement of CSA, based on an implementing agreement with NASA, will allow Canadian scientists to work in collaboration with US and other international partners on scientific and operational aspects of the mission. In addition to the benefits related to sustainable development and climate change, SMAP will reinforce Canada's expertise in several key scientific areas such as land data assimilation for numerical environmental prediction (weather, climate, hydrology, agriculture, forests), as well as radiometric and radar remote sensing of the land surface to retrieve soil moisture and the F/T state. As described below, Canada's scientific contribution to SMAP will consist of *i*) calibration and validation of SMAP measurements and retrievals (active and passive, soil moisture and F/T), and *ii*) research, development, and applications.

2. SMAP Potential Socio-Economical Benefits for Canada

Both soil moisture and F/T components of SMAP potentially have substantial impacts on several sectors of Canada's society and economy. As example, a non-exhaustive list of physical scientific areas sensitive to better knowledge of soil moisture and F/T conditions is given below (in alphabetical order):

Air quality and emergency response: Soil moisture influences the surface energy budget and thus the evolution of atmospheric mixing layer, which has a direct impact on particulate matter concentrations near the Earth's surface.

Agriculture and drought/flood risk assessment: High spatial and temporal resolution soil moisture data could allow early assessment of risk associated with extreme events, i.e., soils too dry or too wet, with implications for estimating and predicting erosion events, flooding, pest infestations, fertilizer-pesticide-seed demand, yields and soil trafficability. F/T has a direct impact on crop subsistence.

Climate: Soil moisture is an integral component of the water cycle, and thus a primary element of climate and seasonal predictions; it greatly influences the dynamical evolution of vegetation and thus the energy and carbon cycles. F/T also has a direct impact on vegetation growth and on the carbon cycle. Moreover, soil thawing in northern regions may lead to significant release of methane gas.

Human health: Because of its impact on near-surface air temperature and humidity, soil moisture provides important information for heat stress outlook at both short, medium, and seasonal ranges. It is also a useful input for disease vector outlook (near and long term).

Hydrology: Both soil moisture and F/T have an effect on surface flow and baseflow currents in hydrological models, and are thus a crucial factor in flood prediction.

Weather: Through its control of the surface energy budget and of the evolution of atmospheric mixing layer, soil moisture has a significant impact on near-surface air temperature and humidity, and on clouds and precipitation, for short, medium, and seasonal range predictions, and at local, regional, and global scales.

As it is often the case in these kind of projections, the sociological and economical impact of soil moisture are difficult to assess in a precise manner. Nevertheless, based on current knowledge, better analysis of soil moisture is expected to lead to:

- better weather forecasts (including near-surface air temperature, clouds, and precipitation);
- better analysis and prediction of air quality;

- improved emergency response related to atmospheric dispersion of toxic materials;
- more refined climate predictions regarding the energy, water, and carbon cycles;
- improved hydrological predictions (including possible insight on water quality);
- better risk assessment models and improved responses to risk for the agriculture sector;
- better risk assessment for forest fires (e.g., susceptibility indices);
- increased security associated with better knowledge of trafficability.

The list of potential benefits (related to both soil moisture and F/T) is much longer than what is provided above. One of these benefits for instance is related to the training of highly-qualified personnel (HQP) in scientific and applications areas that could be important to Canada's development in the decades to come.

It should be mentioned, finally, that a SMAP Applications Plan has been prepared by the Working Group on SMAP Applications (formed in 2009). In addition to providing a list of potential applications for SMAP, this document also presents a process to engage the end users community and to build broad support for the mission. More details about this important aspect of the Canadian Plan are provided in another section below.

3. International and National Context for SMAP

Substantial efforts are now undertaken by the international community to better observe and understand the Earth's water cycle. Earth observation satellites play a major role in the study and monitoring of the water cycle and represent an important element of the observation strategy defined within the Integrated Global Water Cycle Observation (IGWCO), one of the core themes of the Integrated Global Observing Strategy Partnerships (IGOS-P). Using its broad base of scientific researchers and experts throughout the world, IGWCO actively contributes to each of the so-called Water Tasks described in the Work Plan of the Group on Earth Observations (GEO). These contributions (strategic guidance, coordination, and gap analysis) have been influential in the development of the water segment of the Global Earth Observation System of Systems (GEOSS), as it seeks to develop an integrated, sustained operational global water cycle observation system and to increase the use of Earth observations with respect to integrated water resource management by 2015. Also, the Global Climate Observing System (GCOS) has named soil moisture as one of its emerging essential climate variables and is thus placing an emphasis on developing an experimental soil-moisture product from existing networks and satellite observations, in collaboration with the IGWCO.

As a consequence of this recognized importance of soil moisture in understanding and predicting the water cycle (locally and globally), a large number of initiatives have been launched in the last decade or so. For instance, the International Soil Moisture Working Group (ISMWG) was established in 2005 to handle the main objectives of the IGWCO water cycle variable. The main objectives of this working group are related to standardization of measurement protocols, cross-validation among several types of observations, network design, and formation of task groups. Other initiatives such as the Global Soil Wetness Project (GSWP) and the Water Cycle Community of Practice (WCCP) also the objective to improve the representation of soil moisture in environmental prediction systems (e.g., weather, climate, hydrology).

In a similar manner, the Committee on Earth Observing Satellites (CEOS) Working Group on Calibration and Validation (WGCV) Sub-group on Land Products Validation Subgroup (LPVS) expanded in 2010 its focus areas to include soil moisture. The charge of CEOS is to serve as the major international forum for the coordination of Earth observation satellite programs and for interaction of these programs with users of satellite data worldwide. The WGCV was established as a result of the recognition that calibration and validation activities should play a key role in all satellite Earth observation missions to ensure the clear and quantitative understanding of the data they generate. The goal of the WGCV is to ensure long-term confidence in the accuracy and quality of Earth observation data and products.

The international community (including Canada) has attempted to retrieve soil moisture using measurements from existing satellites, such as the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) with its C and X band passive measurements, or the

Advanced Land Observation Satellite (ALOS) with its Phased Array type L-band Synthetic Aperture Radar (PALSAR). Another satellite providing information on Earth's water balance is the Gravity Recovery and Climate Experiment (GRACE), which is a joint mission of NASA and the German Aerospace Center that maps the Earth's gravity field and provides information on total surface and ground water (which includes soil moisture).

A major breakthrough for space-based soil moisture measurement occurred recently, with the launch by ESA in November 2009 of the Soil Moisture and Ocean Salinity (SMOS) satellite. Using two-dimensional interferometric L-band (1.4 GHz) radiometry, SMOS is the first satellite specifically dedicated to soil moisture retrieval. In orbit for nearly 4 years now, measurements from SMOS have proven to provide useful information on soil moisture. Examined and validated by the international community with several in situ networks and field campaigns, the quality of both L-band brightness temperature measurements (Level-1 products) and soil moisture retrievals (Level-2 products) has been verified. As discussed in a subsequent section of this Plan, one of these field campaigns was held in the Canadian Prairies (south of Saskatoon, Saskatchewan) and at the Boreal Ecosystem Research and Monitoring Sites (BERMS), as a joint effort for SMOS validation and SMAP calibration/validation. Several environmental prediction centers are currently monitoring SMOS data, and have projects to test the potential benefits of assimilating these data into their land data assimilation systems (e.g., EC, Meteo-France, the European Centre for Medium-Range Weather Forecasts – ECMWF). Plans are to assimilate SMOS data in an operational manner in 2015.

In addition to being involved in most of the international activities described above, Canadian Government Departments have also emphasized the importance of improving water resource management through better understanding of the water cycle. For instance, EC has already committed at the World Summit on Sustainable Development (WSSD) on improving water resource management and scientific understanding of the water cycle through cooperation in joint observation and research. Water conservation is also high on the themes list given in the environment section of the Federal-Provincial-Territorial Framework Agreement on Agriculture and Agri-Food Policy for the Twenty First Century, as provided on the official site of Agriculture and Agri-Food Canada (AAFC). Moreover, Natural Resources Canada (NRCan) identifies in its Sustainable Development Strategy safeguarding of the nation's water resources as a national priority and supports the development of innovative science and technology based solutions to water-related challenges across the natural resources sectors. A quantitative soil water inventory is also one of the six main priorities of the Federal Freshwater Research Agenda (FFRA).

More generally, the science and applications plan proposed in this document is in line with the "Vision for Canada's Federal Science and Technology" as given in the Framework for Federal Science and Technology (FFST, 2005). According to this vision,

- the Canadian federal Public Service will enhance its research, development, and scientific services in order to secure Canada's place as a world leader in innovation, opportunity and quality of life;
- the federal government's science and technology efforts will identify emerging issues that matter to Canadians, and refocus in response to changing needs in areas such as health and safety, public security, natural resources and the environment, and the growth of the knowledge economy.

The Canadian Science and Applications Plan for SMAP follows the three guiding principles of the FFST, namely alignment (with priorities of Canadians), linkages (between government departments, universities, and other institutions), and excellence. It should be noted, in particular, that this Canadian Plan proposes an integrated approach involving several government research laboratories, as well as universities, with a leadership along the lines proposed by the FFST.

4. Objectives of the Canadian Plan

The main objectives of the Canadian scientific participation in SMAP are the following:

Calibration and validation:

Contribute to the calibration and validation of SMAP soil moisture and F/T products by acquiring and processing experimental data over Canada. This contribution will be achieved by maintaining or establishing surface validation sites and by conducting field campaigns with airborne or surface-based L-band remote sensing.

Research, development, and applications:

Improve the representation of the energy, water, and carbon cycles in Canadian environmental analysis and prediction systems using SMAP soil moisture and F/T data. This implies the development of algorithms to use (separately or combined) SMAP passive and active data with other Earth Observations (e.g., C-band SAR) or modeling results in order to produce soil moisture and F/T state analyses. Both passive and active data will be introduced into the Canadian Land Data Assimilation System (CaLDAS) currently being developed at Environment Canada. Their impact on numerical environmental prediction will be evaluated. Remote sensing data from SMAP will also be evaluated in the context of AAFC's operational assessment of crops and soils in Canada. And a multi-model terrestrial vegetation modeling system will be set up and closely link with CaLDAS to improve the representation of the carbon cycle by assimilating SMAP F/T soil state.

These scientific targets of the Canadian plan are well in line with SMAP general objectives, given in a section below. The first objective of this plan, for Cal/Val of SMAP soil moisture and F/T products, will help the international science team achieve many of SMAP mission's requirements, in particular those related to measurement accuracy of soil moisture and F/T state using microwave emission and/or radar backscatter measurements. The second objective, related to the improvement of energy, water, and carbon cycles using SMAP soil moisture and F/T observations, overlaps and complements scientific activities planned in the United States in relation with SMAP.

5. Calibration and Validation

The meaning of the terms calibration and validation may differ depending on the scientific area of interest. In the SMAP context, and as defined in SMAP's Cal/Val Algorithm Theoretical Basis Document (ATBD), "calibration" is the group of operations that establish under specified conditions the relationship between sets of measurements from a particular instrument or measuring system and the corresponding values realized by standards. The term "validation" refers to the process of assessing by independent means the quality of the data products derived from the system outputs.

The objective of SMAP's Cal/Val program is to calibrate and validate relative to the mission requirements all SMAP products, including Level-1 brightness temperatures and backscatters, Level-3 soil moisture and F/T state retrievals from passive and/or active measurements, and Level-4 assimilation products for soil moisture, F/T state, and carbon fluxes. The Cal/Val plan describes how each requirement (list provided in Appendix A) will be validated.

The SMAP Cal/Val program includes both pre-launch and post-launch activities. At this point in time, i.e., approximately one year before launch, the Cal/Val program is transitioning from pre-launch activities which are mostly completed, to preparation for the post-launch phase. Pre-launch Cal/Val is focused on the validation of the means in place to fulfill the mission objectives. It includes *i*) the acquisition and processing of data essential to calibrate, test, and improve models and algorithms used for retrieving SMAP science data products; and *ii*) the development and testing of techniques and protocols to be used in the post-launch phase to acquire validation data and to validate SMAP science products. Pre-launch activities and results are most valuable in the early stages of the program, as they produced data critical in the preparation for the mission's Preliminary Design Review (PDR) and Critical Design Review (CDR). These activities involve ground-based observations representative of the SMAP footprint or grid cell, satellite product comparisons, model product comparisons, and field experiments with a wide array of measurement systems including airborne measurements. As described below, Canada's main contribution to SMAP's pre-launch Cal/Val was based on two field campaigns that were held in Canada and jointly organized with SMAP Project.

Post-launch Cal/Val is focused on validating that the science products meet their quantified requirements, and on improving the algorithms and quality of products over the mission life. The timeline of post-launch Cal/Val is provided in Fig. 5.1. The post-launch phase is scheduled to start right after In-Orbit Checkout (IOC), 3 months after launch. Validation of L1 products including brightness temperatures and backscatters will last 6 months and will result in the delivery of validated L1 products to data centers at Launch + 9 months. In contrast, the Cal/Val segment for L2 to L4 products will last 12 months and will end with delivery of soil moisture, F/T state and carbon fluxes products at Launch + 15 months. The post-launch Cal/Val segment will be followed by an extended monitoring phase (routine science operations) that will last for the remainder of the mission.

The main tools to achieve the SMAP Cal/Val program are ground-based observational networks consisting of core validation sites and sparse networks, other satellite products, model products, as well as field experiments that include enhanced ground activities together with comparison with other satellite products and airborne passive and active microwave measurements.

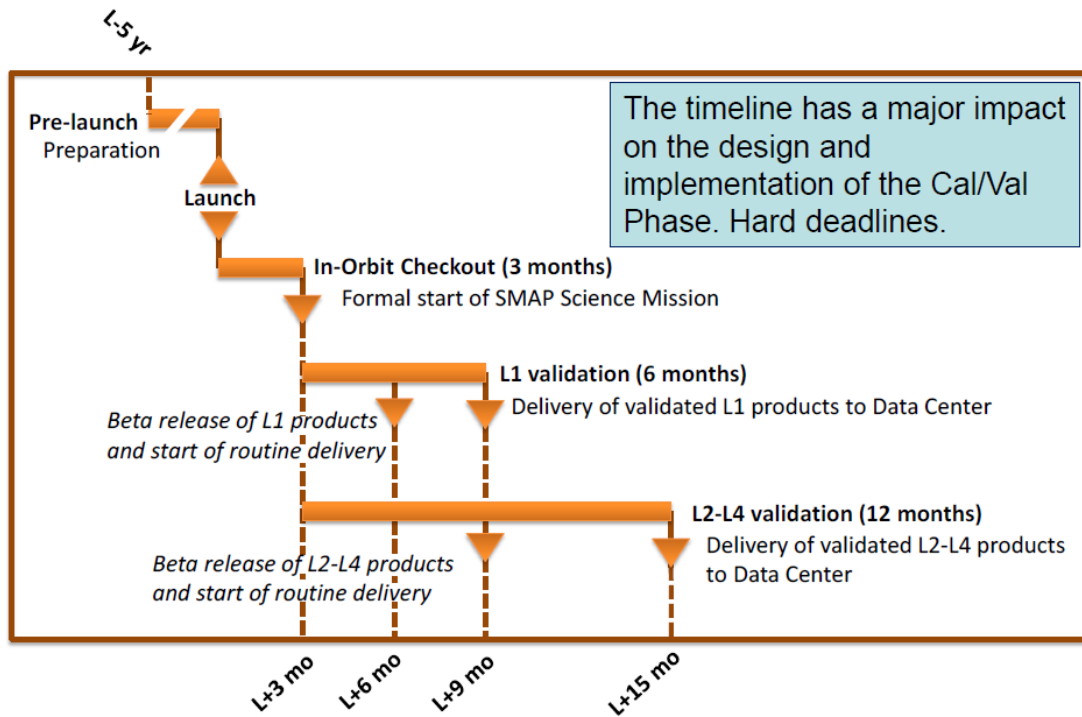


Fig. 5.1. Timeline of Cal/Val activities for SMAP, taken from a presentation by Tom Jackson at the 3rd Canadian SMAP Workshop, held in March 2013 in Ottawa, Canada.

Due to Canada’s geographical location, its typical landscapes, and its recent scientific research and development in both Government and Academia, Canadian institutions have been able to contribute in a significant manner to SMAP’s pre-launch phase. It is proposed as part of this updated version of the Canadian Plan for SMAP to extend this contribution to the post-launch phase, with a limited set of surface validation sites and networks for both soil moisture and F/T state, and with a soil moisture field campaign which could possibly take place in 2016.

a) Soil moisture

Based on SMAP Cal/Val terminology, the ground component involves sparse and dense networks. Sparse networks typically cover wide areas with data usually available in real time. Several of these networks exist throughout the world, such as the Soil Climate Analysis Network (SCAN), the US Climate Reference Network (CRN), and other networks on all the other continents (except South America). In Canada, one such sparse

network is the Alberta DroughtNet, which includes about 36 measurement sites called Agricultural Drought Monitoring Stations (AGDM, see Fig. 5a.1) with full meteorological station at each site and with soil moisture measurements at 5, 20, 50, and 100 cm (with Delta T Theta probes). This data is already considered for the objective evaluation of soil moisture analyses produced by EC. An attempt will be made during the second phase of the Canadian SMAP Project to extend its use to the evaluation of other soil moisture products, including SMAP retrievals.

As could be expected, upscaling is a critical issue for sparse networks, and their comparison with larger-scale retrievals is difficult. For this reason, the denser networks referred to as the SMAP core validation sites are of great importance for SMAP Cal/Val, even though few of these networks exist in the world (with poor global distribution).

The basic science requirements for the core validation sites (or dense networks) are:

- a study domain that matches the spatial scale of the product (i.e., 3, 9, or 36 km for SMAP products);
- in situ measurements that can be used to estimate the geophysical variables for the mission requirements (i.e., soil moisture, FT state, carbon fluxes);
- multiple sampling locations within the site to be used to accurately estimate the product grid average;
- availability of supporting meteorological instrumentation;
- availability of supporting ancillary data such as soils, land use, and vegetation biomass.

Other items, considered as priorities for SMAP, are to have ground-based networks and sites that:

- are deployed over an area that is homogeneous or has a uniform mixture of land covers at the SMAP product scale;
- represent an extensive or important biome;
- complement the overall set of sites; and
- are available (operational) for the rehearsal exercises that are taking place in Summer 2013 and Summer 2014.

The logistic requirements for the core validation sites are: near real-time availability, accessibility of the site to researchers, existing site facilities, heritage of scientific studies to build from, long term commitment by the sponsor or host, and agreement with SMAP Project.

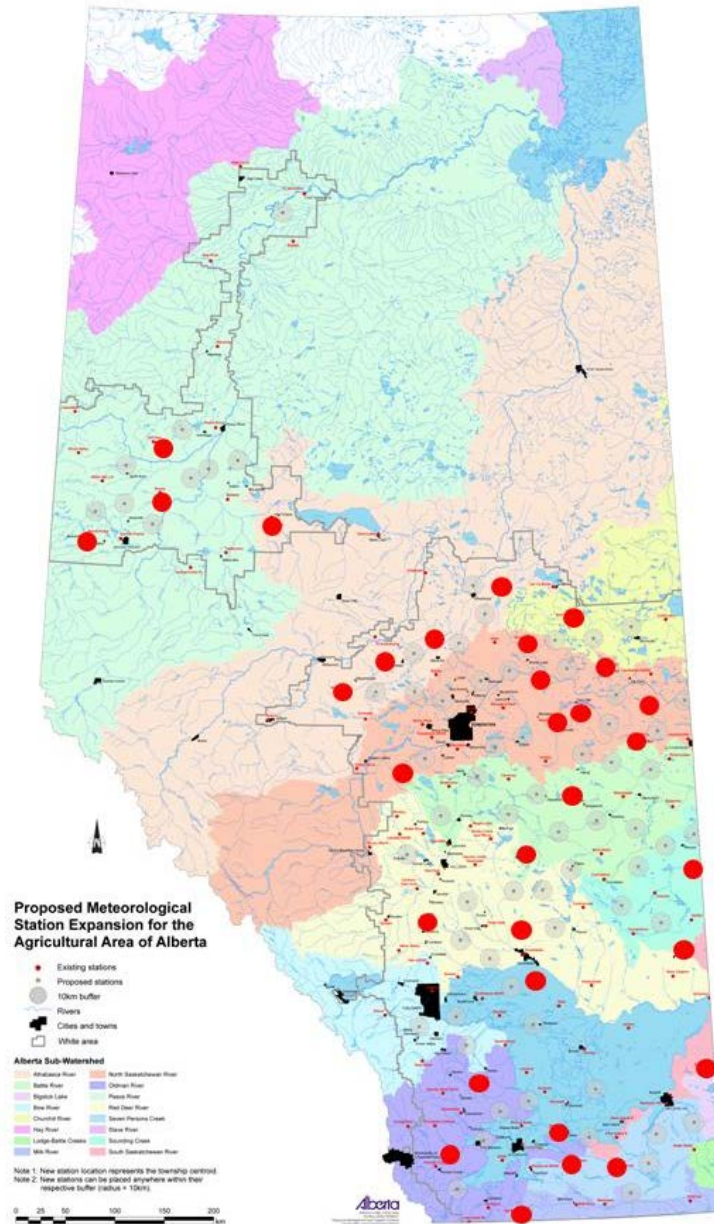


Fig. 5a.1. Alberta DroughtNet. Red circles show the location of AGDM stations.

The requirements and priorities for field experiments are similar to those listed above for ground measurements. The main objectives of these experiments are to support the development of algorithms and to resolve critical algorithmic issues. In such campaigns, the ground measurement networks or sites are enhanced for a short period of time (typically a few weeks) in support of tower-based and/or airborne-based radiometric or radar remote sensing.

The list of SMAP soil moisture products to be calibrated and validated is the following (also listed in Appendix D):

- L1C_S0_HiRes: High-resolution radar backscatters with a 1 to 3-km spatial resolution and available on a 1-km Earth grid;
- L1C_TB: Low-resolution brightness temperatures with a 40-km spatial resolution and available on a 36-km Earth grid;
- L2_SM_P: Daily composite of soil moisture retrievals based on passive measurements (i.e., “P”), with 40-km spatial resolution, to be produced on a 36-km Earth grid;
- L2_SM_A: Daily composite of soil moisture retrievals based on active measurements (i.e., “A”), with 1 to 3-km spatial resolution, to be produced on a 3-km Earth grid;
- L2_SM_A/P: Daily composite of soil moisture retrievals based on combined active and passive measurements (i.e., “A/P”), with 9-km spatial resolution, to be produced on a 9-km Earth grid;
- L4_SM: Assimilation results for surface and root-zone soil moisture to be produced on a 9-km grid Earth grid.

The baseline scientific requirements for the SMAP soil moisture products is to provide estimates of soil moisture in the top 5 cm of soil with an error no greater than $0.04 \text{ m}^3 \text{ m}^{-3}$ (one sigma) at 10-km spatial resolution and 3-day average intervals over the global land area excluding regions of snow and ice, frozen ground, mountainous orography, open water, urban areas, and vegetation with water content greater than 5 kg m^{-2} (averaged over the spatial resolution scale).

The main elements or needs of the SMAP Cal/Val program for each of these products are summarized below:

- Instrument and data gridding calibration (L1C_S0_HiRes and L1C_TB): Verify the scaling of high resolution to moderate resolution radar backscatters over representative and heterogeneous domains using aircraft and satellites. Characterize the errors resulting from processing to a swath based grid.
- Soil moisture retrievals and analysis (L2_SM_P, L2_SM_A, L2_SM_A/P, and L4_SM): Investigate the errors associated with the specification of the effective soil temperature based on ancillary data (from ECMWF, the National Centers for Environmental Predictions - NCEP, or NASA). Refine model parameterizations of vegetation through additional data acquisitions (tower, aircraft). Issues related with vegetation parameterizations will be addressed in the context of field campaigns. Accuracy of the various retrieval algorithms will be assessed by using all the candidate approaches to invert the same sets of observational sensor data, and by comparing the results against in situ data. Datasets from the airborne Passive/Active L/S band Sensor (PALS) and from SMOS will be used in this exercise. Validation of the baseline algorithm for a full range of soil moisture, vegetation, and surface heterogeneity conditions using combined aircraft and satellite data sets; and development and evaluation of alternative time series

algorithms over extended time using combined aircraft and satellite data sets that represent the true resolutions of SMAP (for the active data).

This list of needs summarizes well the issues that have been and can further be examined in the context of the Cal/Val Canadian program. Observational datasets acquired during the pre-launch phase certainly helped address general concerns regarding the accuracy of retrieval and inversion algorithms using passive and active L-band data. Pre- and post-launch Cal/Val data is particularly important over regions with meaningful amounts of vegetation and with significant spatial variability. The presence of a large number of lakes (of various sizes) could greatly complicate soil moisture estimation in Canada, and this effect has to be quantified. Likewise, the ability to retrieve root-zone soil moisture using data assimilation techniques has been investigated during the pre-launch Cal/Val phase, and will continue to be in the post-launch phase.

i) Core validation sites and networks

Several factors have to be considered in the choice and design of in situ measurement sites for SMAP Cal/Val activities. Obviously, measurements of near-surface soil moisture (0-5 cm) have to be done at these sites. In order to provide a more appropriate comparison with SMAP passive soil moisture retrievals, several measurements should be done over areas corresponding to the footprint of the SMAP radiometer, i.e., about 40 km x 40 km. It should be noted that a relatively large number of observations is necessary for each of these 40 km x 40 km areas due to the spatial heterogeneity of soil moisture. The measurement sites should be as homogeneous as possible and preferably be representative of typical land surface climates in Canada (e.g., central Canada's prairies, boreal forests). The measured variables should be similar for all the chosen sites (e.g., 0-5 cm soil moisture, near-surface F/T) using instrumentation as standard as possible. These networks or reference sites should be operational for several years covering both the pre-launch and post-launch Cal/Val phases of the mission. It should be noted here that soil moisture measurements will not be possible during the cold season, due to the frozen state of the soil or due to the presence of snow (an opportunity on the other hand for F/T Cal/Val, as discussed in a section below). The observation period will be coincident with active periods of other missions such as ALOS, SMOS, and RADARSAT-2.

The SMAP Project is currently in the process of formalizing agreements with the data provider. Other aspects that are also worked on include the rigorous evaluation of data quality from each network, the assessment of up-scaling approaches used, as well as data formatting and latency issues.

In order to reduce the risk of not meeting checkpoints and to identify and correct issues encountered in the above exercise, two Cal/Val rehearsals have been proposed. The first one has occurred in Summer 2013, from June to September. The second period will take place from May to July 2014, just a few months before launch. In phase 1 the emphasis is for the development of validation methods and for participants to run their code on the

available software. In phase 2 the emphasis will be on the effective use of tools in an operational setting, and for participants to run their code on the same hardware that will be used during the Cal/Val phase.

To limit the cost (in dollars) of this Canadian Cal/Val program, existing sites and networks were and will be exploited. Following these considerations, a few core validation sites have been suggested to provide in situ measurements for Cal/Val of SMAP algorithms related to soil moisture.

1. Saskatchewan low and high-density networks:

Two soil moisture networks are operating in Saskatchewan and are available for SMAP Cal/Val, as indicated in Fig. 5a.2. The white dots in this figure show the stations location for the so-called low-density network, installed and operated by the University of Guelph (Principal Investigator is Prof. Aaron Berg). The yellow dots indicate the location of the high-density network stations, operated by EC.

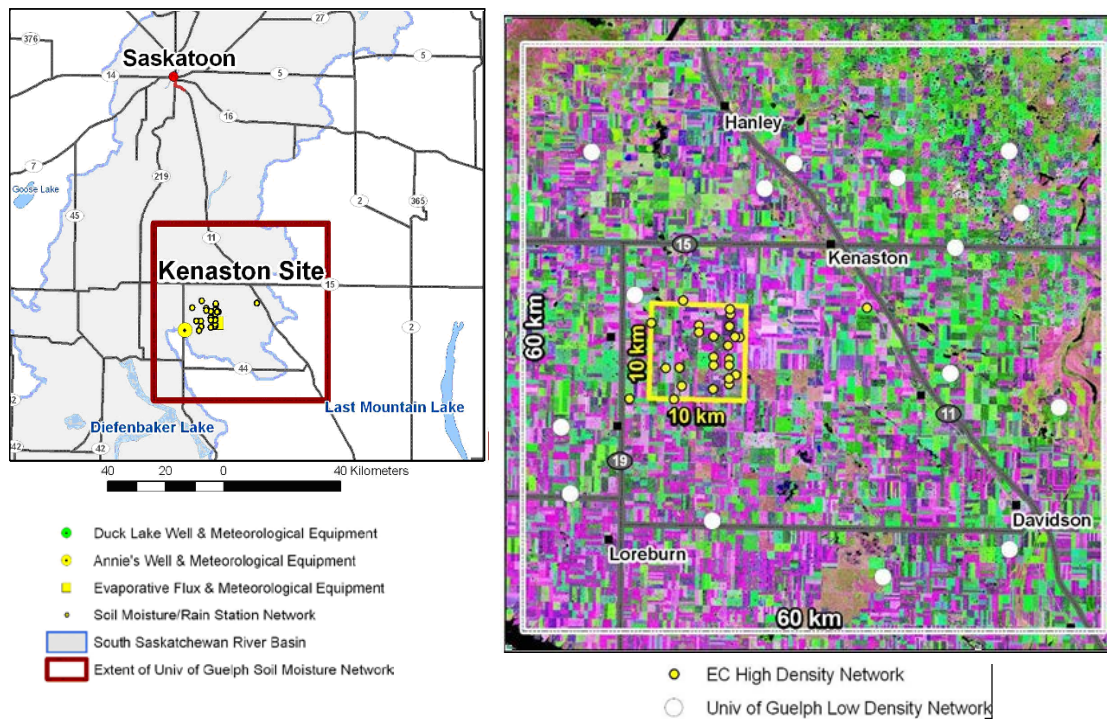


Fig. 5a.2. Saskatchewan soil moisture networks (Kenaston site) located south of Saskatoon. White and yellow dots indicate the location of stations for the low and high-density networks, respectively.

The low-density network includes 16 stations in an area approximately covering 60km x 60km, which is slightly larger than SMAP passive soil moisture retrievals (40 km). In this network soil moisture stations are installed outside of agricultural fields with a single surface Hydro soil moisture probe installed horizontally.

The high-density network consists of 24 soil moisture stations located within agricultural fields over a 10km x 10km area representative of SMAP soil moisture active and passive combined product (9 km). The lower right portion of this region includes a pasture and a flux tower site. A deep well lysimeter installation is located just to the south west of the yellow box shown in Fig. 5a.2. These sensors were installed in the fall of 2006 and during the spring of 2007. Figure 5a.3 illustrates the distribution of EC's soil moisture stations within the high-density area. The area is divided into 0.8 km x 0.8 km grid cells (0.5 mile by 0.5 mile, or one quarter section). The stations locations were chosen to cover the main crop types (cereal crops, pulse crops, oil seeds, grass/alfalfa and pasture), soil textures (clay, clay/loam and loam in this area) and tillage practices. The soil moisture sensors record soil moisture and temperature at 5, 20, and 50 cm depths. This region south of Saskatchewan (referred to as the Kenaston site) is well documented, with detailed information available on topography, watersheds, irrigation, area of open water, land covers, soil texture, and urban versus rural areas.



Fig. 5a.3. High-density network operated by EC. The location of this network is indicated by the yellow box shown in Fig. 5a.2. The dots and squares indicate the location of the soil moisture stations (for different crop types).

2. AAFC RISMA Network

AAFC, through the Growing Forward policy framework, funded a Sustainable Agriculture Environmental Systems (SAGES) project to develop a soil moisture monitoring capability to support the Canadian agriculture sector. As part of the Canadian participation to the SMAP project, AAFC is proposing that their Real-time In situ Soil Monitoring for Agriculture (RISMA) network be used for validation of the SMAP soil moisture products.

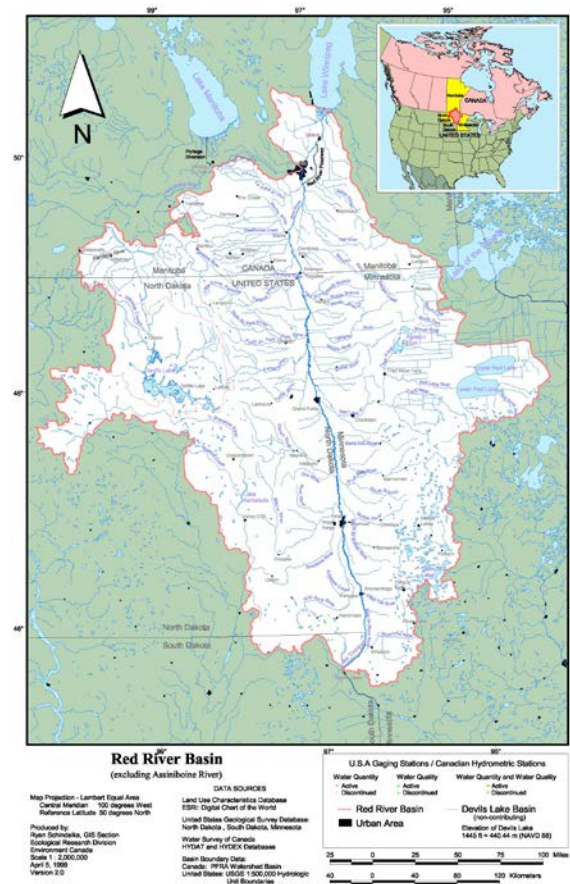


Fig. 5a.4. Reproduced from AAFC (2013). Extent of the Red River Watershed. Approximately 25% of the watershed falls within Canada, with the remainder of the watershed residing within Minnesota, North Dakota and South Dakota, U.S.A

AAFC selected the Canadian Red River Watershed (Fig. 5a.4) as the implementation site for monitoring soil moisture using active and passive microwave satellites. This watershed often experiences extremes in soil moisture. For example, according to the 2008-2009 Annual Report from the Manitoba Agricultural Services Corporation drought and excessive heat have historically (1960-2007) accounted for 37% of reported crop losses, while excessive moisture was responsible for 36% of losses. The watershed is characterized largely by agricultural land use with a wide range of crop and soil conditions. Crops include forage, pasture, canola, flaxseed, sunflower, soybean, corn,

barley, spring wheat, winter wheat, rye, oats, canary seed, potatoes, and field peas. The typical crop rotation is a cereal crop alternating with oilseed/pulse crops. Field sizes range from 20-30 to 50-60 hectares. Crop type mapping via remote sensing techniques is done annually for the entire Canadian agricultural landscape, including the Red River Watershed.

The plan is to install in situ instrumentation in the watershed in an incremental manner, with respect to the geographic coverage of the network and the number of network stations. Initially a small area in the La Salle and Boyne River Watersheds has been selected based on geo-statistical analysis of soil texture and derived soil variables for all of the Red River sub-watersheds. This part of the Red River Basin has an excellent contrast in soil properties from east (fine clay soils) to west (coarser and better drained soils), and covers an area of 60 km (east-west) by 10 km (north-south). It is important to note that this sub-watershed, as well as the larger Red River Basin, is one of the GEO Joint Experiment on Crop Assessment and Monitoring (JECAM) international super sites.

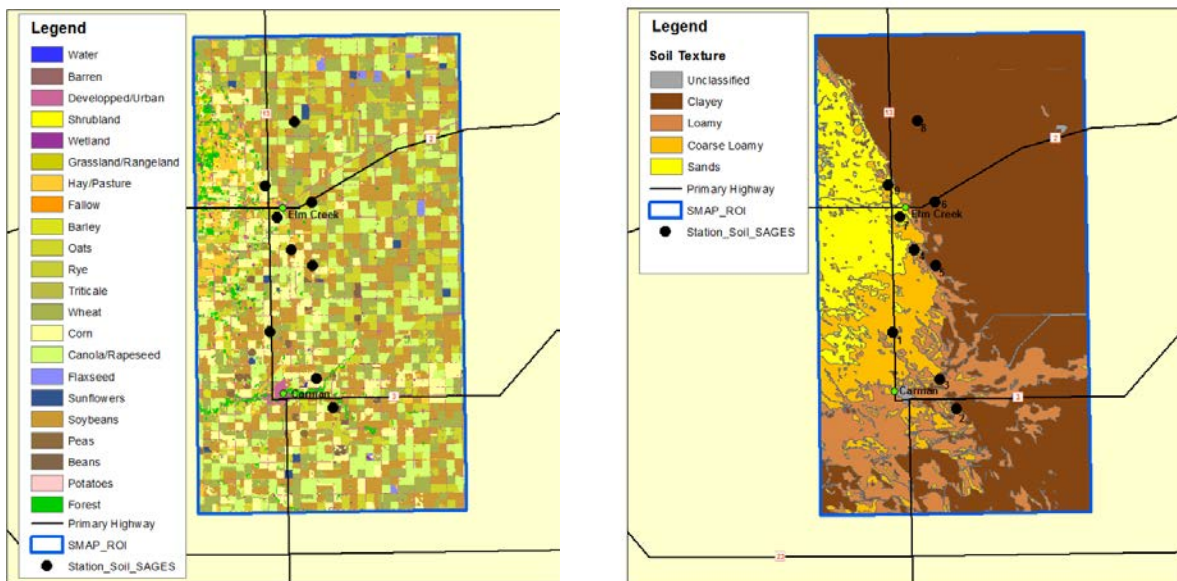


Fig. 5a.5. Reproduced from AAFC (2013). Crop map (left) for the 2012 growing season generated over the AAFC SMAP validation site (corresponding to RISMA, in southern Manitoba). Crop classification is completed using a combination of optical and radar data with a supervised decision tree classifier. In this case, RADARSAT-2 satellite data at 30-m spatial resolution was used. On the right, soil texture classes for the RISMA site are provided. In both figures, black dots identify the location of the in situ RISMA stations.

In 2011, AAFC began installation of their in situ soil moisture network (RISMA) with stations centered over the Carman / Elm Creek area. This site is approximately 80 km southwest of Winnipeg. The positioning of the individual RISMA stations was chosen to capture the maximum soil variability within this sub-watershed (Fig. 5a.5). To maximize this contrast in soil moisture conditions, the stations were located along the east-west divide between the dominant soil texture classes. The network currently consists of nine in situ monitoring stations. The stations are located at the edge of annually cropped

agricultural fields with the soil moisture sensors installed within the field, about 10-30m away from the edge. The stations record liquid precipitation with a tipping bucket rain gauge as well as real dielectric permittivity, soil moisture and soil temperature using hydra probe sensors at surface (0-5cm), 5cm, 20cm, 50cm and 100cm depths. Three hydra probe sensors, or replicas, are installed at each depth. This replication provides a measurement of spatial variability in soil moisture, and redundancy in the event of sensor malfunction. Each station also records air temperature, relative humidity, wind speed and wind direction. All stations are equipped with data loggers and telemetry units. Data are logged every 15 minutes and the data are updated on an SOS server and a web portal once per hour. A quality control process and site specific calibration equations are applied to the soil moisture data, prior to dissemination. Currently data are served via the Geospatial Cyberinfrastructure for Environmental Sensing (GeoSens) web-based platform (Fig. 5a.6).



Fig. 5a.6. AAFC RISMA web site

ii) *field experiments*

1. The Canadian Experiment for Soil Moisture in 2010 (CanEx-SM10)

A first field campaign was conducted in Saskatchewan in June 2010. The Canadian Experiment for Soil Moisture in 2010 (CanEx-SM10) originated as an initiative of Canadian researchers to support the SMOS validation activities over land and to develop soil moisture retrieval algorithms. The experiment was extended to include pre-launch validation and algorithm development for SMAP through a collaboration with US

researchers. The CanEx-SM10 field phase took place from 31 May to 17 June 2010 over agricultural and forested sites located at both the Kenaston and BERMS sites.

The general objective of CanEx-SM10 was to contribute to the validation of SMOS soil moisture estimation and brightness temperature products, and the pre-launch SMAP validation activities. Specifically, through field data measurements over agricultural and forest sites, the following scientific points are being addressed:

- qualitative and quantitative analysis of L-Band microwave data;
- development of soil moisture retrieval algorithms from passive and active microwave data (SMOS, RADARSAT-2, ALOS-PalSAR, L-Band airborne data from EC's radiometer and NASA's UAVSAR); and
- assimilation of SMOS data in land surface systems to improve land surface initial conditions provided to environmental forecast models.

As part of CanEx-SM10, microwave measurements from satellites (SMOS, AMSR-E, RADARSAT-2, and ALOS-PALSAR) were collected along with data from airborne passive and active instruments (L-band radiometer aboard EC's Twin Otter aircraft and NASA's L-band UAVSAR flown in a Gulfstream III piloted aircraft). One important aspect of CanEx-SM10 was to collect field measurements of soil moisture, surface temperature, and surface characteristics (roughness, vegetation, leaf area index - LAI, bulk density) at a time close to the satellite and airborne acquisitions to support the validation of SMOS and pre-launch validation activities of SMAP. Two domains, each covering 33 km x 71 km (about two independent SMOS pixels) were selected in agricultural (Kenaston) and forest areas (BERMS) of Saskatchewan. Measurements from these two sites provide diverse and robust soil moisture for very different types of soil and vegetation.

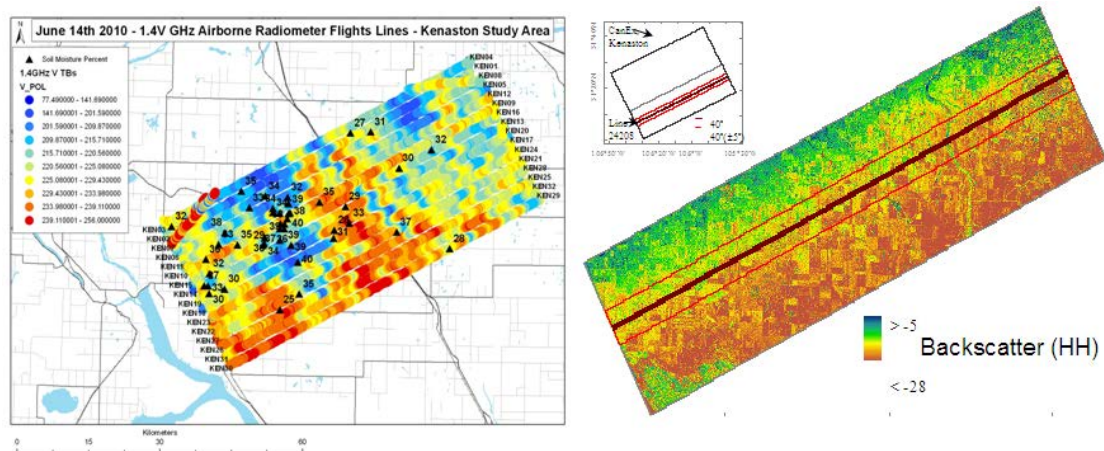


Fig. 5a.7. First airborne results from the CanEx-SM10 field experiment. Left: L-band brightness temperatures (colors) obtained from EC's microwave radiometer aboard the National Research Council (NRC)'s Twin Otter, valid on 14 June 2010. Ground measurements for 0-5 cm soil moisture are indicated. Right: Backscatters (HH) at L-band from NASA's UAVSAR valid on 9 June 2010. These figures are provided courtesy of Anne Walker (EC / Climate Research Division, for the left panel) and Tom Jackson (United States Department of Agriculture, USDA, for the right panel).

Over the agricultural area, about 60 fields were sampled for soil moisture, surface temperature, and surface characteristics measurements for June 2-14, 2010. Two soil moisture sampling strategies were performed. One strategy is related to the validation issue of SMOS products and the calibration of soil moisture retrievals based on SMAP active and passive microwave measurements. The second strategy is a more intensive sampling that would enable to relate the time series (networks) measurements to field averages and to develop scaling method of SMOS data.

The second part of the experiment was conducted over BERMS sites that are essentially composed of 4 forest types (old Aspen, old Jack Pine, Fen, and old Black Spruce). Over this area, soil moisture sampling was conducted on a single day at the end of the experiment, at locations selected on the basis of road access facilities and of proximity to SMOS grid centers. Vegetation characteristics were also measured later.

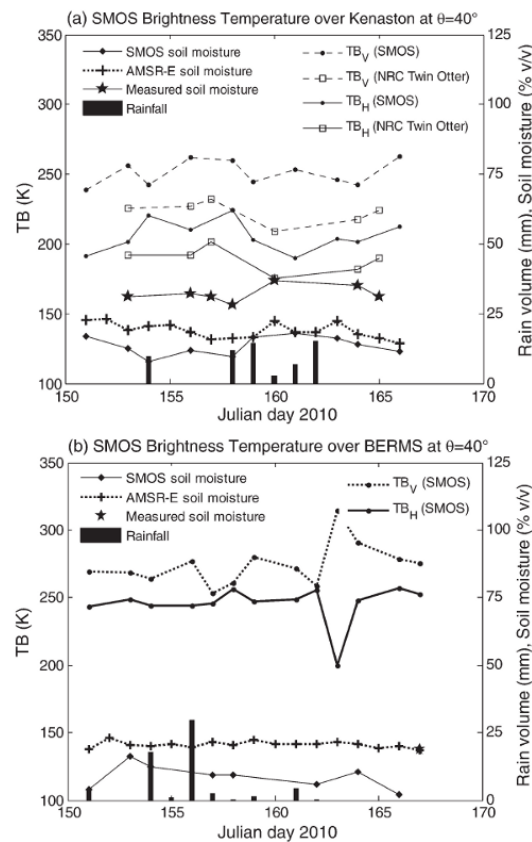


Fig. 5a.8. Reproduced from Magagi et al. (2013). Temporal evolution of SMOS brightness temperature at 6 A.M. and retrieved soil moisture from SMOS, together with field measured soil moisture, precipitation from EC, and AMSR-E/NSIDC soil moisture estimated values at 1:30 P.M. a) Over Kenaston with L-band airborne brightness temperatures in H and V polarizations, b) over BERMS.

The field campaign soil moisture data collected during CanEx-SM10 was complemented by observations from the permanent existing soil moisture measurement networks

managed by EC and the University of Guelph. A temporary network of about twenty stations was installed by the United States Department of Agriculture (USDA) to collect hourly soil moisture data at the BERMS site. Over 50 people participated in the ground and aircraft components of CanEx-SM10.

Preliminary results from the CanEx-SM10 field campaign are presented in Magagi et al. (2013). Examples of both passive and active airborne measurements are provided in Fig. 5a.7. The left panel shows the brightness temperatures from EC's L-band radiometer mounted aboard the National Research Council (NRC)'s Twin Otter aircraft (valid on 14 June 2010). The results show some spatial variability, which seems to realistically fit with ground-based measurements (also displayed in this figure). The right panel provides a first look at HH L-band backscatters from NASA's UAVSAR (for the flight that occurred on 9 June 2010). Again, some spatial variability is observed from the aircraft measurements (but this time at higher resolution). Some of this variability is related to vegetation (roughness), standing water, and soil moisture.

As described in Magagi et al. (2013), the soils over this part of Saskatchewan were uncharacteristically wet during the campaign, with observed volumetric soil moisture content ranging from $0.20 \text{ m}^3 \text{ m}^{-3}$ to $0.45 \text{ m}^3 \text{ m}^{-3}$. Some radio-frequency interference (RFI) was experienced during the campaign, with very clear spatial patterns and pronounced temporal variability as well as polarization dependency. In one of their final figure (reproduced here in Fig. 5a.8), the authors show that the SMOS L2 products (operational at the time) significantly underestimated soil moisture over Kenaston and BERMS, and did not meet the accuracy requirement of $0.04 \text{ m}^3 \text{ m}^{-3}$. It turned out for this case that the AMSR-E soil moisture estimates (obtained from the National Snow and Ice Data Center – NSIDC) were closer to field observations during the field campaign. It should be mentioned that since then several improvements and corrections were made to the SMOS soil moisture retrieval algorithms.

2. The SMAP Validation Experiment 2012 (SMAPVEX12)

Although the CanEx-SM10 field experiment was a real success, not all of the objectives could be achieved with this dataset due to the very wet conditions that existed in the Canadian Prairies in early summer 2010. Because the campaign was relatively short, not enough temporal variability was observed for soil moisture over the region, and the effect of vegetation on the passive and active retrievals could not be properly assessed due to the delayed growing season in Saskatchewan (one of the worst year on record).

In order to further prepare for the availability of SMAP data and to provide the information still required for aspects related to soil moisture retrieval based on active data and to the effect of vegetation, another joint Canada-US field experiment (SMAPVEX12) was conducted from June 7th to July 19th 2012. A general description of the SMAPVEX12 campaign is provided in McNairn et al. (2013). One of the main objective of SMAPVEX12 is to support the development and refinement of forest scattering models and to test the SMAP radar-based soil moisture retrieval algorithms. Another

objective is to prepare and establish protocols for the post-launch Cal/Val phase of the mission.

The SMAPVEX12 field campaign was conducted in southern Manitoba, in the same region of the RISMA network described above. This region is mostly covered by mixed prairie agriculture, and features a wide variety of soil types as well as land use / land cover. The 6-week period of this campaign ensures that a long time series of both radiometer and radar data under diverse soil and vegetation conditions (agricultural and forested sites) is available for SMAP Cal/Val. In the early phase of the campaign crops were in their early development with low amounts of biomass; at the end of the campaign crops had reached their maximum biomass.

As is typical for this kind of experiment, SMAPVEX12 included ground, airborne, and satellite components. For the ground component, sampling was performed over 55 quarter section agricultural fields (800 m x 800 m) and 4 forest sites located north of the dominant agriculture production. About 75 researchers from Canada and the US participated to this effort. For each of the 55 agricultural fields, soil moisture was measured at 16 sampling points, with 3 replicate measurements at each of these sampling points. The crews measured surface soil moisture (0-6 cm) using mostly Stevens Water Hydra probes. Bulk density core measurements (one per field) were collected during flight days for site specific calibration. The surface roughness was measured early in the field campaign in each field using a 1-m portable pin profilometer. Other important features of the agricultural sites were also observed, including planting practices and plant structural characteristics, as well as LAI and crop reflectance.

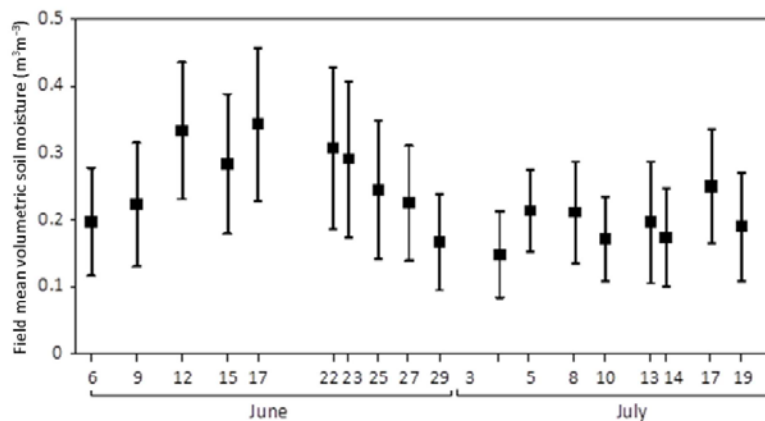


Fig. 5a.9. Reproduced from McNairn et al. (2013). Soil moisture mean and variance over the 55 agricultural fields during SMAPVEX12.

Similar measurements were made over the forest sites, including soil moisture, and surface roughness. Determination of the forest structural characteristics was quite different from what was done over the crops fields. Features such as trunk diameter, tree height, number of branches, leaf count, branches angles, lengths, diameters, leaf clumping, were all estimated when possible.

These measurements were complemented with permanent and temporary soil moisture stations. The AAFC permanent network (RISMA) consists of 9 monitoring stations, with measurements at 5, 20, 50, and 100 cm. An additional 40 temporary soil moisture sensors were provided by USDA and were installed just prior to the field phase. Finally, 4 Manitoba Agriculture, Food and Rural Initiatives (MAFRI) stations were also temporarily installed for SMAPVEX12. All of the temporary stations were deployed over the agricultural fields, except 3 from USDA and 1 from MAFRI which were located in the forest sites.

Throughout the campaign, several times a week, two aircrafts were flown by NASA over the experimental area with sensors similar to what will be flown on SMAP. The PALS instrument was flown on a DHC-6 Twin Otter aircraft and provided both passive and active measurements at L-band. The vertically and horizontally polarized brightness temperatures were obtained on the passive side, whereas the VV, VH, HV, and HH transmit / receive combinations were measured on the active side, as well as the third Stokes parameter and correlations between any pair of combinations. The PALS instrument had a 40° look angle as installed on the Twin Otter aircraft, and data were acquired at two elevations during the campaign. The UAVSAR, on the other hand, is an L-band radar, which was flown at 13-km on a Gulfstream-III aircraft. It collected data over a swath from 20° to 65°, with the portion between 35° and 45° being of greater interest during SMAPVEX12.

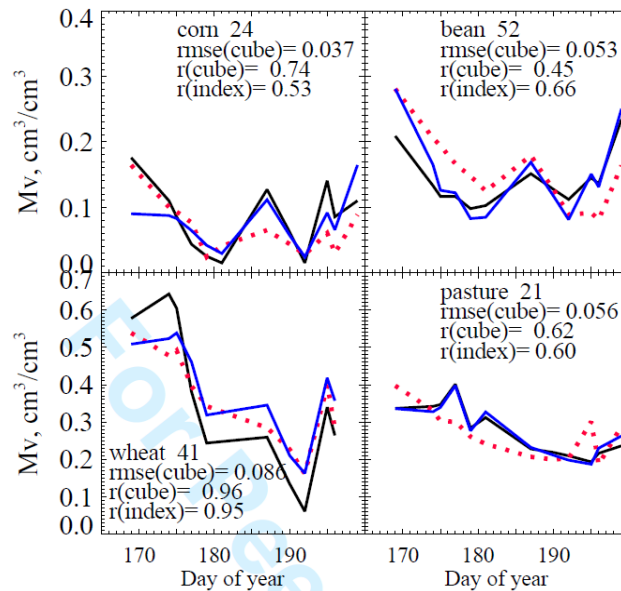


Fig. 5a.10. Reproduced from McNairn et al. (2013). Preliminary retrieval of soil moisture for one field per crop type (pasture, bean, winter wheat, corn) where SMAP's forward scattering models are available: in situ moisture (red dot), data cube retrieval (black), and change index (blue). The legend (top to bottom) reads: crop type and number, RMSE error of the data cube method in $m^3 m^{-3}$, and correlation (r) between retrieval and in situ soil moisture. The retrieved change index was scaled to match in situ soil moisture.

On top of that, data from several satellites were acquired, including SMOS and RADARSAT-2, but also RapidEye, SPOT, Aquarius, and TerraSAR-X.

The general assessment for the SMAPVEX12 field campaign is quite good. Most of the ground measurements as described in the experimental plan were successfully acquired. There were no major technical problems with operation of the aircrafts. And most importantly the weather conditions were as good as could be hoped for. The temporal evolution of the in situ soil moisture averaged over all the sampled fields reflects this, as shown in Fig. 5a.9 reproduced from McNairn et al. (2013). In the early stages of the campaign (first half of June), the soils were wet due to a few precipitation events. This was followed by an extended period of drying until the end of June. The campaign ended with a few small precipitation events, keeping the mean soil moisture quasi-constant over the study area. Figure 5a.9 also indicates there was substantial spatial variability in soil moisture on the ground during the campaign, especially in the wet and drying periods in June.

Data from SMAPVEX12 already proved to be useful for the evaluation and calibration of the SMAP soil moisture retrieval algorithms, especially for those using active data. The effect of vegetation on the backscattering cross section has been clearly observed with SMAPVEX12 data for a few types of crops, including wheat, soybean, and corn. Preliminary results indicate that the SMAP retrieval algorithms based on radar data only perform reasonably well for some of the agricultural fields. Figure 5a.10 shows an encouraging comparison between soil moisture retrievals from the data cube and change detection methods with in situ measurements over a few fields.

3. SMAP post-launch aircraft experiment (SMAPVEX16)

The science objectives of the SMAP post-launch aircraft experiment are to validate the entire L2_SM_AP algorithm process, to understand the effects and contribution of heterogeneity on coarser resolution retrievals (e.g., based on passive measurements only), to evaluate the impact of known RFI sources on soil moisture retrievals, and to investigate and resolve problems associated with anomalous observations and products. Other objectives, including those specific to Canadian team members, may be integrated as the experimental plan is developed.

At this time, the concept of the experiment involves flights over one or more L2_SM_P (36 km x 36 km) grid cells at a site. This could possibly be achieved for several sites with different surface conditions. The Manitoba site used for SMAPVEX12 is being considered for this exercise, as well as other sites in Arizona and Oklahoma. In the post-launch experiment, higher spatial resolution measurements of brightness temperature will cover the entire site to help with the evaluation of the L2_SM_AP (9 km) and L2_SM_A (3 km) products and algorithms. In this context, soil moisture products at both 3 and 9 km will be generated using the SMAP L2_SM_P algorithm.

The total duration of the field campaign (including all sites) is currently expected to be 45 days, i.e., 12 days for each of 3 sites, with 3 days for transit between the sites. The

current number of flight hours is 150h (including transit). Similar to what was done during SMAPVEX12, two aircrafts will be used: a Twin Otter (or C23 or equivalent) with the PALS instrument on board (or possibly the PALScan), and a Gulfstream-III with the UAVSAR instrument.

Some uncertainty remains concerning the time periods that will be chosen for the post-launch experiments. Initially planned for Summer 2015, the campaigns are now expected to occur in Summer 2016, due to logistical reasons. Indeed, many key personnel are expected to be tied up during the first year after launch to focus on the analysis of the SMAP data set and will not be available to support a field campaign or analyze the data in 2015. Also, the analysis of the first year of SMAP data will allow the identification of critical scaling issues as well as problem areas that can then be incorporated in the final design of the field campaign.

The timeline is to prepare for launch and for post-launch Cal/Val activities in 2014, to conduct SMAP Cal/Val activities and refine the plan for SMAPVEX16 in 2015, to carry out the SMAPVEX16 campaign and data processing in 2016, and finally to complete the analysis of SMAPVEX16 data with results applicable to the reprocessing of SMAP data in 2017.

As with SMAPVEX12, participation in the SMAP post-launch field experiment is an important aspect of the present Canadian Plan for SMAP. Participation in a 12-day campaign in southern Manitoba can not be achieved without an important in-kind contribution from AAFC, and from the other Canadian partners. It is unclear at this moment to what extent AAFC can support this effort given that 2016 is outside of the timeframe for currently approved research projects. Confirmation of support from Canada to SMAPVEX16 should be expected in the year to come. In spite of this uncertainty, the budget provided in a subsequent section considers Canada's involvement in the post-launch field campaign.

b) F/T and carbon cycle

The basic concepts and notions presented in the previous subsection for Cal/Val of soil moisture observations and retrievals also apply for F/T and carbon products. As is the case for soil moisture, Cal/Val of F/T and carbon products involves both pre- and post-launch activities, with the same objectives as described above. The items to be evaluated and calibrated in this program are (as found in Appendix D):

- L3 F/T A: Daily global composite of the F/T state based on active measurements (i.e., "A"), with spatial resolution of 1 to 3 km, to be produced on a 3-km grid; and
- L4 C: Modeling and assimilation results for the carbon net ecosystem exchange (NEE), with spatial resolution of 9 km, to be produced on a 9-km grid.

In contrast with the soil moisture Cal/Val program, the nature of the data assimilation products (carbon NEE) is quite different from that of the retrievals (F/T state). This distinction between the Level-3 and Level-4 products has some consequences on the Cal/Val strategy.

At this moment, the requirements for the F/T and carbon products are the following:

- L3_FT_A: spatial resolution of 3 km with an accuracy of 80% for F/T state retrievals, available every 2 days, for regions north of 45° latitude.
- L4_C: spatial resolution of 9 km with an accuracy of 30 gC m⁻² yr⁻¹, available every 14 days.

The Cal/Val F/T and carbon program established by the SMAP Science Definition Team (SDT) in order to meet these requirements can be summarized as follows (more details can be found in the SMAP Calibration and Validation ATBD):

- Surface stations providing measurements for surface air temperature and soil temperatures are the baseline reference for assessing the accuracy of the L3_FT_A product. Figure 5b.1 provides the location of surface stations from SNOTEL (SNOWpack TELEmetry network), and automated system of snowpack and related climate sensors operated by the Natural Resources Conservation Service (NRCS), the Soil Climate Analysis Network (SCAN), and the global surface stations network of the World Meteorological Organization (WMO). The stations shown for SNOTEL, SCAN, and ALECTRA provide information for both air and soil temperature. Stations from WMO have measurements only for air temperature. Assessment of the F/T algorithm in terms of the influence of landscape components (soil, vegetation, snow) is being carried out during the pre-launch Cal/Val phase, using for instance data from the Alaskan Ecological Transect (ALECTRA, see Fig. 5b.1, lower panel).
- Other satellites are also being used for this type of assessment, including ALOS PALSAR, SSM/I, AMSR-E, QuickSCAT, Aquarius, and SMOS.
- FLUXNET towers will provide the primary ground measurements for assessment of the NEE product (L4_C).
- Synergies with NASA Earth Science Venture Class projects such as the Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE) and the Airborne Microwave Observatory of Subcanopy and Subsurface (AirMOSS) are considered in SMAP planning. The CARVE project may restrict PALS availability but measurements can be attached to the SMAP project and used for L3_FT_A development. On the other hand, AirMOSS may restrict UAVSAR availability but again there is potential to provide relevant data for L4_SM development due to the penetration depth of UHF measurement of AirMOSS.

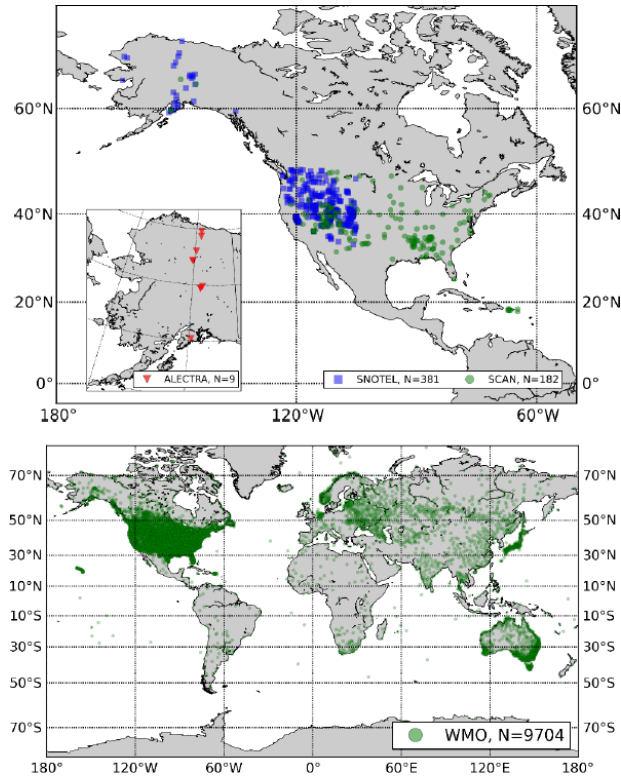


Fig. 5b.1. Upper panel shows the location of surface stations from the SNOTEL (blue), SCAN (green), and ALECTRA (red) networks. The lower panel shows the location of WMO stations. From a presentation by K. McDonald at the 3rd SMAP workshop in Ottawa (2013).

These activities are expected to provide useful information concerning several issues regarding F/T state retrievals and carbon surface fluxes. The most important of these issues are the following: effect of diurnal variability of land surface temperatures and F/T state of the soil in relation with the 6AM / 6PM local sampling times, and the associated uncertainty on F/T retrievals this variability will produce; spatial and temporal distribution, together with the stability of L-band radar backscatters for frozen and non-frozen surfaces; impact of orography and of surface subgrid-scale heterogeneity on footprint-scale radar backscatters and on F/T retrievals; effect of liquid water in snow pack during the melt season; ability to capture both freezing (Fall) and thawing (Spring) transitions; and finally the physical nature of the links between F/T state and carbon NEE.

Canada's contribution to this part of the Cal / Val plan will mainly focus on the validation of F/T products. It consists in providing air and soil temperature from several surface stations and networks throughout the country. Seasonal measurements at a single site (BERMS) from a ground-based L-band radiometer will also be used to evaluate the impact of dry and wet snow on the F/T state retrievals.

The first F/T Cal/Val activity being proposed as part of this Canadian Plan for SMAP is to take advantage of existing networks:

- EC and Guelph soil moisture networks in Saskatchewan,
- AAFC's soil moisture RISMA network in Manitoba,
- NRCan's arctic and subarctic observational networks,
- EC / Climate Research Division (CRD) permafrost monitoring sites,
- EC climate reference network covering the entire country,
- INRS-ETE observational network in Northern Quebec.

The first two entries on the list have already been discussed in a previous subsection, as they are used for soil moisture Cal/Val. Although these observational networks in Saskatchewan and Manitoba have not been designed with F/T in mind, measurements of near-surface soil temperature are available. Some effort will be made to use this information for F/T Cal/Val, while considering questions regarding the stations autonomy and automatic reporting and processing. Permanent stations may report in the fall season, but will be out of power during the winter due to lack of maintenance. So information from these first two networks could be useful in the fall, while the stations still have power from batteries, provided they are able to automatically report the observations. This capability is already existing for the AAFC network, and is planned for the two Saskatchewan networks.

The other networks on the list are more specialized in cold regions measurements. For instance, NRCan uses an extensive surface network to monitor arctic and subarctic permafrost and active layer in North America. As described in Smith et al. (2010), measurements of ground temperature up to 20 m depth are obtained at these sites, from which information on the active layer can be derived using the shallower temperatures. These monitoring sites contribute to the Thermal State of Permafrost (TSP) and the Circumpolar Active Layer Monitoring (CALM) components of the Global Terrestrial Network of Permafrost (GTN-P). The location of these stations is shown in Fig. 5b.2, reproduced from Smith et al. (2010). Most of the stations are located in Alaska and northern Canada. The number of stations has been recently increased in response to the International Polar Year (IPY) in 2007 and 2008.

Some of the stations shown in Fig. 5b.2 have a greater focus on near-surface ground conditions. As described in Duchesne et al. (2013), a network of 61 sites along a transect in the Mackenzie corridor stretching from the outer Mackenzie to northern Alberta has been under the responsibility of the Geological Survey of Canada (GSC), with measurements of air and near-surface ground temperatures. The location of these stations is shown in Fig. 5b.3, reproduced from Duchesne et al. (2013). The network has been used to examine the relationship between air and ground surface temperature for a range of terrain, vegetation, and climatic conditions in that region. As can be seen in Fig. 5b.3 the line of measurements crosses through regions of discontinuous and continuous permafrost. More details concerning the geological and land cover characteristics can be found in Duchesne et al. (2013).

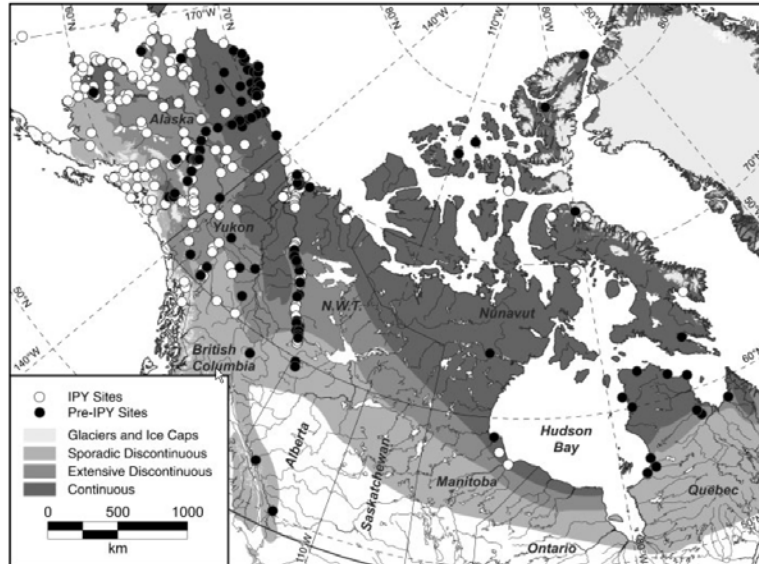


Fig. 5b.2. Permafrost monitoring sites established before and during IPY. The permafrost distribution is based on that of Brown et al. (1997).

The last item on the list is the surface observational network in Nunavik (Northern Québec): a) installed and operated by INRS-ETE (Monique Bernier) and b) by U. Sherbrooke (Alexandre Langlois and Alain Royer).

a) The first observation sites, located at the tree line limit, are near the village of Umiujaq on the eastern shore of Hudson Bay (Qc) Canada (56° N, 76.31° O). This region is characterized by complex landscape including lakes, wetlands, marine, coastal, riparian, permafrost, streams. Permafrost over the area is discontinuous.

The ground truth data acquisition for these stations will be coordinated by INRS-ETE (Monique Bernier). This site has been the subject of more than 20 years of study by the Center for Northern Studies (CEN). (In fact it is part of the CEN SILA network – SILA means “climate” in Inuktitut.) A total of 5 meteorological stations are operated by CEN near Umiujaq, equipped with soil temperature probes for monitoring permafrost (Fig. 5b.4).

Substantial effort has been given to document the three sub-arctic (hemi-arctic) environments characterizing this region: one is a coastal area characterized by sparse tundra vegetation, another is a valley area covered with shrubby vegetation and black spruce trees, and the final one is a second valley (north half of the area) dominated by thermokarst lakes and hollows. A vegetation survey has been done by INRS collaborators (CEN) in summer 2008 and 2009. More than 200 quadrants (5m x 5m) have been inventoried, with measurements of vegetation cover, habitat, soil moisture, substrata types, topographic position, vegetation species, and and vegetation height. Satellite data (Ikonos 2005, Geoeye 2009, TerraSAR-X (since 2009), RADARSAT-2 since 2010, DEM) have also been examined in this context.

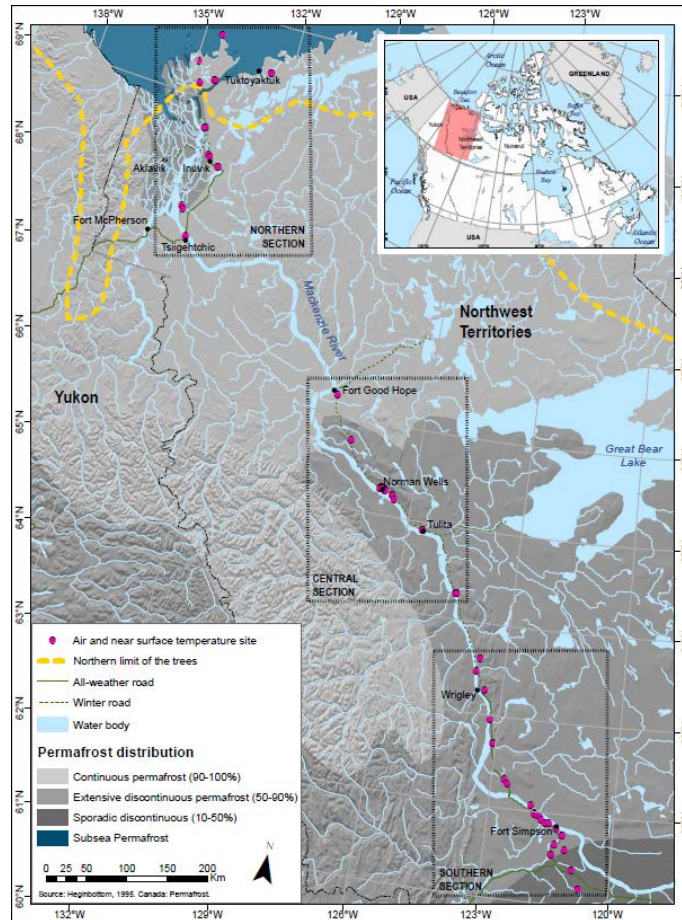


Fig. 5b.3. Location of air and near-surface temperature monitoring maintained by the Geological Survey of Canada. In this figure the permafrost distribution is from Heginbottom (1995). Three sections of data are represented by the dashed lines. Reproduced from Duchesne et al. (2013).

b) The second observation site will be installed further to the north, over tundra and continuous permafrost (61°N, near the Pingaluit National Park site). This fully equipped meteorological station (U. of Sherbrooke’s station) will have the advantage of near-real time access of snow, soil and meteorological data through satellite transmission. Data include snow depth, snow/soil temperature profiles, full radiation budget, atmospheric pressure, radiometric surface temperature, wind, air temperature, and relative humidity. In addition to the meteorological station, and to extend the area analyzed for the SMAP pixel validation around the main central meteorological station (F/T product and soil temperature retrieval), it is suggested that 50 programmable ibuttons temperature sensors be deployed over a square of 20 x 20 km at 2 different depths (under-near surface and -10 cm). This low cost type of sensor will allow us a large spatial deployment with a reasonable budget (but it should be noted that these ibuttons do not transmit data in real time).

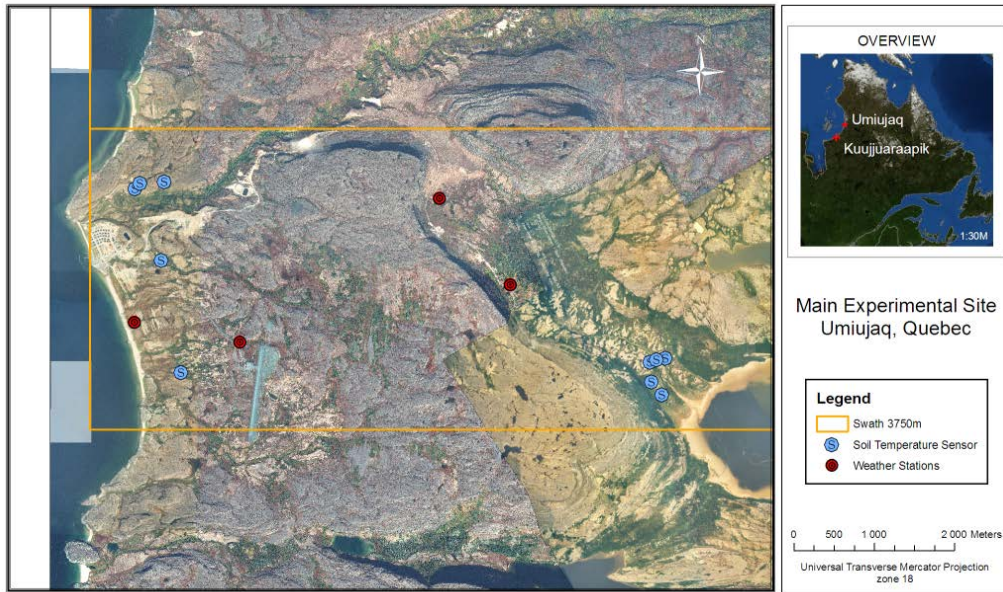


Figure 5b.4: Repartition of the meteorological stations (red dots) and the soil temperature probes (blue dots) under the first flight line near Umiujaq (Hudson Bay area) in Northern Quebec, Canada.

6. Research, Development, and Applications

a) Retrievals

i) Soil moisture

Microwave emission and backscatter at the Earth's surface depend on characteristics such as roughness, physical temperature distributions (vertical and horizontal) of the surface and soil, and the dielectric constant of the medium. The dielectric constant, also called the relative permittivity, is a measure of how an electric field affects and is affected by a dielectric medium. Because the dielectric constant of water is much larger than that of dry soil (values of about 80 compared to typical values of 3-4 for dry soils at frequencies below 5 GHz), microwave emission and backscatter are very different for dry and wet soils, and are thus useful for soil moisture remote sensing (see Fig. 6a.1).

Retrieval of soil moisture based on microwave emission and backscatter is not without complications, and the accuracy of the retrievals depends on the representation of several factors including the surface roughness, attenuation and emission by vegetation, surface and subsurface heterogeneity, and even the soil texture (which affects the dielectric constant). Because the undesirable effects of surface roughness and vegetation are greatly diminished for longer wavelengths (i.e., $\lambda > 10$ cm), and because a deeper soil layer contributes to the microwave emission and backscatter, the low-frequency L-band at 1 to 2 GHz has been determined to be appropriate for soil moisture remote sensing. Another advantage is that the L-band range includes a region of the electromagnetic spectrum that is protected for radio astronomy and Earth remote sensing, and is thus less subject to radio frequency interference (RFI). (This protection is not complete due to uncontrolled leakages.)

With SMAP, soil moisture will be obtained using both passive (radiometer) and active (radar) measurements. Radiometric measurements from SMAP have the advantage of providing relatively accurate retrievals of soil moisture, but at a fairly low resolution (about 40 km grid spacing, similar to SMOS). Active measurements from SMAP SAR on the other hand will provide higher-resolution information on soil moisture, but on a slightly narrower swath. The process of soil moisture retrieval from active measurements is more complex and less accurate due to its greater sensitivity to surface roughness and to vegetation scattering.

In addition to providing soil moisture retrievals based solely on either low-resolution (radiometer, about 40 km) or high-resolution (SAR, 3 km) measurements, SMAP will also combine passive and active measurements to generate a soil moisture product at an intermediate resolution (9 km) with an accuracy approaching that of the radiometer. Details about these algorithms along with general issues and proposed research to make these products more appropriate for Canada are given in the rest of this subsection.

For retrievals based on passive radiometric measurements, the concept of brightness temperature is used to represent the intensity of emitted radiation. The brightness temperature (T_B) is related to the surface physical temperature (T) through the emissivity e in the very simple manner:

$$T_B = eT \quad (6a1)$$

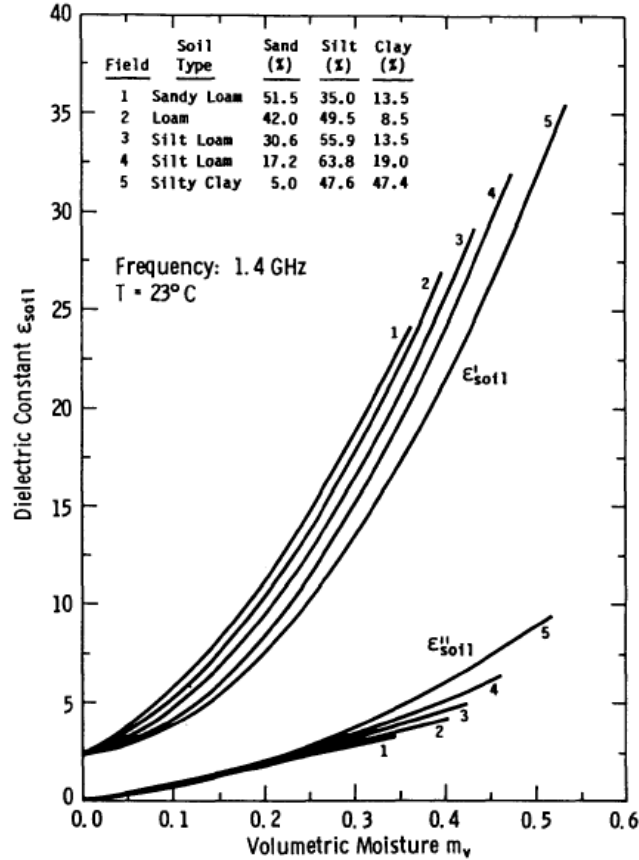


Fig. 6a.1. Dielectric constant as a function of volumetric soil moisture for five soils at 1.4 GHz, from Ulaby et al. (1986).

For the special case of a blackbody, the emissivity $e=1$ and the brightness temperature is the same as the physical temperature. If the subsurface temperature profile is uniform, then the reflectivity r is simply written based on Kirchoff's reciprocity theorem:

$$e = 1 - r \quad (6a2)$$

The reflectivity is derived from the dielectric constant which for a smooth surface and for a medium of uniform dielectric constant is provided by the Fresnel equations:

$$r_v = \frac{\left| \epsilon_r \cos \theta - \sqrt{\epsilon_r - \sin^2 \theta} \right|^2}{\left| \epsilon_r \cos \theta + \sqrt{\epsilon_r - \sin^2 \theta} \right|^2} \quad (6a3)$$

$$r_H = \left| \frac{\cos \theta - \sqrt{\varepsilon_r - \sin^2 \theta}}{\cos \theta + \sqrt{\varepsilon_r - \sin^2 \theta}} \right|^2 \quad (6a4)$$

where the subscripts V and H stand for vertical and horizontal polarizations, ε_r is the complex dielectric constant, and θ is the incidence angle. At L-band, emissivity for wet soils could be on the order of 0.6, compared with values of about 0.9 for dry soils. If the physical temperature of the emitting medium is about 300K, this leads to a dynamic range of about 90K for the brightness temperature, i.e., well above the estimated error level for T_B measurements estimated at a few degrees.

The several algorithms proposed by the SMAP SDT to retrieve soil moisture are all based on the following equation, referred to as the τ - ω model:

$$T_{Bp} = T_S \exp(-\tau_p \sec \theta) + T_C (1 - \omega_p) [1 - \exp(-\tau_p \sec \theta)] + r_p \exp(-\tau_p \sec \theta) \quad (6a5)$$

in which the subscript p refers to the polarization (H or V), T_S is the soil effective temperature, T_C is the vegetation (canopy) temperature, τ_p is the nadir vegetation opacity, ω_p is the vegetation single scattering albedo, r_p is the soil reflectivity, and θ is the look angle (40° for SMAP). It is assumed in (6a5) that multiple scattering and reflection at the vegetation-air interface are negligible. Also, the reflection coefficient of a naturally rough surface is approximated by

$$r_{p \text{ rough}} = r_{p \text{ smooth}} \exp(-h) \quad (6a6)$$

where the parameter h is assumed to be linearly related to the root mean square surface height. Nadir vegetation opacity is related to the total column vegetation water content W (kg m⁻²) by

$$\tau_p = b_p W \quad (6a7)$$

in which the parameter b_p depends on the vegetation type. A further simplification can be used if temperature equilibrium between the air, vegetation, and near-surface soil is assumed (as is done for SMAP 6AM descending pass), which leads to $T_{eff} = T_C = T_S$. Based on the above, soil moisture can be estimated using the Fresnel and dielectric constants relationships (6a1 to 6a4).

The SMAP soil moisture retrieval based on low-resolution passive measurements are the following, as described in details in SMAP L3_SM_40km Algorithm Theoretical Basis Document 40-km Earth-Gridded Soil Moisture:

- **Single-Channel Algorithm (SCA).** This algorithm is based on a single microwave channel approach using only T_{BH} measurements that are sequentially corrected for surface temperature, vegetation water content, and surface roughness. Ancillary

data are used for the parameters h , ω , T_{eff} , b_H , and W , and emissivity is obtained for bare smooth surfaces. Soil moisture is then retrieved using the Fresnel equation for horizontal polarization together with a dielectric model.

- Dual-Polarization Iterative Algorithm (2CA). This algorithm uses both T_{BH} and T_{BV} . Initial (first guess) values for soil moisture and VWC are iteratively adjusted in forward microwave computations of T_{BH} and T_{BV} until convergence is reached based on least square approach.
- Dual-Polarization Reflectivity Ratio Algorithm (RR). In this other algorithm a roughness and vegetation correction factor is estimated based on both T_{BH} and T_{BV} and then used to calculate an H-polarization bare-soil reflectivity which is used to retrieve soil moisture.
- Land Parameter Retrieval Model (LPRM). This algorithm is an iterative optimization and index-based retrieval model taking advantage of dual polarization measurements at a single L-band frequency to derive soil moisture and vegetation optical depth.

An even wider variability of approaches can be found for soil moisture retrievals, from the relatively simple to the exceptionally complex. As an example, the algorithm used to retrieve soil moisture from SMOS multi-angle dual-polarization or full polarization T_B measurements could be considered as being relatively complex. As described in the SMOS level 2 Processor for Soil Moisture ATBD, optimal values of soil moisture and of vegetation characteristics are obtained iteratively by minimizing a quadratic cost function representing the differences between modeled (direct) and measured T_B . This is made possible by the large number of observations given for each Earth-grid node over which the retrievals are attempted, based on the multi-angle nature of the SMOS measurement strategy (i.e., several T_{BH} and T_{BV} measurements, for various incidence angles, are available for each retrieval point).

The complexity of the SMOS soil moisture retrieval algorithm is largely related to the horizontal heterogeneity of the SMOS pixels (with footprints on the order of 55 km). Complications arise from the specification of “retrievable” and “non-retrievable” coverage fractions over the pixel, and on the direct (forward) modeling of microwave (L-band) emission for several types of land cover over the “retrievable” portion of the SMOS pixels. The microwave emission modeling is essentially based on the same equations as those used for SMAP (see above), but with some nuances mostly related to different approximations for the effect of roughness, vegetation, thermal homogeneity, among other aspects.

It should be mentioned that retrieval techniques of a different nature than those for SMOS and SMAP could also be used. They could be of a more empirical or statistical nature (e.g., from regressions), based on neural networks, or on change detection (such as discussed below for F/T retrieval) (e.g., Wagner et al. 1999, Pardé et al. 2004, Lakhankar et al. 2009).

Soil moisture retrievals using radar or SAR data have not been established for as long as their counterparts using passive radiometric data. Originally relying on empirical relationships between the backscattering coefficient σ^o and volumetric soil moisture, algorithms based on active data became more physically based when multi-polarization and polarimetric data came to be available. Several algorithms have been developed since then for quantitatively measuring bare surface soil moisture using dual-polarization L-band SAR image data (Dubois et al. 1995 and Shi et al. 1997) or three-polarization SAR measurements (Oh et al. 1992).

In the presence of vegetation, these bare surface models no longer perform as well and require modifications to infer soil moisture. The total (measured) copolarized radar backscatter σ'_{pp} for a vegetation-covered soil layer at polarization p can be expressed in the following manner,

$$\sigma'_{pp} = \sigma_{pp}^S \exp(-2\tau_p \sec\theta) + \sigma_{pp}^V + \sigma_{pp}^{SV} \quad (6a8)$$

i.e., as the sum of three components including the scattering cross-section of the soil surface σ_{pp}^S modified by the two-way attenuation from vegetation with nadir opacity τ_p , the scattering cross-section of the vegetation volume σ_{pp}^V , and the scattering cross-section resulting from the interaction between the soil and vegetation σ_{pp}^{SV} . Because of the impact of rough vegetation on the radar backscatters, two different methods are currently used by SMAP Project to obtain soil moisture: one for low vegetation surfaces (vegetation water content – VWC less than 0.5 kg m⁻²) and one for vegetated surfaces (VWC greater than 0.5 kg m⁻²) surfaces.

For the low vegetation case, a series of so-called “snapshot” methods have been investigated to retrieve soil moisture. These approaches use each radar acquisition independently to invert soil moisture. The current baseline is a data-cube algorithm in which inversion is performed by searching a two-dimensional (soil moisture and roughness) lookup table generated by a radar scattering model. This is in fact a multichannel retrieval algorithm that iteratively adjusts soil moisture and surface roughness in forward computation of σ_{VV}^o and σ_{HH}^o (and σ_{HV}^o) until the difference between computed and observed backscatters is minimized in the least square sense. A number of radar scattering models for two-dimensional bare surfaces have been examined for the generation of the lookup table, including analytical methods such as the Small Perturbation Method (SPM, Tsang and Kong 2001), the Integral Equation Model (IEM, Fung et al. 1992), the Advanced Integral Equation Model (AIEM, Chen et al. 2003), and the Small Slope Approximation (SSA, Voronovich 1994). Likewise, numerical methods such as the Method of Moments (EBCM, Kuo and Moghaddam 2007), the finite-element method (Lawrence et al. 2010, Lou et al. 1991) and the finite difference time domain method (Chan et al. 1991) are also examined for the generation of the two-dimensional lookup table.

Other approaches are also considered for low vegetation surfaces apart from the data-cube strategy. They include the empirical soil / vegetation empirical model of Dubois et al. (1995) for σ_{vv}^S and σ_{hh}^S and of Oh et al. (1992) for the cross-polarization σ_{hv}^S

(computed from σ_{vv}^S), and the technique described in Sun et al. (2009) based on the reduction of the normalized backscatter standard deviation (K_p) through a combination of co-polarization channels. More details on these techniques can be found in SMAP L2_3_SM_A ATBD.

For vegetation surfaces, time-series of HH and/or VV with HV are used to estimate the vegetation level. This approach assumes time-invariant roughness. In a manner similar to the bare soil case, the baseline approach follows a data-cube algorithm. Inversion for soil moisture and roughness is achieved by minimizing the distance (D) given below in (6a9) by searching a three-dimensional data cube (the equivalent of the two-dimensional lookup table for the low vegetation case) using a time-series of N elements:

$$D = \sum_t^N \sum_{ch}^{HH,VV} w_{ch} \left(\sigma_{ch,measured}^0 - \sigma_{ch,datacube}^0 \right)^2 \quad (6a9)$$

in which ch is for the channel, and $\sigma_{ch,datacube}^0$ is a function of soil moisture (retrieved), roughness (retrieved), and vegetation and is obtained from a radar scattering model. At this time, seven vegetation types are considered in this process (grass, corn, soybean, shrub, tundra, broadleaf and conifer trees).

The three-dimensional data cube is constructed following Xu et al. (2010a,b), in which the discrete scatterer approximation is applied (Lang and Sighu 2983). In this model, each vegetation object is treated as a cylinder or a disk and is assumed to scatter independently. Fields from each vegetation component are summed and averaged over size and orientation distributions. Alternate choices for inversion over vegetated surfaces include the change-detection algorithms of Kim and van Zyl (2009) and of Wagner et al. (1999).

Having radar measurements to inform on high-resolution spatial structures of near-surface soil moisture together with more accurate lower-resolution retrievals based on radiometric observations is certainly a strong feature of the SMAP mission. Using SMAP data alone, it is possible to combine active and passive measurements to obtain high quality soil moisture retrievals at an intermediate resolution.

One method proposed by the SMAP SDT is based on the downscaling of the brightness temperatures to a an intermediate resolution grid based on the high-resolution radar backscatter cross sections. Definitions for the three grids involved in this process, i.e., coarse (passive), fine (active), and medium (combination), are shown in Fig. 6a.2.

The formulation of the downscaling algorithm is based on the linear relationship between the brightness temperature and the co-polarization radar backscatter cross section:

$$T_{Bp}(C) = \alpha(C) + \beta(C) \sum_{i=1}^{nf} \sigma_{pp}(F_i) \quad (6a10)$$

where $T_{Bp}(C)$ is the measured brightness temperatures (polarization p) at 36-km grid spacing (“ C ” stands for “coarse”), $\sigma_{pp}(F_i)$ is the measured co-polarized (PP) radar backscatter cross sections on the fine grid (3 km, “ F ” stands for “fine”), and the regression coefficients $\alpha(C)$ and $\beta(C)$ are dependent on local conditions (mostly vegetation) and are calculated for each season.

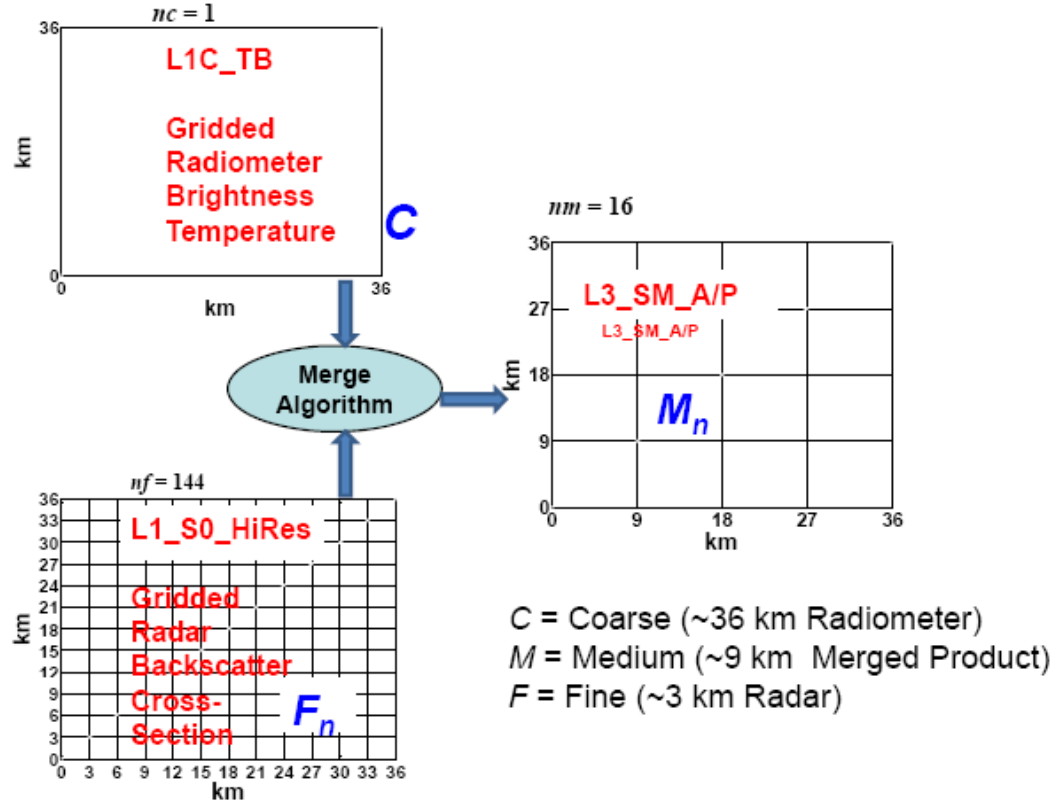


Fig. 6a.2. Grid definitions for the blending of low-resolution radiometric measurements (L1C-TB product on a 36-km “coarse” pixel) and of the high-resolution radar measurements (L1_S0_HiRes on a 3-km “fine” grid) to generate soil moisture retrievals at an intermediate resolution (L3_SM_A/P on a 9-km “medium” grid). From Das et al. (2011).

The same equation can be written for a particular M_j pixel of the “medium” scale:

$$T_{Bp}(M_j) = \alpha(M_j) + \beta(M_j) \sum_{i=1}^{nm_j} \sigma_{pp}(F_i) \quad (6a11)$$

Assuming that the conceptual vegetation and soil roughness conditions apply everywhere in the coarse grid implies that:

$$\alpha(M_j) = \alpha(C) \quad \text{and} \quad \beta(M_j) = \beta(C) \quad (6a12)$$

and

$$T_{Bp}(M_j) = \alpha(C) + \beta(C) \sigma_{pp}^e(M_j) \quad (6a13)$$

where σ_{pp}^e is the co-polarization backscatter cross-section corresponding to the effective vegetation and soil roughness conditions in pixel M_j .

Using the SMAP cross-polarization radar backscatter cross section σ_{pq} which is considered to provide useful information on the vegetation cover and on soil roughness, the following linear relationship is assumed:

$$\sigma_{pp}(M_j) \cong \sigma_{pp}^e(M_j) + \left. \frac{\partial \sigma_{pp}}{\partial \sigma_{pq}} \right|_C [\sigma_{pq}(M_j) - \sigma_{pq}(C)] \quad (6a14)$$

The disaggregation for the brightness temperature at the medium scale thus becomes:

$$T_{Bp}(M_j) = T_{Bp}(C) + \beta(C) [(\sigma_{pp}(M_j) - \sigma_{pp}(C)) - \Gamma(\sigma_{pq}(M_j) - \sigma_{pq}(C))] \quad (6a15)$$

in which $\Gamma = \left. \frac{\partial \sigma_{pp}}{\partial \sigma_{pq}} \right|_C$

As a final step the radiometer retrieval algorithms (described above) are applied to retrieve soil moisture using $T_B(M_i)$ values on the medium-resolution grid, with required ancillary data provided on the same grid.

Although as described above a wide display of methods and techniques exist to retrieve near-surface soil moisture based on L-band passive and active data, there are still several aspects that remain uncertain. In addition to factors that normally have to be considered for space-based microwave remote sensing, such as uncertainty related with Faraday rotation in the ionosphere, sun glint effects due to reflection off the ocean surface, cosmic microwave background radiation, and even with RFI for which mitigation has been the subject of a substantial effort by the JPL SMAP team, several remaining problems specific to soil moisture retrieval could be of importance for the development or adaptation of retrieval algorithms for Canadian products:

- Heterogeneity of the surface, and most specifically the presence in Canada of a very large number of lakes and forests (of all sizes) along with several urban areas will certainly be a source of errors.
- Uncertainty associated with inputs and ancillary data for the retrieval algorithms (e.g., surface and soil temperatures, vegetation and crops types, soil texture, snow on the ground, identification of urban areas, presence of litter on the soil, ...) also has to be considered.
- The difficulties associated with complex orography will limit retrieval capabilities for a large portion of the country.

- The horizontal resolution of SMAP SAR is still not sufficient to resolve agricultural fields.
- Specific aspects of the retrieval algorithms for both soil moisture and F/T remain unresolved, such as soil moisture retrieval under dense vegetation, the role and impact of litter under tall forest canopy, or the respect of certain assumptions like thermal equilibrium.

The research and development proposed in this plan regarding soil moisture retrieval essentially focus on the use of SMAP high-resolution active data to refine soil moisture retrievals and to be included in a 1-km version of CaLDAS.

More specifically, a synergistic approach including passive (SMOS, SMAP) and active (e.g., ALOS, ASAR-Envisat, RADARSAT-2, SMAP) remote sensing data will be envisioned, accounting for strengths and weaknesses of each type of data in order to produce soil moisture retrievals of optimal quality. One of the research group (i.e., Université de Sherbrooke) will focus on the τ - ω model for passive L-band data, with crop parameters (roughness, water content, height) obtained from RADARSAT-2 and forest parameters (height, canopy) obtained from ALOS/PALSAR. Another research group (AAFC) will emphasize the design of a robust method to estimate soil moisture based on active measurements (RADARSAT-2, SMAP), using the IEM model mentioned above. Obviously more oriented towards agricultural applications, AAFC will adapt and refine methods for estimating residue type and cover from SPOT and Landsat for fine resolution as well as AWIFS (Advanced Wide Field Sensor) for wide swath coverage. There is also interest in developing methods with active radar data to identify when tillage occurs.

In all this research done in Canada concerning soil moisture retrieval from SMAP and other space-based instruments, some emphasis is placed on providing relevant data to inform on the best strategy to use in CaLDAS related to forward modeling. This is especially true for the active component, which has not been examined in previous work with CaLDAS. Finally, in the context of land surface data assimilation, providing realistic estimate of the uncertainty associated with the soil moisture retrieval is almost as important as providing accurate soil moisture values.

ii) F/T surface state

The seasonal F/T cycle is a major phenomenon in the climate system and plays an important role in ecosystem functioning (Lagacé 2000) by influencing the rate of photosynthesis and respiration of the vegetation (Smith et al. 2004), reducing evaporation as well as water penetration into the soil thereby altering surface runoff (Lagacé et al. 2002). Boreal and arctic regions form a complex land cover mosaic where vegetation structure, condition, and distribution are strongly regulated by environmental factors such as soil moisture and nutrient availability, permafrost, growing season length, and disturbance. In these seasonally frozen environments, the growing season is determined primarily by the length of the non-frozen period. Variations in both the timing of spring thaw and the resulting growing season length have been found to have a major impact on

terrestrial carbon exchange and atmospheric CO₂ source/sink strength in boreal regions (Frolking et al. 1996, Randerson et al. 1999, McDonald et al. 2004). The timing of spring thaw in particular can influence boreal carbon uptake dramatically through temperature and moisture controls to net photosynthesis and respiration processes (Jarvis and Linder 2000, Tanja et al. 2003). With boreal evergreen forests accumulating approximately 1% of annual Net Primary Production (NPP) each day immediately following seasonal thawing, variability in the timing of spring thaw can trigger total interannual variability in carbon uptake on the order of 30% (Frolking et al. 1996, Kimball et al. 2004, McDonald et al. 2004). Temporal variations in the onset of frozen conditions in the fall are also significant but generally have less impact on annual productivity due to the increased importance of other controls on vegetation photosynthetic activity such as photo-period length (Kimball et al. 2004).

The freezing of the soil is, in fact, the freezing of water in soil pores. The dielectric constant is related to the soil water content, because water creates heterogeneity in electrical charge at the molecular level, this causes the polarity in the molecule. The frozen ground also influences the dielectric constant. It decreases the rotational energy of the molecule which has a positive linear relationship to the dielectric constant (Lagacé 2000, Kalantari et al. 2009). Consequently, backscattering energy is reduced (Ulaby et al. 1986, Lagacé 2000, Kalantari et al. 2009). The values of dielectric constant of air, dry soil and water are 1, 3 and 80 respectively.

Mostly based on active measurements, space-based sensors operating at Ku, C, and L-band have been tested for this application. Studies in Ku-band include Frolking et al. (1999) and Kimball et al. (2004) using NSCAT and QuickSCAT data. Also, the possibility of using ERS-1 C-band active data has been investigated by many (Rignot and Way 1994; Rignot et al. 1994; Way et al. 1997; Wisman 2000, Lagacé et al. 2002, Khaldoune 2006), and JERS (L band) data by Werner et al. 2003. The use of SAR images like RADARSAT-1 or 2 (C-band) data allows for very detailed mapping of on the F/T state depending on vegetation coverage and density and on the presence of dry snow. (The determination of the snowmelt period could also be derived from SAR images.)

It is expected that SMAP will lead to substantial advancement in the status of global F/T state detection from space, because of its use of L-band frequency, of its relatively frequent revisit (essentially every one or two days at mid to high latitudes), of its horizontal resolution, and of its combined active and passive (quasi simultaneously) sensing of the Earth's surface.

The primary purpose of F/T retrieval techniques is to identify the transitions between frozen and non-frozen states. The most common approach is temporal change detection. This approach supposes that observed large changes in microwave emissions and backscattering are caused by the F/T transition and not by other factors, such as changes in the canopy structures, biomass, or precipitation. The baseline algorithm is based on a seasonal threshold approach (Rignot et al. 1994; Way et al. 1997; Entekhabi et al. 2004, Khaldoune, 2006). Other algorithms, based on moving window (Frolking et al. 1999;

Kimball et al. 2004; Rawlins et al. 2005) or temporal edge detection (McDonald et al. 2004) are also being considered.

The expected SMAP product is a global map of the F/T state on a 1 to 3 km grid. This product will be based on the L1C_S0_HiRes radar product, from both AM and PM overpasses.

There are several issues regarding F/T retrieval, which are described below.

- Freezing of different components of the landscapes: In general, landscapes of the terrestrial cryosphere consist of a soil substrate that may be covered by some combination of vegetation and seasonal or permanent snow. The composite remote sensing signature represents a sampling of the aggregate landscape dielectric and structural characteristics, with sensor wavelength having a strong influence on the sensitivity of the remotely sensed signature to the various landscape constituents (trunks, stems, leaves, versus soil). First-order contributions to the landscape brightness temperature are emission by the underlying surface that is attenuated by upward propagation through the vegetation canopy, vegetation volume emission propagating in the upward direction, and vegetation volume emission propagating in the downward direction that is reflected back through the vegetation volume by the underlying surface (Robinson et al. 1993; Frohling et al. 1996; Randerson et al. 1999).
- Spatial heterogeneity (same problem as for soil moisture): Lagacé (2002) showed that for frozen soils the radar backscatter coefficient decreases on average by 2 dB in a boreal forest area (taiga). Other areas exhibit even steeper decline (3-5 dB). In this case spatial variability depends on soil type (sand, silt, organic soil) and land cover (burning, forest on mineral lichen). In comparison, studies performed in the 1990s indicate that a decrease of 3 dB (similar to the effect above) would correspond to a freezing of the soil and vegetation (Villasenor, et al. 1993), making this an issue. Spatial heterogeneity also influences soil temperature and emissivity (passive microwave).
- Open water fractional coverage: The presence of open water such as lakes, rivers, and reservoirs has an influence on the brightness temperature, emissivity, dielectric constant, and backscatter cross section. This effect will have to be mitigated using accurate and high-resolution geophysical information. For water bodies smaller than the SMAP retrieval grids, the fractional portion of water in the pixel could be taken care of using algorithms similar to what is done for passive microwave retrievals (DeSeve 1999).
- Snow on the ground: More than its presence and depth, it is mostly the presence of liquid water in the snow pack that will influence the radar backscattering cross section at L-band. For dry snow covers, the dielectric constant at L-band is only slightly superior to that of air and (similar to that of dry soil). At this frequency band, dry snow is thus almost “transparent” from a radiative transfer point of view

and backscattering mainly depends on soil conditions (moisture, roughness) and incidence angle. In the presence of liquid water in the snow pack, however, the dielectric constant considerably increases and produce an effect similar to having a wet soil, leading to a significant decrease in backscatter cross section. When liquid water content exceeds 3% in snowpack, the radar signal is completely absorbed by the snowpack and the status of the soil cannot be detected (De Sève 1999; Lagacé 2000; Kalantari et al. 2009)

- Topographic slope and aspect: Local topographic slope and aspect play a crucial role on the backscattering signal because they determine the local incidence angle. This angle determines the appearance of the target on an image (signal backscatter) because the signal is greatly affected by surface roughness at high incidence angles.

These aspects are being examined in the context of this Canadian Plan for SMAP with projects at both INRS-ETE and University of Sherbrooke. These efforts are aimed to facilitate the inclusion of L-band active data from SMAP in their algorithms to retrieve the F/T state of the soil. As was the case for soil moisture retrieval, results and methods arising from this work should be used for the forward modeling in CaLDAS, and careful attention should be given to the specification of the uncertainty of the retrievals.

As a collaboration between University of Sherbrooke (Royer) and Environment Canada (Derksen), two L-band passive radiometers including L-band will be installed in a forested site (likely at the old BERMS site). Passive microwave information for F/T state monitoring could bring a significant additional value to this product by monitoring the dynamics of the surface and soil temperatures. It has been shown that passive microwave brightness temperatures at 19 and 37 GHz are sensitive to the timing of snowmelt and soil state. Lower frequencies such as 10.7 GHz also show a signal to F/T transition under snow (Kohn and Royer 2010). Low frequency passive microwave measurements are less affected by snow with the signal related in large part to soil temperature (which is not the case in active scatterometry). Considering the sensitivity of low microwave frequencies to snowmelt and soil temperature, data from the SMAP 1.41 GHz radiometer could be used to enhance the monitoring of F/T in northern regions (Rautiainen et al., 2012).

The general objective of this specific component of the Canadian Plan is to improve methods for monitoring F/T processes using the SMAP passive microwave measurements. More specific objectives are to:

- model the different contributions (soil dielectric constant, vegetation, snow) affecting the monitoring of frozen ground and soil temperature through an annual cycle (including under snow) in boreal forest and tundra environments;
- use multi-frequency analysis (including ground-based measurements, 1.4 – 36.5 GHz) to validate radiometric models and to better understand the different contributions in the signal variability at L-band during F/T episodes over arctic and subarctic land cover (boreal forest, tundra);
- demonstrate the sensitivity of L-band microwave emissions to soil F/T transition under snow (both wet and dry);

- couple physical snow-soil models with microwave emission models in order to monitor soil temperature to support data assimilation activities; and to
- improve the SMAP F/T product by assessing the active F/T product with existing distributed networks of in situ ground temperature measurements and by evaluating the expected improvement of this product based on a combination of active and passive SMAP measurements.

The proposed method is based on multi-frequency (1.4, 10.7, 18.7 and 36.5 GHz, possibly 89 GHz) and continuous tower-based and ground-based radiometer measurements in a forested area. The necessary ancillary measurements include characterization of soil (permittivity, temperature, moisture), snow (temperature, density, liquid water content and grain size), and vegetation (stem volume, LAI, temperature, permittivity). It is proposed that one radiometer be installed above the canopy, with the other at ground level. This set up will allow the evaluation of the impact of the vegetation on the F/T retrievals.

As part of this project parameterizations and sensitivity analysis of radiative transfer models will be developed based on the ground-based measurements. These aspects will include the vegetation τ - ω model for forest transmissivity and scattering albedo (Mo et al., 1982; Roy et al., 2012), the soil Q-h model for soil reflectivity parameterization (Wang et al. 1983), and the Dense Media Radiative Transfer – Multi-Layers (DMRT-ML) model for snow (Picard et al., 2013; Roy et al., 2013).

Finally, some emphasis will be placed on the physical snow-soil coupling and on microwave emission modelling to monitor soil temperature and to develop an algorithm for F/T monitoring. The newly developed method will be evaluated with SMAP data (brightness temperatures and F/T product), with a performance comparison with AMSR2 and SMOS data.

b) Soil moisture data assimilation

Soil moisture influences the partitioning of the incoming energy into latent and sensible heat fluxes, which in turn exerts important controls upon land-atmosphere interactions. NWP operational centers typically infer changes in soil moisture by using proxy information from forecast errors in screen-level parameters such as air temperature and humidity. Given the significant advances in the development of earth observation systems over the last several years real opportunities exist to improve the representation of the land-surface, and soil moisture in particular, within NWP systems.

The CaLDAS system has been in development at EC/MRD for several years in an effort to improve the initial conditions provided to EC NWP models. The main components of CaLDAS are shown in Fig. 6b.1. Of particular importance within CaLDAS is the emphasis placed upon the incorporation of satellite-based remote sensing observations of the land-surface state. CaLDAS has been accepted as an experimental operational product at EC and is anticipated to become fully operational in 2014.

CaLDAS is built around an external land-surface modeling system which provides first guess estimates of the land-surface state. The land surface model is driven by three types of information: atmospheric forcing, geophysical land surface characteristics (ancillary data), and initial conditions. Short-range forecasts from EC’s NWP prediction models are used to provide the atmospheric forcing which consists of shortwave and longwave radiation incident at the surface, temperature, specific humidity, wind, surface pressure. Precipitation, which is arguably the most important atmospheric forcing for the evolution of soil moisture is provided by the Canadian Precipitation Analysis (CaPA).

Land surface characteristics, the second type of inputs to the land surface model, include topography, vegetation fraction, land-cover type, open water coverage fractions, and canopy density. Accurate specification of these characteristics is of utmost importance (as important in fact as having good quality physical models) to provide a reasonable first guess of soil moisture and other geophysical variables. Considerable effort has been devoted at EC to obtain global, regional, and local high-resolution land surface ancillary databases to drive EC/MRD’s land surface models.

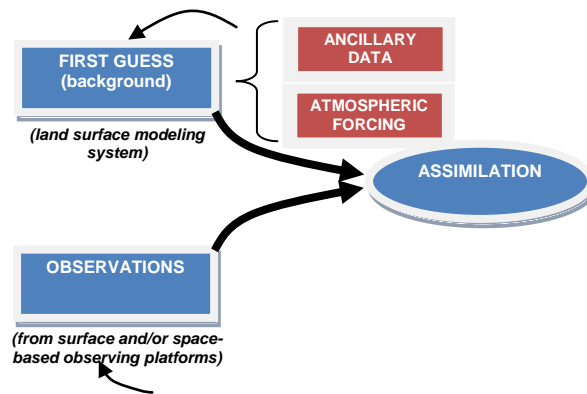


Fig. 6b.1. Schematic description of CaLDAS with components shown in blue.

Within CaLDAS the Ensemble Kalman Filter (EnKF) methodology is used to optimally combine the land-surface first-guess states with observations. The EnKF is a sequential data assimilation method for which a finite number of randomly generated model trajectories are used to approximate the model error distribution (related to the spread of the ensemble of first guess short integrations). Compared to other assimilation methods, the EnKF has the advantage that it is able to handle nonlinear problems and is more flexible in treating model errors.

The analysis equation for a general data assimilation scheme is the following:

$$\mathbf{x}^a = \mathbf{x}^b + \mathbf{K} [\mathbf{y} - H(\mathbf{x}^b)] \quad (6b1)$$

where \mathbf{x}^a is the analysis or best estimate of the geophysical variable, \mathbf{x}^b is termed the model first-guess or background value, \mathbf{y} is the observation vector and H is the forward

operator (microwave radiative transfer model) which maps the model first-guess into observation space. In (6b1) \mathbf{K} represents the gain matrix which summarizes the relative weights of the observations and model background. The Community Microwave Emission Model (CMEM) developed at ECMWF has been coupled to the land surface model as a forward operator microwave emission model to calculate a model L-band brightness temperature.

Regional and continental-scale data assimilation experiments have been performed assimilating passive microwave L-band SMOS data with CaLDAS. A comprehensive bias correction strategy, based upon a cumulative distribution function (CDF) matching procedure, was developed for the brightness temperatures along with appropriate data assimilation masks for land-water fraction and frozen soils. Several configurations of the CMEM forward operator were examined to determine the optimal setup. Additionally, these experiments afforded the opportunity to assess the impact of perturbing model geophysical parameters to increase the spread in the model first-guess ensemble.

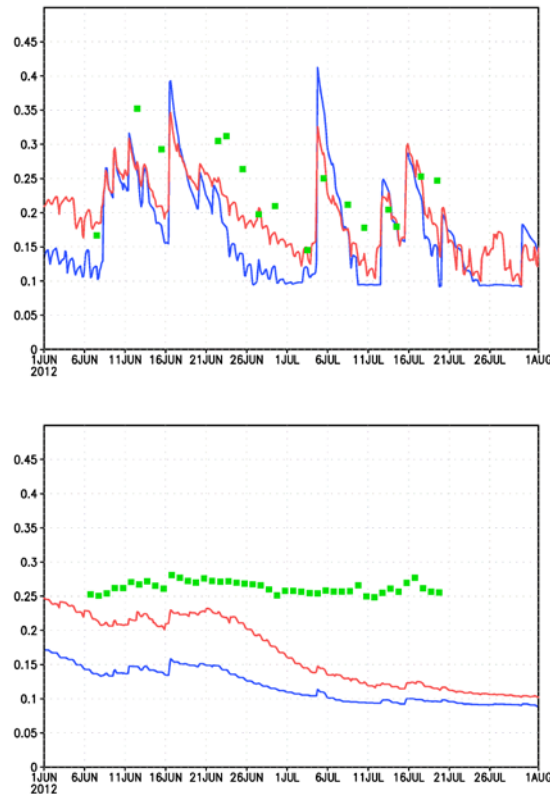


Fig. 6b.2. Time-series of soil moisture for the superficial layer (top panel) and the root-zone layer (bottom panel) for the SMAPVEX12 field experiment. Units are $\text{m}^3 \text{m}^{-3}$. The CaLDAS EnKF experiment is shown in red, while the open loop experiment is shown in blue. Soil moisture observations are shown in green.

Figure 6b.2 shows the positive impacts of assimilating SMOS data upon the analysis of the soil moisture state for the SMAPVEX12 extensive field campaign conducted over southern Manitoba in the summer of 2012. The superficial (root zone) soil moisture is shown in the top (bottom) panel, and the red curve denotes the analyzed soil moisture

from CaLDAS which assimilated the SMOS brightness temperatures and for comparison the black curve shows that results from an open loop simulation with no assimilation. The soil moisture observations are shown in green. It is clear for the superficial zone that the SMOS data aids in dry-down periods where the model tends to dry too fast. Note that superior performance during the extensive dry-down period at the end of June. Also very encouraging is the more humid root-zone layer in CaLDAS in better agreement with observations.

Evaluations of various configurations of the CMEM forward operator were carried for the summer 2012 drought period out to determine the optimum configuration with the modelled brightness temperatures. Figure 6b.3 shows the spatial distribution of the temporal correlation coefficient between the land-surface model brightness temperatures and SMOS for the summer 2012 period. Strong positive correlations are seen over much of the agricultural and short grass regions of the North American continent.

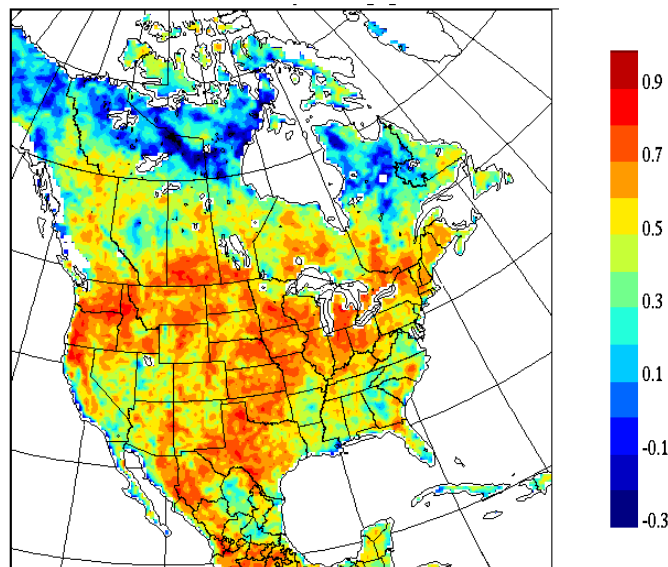


Fig. 6b.3. Temporal correlation coefficient between modelled and SMOS brightness temperatures for the 2012 warm season period.

A key feature of the SMAP mission will be a higher-resolution soil moisture (~ 9 km) product generated by combining these higher-frequency active radar data with the lower-resolution passive radiometer data. The main objectives of the data assimilation component of the scientific plan are twofold; (i) evaluate different methodologies to produce higher-resolution soil moisture analyses (5-10 km) , and (ii) determine how best to combine the traditional screen-level observations with the satellite based observations to produce a superior soil moisture analysis.

For the first objective the strategy will be the production of higher-resolution soil moisture analyses by combining the passive L-band observations with higher-resolution land-surface modeling first-guess fields in a downscaling approach. CaLDAS is

currently being configured to perform the downscaling and will be tested with the available passive radiometer data from SMOS. This code will be easily transferrable to SMAP after launch. Plans will be to additionally compare the downscaled soil moisture product with the higher-resolution passive-active soil moisture analyses produced by SMAP.

The second objective is still an open research question at this time. Screen-level observations have been successfully used to analyze the soil moisture state, but do have their limitations. Three configurations of CaLDAS will be tested; (i) atmospheric forcing at ~40 m, assimilating both screen-level observations and passive L-band data, (ii) atmospheric forcing at ~40 m assimilating passive L-band data, and (iii) atmospheric forcing at screen-level assimilating passive L-band data.

c) Carbon cycle and ecosystem modeling / assimilation

With all the current focus on climate change, the global carbon cycle has been and continue to be the subject of considerable attention by the scientific community. Exchanges of carbon between the atmosphere, biosphere, pedosphere, geosphere, and hydrosphere is one of the basic cycles of the Earth system, along with the energy and water cycles. Because of the close connections between the three types of cycles, there are strong linkages between the environmental variables measured by SMAP (soil moisture and F/T) and carbon exchanges between the land surface and the atmosphere. For instance, lack of soil moisture will reduce respiration, slow or stop vegetation growth, and may even lead to vegetation death, whereas near-saturated soils could be damaging to plant growth. Due to the crucial importance of northern regions in the global carbon cycle, F/T also plays a major role. For example, the considerable amount of carbon stored in permafrost may become available and be transferred to the atmosphere if thawing occurs. The F/T status of the soils also influences vegetation activity, to a degree even greater than that of soil moisture.

The following variables are important to the study of the carbon cycle. The Gross Primary Production (*GPP*) is the rate at which vegetation captures and converts chemical energy as biomass. Part of this energy is used by primary producers for so-called autotrophic respiration (R_a , also conveyed as growth or maintenance respiration) while the rest is referred to as the *NPP*:

$$NPP = GPP - R_a \quad (6c1)$$

The total respiration also includes an heterotrophic component (R_h) caused by decomposition by bacteria and fungi, so that the total respiration is $R_a + R_h$. The *NEE* is the net CO₂ flux to the atmosphere from the surface, and is given by:

$$NEE = (R_a + R_h) - GPP \quad (6c2)$$

This net CO₂ flux is obviously of great significance in the study of the global carbon cycle. It is closely related to the *NPP*, i.e.,

$$NEE = R_h - NPP \quad (6c3)$$

and to the so-called Net Ecosystem Production (*NEP*):

$$NEE = F_{lateral} - NEP \quad (6c4)$$

in which $F_{lateral}$ are lateral fluxes of carbon in and out of ecosystems. Very often the lateral fluxes are neglected so that $NEE = -NEP$ (as will be assumed in this document). It is also worth mentioning that dry soil conditions will have the impact of reducing both *GPP* and *NPP*, while also decreasing R_h , and that this impact is similar to that of soil freezing.

Several physically-based (i.e., process-based) models have been developed in the last two or three decades to represent production and respiration, as well as the balance between these two processes which lead to *NEE* and *NEP*. As found in the literature, these terrestrial ecosystem models (also called terrestrial biogeochemical models or terrestrial biosphere models) are typically able to represent the state and fluxes of water, carbon, and nitrogen by growing vegetation and including processes of photosynthesis, net plant carbon fixation, autotrophic and heterotrophic respiration, phenology, biomass and nutrient allocation, litterfall, mortality, soil nutrient mineralization, land use change, fire, and competition between plant functional types. The most well known of these terrestrial ecosystem models include the Biome-BioGeoChemical Cycles model (Biome-BGC) developed at the University of Montana (Running and Hunt 1993), the Boreal Ecosystem Productivity Simulator (BEPS, Chen et al. 1999, Liu et al. 1999), the Century model described in Parton et al. (1987, 1993) and in Ise and Moorcroft (2006), the NASA Carnegie-Ames-Stanford Approach (CASA) model (Potter et al. 1993), the High-Resolution Biosphere Model (Esser et al. 1994), the Integrated Biosphere Simulator (Foley et al. 1996), the Terrestrial Ecosystem Model (Tian et al. 1999), and finally the Canadian Terrestrial Ecosystem Model (CTEM) developed at the Canadian Climate Centre (CCC) and included in the Canadian General Circulation Model (GCM).

As a typical example of the processes and pools that are represented in these models, two schematic diagrams are shown in Fig. 6c.1 for Biome-BGC's carbon and nitrogen dynamics and primary linkages in the plant-litter-soil system, adapted from Running et al. (1999). Without providing any details on the parameterizations used in this model, the diagrams indicate the processes represented in Biome-BGC (growth, maintenance and heterotrophic respiration, allocation, litterfall, decomposition, ...) and the different pools of carbon and nitrogen (plant, litter, and soil).

Most of the above terrestrial ecosystem models are used to estimate carbon surface fluxes and investigate consequences from and impacts on climate change. They require extensive information related to atmospheric composition (concentrations of CO₂ and other gases), remote sensing (e.g., Normalized Difference Vegetation Index - NDVI),

weather (near-surface atmosphere, precipitation), land surface characteristics (vegetation), and soils (texture). They are typically integrated over very long periods of time with daily or monthly time steps, which are required for simulation and prediction but also to spin up the different pools of carbon and nitrogen (a few hundreds or a few thousand years necessary for this). The characteristic grid spacing for these models is on the order of a few tens of kms up to 100 km or so.

Because of the strong interconnections between the energy, water, and carbon global cycles, and because of the benefits that are expected by analyzing and representing processes associated with all three cycles in a single analysis and assimilation system, it is proposed as part of the Canadian Plan for SMAP to include (or closely link) terrestrial ecosystem models into (with) CaLDAS in order to assimilate or analyze vegetation characteristics (LAI, canopy conductance) and produce estimates of CO₂ fluxes and of *NEE* (*NEP*).

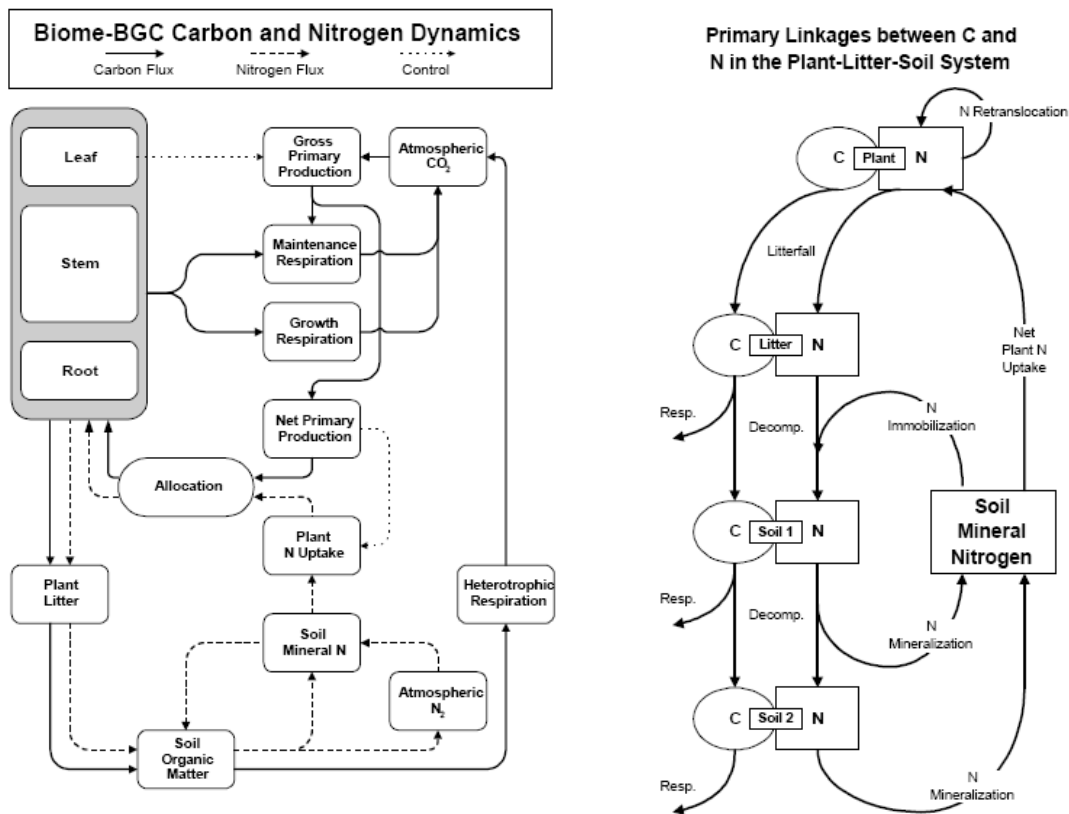


Fig. 6c.1. Schematic diagrams of the carbon and nitrogen dynamics and primary linkages in the plant-litter-soil system of the Biome-BGC model (adapted from Running et al. 1999).

As described in the previous subsection on soil moisture assimilation in CaLDAS, joint representation of the energy and water cycles has been part of land data assimilation systems for some time. A natural extension of this link has been to use land data assimilation systems to provide initial and forcing conditions to hydrological models (e.g., soil moisture, surface, lateral, and base flows, see Habets et al. 1999). But although

the relationship with the carbon cycle is just as important, connections between land data assimilation systems and ecosystem models are still very limited, with both types of systems usually working independently.

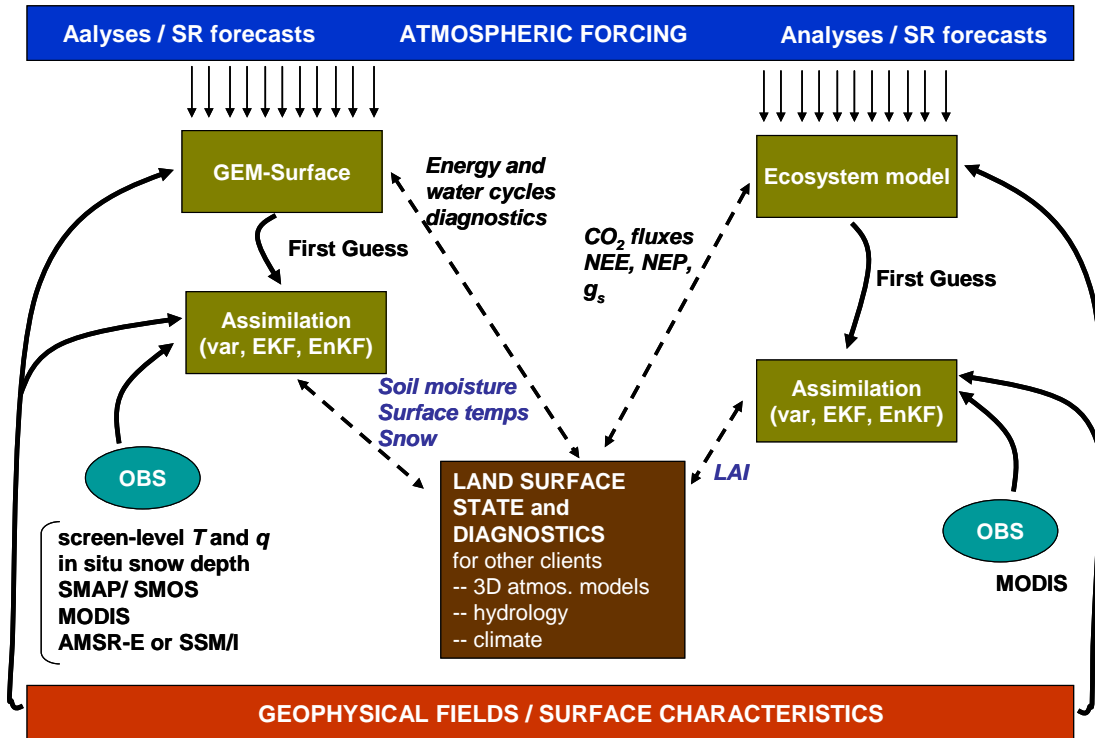


Fig. 6c.2. Schematic diagram of the proposed expanded version of CaLDAS, with inclusion of an ecosystem model and assimilation of MODIS data for the specification of LAI.

But following successes achieved in the climate community to include ecosystem models in their GCMs (e.g., in CCC's GCM, Arora 2003), several NWP centers have done the same in their land data assimilation and modeling systems – although to the author's knowledge none of these efforts have been transferred yet to operational weather prediction. For example, ECMWF has developed a “carbon” version of their land surface model, called C-TESSSEL, and have been generating *NEE* products under the GEOLAND2 project. This approach is based on progress achieved at Meteo-France regarding the vegetation extension of the Interactions between Surface, Biosphere, and Atmosphere (ISBA) land surface model (i.e., ISBA-A-g_s), as described in Calvet et al. (1998). These efforts are precursors to a current emphasis at GEWEX (Global Energy and Water Cycle Experiment) on combined energy / water / carbon cycle modeling as evidenced by an upcoming follow-up to the GSWP which will include carbon models to explore possible carbon-related effect on energy and water cycles and changes in ecosystems for a period from 1979 to now.

Following these recent developments, it is thus proposed to include as part of this Canadian Plan for SMAP a carbon component to CaLDAS, in addition to the assimilation of surface temperatures, soil moisture, and terrestrial snow. Based on Fig. 6c.2, this

expanded version of CaLDAS will provide a more complete set of initial conditions to EC's NWP forecasting systems (for vegetation characteristics and for canopy conductance g_s), as well as real-time vegetation analysis (*LAI*) and *NEE* estimates, all based on EC's state-of-the-art land surface analyses.

The left portion of Fig. 6c.2 portrays CaLDAS as it is currently being developed at EC, with the assimilation of both surface and space-based remote sensing data to specify initial conditions (analyses) for surface temperatures, soil moisture, and snow. The right part of the diagram shows the additional components required to include vegetation and the carbon cycle in CaLDAS. They include first an ecosystem model which provides a first guess of vegetation conditions (mainly *LAI*) that is combined with retrievals from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite (or other satellite products for vegetation characteristics, e.g., the upcoming Visible Infrared Imager Radiometer Suite - VIIRS) to provide an analysis of *LAI* (and possibly other vegetation characteristics). The first guess runs with the ecosystem models are initialized with surface analyses of soil moisture, surface temperatures, snow. These runs are driven by EC's best estimate of atmospheric forcing including precipitation analyses from CaPA and are fed with vegetation / soil characteristics based on the best available datasets. The ecosystem model could either be Biome-BGC, CTEM or BEPS, all currently used in Canada. The surface carbon fluxes as well as the *NEE* and *NEP* are obtained from the first guess runs, in a way similar to the sensible heat and latent heat fluxes obtained from the current CaLDAS. It should be emphasized here that no surface fluxes are actually assimilated in CaLDAS (very few such data in fact exists...). Instead, the focus is on the specification of the land surface characteristics and of the prognostic variables initial conditions, as well as on the atmospheric forcing, to provide the best possible estimate on a global scale of all the surface fluxes.

Evidently, the estimates provided by this system for the surface carbon fluxes, *NEE*, and *NEP* do not include all surface contributions and have to be coupled with other modules for anthropogenic sources and for contributions from oceans and glaciers in order to be used or be coupled with atmospheric GCMs. In this regard, it is not as complete as other more ambitious systems with their main emphasis on the carbon cycle such as CarbonTracker (Peters et al. 2007). Such a system is not out of reach for the Canadian community, but would require closer collaboration between EC's NWP and climate research divisions, and with a few key partners in universities.

d) Impact studies

Accurate representation of soil moisture is of primary importance for several types of environmental prediction systems. In this section, the role and impact of soil moisture is presented for NWP, but other studies related to hydrology and risk assessment for agriculture could (and may eventually) also be included.

For most of land areas, soil moisture is a factor of primary importance that controls the partitioning of the available radiative (solar and thermal) energy incident at the surface.

When soils are humid, more of this available energy is used to evaporate the water present in the soil. In these conditions, evaporation fluxes from the surface to the atmosphere are generally large, whereas sensible heat fluxes (direct heat transfers to the atmosphere) are small. The resulting atmospheric boundary (or well-mixed) layer near the surface is shallow, cool, humid and not very turbulent. The reverse occurs when soils are dry. The sensible heat fluxes are then greater (and evaporation less), leading to a deep, warm, dry, and more turbulent boundary layer. These concepts are depicted in Fig. 6d.1 with examples of real boundary-layer evolution in humid and dry situations.

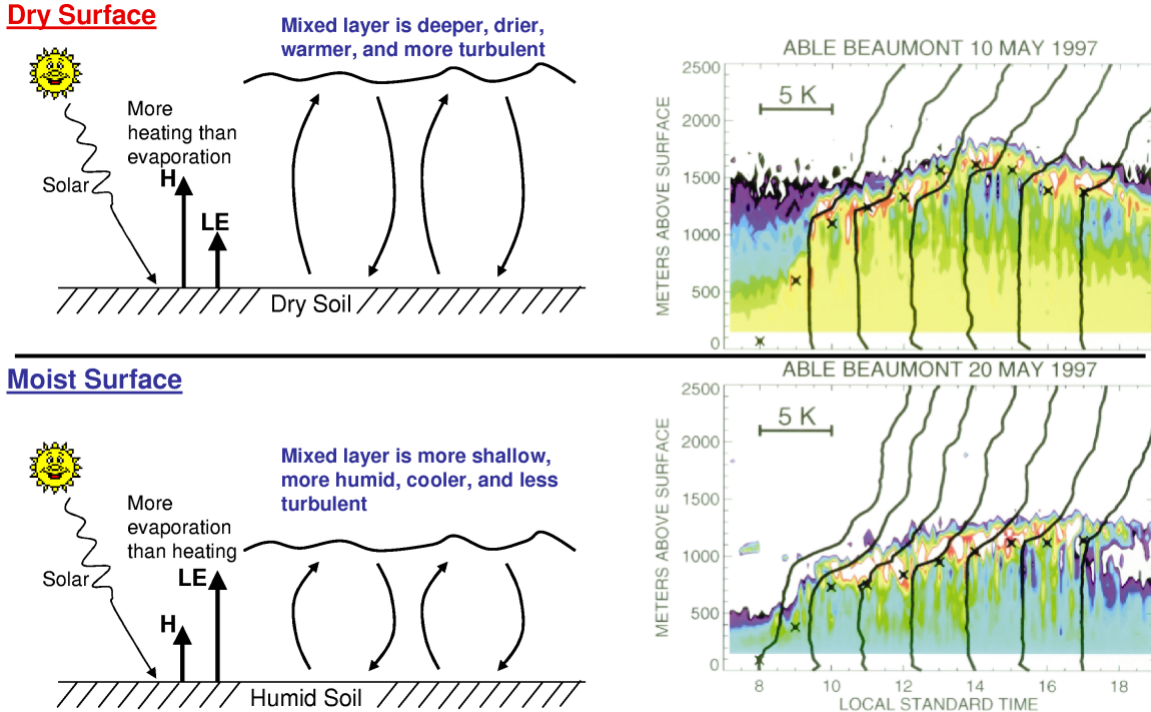


Figure 6d.1. On the left, schematic representation of the effect of soil wetness on the characteristics of the atmospheric boundary (or well-mixed) layer. On the right, lidar cross-sections of real case studies during the Atmospheric Boundary Layer Experiments (ABLE) are shown for Beaumont, Kansas, during dry and wet situations. Right panels from Lemone et al. (2000).

The characteristics of the low-level atmosphere (e.g., turbulence, temperature, humidity) exerts a great influence on meteorological events such as mesoscale and large-scale precipitation systems. For this reason, a large number of studies have revealed how crucial it is to correctly represent surface fluxes of heat, moisture, and momentum in atmospheric numerical models. These fluxes, which greatly depend on soil wetness, have been shown to influence short, medium, and long-range weather forecasts. As shown in Fig. 6d.2, weather elements such as low-level air characteristics (temperature, humidity, winds) and precipitation are particularly sensitive to surface fluxes, and thus to soil moisture.

Therefore, improving initial conditions for soil moisture is expected to (and has been shown to) lead to better weather forecasts if surface physical processes and their impact on the atmosphere are represented realistically in atmospheric models. As part of the

Canadian SMAP science and applications plan, the impact of more realistic soil moisture and F/T soil conditions on weather forecasts will be evaluated, and the physical mechanisms responsible for improvements will be examined. These mechanisms could operate over very long distances since it is possible, for example, that improved soil moisture in the southeastern United States may lead to more realistic intensification of large-scale wintertime systems over Eastern Canada, or better soil moisture in the Northern Central United States could influence the intensity of summertime severe thunderstorms over Alberta.

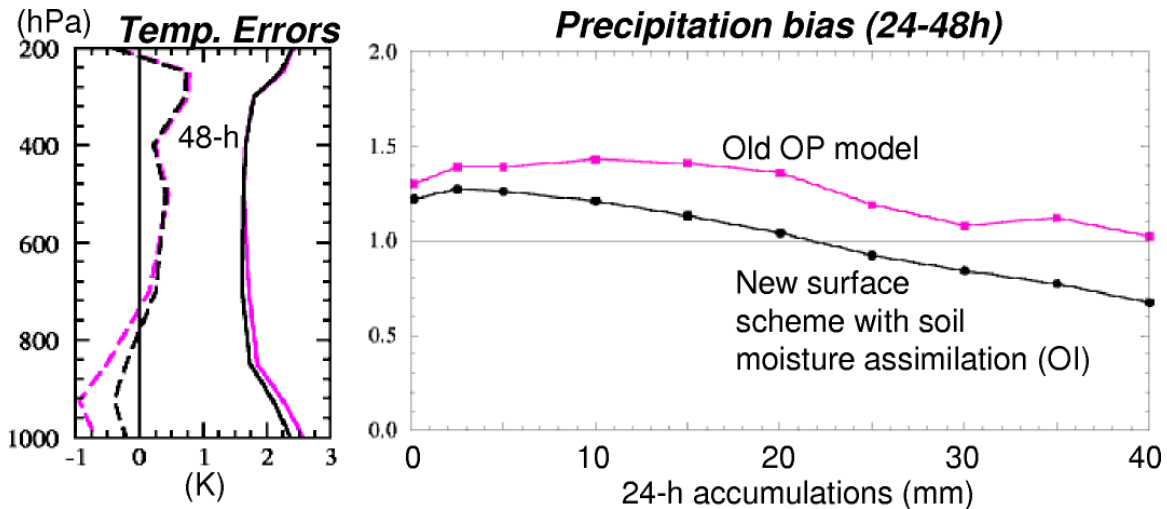


Figure 6d.2. Impact of new land surface scheme (including a sequential assimilation system for soil moisture) on short-range weather forecast over North America. Left panel shows upper-air evaluation of 48-h forecasts against radiosondes, with root-mean-squares errors in full lines and biases in dashed lines. Right panel shows the objective evaluation of precipitation (biases) accumulations against high-density surface stations. Black lines are for the previous operational system, and magenta lines are for the new system.

The atmospheric impact of the soil moisture analyses provided by CaLDAS will be evaluated in the context of short (1 to 2 days, local and continental), medium (up to 2 weeks, global), and long (seasonal, global) range weather forecasts that are done in an operational manner at the Meteorological Service of Canada (MSC).

7. Data, Products, and Outreach

a) Canadian products

The science data products that will be generated by the SMAP mission are provided in Appendix D. It includes Level-1 brightness temperatures and backscatters, Level-2 retrievals, Level-3 composite products, and Level-4 modeling and data assimilation products. As could be expected considerable research and development has gone into the algorithms that will be used for these products. Although these official SMAP retrievals and data assimilation results will be generated globally, some emphasis is expected for products over the US continental region which may not be optimal for the Canadian territory or for Canadian needs.

Table 7a.1: List of Canadian main products related to SMAP.

Product	Domain	Resolution	Frequency	Latency
Soil moisture (near surface and root zone)	Canada*	10 km (1 km)	Hourly	24h (12h)
F/T state	Canada*	3 km (1 km)	Hourly	24h (12h)
Vegetation (LAI, biomass)	Canada*	10 km (1 km)	Daily (Hourly)	24h (12h)
Net ecosystem exchange	Canada*	10 km (1 km)	Daily (Hourly)	24h (12h)

*) Global products will also be generated

Baseline
(target)

It may therefore be advantageous for the Canadian project to generate another set of SMAP products specific to Canada. This set of results, listed in Table 7a.1, would cover the Canadian territory (including regions interest such as northern Canada and the prairies) and would focus on targeted communities and scientific needs (e.g., agricultural risk assessment, numerical weather prediction, hydrology). This would imply application of different strategies for the generation of both retrievals and data assimilation products (soil moisture and F/T state), possibly involving the use of ancillary datasets more appropriate for Canada, as well as new (or at least different) retrieval algorithms and/or data assimilation techniques.

Similar to the list presented in Appendix D, the Canadian SMAP products would include retrievals for near-surface soil moisture and for the F/T state, as well as analyses (from data assimilation) of near-surface and root-zone soil moisture, F/T state, and carbon NEE. This is in addition to all the other variables and diagnostics that will be engendered with the Level-4 land surface modeling and data assimilation systems related to the water, energy, and carbon cycles (see the list in Table 7a.2), at an hourly frequency over the entire country and at spatial resolution between 1 and 10 km. Taking advantage of MSC's computing facilities and operational capabilities, all the Canadian retrievals and analyses could be produced in near-real-time fashion at MSC as part of EC's environmental analysis and prediction systems, with scientific oversight and collaboration from the Canadian SMAP scientific team.

Table 7a.2: Other products available from EC's modeling and assimilation systems

Temperatures	Soil profiles, vegetation, snow
Snow	Mass, water equivalent, density, albedo
Vegetation	LAI, albedo, coverage, height
Near-surface meteorology	Winds, air temperature and humidity
Atmospheric forcing	Precipitation, downward radiation
Turbulent fluxes	Sensible, latent heat, ground heat fluxes

b) Dissemination methods

A wide variety of methods can be used to distribute products and outputs such as those described above. Several advancements have been achieved in recent years to accommodate an information savvy society with its ever increasing amount of technological devices. Three approaches are proposed in this Plan to disseminate SMAP and SMAP-related Canadian products: a) access to numerical raw data, b) traditional web site, and c) web mapping service (WMS).

The first of these methods provides direct access to numerical data through what is called at EC a "datamart". The people or organizations choosing to access the information in this manner are typically quite informed since software is required to decode the data. Due to constraints related to data storage and transfer volume, only a limited number of variables are made available with the datamart. Very high horizontal resolution for the two-dimensional field could also be a problem.

The address for EC's datamart is the following: <http://dd.meteo.gc.ca/>.

The traditional web site approach (second in the list) provides easier access to a much wider user base. More variables can be made available this way with maps on a pre-defined set of domains. In the first phase of the Canadian SMAP project, such a web site was made available to the general public at the following address:

<http://collaboration.cmc.ec.gc.ca/science/rpn/SMAP/SMAP.html>

username = smap ; password = smap

General documentation on the SMAP project can be found on this site, along with useful documents and presentations. As can be seen in Fig. 7b.1, a monitoring system is also available at the same address, with access to real-time land surface analyses for surface temperatures, snow, and soil moisture. Real-time maps of brightness temperatures from SMOS are also displayed, as will be maps from SMAP Level-1 observations for brightness temperatures and backscatters.

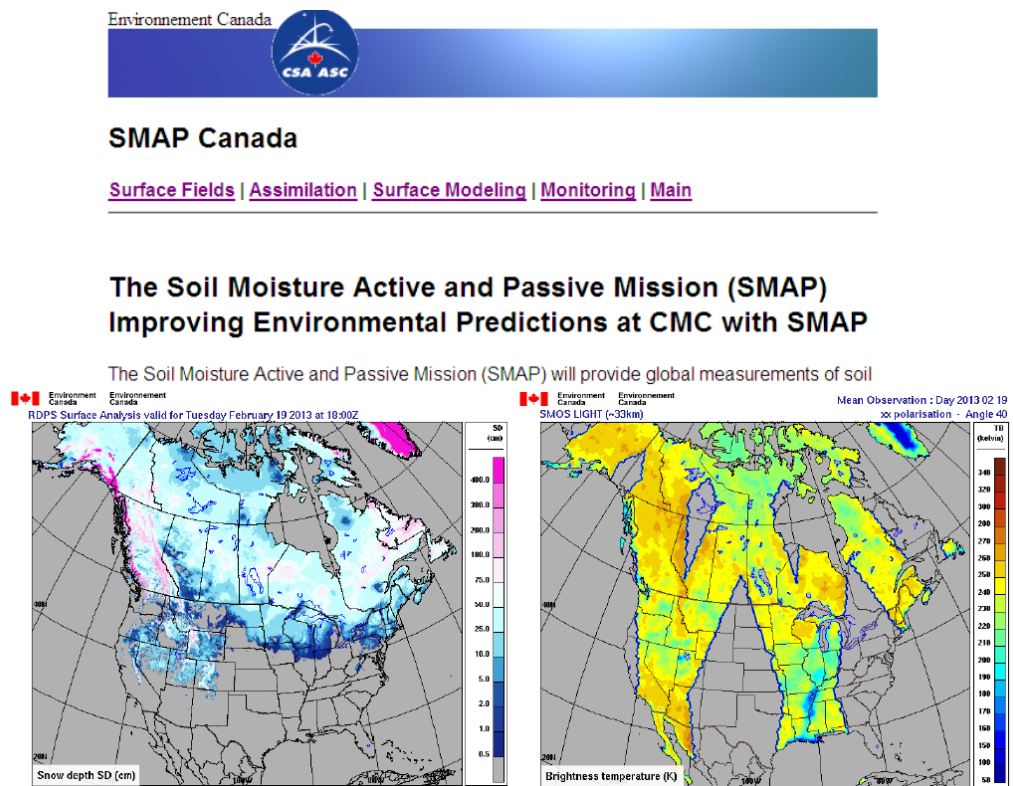


Fig. 7b.1: Snapshot of the SMAP Canada web site.

The third approach, taking advantage of WMS, is now becoming more popular in data centers. With WMS, georeferenced maps are build and made available upon request to external users through a server (visible to the World). The raw and original outputs for the SMAP products and land surface analyses remain on internal machines at EC, and only the georeferenced maps are communicated as they are requested. These maps can then be superimposed by the users with other “layers” of information available to them (also georeferenced). The users favoring this method are normally quite specialized since it often requires them to have their own “viewer”. But the goal in this project is to make it possible for external users to use an EC-developed viewer which will be directly accessible from outside EC’s firewall. Also, ‘kml’ files will be provided for Google Earth applications.

The WMS site currently available at EC is at this location :
<http://collaboration.cmc.ec.gc.ca/rpn-wms/?LANG=E>

An example of a land surface analysis field (snow depth in this case) viewed with Google Earth is shown in Fig. 7b.2.

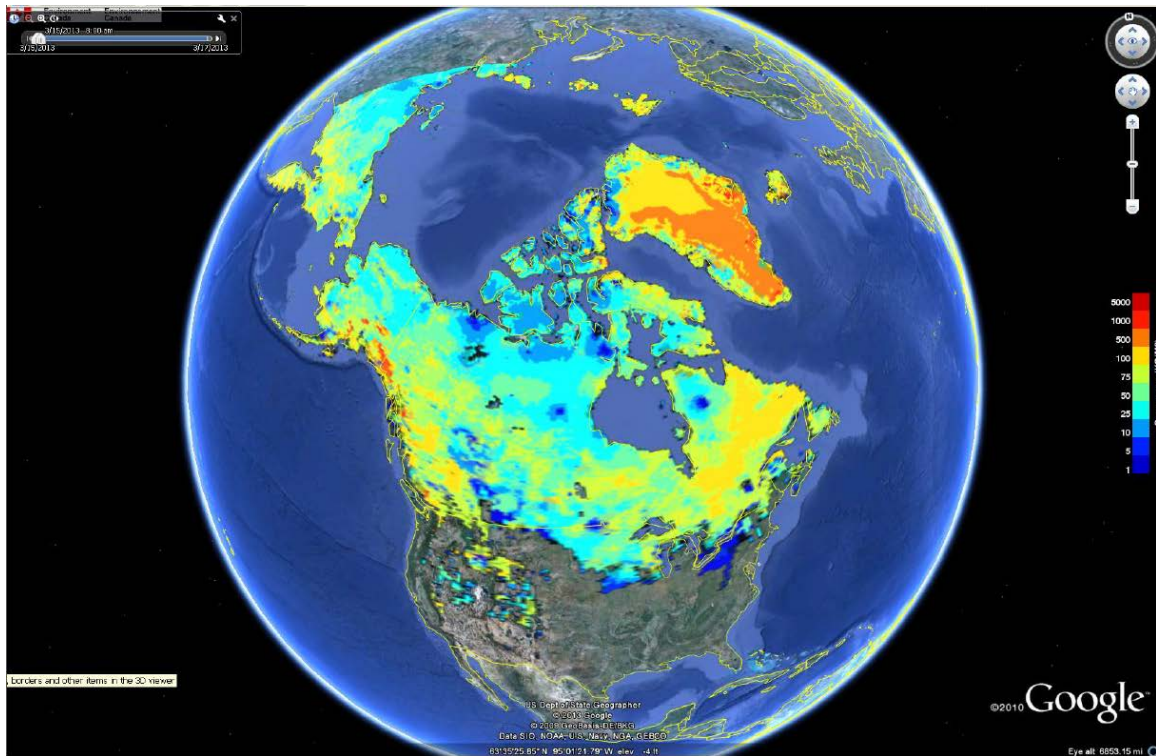


Fig. 7b.2. Example of surface analysis (here snow depth) viewed with Google Earth.

c) Other possible applications of SMAP products and outreach plan

As briefly described in the Introduction section of this document, the SMAP soil moisture, F/T, and carbon products have the potential to benefit several areas of Canadian social and economical development. A list of these potential applications, along with the name of Canadian institutions which could be involved, is provided in Table 7c.1. As could be expected, this list is not exhaustive, and for many applications the institutions to be involved remain to be determined.

An important component of the Canadian Plan is to engage potential SMAP end users through an inclusive process. The steps to increase collaboration with the a broad Canadian applications community include: implementing open access to SMAP data products (as described above), making SMAP products available with the shortest possible latency, cooperating with the US SMAP team which has its own outreach program, engaging end users in pre- and post-launch activities, and making value-added products generated during pre-launch development available for applications development.

Unfortunately resources for this aspect of the Canadian Plan are scarce and the effort will be limited. It is planned however to organize one applications workshop to engage a few selected end users. In addition, the SMAP mission and the related Canadian activities and products will be publicized through team members participation to conferences, symposium, and workshops. Outreach will be more targeted within the Canadian Government, with a presentation to the Federal Committee on Geomatics and Earth Observation (at the ministers level).

Table 7c.1. List of potential SMAP applications and institutions.

Potential SMAP Applications	Institutions
Air quality	Environment Canada (Air quality Operations)
Chemical, biological, radiological, nuclear (CBRN) response	Environment Canada (Field and Response Section) Defence Research Development Canada (DRDC) First responders (list to be provided)
Defence, national security	Department of National Defense (DND)
Ecology, biodiversity, ...	Canadian conservation organizations (to be determined)
Health	Provincial and federal public health institutions and departments
Insurance	National and provincial crops / floods / tourism programs
Sea-ice detection	Canadian Ice Centre (CIC) Environment Canada (Data assimilation research)
Wildfires	Société de protection des forêts contre le feu (SOPFEU) Canadian Forest Service (CFS) Canadian Interagency Forest Fire Centre (CIFFC)

8. Canadian Science Team and Community

The Canadian science team members are responsible for carrying out the scientific activities described in the Canadian SMAP Plan. This team (see Table 8.1), with expertise in the fields of soil moisture and F/T measurements, retrieval methods (i.e., microwave remote sensing), modeling, and data assimilation, is composed of a group of scientists that have successfully worked together in the context of previous research projects, field experiments, and science working groups. This group comprises scientists from both government and academic institutions, and from several regions of the country.

Table 8.1. Canadian science team

Name	Institute	Roles and Responsibilities
Stéphane Bélair	Environment Canada / Meteorological Research Division	Lead of Canadian science team Data assimilation, NWP, air quality
Aaron Berg	University of Guelph	Soil moisture field measurements, data assimilation
Monique Bernier	Institut national de la recherche scientifique/Eau,terre et environnement	F/T field measurements, microwave remote sensing
Paul Bullock	University of Manitoba	Soil moisture field measurements, data analysis
Jing Chen	University of Toronto	Ecosystem (carbon) and land surface modeling
Chris Derksen	Environment Canada	Snow and F/T remote sensing.
Ramata Magagi	Sherbrooke University	Soil moisture field measurements, microwave remote sensing.
Heather McNairn	Agriculture and Agri-Food Canada	Soil moisture field measurements, microwave remote sensing, agriculture
Alain Royer	Sherbrooke University	Snow and F/T remote sensing.
Brenda Toth	Environment Canada National Hydrology Research Institute	Soil moisture field measurements
Anne Walker	Environment Canada / Climate Research Division	Airborne measurements

Stéphane Bélair, research scientist at EC/MRD, is responsible for the overall implementation of the Canadian Science and Applications Plan for SMAP. He is responsible for the development of scientific aspects of SMAP in Canada, and for ensuring that the science data products are effectively used, maximizing the benefits of the Canadian participation in SMAP.

An important duty of the Canadian science team lead is to develop and maintain a SMAP Canadian science community. This community consists of individuals (scientists or others) and institutions (government, academic, private, or other) that are interested in

using SMAP data products. (Note that this community is different from the list given in the previous section for SMAP applications.)

In order to develop this community, a list of scientists and organizations involved in fields concerned with soil moisture and F/T will first be put together. Through announcements and presentations in diverse meetings, potential members of the Canadian SMAP community will be provided information about SMAP and its Canadian component, and will propose ways to take advantage of SMAP products.

In addition to being in contact with the Canadian science team lead, the members of this science community will have diverse opportunities to exchange among themselves and with the Canadian science team. Occasions such as national conferences of the Canadian Meteorological and Oceanic Society (CMOS), the Canadian Geophysical Union (CGU), the Canadian Remote Sensing Symposium (CRSS), or any other national or international meetings, could be exploited to further extend any collaborations. Special workshops could also be organized to allow interactions between the community and the science team, depending on resources and time. Participants will be encouraged to seek funding from Canadian and International agencies, and gatherings at workshops and conferences could be used to shape these proposals, focusing on challenges specific to SMAP.

9. Budget

To achieve the objectives presented in this Canadian Plan for SMAP and conduct the activities described above, the in kind contribution from each participating organization is significant. Funding to universities is achieved through the Grants and Contributions (G&C) program of the Government of Canada. For Government departments (i.e., EC and AAFC), it is done through the Government Related Initiative Program (GRIP).

In the first 3 years of the project, the total in kind contribution from Government and Academia was \$3.1M and \$1.1M respectively (\$4.2M in total). The contribution from CSA through G&C was \$1.1M and its co-investment with Other Government Departments (OGD) was \$0.7M, for a total of (\$1.8M in total).

The budget expected for the last three years has similar numbers. The total in kind contribution from OGD and Academia is expected to be \$3.7M and \$1.0M (total of \$4.7M), whereas CSA's G&C contribution could be on the order of \$1.0M and its co-investment to OGDs of about \$0.9M (total of \$1.9M).

The total cost of the project is thus \$12.9M, based on in kind contributions from OGDs and Academia of \$8.9M, G&C contributions from CSA of \$2.1M, and CSA's co-investment with OGDs of \$1.6M.

Appendix A. SMAP Scientific Measurement Requirements

Duration	3 years minimum
Location of measurements	Over land areas where soil moisture and surface F/T are primary environmental controls on land-atmosphere water, energy, and carbon exchanges
Types of measurements	Radiometric brightness temperature and radar backscatter cross-section
Depth of soil moisture measurements	2-10 cm, i.e., sufficient to enable characterization of surface evapotranspiration using hydrologic modeling and land data assimilation
F/T measurements	Shall be sufficient to characterize the low-temperature constraint on vegetation net primary productivity, and the surface-atmosphere CO ₂ exchange
Spatial resolution (soil moisture)	40 km (passive only), to match the scale of hydroclimatological processes, and 10 km (combined passive and active), to match the scale of hydrometeorological processes.
Spatial resolution (F/T)	1 to 3 km
Soil moisture accuracy	RMS errors no larger than 4% volumetric soil moisture over regions free of snow and ice, and where the vegetation water content is less than 5 kg m ⁻² to allow sufficient sensitivity to the underlying soil
F/T accuracy	Sufficient to capture F/T state transitions in integrated vegetation-soil continuum with 2-day precision
Temporal sampling (soil moisture)	Global: 3 days or better
Temporal sampling (F/T)	Boreal: 2 days or better

Appendix B. SMAP Satellite and Instrument Specifications

Orbit	Sun-synchronous 6AM / 6PM overpass at Equator 680 km altitude
Shared antenna	6-m diameter deployable mesh antenna Conical scan at 14.6 rpm Constant incidence angle at 40° ~ 1000 km-wide swath
L-Band radiometer	Frequency: 1.41 GHz Polarization: V, H, U Resolution: 40 km Radiometric uncertainty (req.): 1.3 K
L-Band Radar	Frequency: 1.26 GHz Polarization: VV, HH, HV (or VH) Resolution: 1-3 km Real-aperture mode: resolution of 30 x 6 km SAR mode: resolution of 3 km Relative accuracy (req): 0.5 dB (VV and HH)

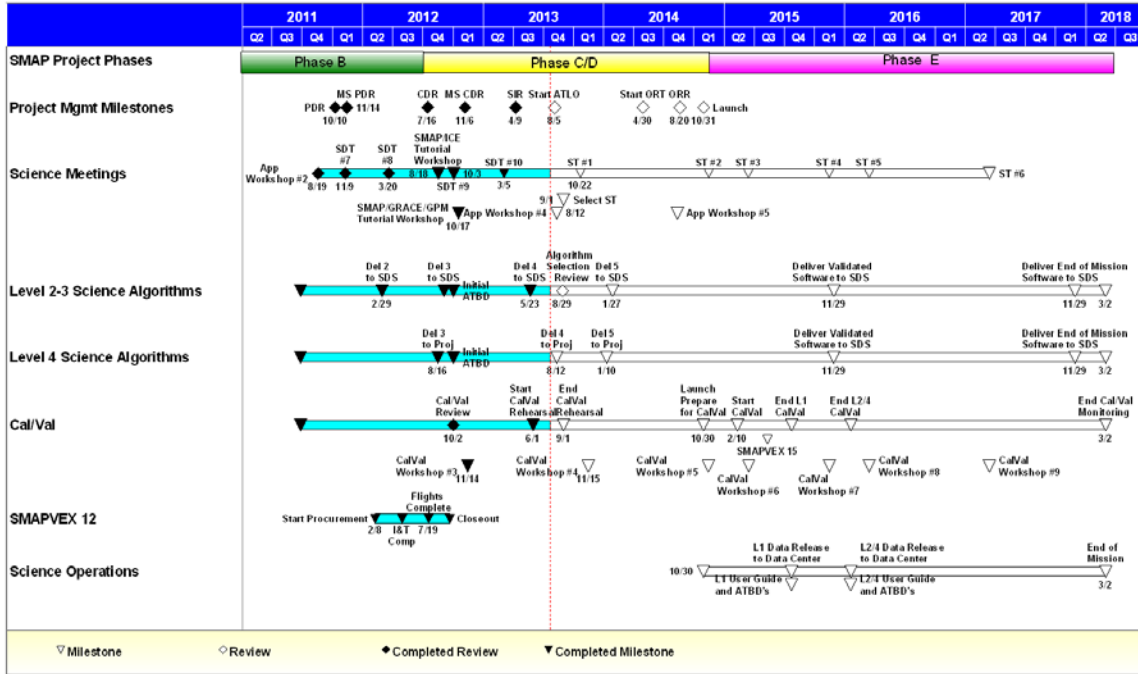
Appendix C. SMAP Data Acquisition Strategy

Radiometer	Data collected continuously Entire orbit All 360 degrees of antenna scan (both forward and aft) Capability for periodic “cold sky” looks
High-resolution SAR	Collected only on forward arc of scan Collected only on descending (AM) portion of orbit Collected only over land (using built-in land mask file)
Low-resolution real aperture radar	Collected continuously like radiometer data

Appendix D. SMAP Data Products

Product	Description	Gridding (Resolution)	Latency**	
L1A_Radiometer	Radiometer Data in Time-Order	-	12 hrs	Instrument Data
L1A_Radar	Radar Data in Time-Order	-	12 hrs	
L1B_TB	Radiometer T_B in Time-Order	(36x47 km)	12 hrs	
L1B_S0_LoRes	Low Resolution Radar σ_o in Time-Order	(5x30 km)	12 hrs	
L1C_S0_HiRes	High Resolution Radar σ_o in Half-Orbits	1 km (1-3 km)	12 hrs	
L1C_TB	Radiometer T_B in Half-Orbits	36 km	12 hrs	
L2_SM_A	Soil Moisture (Radar)	3 km	24 hrs	Science Data (Half-Orbit)
L2_SM_P	Soil Moisture (Radiometer)	36 km	24 hrs	
L2_SM_AP	Soil Moisture (Radar + Radiometer)	9 km	24 hrs	
L3_FT_A	Freeze/Thaw State (Radar)	3 km	50 hrs	Science Data (Daily Composite)
L3_SM_A	Soil Moisture (Radar)	3 km	50 hrs	
L3_SM_P	Soil Moisture (Radiometer)	36 km	50 hrs	
L3_SM_AP	Soil Moisture (Radar + Radiometer)	9 km	50 hrs	
L4_SM	Soil Moisture (Surface and Root Zone)	9 km	7 days	Science Value-Added
L4_C	Carbon Net Ecosystem Exchange (NEE)	9 km	14 days	

Appendix E. Top-Level Science Schedule



Important dates:

- Feb 2014: Algorithm Software Delivery 5
- June 2014 (2 Months): Cal/Val Rehearsal Phase 2
- IOC+0 Months: Cal/Val Phase Start
- IOC+3 Months: Initial-Release L1 Data Products
- IOC+6 Months: Validated-Release L1 Data Products Cal/Val
- IOC+6 Months: Initial-Release L2-L4 Data Products Cal/Val
- IOC+12 Months: Validated-Release L2-L4 Data Products
- IOC+12 Months: End Cal/Val Phase

Fig. E.1. Schedule of the SMAP project.

References

- AAFC, 2013: Scaling approach for the validation of SMAP soil moisture products. Available from AAFC (Heather McNairn, Catherine Champagne).
- Arora, V.K., 2003: Simulating energy and carbon fluxes over winter wheat using coupled land surface and terrestrial ecosystem models. *Agri. Forest Meteorol.*, **118**, 21-47.
- Brown, J., O.J. Jr. Ferrians, J.A. Heginbottom, E.S. Melnikov, 1997: Circum-arctic map of permafrost and ground-ice conditions. U.S. Geological Survey, Map CP-45, U.S. Dept. of the Interior.
- Calvet, J.-C., J. Noilhan, J.-L. Roujean, P. Bessemoulin, M. Cabelguenne, A. Olioso, and J.-P. Wigneron, 1998: An interactive vegetation SVAT model tested against data from six contrasting sites. *Agri. Forest Meteorol.*, **92**, 73-95.
- Chan, C. H., S. H. Lou, L. Tsang, and J. A. Kong, 1991: Electromagnetic scattering of waves by random rough surface: a finite-difference time-domain approach. *Microwave & Optical Technology Letters*, **4**, 355-359.
- Chen, J.M., Liu, J., Cihlar, J. & Goulden, M.L., 1999: Daily canopy photosynthesis model through temporal and spatial scaling for remote sensing applications. *Ecological Modelling*, **124**, 99–119.
- Chen, K.S., T.-D. Wu, L. Tsang, Q. Li, J. Shi, and A.K. Fung, 2003: Emission of rough surfaces calculated by the Integral Equation Method with comparison to three-dimensional moment method simulations. *IEEE Trans. Geosci. Rem. Sens.*, **41**, 90-101.
- Das, N., D. Entekhabi, and E. Njoku, 2011: An algorithm for merging SMAP radiometer and radar data for high-resolution soil-moisture retrieval. *IEEE Trans. Geosci. Rem. Sens.*, **49**, 1504-1512.
- DeSève, D. , 1999 : Développement d'un algorithme pour cartographier l'équivalent en eau de la neige au sol dans un environnement de taïga à partir des données de micro-ondes passives du capture SSM/E. INRS-ETE. Québec, Philosophie doctorate: 121.
- Dubois, P.C., J. van Zyl, and T. Engman, 1995: Measuring soil moisture with imaging radar. *IEEE Trans. Geosci. Rem. Sens.*, **33**, 915-926.
- Duchesne, C., D.W. Riseborough, and S.L. Smith, 2013: Air and near surface ground temperatures, indices and summary statistics from 1993 to 2012 for the Mackenzie valley corridor, Northwest Territories. Available at http://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/geoscan_e.web
- Entekhabi, D., E. Njoku, P. Houser, M. Spencer, T. Doiron, J. Smith, R. Girard, S. Belair, W. Crow, T. Jackson, Y. Kerr, J. Kimball, R. Koster, K. McDonald, P. O'Neill, T. Pultz, S. Running, J.C. Shi, E. Wood, and J. Van Zyl, 2004. The Hydrosphere State

- (HYDROS) mission concept: An Earth System Pathfinder for global mapping of soil moisture and land freeze/thaw. *Transactions in Geoscience and Remote Sensing* 42, 10, 2184-2195.
- Esser, G., J. Hoffstadt, F. Mack, and U. Wittenberg, 1994: High-Resolution Biosphere Model (HRBM) – Documentation model version 3.00.00. Mitteilungen aus dem Institut für Pflanzenökologie der Justus-Liebig-Universität Gießen, Vol. 2 (ed. G. Esser), Gießen, Germany, 70 pp.
- Foley, J.A., I.C. Prentice, N. Ramankutty, S. Levis, D. Pollard, S. Sitch, and A. Haxeltine, 1996: An integrated biosphere model of land surface processes, terrestrial carbon balance, and vegetation dynamics, *Global Biogeochem. Cycles*, **10**, 603-628.
- Frolking, S., Goulden, M. L., Wofsy, S. C., Fan, S. M., Sutton, D. J., Munger, J. W., Bazzaz, A. M., Daube, B. C., Crill, P. M., Aber, J. D., Band, L. E., Wang, X., Savage, K., Moore, T., and Harriss, R. C., 1996: Modeling temporal variability in the carbon balance of a spruce/moss boreal forest, *Global Change Biol.* **2**, 343-366.
- Frolking S., K. McDonald, J. Kimball, R. Zimmermann, J.B. Way and S.W. Running, 1999. Using the space-borne NASA Scatterometer (NSCAT) to determine the frozen and thawed seasons of a boreal landscape. *Journal of Geophysical Research* 104(D22), **27**, 895-27,907.
- Fung, A. K., Z. Li, and K. S. Chen, 1992: Backscattering from a randomly rough dielectric surface. *IEEE Trans. Geosci. Remote Sens.*, **30**, 356-369.
- Habets, F., and co-authors, 1999: The ISBA surface scheme in a macroscale hydrological model applied to the Hapex-Mobilhy area. Part I: Model and database. *J. Hydrology*, **217**, 75-96.
- Heginbottom, J.A., M.-A. Dubreuil, and P.A.C. Harker, 1995: Canada – permafrost. National Atlas of Canada Ottawa. National Atlas Information Service and Geological Survey of Canada. Plate 2.1, (MCR 4177).
- Ise, T., and P.R. Moorcroft, 2006: The global-scale temperature and moisture dependencies of soil organic carbon decomposition: An analysis using a mechanistic decomposition model. *Biogeochemistry*, **80**, 217-231.
- Jarvis, P., and Linder S., 2000: Constraints to growth of boreal forests, *Nature*, **405**, 904-905.
- Kalantari, Bernier, M, P., Poulin, J., 2009 : Utilisation conjointe de données de micro-ondes passives et actives pour le suivi du gel saisonnier du sol de la toundra dans le Nord du Québec. 30ième Symposium Canadien de télédétection, 22-26 juin, Lethbridge, Alberta, Canada, 12 pages.
- Khaldoune, J., 2006 : Développement d'une méthode de mesure et cartographie de gel du sol en milieu agricole à l'échelle d'un bassin versant à partir d'images radar monopolarisées (RADARSAT-1), multipolarisées (ENVISAT) et polarimétriques (RADARSAT-2/CONVAIR-580)._INRS-ETE. Québec, Philosophie doctorate: 214.

- Kim, Y., and J. J. van Zyl, 2009: A time-series approach to estimate soil moisture using polarimetric radar data. *IEEE Trans. Geosci. Remote Sens.*, **47**, 2519-2527.
- Kimball, J., McDonald K. C., Running S. W., and Froking S., 2004: Satellite Radar Remote Sensing of Seasonal Growing Seasons for Boreal and Sub-alpine Evergreen Forests, *Remote Sensing of Environment*, **90**, 243-258.
- Kohn, J. and Royer, A., 2010: AMSR-E data Inversion for soil temperature estimation under snow cover. *Remote Sens. Environ.*, **114**, 2951–2961.
- Kuo, C. h., and M. Moghaddam, 2007: Electromagnetic Scattering From Multilayer Rough Surfaces With Arbitrary Dielectric Profiles for Remote Sensing of Subsurface Soil Moisture. *IEEE Trans. Geosci. Remote Sens.*, **45**, 349-366.
- Lagacé, C., 2000: Développement et validation d'une approche pour faire le suivi du gel saisonnier du sol sur le bassin de la rivière La Grand à partir de l'utilisation conjointe d'image Radar et d'images SSM/E. INRS-ETE. Québec, Maîtrise: 164.
- Lagacé, C., M. Bernier, et al., 2002 : Cartographie du gel saisonnier du sol en zone de taïga à partir d'images RSO de RADARSAT-1 et SSM/E de DMSP F-8. *Téledétection*, **2**, 161-175.
- Lakhankar, T., H. Gherira, M. Temimi, M. Sengupta, R. Khanbilvardi, and R. Blake, 2009: Non-parametric methods for soil moisture retrieval from satellite remote sensing data. *Rem. Sensing*, **1**, 2-21.
- Lawrence, H., and Coauthors, 2010: L-Band emission of a bare soil rough surface and a rough soil surface covered with a grass litter layer: Comparison between experimental data and a numerical modeling approach. *IGARSS 2010*.
- Lemone, M.A., and Coauthors, 2000: Land–atmosphere interaction research, early results, and opportunities in the Walnut River watershed in southeast Kansas: CASES and ABLE. *Bull. Amer. Meteorol. Soc.*, **81**, 757-779.
- Liu, J., Chen, J.M., Cihlar, J. & Chen, W., 1999: Net primary productivity distribution in the BOREAS region from a process model using satellite and surface data. *J. Geophys. Res.*, **104**, 27 735–27 754.
- Lou, S. H., L. Tsang, and C. H. Chan, 1991: Application of the finite element method to Monte Carlo simulations of scattering of waves by random rough surfaces: penetrable case. *Waves in Random Media*, **1**, 287 - 307.
- Magagi, R., and co-authors, 2013: Canadian Experiment for Soil Moisture in 2010 (CanEx-SM10): Overview and preliminary results. *IEEE Trans. Geosc. Remote Sens.*, **51**, 347-363.
- McDonald, K.C., J.S. Kimball, E. Njoku, R. Zimmermann, and M. Zhao, 2004: Variability in springtime thaw in the terrestrial high latitudes: Monitoring a major control on the biospheric assimilation of atmospheric CO₂ with spaceborne microwave remote sensing. *Earth Interactions*, **8**, 1-23.

- McNairn, H., and co-authors, 2013: The Soil Moisture Active Passive Validation Experiment 2012 (SMAPVEX12): Pre-launch calibration and validation of the SMAP satellite. Submitted to *IEEE Trans. Geosc. Remote Sens.*
- Mo, T., B.J. Choudhury, T.J. Schmugge, J.R. Wang, and T.J. Jackson, 1982: A model for microwave emission from vegetation-covered fields. *J. Geophys. Res.*, **7**, 11229.
- Oh, Y., K. Sarabandi, and F.T. Ulaby, 1992: An empirical model and an inversion technique for radar scattering from bare soil surfaces. *IEEE Trans. Geosci. Rem. Sens.*, **30**, 370-381.
- Pardé, M., J.-P. Wigneron, P. Waldteufel, Y.H. Kerr, A. Chanzy, S. Schmidl Sobjaerg, and N. Skou, 2004: N-Parameter retrievals from L-band microwave observations acquired over a variety of crop fields. *IEEE Trans. Geosci. Rem. Sens.*, **42**, 1168-1178.
- Parton, W.J., D.S. Schimal, C.V. Cole, and D.S. Ojima, 1987: Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *Soil Science Soc. Amer. J.*, **51**, 1173-1170.
- Parton, W.J., and co-authors, 1993: Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide. *Global Biogeochem. Cycles*, **7**, 795-809.
- Peters, W., and co-authors, 2007: An atmospheric perspective on North American carbon dioxide exchange: CarbonTracker, Proceedings of the National Academy of Sciences of the United States of America, **104**, 18925-18930.
- Picard, G., L. Brucker, A. Roy, F. Dupont, M. Fily, A. Royer, and C. Harlow, 2013: Simulation of the microwave emission of multi-layered snowpacks using the Dense Media Radiative transfer theory: the DMRT-ML model, *Geosci. Model Dev.*, **6**, 1061-1078, doi:10.5194/gmd-6-1061-2013.
- Potter, C.S., J.T. Randerson, C. Field, P.A. Matson, P.M. Vitousek, H.A. Mooney, and S.A. Kooster, 1993: Terrestrial ecosystem production: A process model based on global satellite and surface data. *Global Biogeochem. Cycles*, **7**, 811-841.
- Randerson, J.T., Field C.B., Fung I.Y., and Tans P.P., 1999: Increases in early season ecosystem uptake explain recent changes in the seasonal cycle of atmospheric CO₂ at high northern latitudes, *Geophys. Res. Letters*, **26**, 2765-2768.
- Rautiainen K., J. Lemmetyinen, J. Pulliainen, J. Vehviläinen, M. Drusch, A. Kontu, J. Kainulainen, and J. Seppänen, 2012: L-Band Radiometer Observations of Soil Processes in Boreal and Subarctic Environments. *IEEE Trans. Geosci. Remote Sens.*, **50**, 1483-1497.
- Rawlins, M.A., K.C. McDonald, S. Frolking, R.B. Lammers, M. Fahnestock, J.S. Kimball, and C.J. Vorosmarty, 2005: Remote sensing of snow that at the pan-Arctic scale using the SeaWinds scatterometer. *Journal of Hydrol.*, **312**, 294-311.
- Rignot E., and Way, J.B., 1994: Monitoring freeze-thaw cycles along north-south Alaskan transects using ERS-1 SAR. *Remote Sens. Environment*, **49**, 131-137.

- Rignot, E., Way, J.B., McDonald, K., Viereck, L., Williams, C., Adams, P., Payne, C., Wood, W., and Shi, J., 1994: Monitoring of environmental conditions in taiga forests using ERS-1 SAR. *Remote Sens. Environment*, **49**, 145-154.
- Robinson D. A., Dewey K. F., and Heim R. R., 1993: Global snow cover monitoring: An update," *Bull. American Meteorol. Soc.*, **74**, 1689-1696.
- Roy, A., A. Royer, J.-P. Wigneron, A. Langlois, J. Bergeron, and P. Cliché, 2012: A simple parameterization for a boreal forest radiative transfer model at microwave frequencies. *Remote Sens. Environ.*, **124**, 371–383. DOI: 10.1016/j.rse.2012.05.020
- Roy, A., G. Picard, A. Royer, B. Montpetit, F. Dupont, A. Langlois, C. Derksen, and N. Champolion, 2013: Brightness temperature simulations of the Canadian seasonal snowpack driven by measurements of snow specific surface area. *IEEE Trans. Geosci. Remote Sens.*, In press (TGRS-2012-00591).
- Running, S.W., and E.R. Hunt, Jr., 1993: Ecosystem process model for other biomes, BIOME-BGC, and an application for global-scale models. *Scaling Phys. Processes: Leaf to Globe*, 141-158.
- Running, S.W., R. Nemani, J.M. Glassy, and P.E. Thornton, 1999: MODIS daily photosynthesis (PSN) and annual net primary production (NPP) product (MOF17). Algorithm Theoretical Basis Document (ATBD) for MODIS.
- Shi, J. C., J. R. Wang, A. Y. Hsu, P. E. O'Neill, and E. T. Engman, 1997: Estimation of bare surface soil moisture and surface roughness parameter using L-band SAR image data. *IEEE Trans. Geosci. Remote Sens.*, **35**, 1254-1266.
- Smith, N. V., S. S. Saatchi, et al., 2004: Trends in high northern latitude soil freeze and thaw cycles from 1988 to 2002. *J. Geophys. Res.*, **109**, 1-14.
- Smith, S.J., V.E. Romanovsky, A.G. Lewkowicz, C.R. Burn, M. Allard, G.D. Clow, K. Yoshikawa, and J. Throop, 2010: Thermal state of permafrost in North America: A contribution to the International Polar Year. *Permafrost and Periglac. Processes*, **21**, 117-135.
- Sun, R., J. C. Shi, T. J. Jackson, K. S. Chan, and Y. Oh, 2009: Improvement of bare surface soil moisture estimation with L-band dual-polarization radar. *IGARSS*, Cape Town, South Africa, IV, 971-974 pp.
- Tanja, S., Berninger F., Vesala T., Markkanen T., Hari P., Makela A., Ilvesniemi H., Hanninen H., Nikinmaa E., Huttula T., Laurila T., Aurela M., Grelle A., Lindroth A., Arneth A., Shibistova O., and Lloyd J., 2003: Air temperature triggers the recovery of evergreen boreal forest photosynthesis in spring. *Global Change Biol*, **9**, 1410-1426.
- Tian, H., J.M. Melillo, D.W. Kicklighter, A.D. McGuire, and J. Helfrich, 1999: The sensitivity of terrestrial carbon storage to historical climate variability and atmospheric CO₂ in the United States. *Tellus*, **51B**, 414-452.
- Tsang, L., and J. A. Kong, 2001: *Scattering of Electromagnetic Waves, Vol3 : Advanced Topics*. Vol3 : Advanced Topics, Wiley Interscience.

- Ulaby, F.T., R.K. Moore, and A.K. Fung, 1986: *Microwave Remote Sensing, Active and Passive, Vol. III: From Theory to Applications*. Artech House, Norwood, MA.
- Villasenor, J. F., D. R. Fatland, et al., 1993: Change detection on Alaska's north slope using repeat-pass ERS-1 SAR image. *IEEE Trans. Geosc. Remote Sens.* **31**, 227-236.
- Voronovich, A., 1994: Small-slope approximation for electromagnetic wave scattering at a rough interface of two dielectric half-spaces. *Waves in Random Media*, **4**, 337 - 367.
- Wagner, W., G. Lemoine, and H. Rott, 1999: A method for estimating soil moisture from ERS scatterometer and soil data. *Rem. Sens. Environ.*, **70**, 191-207.
- Wang, R.W., P.E. O'Neill, T.J. Jackson, and E.T. Engman, 1983: Multifrequency measurements of the effects of soil moisture, soil texture and surface roughness. *IEEE Trans. Geosci. Remote Sens.*, **GE-21(1)**, 44-51.
- Way, J. B., Zimmermann, R., Rignot, E., McDonald, K. and Oren, R., 1997: Winter and Spring Thaw as Observed with Imaging Radar at BOREAS, *J. Geophys. Res.*, **102(D24)**, 29673-29684.
- Werner, C.L., et al, 2003: Interferometric point target analysis for deformation mapping. *IGARSS'03 Proceedings*, Toulouse, France, 2003.
- Wismann, V., 2000: Monitoring of seasonal thawing in Siberia with ERS scatterometer data. *IEEE Trans. Geosci. Rem. Sens.*, **38**, 1804-1809.
- Xu, X., L. Tsang, S. Huang, and E. Njoku, 2010a: A Microwave scattering model of vegetated surfaces based on BOR and NMM3D for SMAP mission. *IGARSS 2010*.
- Xu, X., L. Tsang, S. Huang, and E. G. Njoku, 2010b: A microwave scattering model of vegetated surfaces based on BOR/DDA and NMM3D for SMAP mission. *IGARSS 2010*.

Other publications:

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