Joint Cryopshere-Ocean-Land-Ecosystems Copernicus Imaging Microwave Radiometer (CIMR) Science Workshop

August 13-15, 2019
Arcadia, California

Report

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Workshop Participants

September 9, 2019

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Acronym List

CIMR: Copernicus Imaging Microwave Radiometer
ESA: European Space Agency
ESR: Earth and Space Research
ESTEC: European Space Research and Technology Centre
JPL: Jet Propulsion Laboratory
GSFC: Goddard Space Flight Center
MIT: Massachusetts Institute of Technology
NASA: National Aeronuatics and Space Administration
NOAA: National Oceanic and Atmospheric Administration
NSIDC: National Snow and Ice Data Center
SIO: Scripps Institution of Oceanography
UAF: University of Alaska at Fairbanks
UIUC: University of Illinois at Urbana-Campaign
UW: University of Washington
USC: University of Southern California
USDA: United States Department of Agruculture
UNH: University of New Hampshire
WHOI: Woods Hole Oceanographic Institution

Executive Summary

The Joint Cryopshere-Ocean-Land-Ecosystems CIMR Science Workshop was held in Arcadia, California from August 13-15, 2019. The Copernicus Imaging Microwave Radiometer (CIMR) is one of the six High Priority Copernicus-expansion Mission (HPCM) concepts being developed by the European Space Agency for the European Union (EU). The objective of the workshop is to document the potential utility of the CIMR mission for NASA earth science programs, which can be used to develop potential NASA contributions to a collaborative ESA-NASA CIMR mission. Four specific questions were addressed during the workshop:

1. How will CIMR ensure continuity of important data records in your field?
2. What new or enhanced products can be developed with simultaneous multi-frequency microwave measurements?
3. What science questions can be addressed with simultaneous CIMR products on land, ocean and cryosphere?
4. Which measurements of Most Importance and Very high Importance in the 2017 Decadal Survey can be done with CIMR?

US Scientists from four panels, Cryosphere, Oceanography, Terrestrial Hydrology, and Terrestrial Ecology were invited. The workshop participants find significant relevance of CIMR to NASA earth science objectives for all four disciplines. This report documents the conclusions on the discussion of these four questions. The specific recommendations by the four panels are summarized below.

<u>Cryosphere Panel Recommendations</u>

CIMR will

- Provide continuity and significantly enhanced data quality over the entire spectrum of geophysical products of the ice-covered Arctic and Southern Oceans currently used by the science and operational community.
- Allow the observation of sub-daily surface and atmospheric processes in the polar regions that are not available from current instruments.
- Provide short latency products for support of near real-time operational requirements (e.g., navigation, search and rescue) and for short-term forecasting.
- Allow the enhancement of land ice products for improving our understanding of the mass balance of the ice sheets and associated sea level changes.
- Enhance our understanding of marginal ice zone with coincident high-resolution ice and ocean (temperature and salinity) observations.

<u>Recommendations:</u>

1. Support development of an airborne testbed to explore CIMR capability and support the design of pre-launch geophysical algorithms.
2. Support development of CIMR algorithms for generation of enhanced products for ice and ocean.
3. Coordination with operations and forecast communities to develop near real-time requirements for product delivery.
4. Collaboration between Copernicus and US Science teams for development of polar ocean products.

Oceanography Panel Recommendations

CIMR will

- Provide significant capability to extend the data record, enhance the sampling, and reduce the uncertainties of all-weather Sea Surface Temperature (SST), Sea Surface Salinity (SSS), and high winds;
- Improve estimates of air-sea turbulent heat and moisture fluxes, surface density, and surface current products;
- Benefit science and applications over a broad area of the Earth system described in the Decadal Survey, including topics related to air-sea interaction, land-sea linkages, and ocean-ice interaction as well as physical oceanography and marine biogeochemistry, complementing measurements from other ongoing and planned satellite missions;
- Enhance emerging science and applications related to the linkages of ocean salinity and the water cycle, including using SSS as a predictor for sub-seasonal to seasonal forecast terrestrial rainfall.

Recommendations:

1. Further enhancement at the lower frequencies (near L-band) using broad-band radiometry (0.5-3 GHz) is recommended as this is expected to revolutionize science and applications related to polar oceanography, especially Arctic freshwater changes and their impacts. The broader bandwidth also improves the resilience against radio frequency interference. Therefore it is recommended to replace the narrow L-band band instrument with a low-frequency broad-band radiometer (0.5-3 GHz) to enhance monitoring capability for polar ocean SSS.
2. To develop new approaches to exploit the unique high-spatial resolution low frequency multichannel measurements from CIMR for ocean applications.
3. Collaboration on ocean and sea-ice Observing System Simulation Experiments to evaluate the impacts of sampling on the uncertainties of CIMR-derived gridded products as well as ocean and sea ice state estimation.
4. Collaboration on field campaigns for Cal/Val of CIMR ocean and sea ice variables.

Terrestrial Hydrology and Ecology Panel Recommendations

Given CIMR's anticipated:

- Multi-channel simultaneous and multi-resolution microwave measurements including L-band,
- High data refresh rate that provides near daily measurements,
- High measurement precision, and
- Extended duration record,

surface soil moisture and freeze/thaw products from existing L-band missions can be extended and potentially can be significantly enhanced in the future. In addition, multichannel measurements and frequent-revisit data provide the opportunity for developing new capabilities to understand and monitor water storage and movement across the soil vegetation continuum.

We recommend that the US terrestrial hydrology and ecosystems communities develop the following studies that assess the science and application potentials of the above-listed and other CIMR attributes.

Recommendations:

1. Confidence in the continued availability of L-band soil moisture products will facilitate the research-to-operations transition in the Applications and Operational communities. CIMR can serve as a soil moisture "gap filler" until future L-band missions can be developed for flight.
2. Addition of lower-than-L-band frequencies on CIMR will enable new science and applications (e.g., root-zone soil moisture, permafrost and active layer dynamics). We recommend that investigations be carried out to explore these opportunities.
3. In order to more fully utilize the information content of multi-channel and multi-resolution microwave observations, we need to develop a high-fidelity test-bed to simulate the complex electromagnetic interactions over vegetation-covered landscapes. We recommend the launch of a test-bed development initiative that incorporates the most advanced understanding and tools available in the community.
4. Key to the development of algorithms for enhanced and new science data products is the availability of realistic multichannel microwave observations. We recommend that simulator instruments (tower and/or airborne) be developed and field campaigns be planned to collect these data, along with matchup data analyses from existing similar radiometers such as SMAP, SMOS, GMI, and AMSR2.

Table of Contents

1. Workshop Objectives 1

2. Copernicus Imaging Microwave Radiometer Mission Design 2

3. Workshop Panel Reports 14

3.1 Cryosphere Panel Report 14

3.2 Oceanography Panel Report 24

3.3 Terrestrial Hydrology Panel Report 35

3.4 Terrestrial Ecosystem Panel Report 47

1. Workshop Objectives

The Joint Cryopshere-Ocean-Land-Ecosystems CIMR Science Workshop was held in Arcadia, California from August 13-15, 2019. The Copernicus Imaging Microwave Radiometer (CIMR) is one of the six High Priority Copernicus-expansion Mission (HPCM) concepts being developed by the European Space Agency for the European Union (EU). The CIMR mission will provide global mapping using multi-frequency (L-/C-/X-/Ku-/Ka-band) imaging microwave radiometry, with a focus on high-latitude regions in support of the Integrated European Union (EU) Policy for the Arctic. It is an expansion of the current Copernicus Space Component (CSC) capability described in the CSC Long Term Scenario (LTS) to address the user requirements expressed by the European Commission (EC). The primary mission focus is on global cryosphere and oceans, but extends to other global communities and priority science objectives highlighted in the recent Decadal Survey. The targeted observations of CIMR include relatively high-resolution sea ice (5 km resolution), sea surface temperature (15 km resolution), sea surface salinity, extreme ocean winds, and soil moisture retrievals. CIMR is currently in the phase B1 study. The current plan includes the launches of CIMR-A in the 2027 timeframe and CIMR-B shortly afterwards to provide observations from the same sensors on two complimentary satellite platforms for enhanced global coverage.

CIMR is an operational mission, which consists of two wide-swath (>1900 km) satellites on orbit at the same time providing operartonal redundancy and enhanced temporal coverage, will make coincident multi-frequency microwave measurements at L-band (< 60 km), C- and X-band (< 15 km), and Ku-band (< 5.5 km) and Ka-band at (< 5 km) with better than 1.5 days revisit globally (subdaily in the Arctic). Colocation with the MetOp-SG A and B satellites is achieved within 10 minutes over the polar regions.

The objective of the workshop is to document the potential utility of the CIMR mission for NASA Earth Science programs, which can be used to develop potential NASA contributions to a collaborative ESA-NASA CIMR mission. Four specific questions were addressed during the workshop:

1. How will CIMR ensure continuity of important data records in your field?
2. What new or enhanced products can be developed with simultaneous multi-frequency microwave measurements?
3. What science questions can be addressed with simultaneous CIMR products on land, ocean and cryosphere?
4. Which measurements ranked Most Important and Very Important in the 2017 Decadal Survey can be done with CIMR measurements?

The workshop included a combination of plenary sessions and splinter-group meetings with a report produced at the end of workshop that will be submitted to NASA for consideration in a partnership with the EU.

2. Copernicus Imaging Microwave Radiometer Mission Design

Copernicus [http://www.copernicus.eu/] is a European system for monitoring the Earth in support of European policy. It includes Earth Observation satellites (notably the Sentinel series developed by the European Space Agency (ESA)), ground-based measurements and, services to process data to provide users with reliable and up-to-date information through a set of Copernicus operational services related to environmental and security issues. These include:

- Copernicus Marine Environmental Monitoring Service (CMEMS [http://marine.copernicus.eu]),
- Copernicus Land Monitoring Service (CLMS [http://land.copernicus.eu/]),
- Copernicus Atmospheric Monitoring Service (CAMS [https://atmosphere.copernicus.eu/]),
- Copernicus Emergency Management Service (CEMS) [http://emergency.copernicus.eu/] and
- Copernicus Climate Change Service (C3S) [http://climate.copernicus.eu].

Copernicus services provide critical information to support a wide range of applications, including environmental protection, management of urban areas, regional and local planning, agriculture, forestry, fisheries, health, transport, climate change, sustainable development, civil protection and tourism. Copernicus satellite missions are designed to provide 'upstream' inputs to all Copernicus Services as systematic measurements of Earth's oceans, land, ice and atmosphere to monitor and understand large-scale global dynamics. The primary users of Copernicus services are policymakers and public authorities that need information to develop environmental legislation and policies or to make critical and timely decisions in the event of an emergency, such as a natural disaster or a humanitarian crisis. The Copernicus programme is coordinated and managed by the European Commission. The development of the observation infrastructure is performed under the aegis of the European Space Agency for the space component (with collaboration on specific aspects from EUMETSAT) and of the European Environment Agency (EEA) and the Member States for a separate, but important, in-situ measurement component.

Copernicus has developed, deployed and maintains a fleet of operational Earth Observation missions that provide core measurements including:

- Sentinel-1: C-band synthetic aperture radar imaging (polar orbit)
- Sentinel-2: Multispectral high-resolution (10 m) optical imaging (MSI) of land and coastal zones (polar orbit)
- Sentinel-3: Multispectral (20 band) 300m resolution Ocean and Land Color Instrument (OLCI), multi-spectral Sea and Land Surface Temperature Radiometer (SLSTR) providing 0.5-1km visible and thermal infrared measurements, SAR Ku-band Radar Altimeter (SRAL) and Microwave Radiometer (MWR) providing contiguous mapping of all quantities (polar orbit)
- Sentinel-4: High-resolution spectrometer measurements of trace gas concentrations and aerosols in the atmosphere (geostationary orbit)
- Sentinel-5: high resolution spectrometer system operating in the ultraviolet to shortwave infrared range with 7 different spectral bands flown as part of the MetOp-SG A. Sentinel-5P is a precursor mission (now in orbit)

- Sentinel-6: Ku-band SAR interleaved radar altimeter and NASA Advanced Microwave Radiometer for Climate (AMR-C) to replace Jason series of reference altimeters.

With the exception of Sentinel-5P (a precursor mission), all Sentinel missions deploy two satellites on-orbit at the same time in order to assure operational robustness. More information on the Copernicus Sentinel satellites can be found at https://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Overview4. Information relating to mission operations can be found at https://sentinel.esa.int/web/sentinel/home

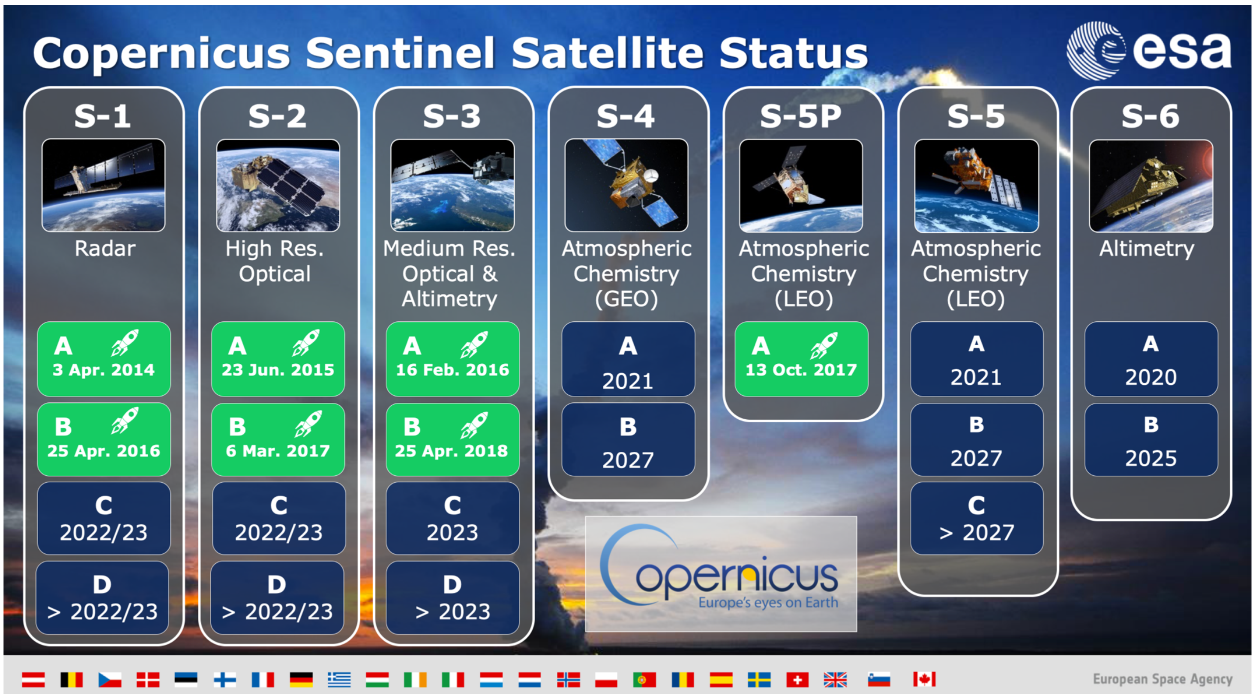


Figure 1. Launch dates of the Sentinel-1 to Sentinel-6 series. Green indicates satellite on orbit.

Copernicus Evolution

The intense use and increased awareness for the potential of Copernicus have generated great expectations for an evolving Copernicus system. There is now a large set of concrete needs and requirements for the future configuration of the Copernicus Space Component (CSC). User and observation requirements have been identified, structured and prioritized in a continuous reflection process led by the European Commission (EC). Results from EU policy analyses, consultation of Services and Member States, as well as various workshops, gap analyses, studies and task forces now provide the rationale for the CSC LTS. Clearly, a resolute approach is needed to achieve the time-critical objectives of new policies, such as the Integrated European Union Policy for the Arctic, Climate Change, the Sustainable Development Goals of the UN or European EO Data Commercialization.

Two distinct sets of expectations have emerged from the user consultation process:

1. **Stability and continuity**, while increasing the quantity and quality of CSC products and services, lead to one set of requirements. These requirements are addressed by an

Extension of the current Sentinel 1 to 6 satellite capability by providing enhanced continuity of baseline Copernicus observations.
2. **Addressing emerging and urgent needs for new types of observations** that are addressed by a timely ***Expansion*** of the current Sentinel satellite fleet.

Both sets of expectations have been systematically reflected and integrated by ESA (as the CSC System Evolution Architect) in response to formal documented EC requirements.

The 'Extension' and the 'Expansion' components are organized around broad observation domains. The distinction between 'Expansion' and 'Extension' components is not schedule-based. The 'Expansion' component corresponds to the enlargement of the present measurements through the introduction of new missions to answer emerging and urgent user requirements. The 'Extension' component corresponds to a more progressive improvement of the current measurement capabilities, mostly by means of new generation of similar instrumentation compared to the ones currently deployed by Copernicus today. The "CSC Expansion" programme includes new ***High Priority Copernicus Missions*** (HPCM) that have been identified by the EC as priorities for implementation in the coming years by providing new capabilities in support of current emerging user needs.

New High-Priority requirements from key Arctic users' communities have emerged within Copernicus that highlight the need for new satellite measurements not available as part of the current Copernicus satellite fleet. The new requirements were reviewed at a Polar Ice and Snow workshop held in June 2016, organized by the European Commission DG GROW involving relevant European Commission Directorates General (DGs) leading scientists and Copernicus Service representatives. The workshop gathered inputs from 70 attendees across EU Member States working in various domains. A strong interest for a *Polar Ice and Snow Mission* was further reinforced when discussed in a wider international context that considered UN Conventions and pan-Arctic cooperation activities. This situation led the DG for Industry and Entrepreneurship (GROW) to set up a new group of European Polar Experts Group (PEG) in spring 2017. The mandate of PEG was to update and/or complete the review and analysis of the Users' needs, thus allowing the Commission to assess the relevance of the development of a "Copernicus expansion mission" dedicated to Polar and Snow monitoring.

The EC Polar Expert Group process concluded with two dedicated reports: "*Polar Expert Group User Requirements for a Copernicus Polar Mission Phase-I report*" (12 June, 2017) and "*Polar expert group, Phase 2 report on Users' requirements*" (31 July, 2017). **The Phase-I report provided a detailed inventory of user requirements that were consolidated and prioritized in a Phase-II report.** This report highlighted the fragile future continuity of low-frequency satellite microwave radiometers and the need for high spatial resolution. Notably, at the end of the JAXA GCOM-2 mission (e.g. *Kasahara et al.* 2012) there could be a gap in long-term capability, depending on the the approval of AMSR-3. Based on an assessment of Users needs and the likely gap in capability, the PEG recommended, **as first priority**, an Imaging Microwave Radiometry Mission that meets the Joint EC Communication high priorities, in particular the provision of operational sea-ice services that are of prime importance for navigation safety in the Arctic and adjacent seas **with at least daily revisit in Polar regions**.

The Copernicus Imaging Microwave Radiometer (CIMR)
Climate change and globalization are the dominant drivers of societal impacts in the Arctic with economic development rapidly transforming the geo-politics and the physical and biogeochemical environment of the region. For example, new prospectors are increasing their activities using modern techniques for oil and gas, fisheries and mineral resources assessments, and commercial ship traffic is growing dramatically. Several areas of extreme concern were recently raised by the International Panel for Climate Change: "*There is high confidence that the probability of a sea-ice-free Arctic Ocean during summer is substantially lower at global warming of 1.5°C when compared to 2°C. With 1.5°C of global warming, one sea ice-free Arctic summer is projected per century. This likelihood is increased to at least one per decade with 2°C global warming. Effects of a temperature overshoot are reversible for Arctic sea ice cover on decadal time scales.*" Permafrost thaw, extreme weather events, flooding, diminishing sea and land ice, and coastal erosion lead to unreliable ice roads, damage to houses, pipelines, railways, airports, ports and harbors, and with likely significant adverse effects on ecosystem goods and services including energy and water supplies. As a consequence, the relocation of entire communities may be required. The societal impacts of a rapidly changing Arctic are complex, uncertain and ambiguous. As an increasing number of national and international stakeholders place more demands on the Arctic region, tensions and insecurity across the region as a whole are evident. In this evolving complex setting Arctic indigenous peoples remain extremely vulnerable.

In response, the European Commission and the High Representative of the Union for Foreign Affairs and Security Policy issued to the European Parliament and the Council, on 27 April 2016, a joint communication that proposed "*An integrated European Union policy for the Arctic*". Continuously monitoring the vast and harsh Arctic environment in a changing world is considered essential to the successful implementation and effective management of the *Arctic Policy*. The existing Copernicus programme already offers operational thematic services to monitor the atmosphere, marine environment, land, climate change, emergency management and security. However, new high-priority requirements from key Arctic user communities have emerged that highlight the need for new satellite measurements that are not currently available as part of the Copernicus satellite fleet.

The Arctic's fragile environment is a direct and key indicator of climate change.
It requires specific mitigation and adaptation actions in three priority areas:

1. **Climate Change and Safeguarding the Arctic Environment** (livelihoods of indigenous peoples, Arctic environment).
2. **Sustainable Development in and around the Arctic** (exploitation of natural resources e.g. fish, minerals, oil and gas), "Blue economy", safe and reliable navigation (e.g. the Arctic Northern Sea Route).
3. **International Cooperation on Arctic Issues** (scientific research, EU and bilateral cooperation projects, fisheries management/ ecosystems protection, commercial fishing).

Against this background, and starting from user needs articulated and prioritized by the European Commission Polar Expert Group (PEG), a CIMR mission is under Phase A/B1 study by the European Space Agency. CIMR will uniquely observe a wide range of floating sea ice parameters (concentration, drift, type, thickness), sea surface temperature over the Polar and global oceans at high spatial resolution (4-15 km) and sea surface salinity, thin sea ice thickness, snow products, and surface wind speed at ~40 km. Additional measurement of other parameters (e.g. soil moisture, precipitation) will also be possible. In the next years there is a potential gap in operational provision of low-frequency (1.4-10 GHz) satellite microwave radiometry that has been the foundation of operational sea surface temperature observations for CMEMS. Furthermore, operational continuity of sea surface salinity and thin sea ice thickness measurements pioneered by the L-band satellite microwave radiometers flown by the SMOS/SMAP research missions is not guaranteed. All of these products will have high geophysical accuracy and temporal resolution. Through these measurements, CIMR will address the needs of Copernicus and provide evidence to underpin the management and monitor the impact of the Integrated European Policy for the Arctic.

Mission description
The aim of the CIMR Mission is:

> *"to provide high-spatial resolution microwave imaging radiometry measurements and derived products with global coverage and sub-daily revisit in the Polar regions to address Copernicus user needs and the Integrated EU Arctic Policy."*

The CIMR Mission Requirements Document is available at http://cimr.eu.

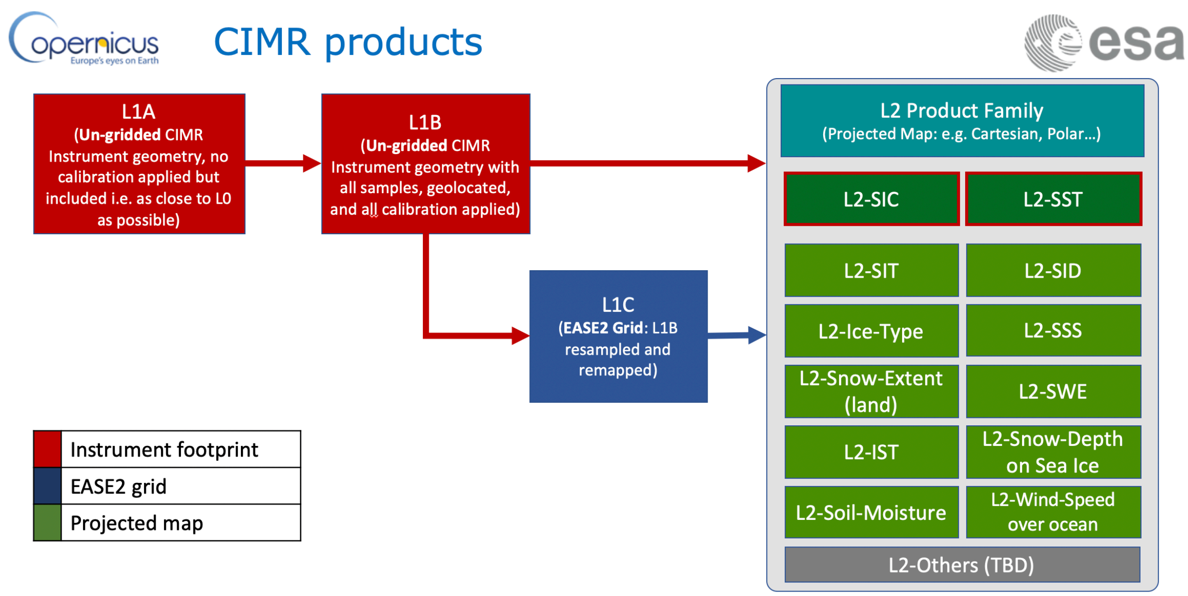
CIMR Mission Products
CIMR will provide the following products:

- Sea Ice Concentration (SIC) and Sea Ice Extent (SIE) at a spatial resolution of ≤5 km, with a total standard uncertainty of ≤5%, and sub-daily coverage of the Polar Regions and daily coverage of Adjacent Seas[1].

[1] Polar Regions: encompass: The pan-Arctic domain (>55°N latitude, 0-360° longitude) and Antarctic (>50°S latitude, 0-360° longitude).

- Sea Surface Temperature (SST) at an effective spatial resolution of ≤15 km, with a total standard uncertainty of ≤0.2 K and focusing on sub-daily coverage of Polar Regions and daily coverage of Adjacent Seas.
- Sea Surface Temperature (SST) at an effective spatial resolution of <15 km, with a standard uncertainty of ≤0.2 K with daily coverage of the global ocean and inland Seas
- Thin Sea Ice (<0.5 m depth) at an effective spatial resolution of <50 km, with a thickness standard uncertainty of 10% with daily coverage of the Marginal Ice Zone in the Polar Regions and Adjacent Seas.
- Sea Surface Salinity (SSS) over the global ocean with a target gridded spatial resolution of 40 km and uncertainty ≤0.2 pss over monthly time-scales.
- Sea Ice Drift at an effective spatial resolution of ≤25 km with a standard uncertainty of 3 cm/s with daily coverage in the Polar Regions and Adjacent Seas.
- Ice type/Stage of development in combination with other satellite data including scatterometer and SAR measurements with daily coverage in the Polar Regions and Adjacent Seas.
- Snow depth on sea ice with an effective spatial resolution of ≤15 km and standard uncertainty of 10 cm with daily coverage in the Polar Regions and Adjacent Seas
- Total Snow Area with an effective spatial resolution of ≤15 km with daily coverage in the Polar Regions and Adjacent Seas.
- Snow Water Equivalent (SWE) with an effective spatial resolution of ≤15 km with daily coverage in the Polar Regions and Adjacent Seas.
- Ice Surface Temperature (IST) with an effective spatial resolution of ≤15 km standard uncertainty of 1.0 K in combination with other satellite data including thermal infrared imagery in the Polar Regions and Adjacent Seas.
- Soil moisture, land surface temperature, terrestrial surface water extent
- Wind speed over ocean, cloud liquid water over ocean, precipitation over ocean.

Adjacent Seas encompass all Seas and water bodies adjacent to the Arctic including Gulf of Bothnia, Gulf of Finland, Baltic Sea, Caspian Sea, Sea of Azov, Bering Sea, Sea of Okhotsk, Yellow Sea, Bohai Sea, Baikal Lake, Labrador Sea, Gulf of St Lawrence, American Great Lakes, Gulf of Alaska,

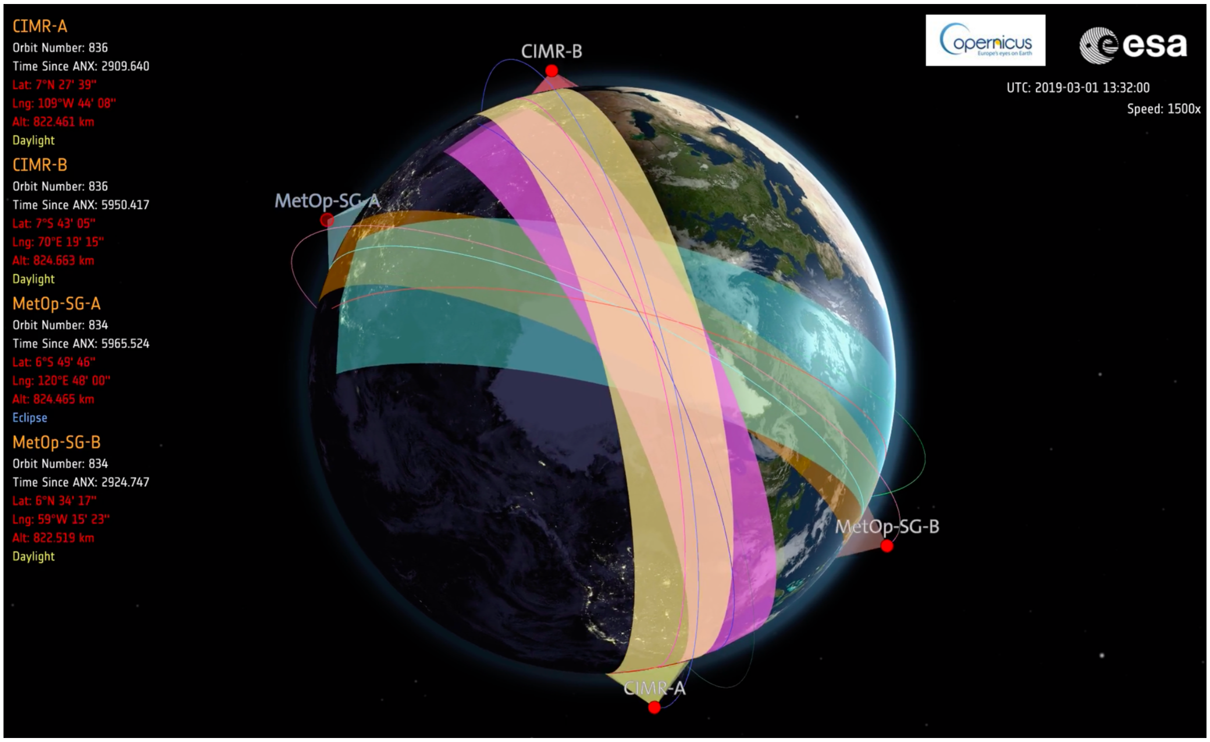


Schematic overview of the main data products for the CIMR mission

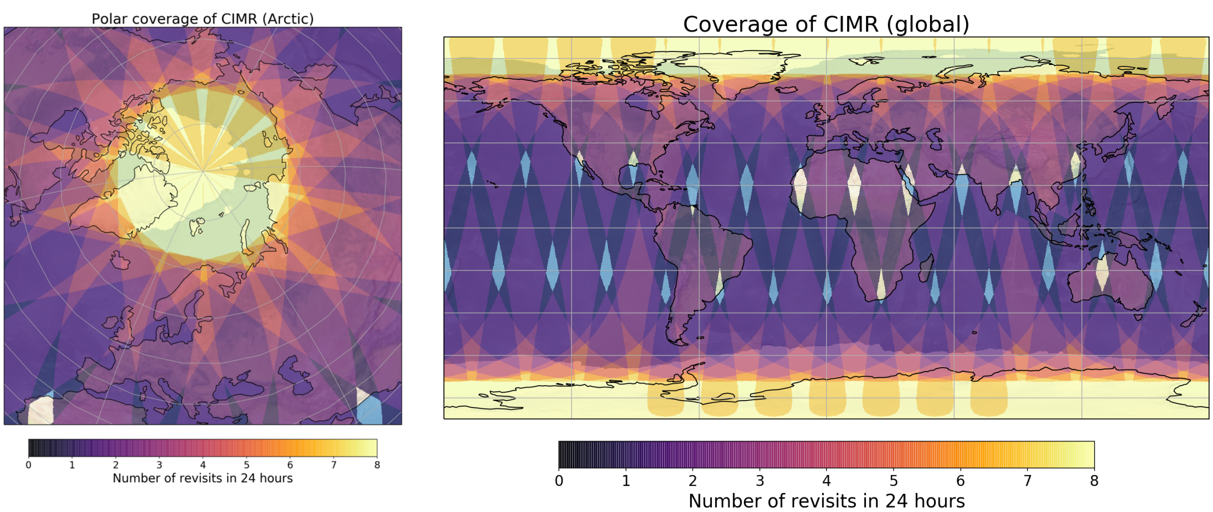
CIMR will deliver all L1a, L1b, L1c and L2 products in NRT expressed as ≤3 hours of measurement acquisition at the user point of pickup. In support of Arctic polar navigational applications, specific CIMR products (TBD) shall be available at the user point of data pickup within ≤1 hour (TBC) of measurement acquisition at the baselined ground station(s).

CIMR Mission Implementation Approach

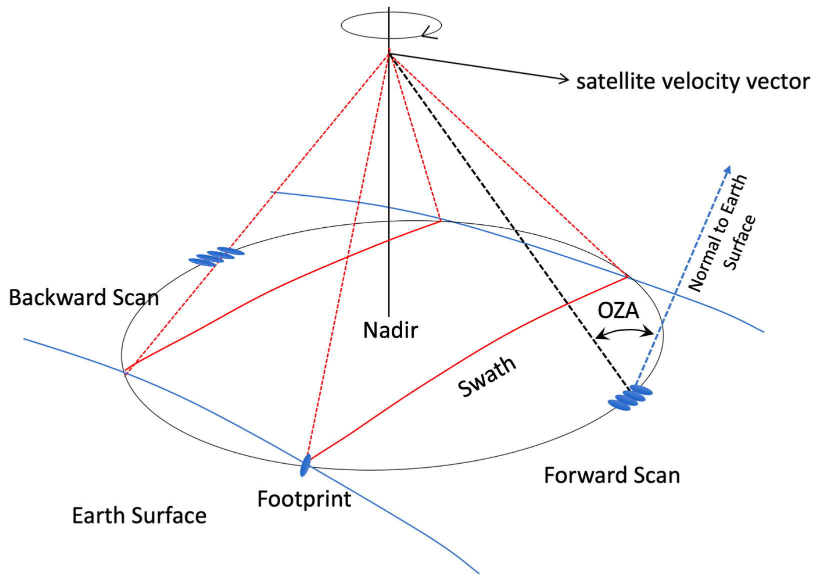
The CIMR mission is composed of two identical satellites (CIMR-A and CIMR-B) nominally placed 180° out of phase on the same orbit plane. The orbit is a frozen sun-synchronous with a mean local solar time at descending node of 06:00 ±10 minutes with an inclination of 98.7°. Each satellite has a design lifetime of 7 years with consumables for additional operations. CIMR-A will operate in synergy with the EUMETSAT MetOp-SG(1B) mission so that in the polar regions (>65°N and 65°S) collocated and contemporaneous measurements between CIMR and MetOp microwave radiometer (MWI) and scatterometer (SCA) measurements will be available within +/-10 minutes. In addition, CIMR-B will be collocated with MetOp-SG(1A) mission providing collocated measurements from the MetImage multi spectral imager carrying 20 spectral bands from 443 to 13.345 μm with 500m spatial resolution at nadir) amongst others. A full description of the MetOp-SG missions can be found at https://www.eumetsat.int/website/home/Satellites/FutureSatellites/EUMETSATPolarSystemSecondGeneration/index.html. This architecture provides unpresented coverage of the polar regions in support of the EU integrated Arctic Policy.



Simulation showing the swath of CIMR-A and CIMR-B together with the MetOp-SG(B1) MWI and the MetOp-SG(A1) MetImage for a single orbit over the Arctic regions. The unprecedented coverage of the Arctic is evident.

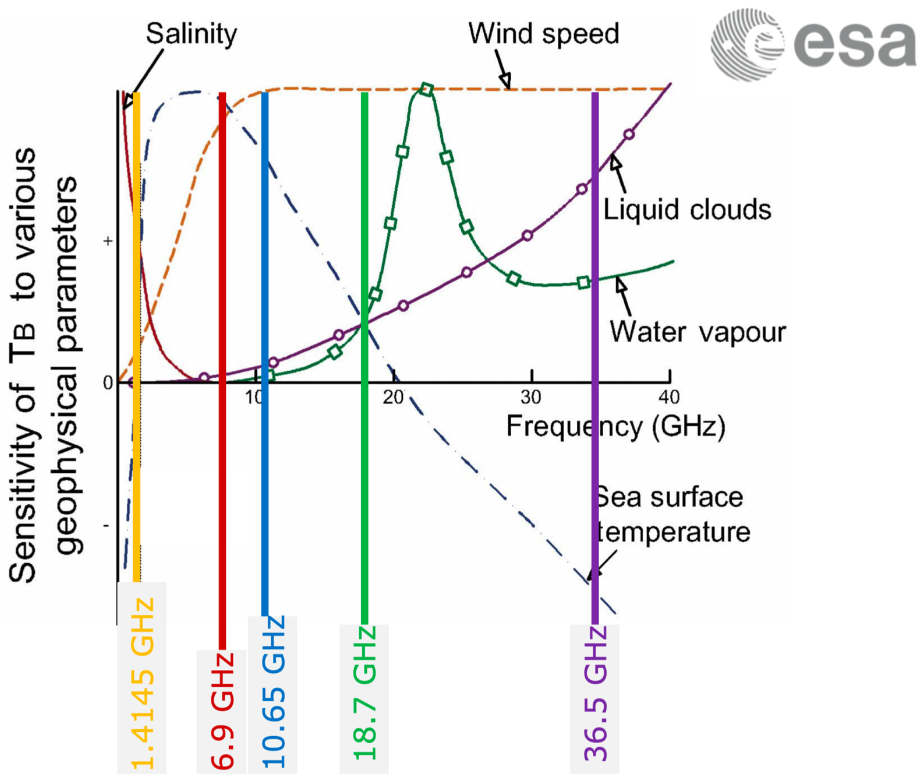


Example plots showing a simulation of the expected global coverage and over the Arctic from one CIMR satellite highlighting the number of revisits each day with no hole at the pole. Daily coverage of the Copernicus Imaging Microwave Radiometer mission in the Arctic regions. The colormap shows the number of revisit overpasses in a 24 hours period. The CIMR mission is specifically designed to ensure sub-daily coverage in all the Arctic region. Particularly, CIMR will achieve full sub-daily coverage of the Arctic region (i.e. "no hole at the pole" requirement). By symmetry, the coverage is also excellent in the Antarctic region. Over 95% of the globe will be covered on a daily basis (Lavergne, T., Pinol Sole, M. and Donlon, C.: Daily coverage of CIMR (Arctic, Antarctic, and Global views), figshare, doi:10.6084/m9.figshare.7749284.v1, 2019).



Schematic overview of CIMR conical scanning approach and geometry (Donlon, Craig; Vanin, Felice (2019): Scanning Geometry of the CIMR instrument. Figshare https://doi.org/10.6084/m9.figshare.7749398.v1)

Each CIMR satellite will deploy a wide-swath (>1900 km) conically scanning multi-frequency microwave radiometer. CIMR measurements will be made using a forward scan arc followed by a second measurement of the same location using a backward scan arc within about 260 seconds. Full Stokes channels centered at 1.4145, 6.925, 10.65, 18.7 and 36.5 GHz are included in the mission design. A key requirement is to provide contiguous and complete (i.e. no "hole at the poles") coverage of the Polar Regions by all channels. >95% global coverage of all Earth surfaces is possible every day using a single satellite with complete coverage in ≤2 days. Daily revisit of the Polar Regions and Adjacent Seas, with a sub-daily revisit at high latitudes (>55°N and >55°S) is required.



Location of CIMR bands and sensitivity of brightness temperature for open seawater over a range of microwave observing frequencies for a set of key geophysical parameters (From Gabarro et al, 2017). This figure clearly highlights why CIMR channels are chosen to maximize the information available in the 1.4-37 GHz frequency range. See Figure MRD-2.4.1.1 for CIMR frequency relationships for SIC.

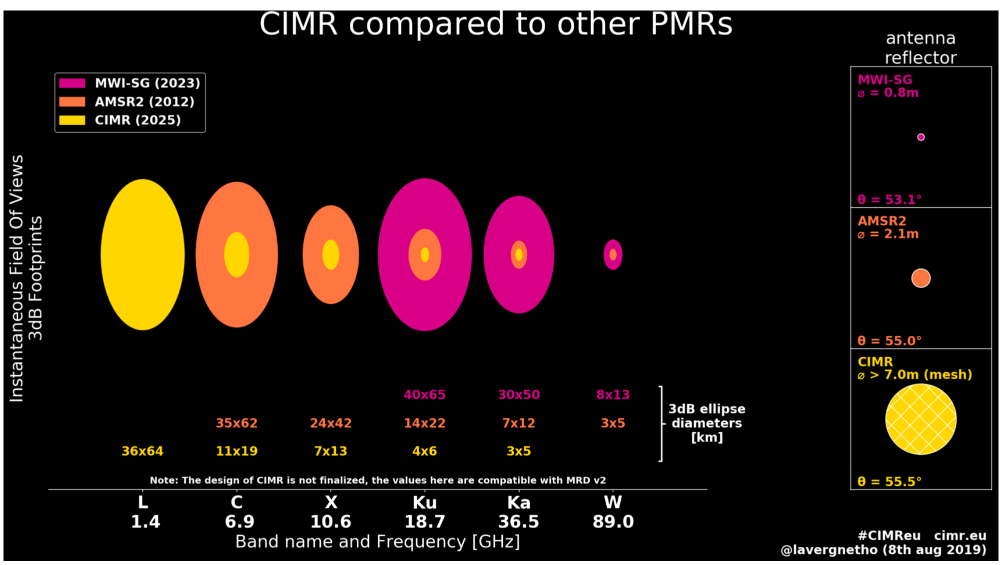


Illustration of the frequency channels of the CIMR mission, and their targeted spatial resolutions. CIMR is also compared to two other similar Passive Microwave Radiometers (PMR): the Japanese AMSR2 in orbit since 2012, and the MWI to fly on-board the European EPS-SG satellites from ~2023 (MWI-SG). (Lavergne, Thomas (2018): CIMR compared to other PMRs: Channels and Spatial resolution. Figshare. https://doi.org/10.6084/m9.figshare.7177730.v1)

The resolution of the 6.925/10.65 GHz channel -3dB footprint on the Earth surface is <15 km. For the 18.7/36.5 GHz channels the spatial resolution is 5 and <5 km (goal of 4 km) respectively.

The 1.414 GHz channel will have -3dB footprint resolution of about 60 km (fundamentally limited by the size of the ~8m deployable mesh reflector). However, most channels will be oversampled allowing gridded products to be generated at much better spatial resolution. The anticipated L1c resolution at L-band is expected to be 40 km providing continuity to SMOS and SMAP. Channel NEdT is 0.2-0.8 K (dpending of chnnel frequency) with an absolute radiometric accuracy goal of ~0.5K. Each CIMR feed will have a dedicated RFI detection and mitigation processors on-board the satellite implementing anomalous amplitude, kurtosis and cross-frequency algorithms. It is intended that RFI contaminated data will be sent to ground.

Summary characteristics of the CIMR mission

Mission Priority	Primary	Primary	Primary	Primary	Primary
Addressing CIMR Objectives	ALL	ALL	ALL	ALL	ALL
ITU EESS (passive) allocated band and band centre frequency (MHz)	1.4 – 1.427 27	6.425–7.250 6.8375	10.6-10.7\ 10.65	18.6-18.8 18.7	36-37 36.5
Channel centre frequency[2] [GHz]	1.4135	6.925	10.65	18.7	36.5
Maximum channel bandwidth [MHz]	27	825 [3]	100	200	1000
Footprint Size [km] (see definition)	<60[4]	≤15	≤15	≤5.5	≤5 (goal=4)
Over sampling in flight direction [%]	≥20	≥20	contiguous	Interscan gap < 1 km	Interscan gap < 1 km
Radiometric resolution [K] NEΔT for zero mean, 1-sigma at 150 K	≤0.3	≤0.2	≤0.3	≤0.4 (goal: ≤0.3)	≤0.7
Dynamic Range [K]	Kmin=2.7, Kmax=340				
Radiometric Total Standard Uncertainty[5] [K, zero mean, 1-sigma)]	≤0.5	≤0.5 (goal ≤0.4)	≤0.5 (goal: ≤0.45)	≤0.6 (goal: ≤0.5)	≤0.8
Polarisation	Acquisition in Vertical and Horizontal with provision of Full Stokes based on computation.				
Swath width [km]	>1900. Separate forward swath and backward swath				
Observation Zenith Angle [deg]	55.0 ±1.5				
Radiometric stability over lifetime [K, zero mean, 1-sigma]	≤0.2	≤0.2	≤0.2	≤0.2	≤0.2
Radiometric stability over orbit [K, zero mean, 1-sigma]	≤0.2	≤0.1	≤0.1	≤0.2	≤0.2

2 The channel center frequency is not necessarily the same as the ITU EESS (passive) allocated band centre frequency.

3 ITU RR footnote No.5458 indicates that when planning future active systems, the Administrations "should bear in mind" the needs of EESS(passive) in the band 6.425 to 7.250 GHz (6.8375 GHz centre frequency, 825 MHz bandwidth). For the band 6.425-7.075 GHz (650 MHz), this footnote indicates that "passive microwave sensors measurements are carried out over the oceans" and for the band 7.075-7.250 GHz (175 MHz) the remote sensing measurements acknowledged in general. Use of this full bandwidth may bring advantages for radiometric accuracy.

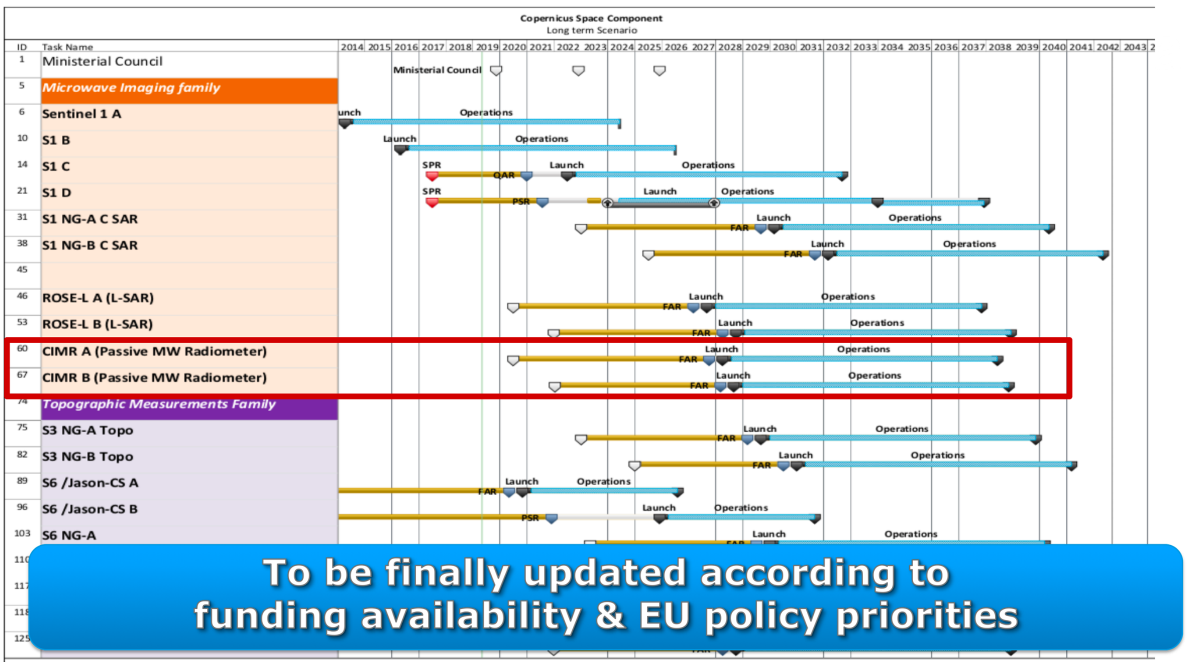
4 While the native 1.4135 GHz channel footprint is about 60 km, L2 products on about 40 km grids shall be produced.

5 For CIMR Absolute Radiometric Accuracy (ARA) is not used in the traditional manner but instead we calculate the Total Standard Uncertainty (which is a "zero mean, 1-sigma" total uncertainty). It is noted that this approach, while consistent with international agreements on uncertainty specification (JCGM, 2008), is different compared to other formulations (e.g. as for the MetOp-SG(B) MWI) that do not include NEΔT as part of the absolute radiometric accuracy definition.

Geolocation uncertainty [km]	≤1/10 of the footprint size
Number of satellites	Two satellites on-orbit to provide operational redundancy nominally spaced 180° out of phase.
Coverage and Revisit (with one satellite)	>95% global coverage of all Earth surfaces every day Complete global coverage in ≤2 days. Daily revisit of the Polar Regions and Adjacent Seas with a sub-daily revisit of the Polar Regions >55°N and >55°S latitude Contiguous and complete coverage of the Polar Regions by all channels (i.e. no "hole at the poles").

CIMR development schedule

The CIMR Mission began preparatory activities in 2017 running phases A during 2018 and Phases B1 completing in fall 2019. Industry bids (for implementation Phase B2/C/D/E1) are expected in 2019/20 with a KO in mid 2020. The first launch of CIMR-A is anticipated in the 2027+ timeframe with CIMR-B following afterwards.



3. Workshop Panel Reports

3.1 Cryosphere Panel Report

1. How will CIMR ensure continuity of important cryospheric records?

Passive microwave radiometers have provided some of the longest and most notable satellite-derived climate records, now constituting 40+ year record of climate variability. These records have revealed significant changes in the cryosphere. For example, Arctic summer sea ice extent has declined by over 40% over the last four decades. In addition, these data products have also lent themselves to process studies, model development and validation, assimilation into model reanalysis, and for operational use and forecasts.

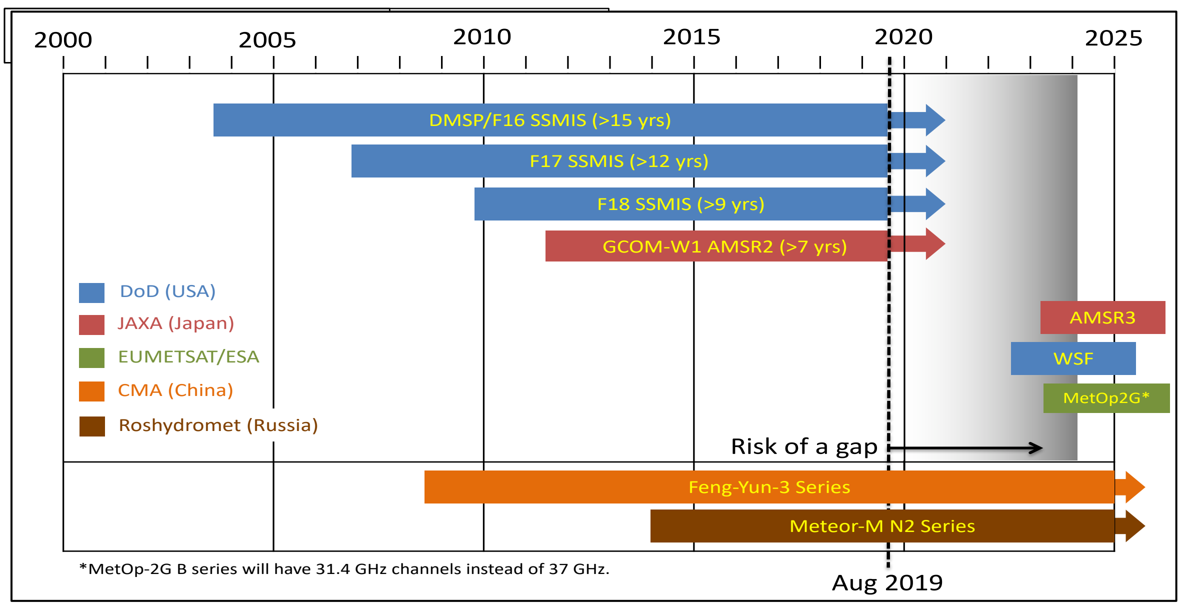


Figure 1 Current and planned passive microwave sensors for polar applications

These records began with the launch of the Scanning Multichannel Microwave Radiometer (SMMR) on the NASA Nimbus-7 platform and have continued with a series of U.S. Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSMI) and Special Sensor Microwave Imager and Sounder (SSMIS) instruments. The instruments have had generally consistent sensor frequencies, spatial resolutions, and orbits. There have always been at least two instruments operating simultaneously for at least some period of time to allow sensor inter-calibration.

There are three SSMIS sensors operating as of August 2019. However, all three are well beyond their planned mission lifetimes (the youngest being over 9 years old) and the DMSP program has ended; there will be no future SSMIS launches. In parallel, there have been two missions with enhanced capabilities: The Advanced Scanning Microwave Radiometer (AMSR-E) for the NASA Earth Observing System and a follow-on (AMSR2) launched by JAXA. AMSR2 is currently operating, but is now over 7 years old and also well past its planned mission lifetime.

Russia and China are also operating satellite microwave radiometers, but data quality is uncertain and data access by NASA is not feasible at this time. Future sensors are being planned: AMSR3 by JAXA, the U.S. DoD Weather Satellite Follow-on (WSF), and the European MetOp 2nd Generation. However, it is unlikely that these will be launched before 2023 at the earliest. For sensor overlap and intercalibration then, at least one of the current DMSP or AMSR2 must survive at least five more years. This may be possible, but there is a looming risk of a gap in satellite coverage (see Figure 1) for operational and scientific use.

CIMR will not be developed in time to address this gap in passive microwave coverage. However, CIMR's long-term plan will extend passive microwave data into the mid- to late-2030s. In addition, CIMR's advanced capabilities (described earlier) will yield new and enhanced products that address key science questions in the cryosphere as well as the needs of the operational community that have been deemed Most Important and Very Important by the 2017 Decadal Survey.

2. What enhanced products can you develop with simultaneous multi-frequency microwave measurements?

CIMR-A and -B will substantially enhance passive microwave retrievals of key cryospheric parameters over current capabilities. It will also facilitate new products through the combination of multiple frequencies, higher spatial resolution, more frequent coverage (with no pole hole), and near coincident coverage with the Copernicus MetpOp-SG(B) Scatterometer. As well, the anticipated high temporal frequency and short latency delivery of the CIMR products is especially important for supporting and improving operational and short-term forecasts. Here, we address the current cryospheric products and potentially enhanced CIMR products that could be developed in the consolidated and marginal sea ice zones. Separately, below, the products over land ice are discussed.

a. Consolidated Arctic Sea Ice

Two important products will be ice concentration and ice drift. For CIMR, ice concentration and ice edge precision will be available at 3-5 km resolution. While high-frequency AMSR2 channels (89 GHz) can approach that resolution, the large weather effects at 89 GHz limits accuracy of derived parameters, especially near the ice edge. CIMR will provide the same resolution at 18 and 36 GHz, for which well-validated algorithms exist that are minimally contaminated by weather. In addition, CIMR 6.9 GHz will have 15 km resolution – greater than SSMIS and similar to AMSR2 – with greater sensitivity to ice with reduced atmospheric effects. Ice drift will also benefit from the higher spatial resolution. Higher frequencies yield better resolution but have larger weather effects that limit drift retrievals. Summer melt also benefits from drift estimates from lower frequencies. Table 1 compares our current capability with potentially enhanced data quality afforded by CIMR capabilities.

Table 1 Current products and potentially enhanced retrievals from CIMR
(Note: The near co-incident CIMR and MetImage visible-infrared observations from MetOp-SG(A1) will benefit all retrievals under cloud-free conditions)

Sea ice variable	Current Capability	Enhanced with CIMR Capability
Sea ice concentration 18 and 36 GHz algorithms	SSMIS: 25 km resolution AMSR2: 10 km resolution Daily or twice-daily averages	Expected: 3-5 km Multiple times per day (8X per day >70° latitude with a single satellite, 16X per day with two satellites)
Ice edge detection precision with 18 and 36 GHz algorithms	SSMIS: ~50 km AMSR2: ~15 km	3-5 km multiple times per day Extremely useful for operational support and forecasting.
Ice concentration and edge with 6.9 GHz	Not available for SSMIS, not used for AMSR2 standard products	~15 km resolution, potentially more stable than 18 GHz and 36 GHz. Potential to use Ku/Ka bands to "sharpen" 6.9GHz channels to ~5 km spatial resolution.
Ice drift	SSMIS: 6-7 cm/s AMSR2: 4-5 cm/s Daily motion with large time uncertainty due to daily composite grids	~2-3 cm/s for daily 4-5 cm/s for sub-daily Multiple overpasses make use of swath data viable for drift calculation. Precise timing for ice displacement; and multiple looks per day Potential to detect inertial and tidal motions.
Summer ice drift	Limited retrievals, large errors.	Much better retrieval coverage with 18 GHz, smaller errors. Potential to use 15 km C- and X-band measurements with better ice/water discrimination
Landfast ice	Limited by low spatial resolution and land-spillover effects (mixed land-ocean scenes).	Landfast ice capability: operational support for coastal communities, biogeochemical processes, coastal processes, monitoring marine mammal habitat.
Leads	No practical capability	Larger leads will be detectable (Ka-band channel will be ~4 km spatial resolution), some info on heat flux through leads possible; multiple passes will allow detection of evolution of leads.
Polynyas	Large polynyas, but uncertainties near coast due to land-spillover (sidelobes)	Much more accurate polynya estimates, useful heat and salinity fluxes by multi frequency measurements (notably C- and X-band at 15 km spatial resolution
Thin ice thickness	SMOS/SMAP at 30-50 km spatial resolution up to ~0.5 m thickness (retrievals require additional validation)	Similar capabilities in CIMR after re-gridding substantially over-sampled L-band measurements.
Ice type (multiyear, first-year)	Detectable during winter, but often with ambiguities. Low resolution results in grid cells with mixed types	Multiple frequencies and near coincident scatterometer observations (from METop) should be able to resolve many ambiguities in these estimates. Higher resolution results in fewer mixed grid cells.
Timing of melt and freeze onset	Using temporal information of 19 and 37 GHz to detect changes in the physical properties of the surface	Using temporal information of 19 and 37 GHz to detect changes in the physical properties of the surface at higher spatial and temporal resolution.
Snow depth	Similar to terrestrial SWE algorithm	High temporal resolution could enable the identification of snowfall events.

	Microwave signal mostly from snow/ice interface, snow acts as a scatterer and scattering is stronger at 37 GHz compared to 19 GHz -> the greater the TB difference the thicker the snow.	Higher spatial resolution: higher fidelity ice concentrations and less mixing of ice types should improve snow depth retrievals. Near coincidence with scatterometer: Improved identification of multi-year ice mask.

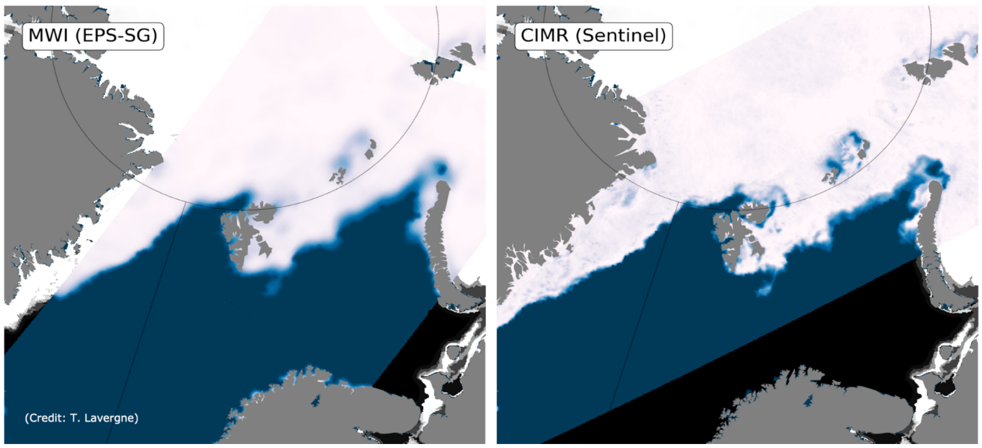


Figure 2. Example SIC comparison between MetOp-SG(B1) Microwave Radiometer and CIMR.

2.2 Enhanced atmosphere-ice-ocean observations at the sea ice margin (Sea surface salinity-SSS and sea surface temperature-SST)

Among the processes in the marginal ice zones related to sea ice are polar lows which are small scale cyclones that form over the polar regions during the cold season and are usually followed by the occurrence of cold-air outbreaks. In the Arctic, they have been called Arctic hurricanes because they form spiral patterns often with an eye that are similar to those of tropical hurricanes when observed from space including passive microwave data. They are relatively small depressions about a few hundred kilometers in diameter that usually form in the cold water in winter in both polar regions. They are known to cause adverse weather conditions in the polar regions with winds at near hurricane intensity of about 90 km/hour. The surface expression of these cyclones will be available in CIMR.

The ocean adjacent to the marginal ice zones has also been regarded as are regions of high biological activity, especially during spring and summer when the surface is covered by a meltwater layer that stays on the surface because of low density. The region becomes scenes of phytoplankton blooms during this time period primarily because of the abundance of sunlight and nutrients ideal for photosynthesis. Studies of this process are enhanced considerably with the availability of high-quality salinity data which provide spatial distribution of meltwater during the retreat of the sea ice cover. This allows quantitative analysis of how the meltwater contributes to the bloom and how the productivity of the ocean is affected by the changing salinity. More accurate sea surface salinity (SSS) estimates are also expected from CIMR and with concurrent and more accurate determination of the sea ice edge because of its multi-channel capability and low NeDT. This is a significant improvement from SMAP, SMOS, and Aquarius where the sea ice concentration retrieval from the L-band is too coarse for SSS retrievals and sometimes erroneous. SSS is also important to monitor in the polar regions because coastal polynyas are sites of bottom water formation, the understanding of which will significantly improve with the use of the high resolution CIMR data. Bottom water is an integral part of the global thermohaline circulation that is a key component of the climate system.

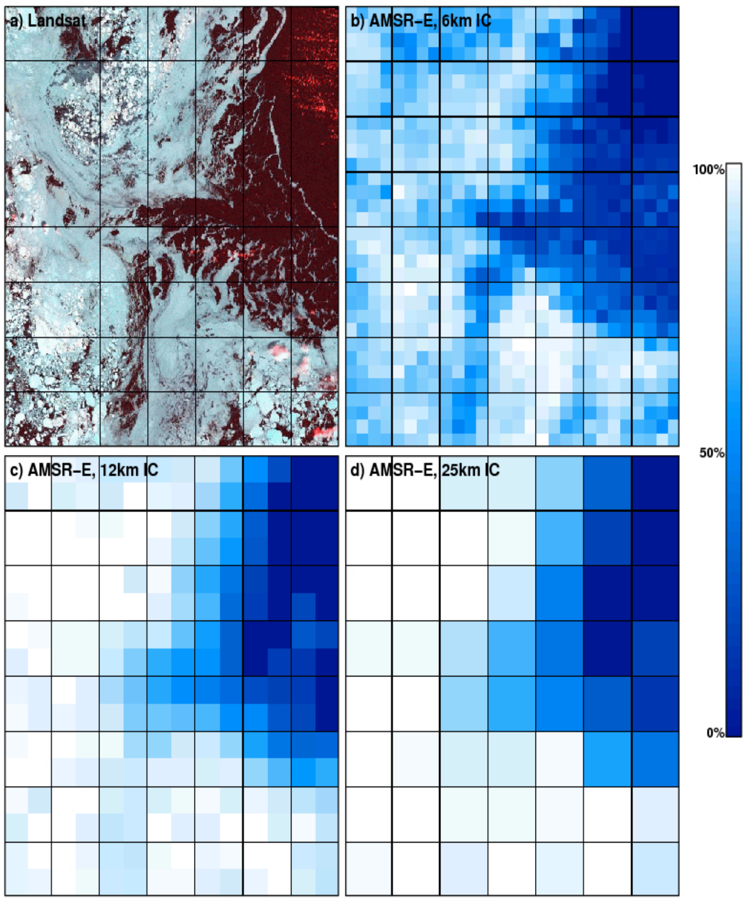


Figure 3. Sea ice cover as represented by (a) Landsat; (b) AMSR-E 89 GHz channels at 6 km resolution; (c) AMSR-E at 12.5 km resolution and (d) AMSR-E at 25 km resolution.

Accurate characterization of the marginal ice zone also allows for improved determination of the location of the sea ice edge which together with land boundaries limit the area where sea surface temperature (SST) from CIMR can be derived. SST can be derived from CIMR at an ungridded native resolution of 15 km, which is much better the 50 km data from AMSR. In the Arctic region, determining surface temperature near the ice edge at higher resolution unlocks the ability to assess how temperature affects the growth and decay of sea ice. It also enables more accurate measurements of average temperature in the Arctic that has been observed to be increasing at a rate that is up to 3 times that of the global average. Accurate measurements of this variable would also help in projections of the future state of the Arctic sea ice cover by Earth system models. Accurate ice edge determination would also lead to more accurate estimates of the ice extent and ice area which is essential for interannual variability and ice extent studies.

2.3 Land-ice products and enhancements from CIMR

The capability of CIMR suggests a number of potential new applications and significant enhancements to existing applications for passive microwave analysis of the polar ice sheets. Overall, the new capabilities of CIMR will strongly support several aspects of ice sheet snow cover, melt and firn evolution. Below we first summarize the existing method that will be significantly improved by CIMR (e), and then the new methods made feasible by CIMR capabilities (n).

(e) surface snow melt extent mapping. Improved resolution in the Ku (18.7 GHz) and Ka (35 GHz) bands (to ~5 km) will support a more detailed evaluation of melt distribution and the interplay of topography, crevassing, and surface melting. High rate of overpasses per day for ice sheet areas will facilitate more accurate timing of melting and melt area expansion /contraction on diurnal and seasonal scales. (Distinct algorithms described in Mote and Anderson, 1995; Abdalati and Steffen, 1997; Tedesco, 1997, would all be potentially improved by application of CIMR data)

(e) mapping of firn aquifer regions. In areas of both high summer melting and high snow accumulation, percolated meltwater can accumulate in the firn at depth (5 – 50 meters) forming a isothermal melt-saturated aquifer layer in the snow (Forster et al., 2014; Koenig et al., 2014; Miege et al., 2016). Although well-known in mountain glacier systems, their presence on ice sheets was only recently appreciated. These areas are important reservoirs on the ice sheet periphery, with the potential to drain through the ice (similar to melt ponds) and contribute to basal meltwater lubrication and thereby accelerate glacier outflow. Firn aquifers have now also been discovered on ice shelf areas in Antarctica (T. Scambos and J. Miller, pers. comm.) and are likely a causal component of past ice shelf disintegration events on some ice shelves, through hydrofracture. The CIMR application would be an augmentation of existing methods using L (SMAP) and C bands (Miller et al., submitted) with a multifrequency approach, and at much higher spatial resolution. The existing method uses the passive microwave time-series signature of the gradual re-freezing of a deep isothermal firn column above the aquifer to identify aquifer regions. A signature that continues to exhibit characteristics of deep meltwater below the re-frozen firn (e.g. by having a persistently low brightness temperature well into spring) is an indication of perennial water below the surface.

(n) firn scatterer structure profiling. An assessment of melt-derived microwave scatterers (scatterer size distribution and variation with depth) within the snow and firn in percolation zone regions can be extracted from post-freeze-up autumn and winter multi-frequency time-series data (e.g., Jezek et al., 2017). Over several years, changes in the ice drainage structures should be evident as melt intensity of the surface snow during summer (likely increasing, given recent decadal trends) changes the winter firn structure. The algorithm concept involves tracking the passive microwave brightness temperatures in L, C, X, and the Ku and Ka bands during firn freeze-up and comparing to dry snow areas. This method would require an independently known temperature profile, and would need to be linked to a model of microwave interaction with firn structures.

(n) snow and firn temperature profiling. A multifrequency extraction of snow and firn T versus depth (to ~100 m) is possible in meltwater-free snow and firn by comparing brightness temperatures in L, C, and X bands. These bands have mean emission depths that span the range of the annual temperature cycle penetration (0 to ~12 meters) and extend to mean annual temperature depths. Tracking the temperature profiles over time would be a sensitive indicator of warming (or cooling) conditions over the ice sheet. Jezek et al. (2014) discussed deeper profiling using several frequencies in the L-band and P-band range; however shallow temperature profiling, supported by CIMR frequencies, would be more appropriate for tracking decadal-scale temperature trends.

3. **What science questions can you address with simultaneous products on land, ocean, and cryosphere**

Sea Ice

The sea ice environment is complex with the sea ice cover, ocean, and atmosphere continually interacting with one another. Processes occur rapidly, whereby – e.g., leads can form within minutes, increasing the ocean to atmosphere heat and moisture fluxes by orders of magnitude during winter. Polynyas are locations of substantial ice formation, salinity fluxes, and important biogeochemical processes. The ice edge is often heterogenous with thin ice, small and large thick ice floes transitioning in a disordered fashion towards open water. Such regions are critical for human navigation, indigenous activities, and biogeochemical processes. The multiple frequency capabilities will yield simultaneous and integrated retrievals of sea ice, SST, and SSS, allowing for a consistent estimate of heat and salinity fluxes and sea ice mass balance. These capabilities of CIMR under all-sky conditions, multiple times per day will help answer key science questions on the drivers and impacts of these processes.

Land Ice

The main scientific questions that can be addressed by the sensor are: *what are the physical characteristics of the upper 0.1 to 100 meters of the ice sheet surface? How are they evolving over time? To what extent is climate change impacting ice sheet surface conditions?* The observations of surface melt and snow/firn temperature will enhance our understanding of the overall linkages between the short- and longer- time scale linkages between the atmosphere, snow/ice, and the drainage of meltwater into the oceans. This will contribute to our understanding of the mass balance of the ice sheets and and the consequences of the negative balance on sea level rise.

4. What Most and Very Importance measurements (MI & VI) in the 2017 Decadal Survey will be done with CIMR measurements?

The observations from CIMR will help address the following science questions.

QUESTION C-1. How much will sea level rise, globally and regionally, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage?	C-1a. Determine the global mean sea-level rise to within 0.5 mm/yr over the course of a decade.[b]	Most Important
	C-1b. Determine the change in the global oceanic heat uptake to within 0.1 W/m^2 over the course of a decade	Most Important
	C-1c. Determine the changes in total ice-sheet mass balance to within 15 Gton/yr over the course of a decade and the changes in surface mass balance and glacier ice discharge with the same accuracy over the entire ice sheets, continuously, for decades to come.	Most Important
	C-1d. Determine regional sea-level change to within 1.5-2.5 mm/yr over the course of a decade (1.5 corresponds to a ~6000 km^2 region, 2.5 corresponds to a ~4000 km^2 region).	Very Important

QUESTION C-6. Can we significantly improve seasonal to decadal forecasts of societally relevant climate variables?*	C-6a. Decrease uncertainty, by a factor of 2, in quantification of surface and subsurface ocean states for initialization of seasonal-to-decadal forecasts.	Very Important

QUESTION C-7. How are decadal-scale global atmospheric and ocean circulation patterns changing, and what are the effects of these changes on seasonal climate processes, extreme events, and longer term environmental change?	C-7a. Quantify the changes in the atmospheric and oceanic circulation patterns, reducing the uncertainty by a factor of 2, with desired confidence levels of 67% (likely in IPCC parlance).	Very Important

QUESTION C-8. What will be the consequences of amplified climate change already observed in the Arctic and projected for Antarctica on global trends of sea-level rise, atmospheric circulation, extreme weather events, global ocean circulation, and carbon fluxes?	C-8a. Improve our understanding of the drivers behind polar amplification by quantifying the relative impact of snow/ice-albedo feedback, versus changes in atmospheric and oceanic circulation, water vapor, and lapse rate feedback.	Very Important
	C-8b. Improve understanding of high-latitude variability and midlatitude weather linkages (impact on midlatitude extreme weather and changes in storm tracks from increased polar temperatures, loss of ice and snow cover extent, and changes in sea level from increased melting of ice sheets and glaciers).	Very Important
	C-8c. Improve regional-scale seasonal to decadal predictability of Arctic and Antarctic sea-ice cover, including sea-ice fraction (within 5%), ice thickness (within 20 cm), location of the ice edge (within 1 km), timing of ice retreat, and ice advance (within 5 days).	Very Important
	C-8d. Determine the changes in Southern Ocean carbon uptake due to climate change and associated atmosphere/ocean circulations	Very Important
	C-8e. Determine how changes in atmospheric circulation, turbulent heat fluxes, sea-ice cover, freshwater input, and ocean general circulation affect bottom water formation.	Important
	C-8i. Quantify how increased fetch, sea-level rise, and permafrost thaw increase vulnerability of coastal communities to increased coastal inundation and erosion as winds and storms intensify.	Important

QUESTION W-3. How do spatial variations in surface characteristics (influencing ocean and atmospheric dynamics, thermal inertia, and water) modify transfer between domains (air, ocean, land, and cryosphere) and thereby influence weather and air quality?	W-3a. Determine how spatial variability in surface characteristics modifies regional cycles of energy, water, and momentum (stress) to an accuracy of 10 W/m2 in the enthalpy flux, and 0.1 N/m2 in stress, and observe total precipitation to an average accuracy of 15% over oceans and/or 25% over land and ice surfaces averaged over a 100 × 100 km region and 2- to 3-day time period.	Very Important

QUESTION W-1. What planetary boundary layer (PBL) processes are integral to the air-surface (land, ocean, and sea ice) exchanges of energy, momentum, and mass, and how do these impact weather forecasts and air quality simulations?	W-1a. Determine the effects of key boundary layer processes on weather, hydrological, and air quality forecasts at minutes to subseasonal time scales.	Most Important

5. What are emerging applications from CIMR capabilities?

CIMR will provide time-critical information to operational activities – e.g., providing safe navigation through ice-infested waters. The high temporal sampling and high spatial resolution will be a giant leap forward in data quality and quantity for operational forecasting. For seasonal forecast models, a better characterization of the marginal ice zone, mass balance, and heat fluxes as the melt season begins will allow better initialization and better process modeling to improve the seasonal evolution of the models. For climate models, the improved capabilities of CIMR will provide better validation of key climate variables, and especially of smaller-scale processes that are added or enhanced as model resolution increases. Finally, sea ice is important input into weather models and atmospheric reanalyses. Higher spatial resolution, more frequent sampling, and improved estimates of sea ice will improve global atmospheric forecasts and analyses.

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3.2 Oceanography Panel Report

We have discussed the four questions posed to the panel. The panel conclusions are indicated below.

1. How will CIMR ensure continuity of important data records in your field?

All-weather SST

Accurate all-weather Passive Microwave (PMW) Sea Surface Temperature (SST) has been routinely measured since December 1997 with the launch of the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI). Observations were extended to global coverage with the launch of Advanced Microwave Scanning Radiometer for EOS (AMSR-E) in 2002, WindSAT in 2003, Advanced Microwave Scanning Radiometer 2 (AMSR2) in 2012, and Global Precipitation Measurement (GPM) Microwave Imager (GMI) in 2014. This series of instruments has provided diurnal resolution (TMI and GMI) and global coverage (AMSR-E, AMSR2, WindSAT) of PMW SST for over two decades. Despite having coarse spatial resolution, PMW SST provides significant value beyond infrared SST because PMW SST is not obscured by clouds, and is relatively insensitive to atmospheric effects such as aerosols and water vapor, thus providing all-weather capabilities. This is particularly critical for the Arctic region, where cloud cover severely limits infrared SST retrievals [Liu and Minnett 2016]. A discontinuity of the PMW SST record would jeopardize our ability to accurately monitor SST in terms of global climate trends (for instance, a major volcanic eruption could affect IR SSTs), in regions with persistent cloud cover (especially in the Arctic), and in severe storms (where SST is a proxy for oceanic heat content). The CIMR would provide continuity to this important environmental parameter. ESAS 2017 identified SST as part of the Program of Record and specifically calls out PMW SSTs for a possible Earth Venture Continuity or international partnership opportunity [Box 4.4; ESAS 2017].

Sea Surface Salinity (SSS)

The era of satellites capable of measuring sea surface salinity (SSS) began in 2009 with the launch of the European Space Agency's Soil Moisture and Ocean Salinity (SMOS) satellite. This was followed by NASA's Aquarius instrument and the Soil Moisture Active Passive (SMAP) satellite, all of which provide a near-synoptic view of near-global ocean salinity. Satellite salinity is now routinely ingested into global ocean and coupled ocean-atmosphere models (Hackert *et al.*, 2014) and has proven to significantly improve El Niño Southern Oscillation (ENSO) forecasts (Zhu *et al.*, 2014), terrestrial precipitation and drought forecasting (Li *et al.*, 2016a), and intraseasonal variations such as Madden-Julian Oscillations (Subrahmanyam *et al.*, 2018) that have direct societal relevance. Additionally, the high resolution and frequency of observations provided by satellite SSS sensors have enabled detailed observations of Tropical Instability Waves, Inter-Tropical Convergence Zone dynamics, and climate variability (Vinogradova et al., 2019, and references therein). CIMR would extend the SSS records provided by the SMOS, Aquarius, and SMAP, which have been proven to be very important to science and applications for physical oceanography, marine biogeochemistry, environmental monitoring, ocean and climate forecasts, and water cycle studies.

High Winds

Ocean surface vector winds and wind speeds have been traditionally provided by microwave scatterometers (e.g., ERS, QuikSCAT, OSCAT, ASCAT) and radiometers (e.g., WindSat, SSMI, TMI) with C-band, Ku-band, or higher frequencies. A significant limitation of these wind sensors is the lack of ability to detect high winds because the ocean surface backscattering associated with capillary and capillary-gravity waves is saturated at high winds associated with extreme weather events. L-band radiometry shows a great capability of measuring extreme wind events due to longer wavelength as compared to traditional scatterometers with C- and Ku-band radars (Yueh et al. 2016). The Ku-band is significantly impacted by rain and both C- and Ku-bands have significant saturation (Stiles and Yueh 2002) or even non-monotonicity of the wind speed-$\sigma 0$ relationship (Fernandez et al. 2006; Shen et al. 2009; 2016) at high wind speeds for the co-polarizations. L-band is less affected by attenuation due to rain and can measure extreme wind events of tropical cyclones/hurricanes. The application of L-band measurements to measure extreme wind speed over the ocean using SMAP or SMOS measurements has been pioneered by a number of recent studies (e.g., Yueh et al. 2016, Reul et al. 2017, Meissner et al. 2017, Fore et al. 2018). Estimates of storm intensity and sizes are being produced in near-real time from SMOS (www.smosstorm.org) and SMAP (www.remss.com) for operational applications by the US Navy and the Joint Typhoon Warning Center has started to ingest this information into their Automated Tropical Cyclone Forecasting Systems (Sampson and Schrader, 2000; Bender et al. 2017, Knaff et al. 2018).

In the Arctic region, Polar Lows (PL) are intense mesoscale cyclones that are associated with cold air outbreaks and form poleward of the main baroclinic zone. Sometimes referred to as Arctic hurricanes, polar lows are short-lived (the mean lifetime is ~15 h) and small-scale cyclones (diameters ranging from 200 to 600 km), unlike their tropical counterparts (*Smirnova et al.,* 2015). What they do have in common is strong surface winds: at least gale force is required for a polar low (*Rasmussen and Turner* 2003). Early detection and evaluation of PL parameters are extremely important to ensure the safety of navigation, fishing and oil industry, and expanding construction on the Arctic shelf. These extreme storms, characterized by strong and rapidly changing winds, are known to enhance vertical mixing processes. This can affect the cold halocline layer, possibly leading to a positive feedback to impact sea-ice formation. Because of the sparse network of weather stations and irregular meteorological observations at the sea, the fast movement and short life cycle of PLs, the phenomena are not always identified in the pressure fields on the surface weather maps. Thus, satellite data remain the basic source of information on PLs. Polar lows can be identified in integrated Water Vapor Content (WVC) fields (*Sminorva et al.,* 2016), but in some regions (Chukchi Sea, Laptev Sea and the East Siberian), they are associated with extremely low WVC values which make their detection from high-frequency radiometers (e.g., SSM/I) difficult (*Zabolotskikh et al.,* 2016). Efficient masking of the areas over the oceans, where geophysical parameter retrievals are objectively impossible due to non-transparent atmosphere, is still an important issue for satellite radiometer measurements working at frequencies higher than or equal to C-band. As demonstrated for Tropical cyclones (Yueh et al., 2016, *Reul et al.,* 2012b, 2016, 2017, *Meissner et al.,* 2017) L-band radiometer data can provide a direct way to probe surface wind speeds during extreme weather events, being almost transparent to the atmosphere. Estimation of the total atmospheric absorption can be also done from the ~10 GHz channel with high accuracy due to the weak influence of liquid water and especially water vapour (*Zabolotskikh et al.,* 2013). This helps to refine a new filter to considerably reduce masking ocean areas in e.g., AMSR2 radiometer data for severe weather systems such as PL, characterized by high wind speeds and moderate atmospheric absorption. Combining, X- with C- and L-band channels, a methodology can be proposed to jointly retrieve sea surface wind speed and sea surface temperature in PL.

The combined usage of both CIMR passive and MetOp-SG(B1) active microwave sea surface wind estimates will demonstrate the potential of the highest spatial and temporal resolution in the investigation of PL intensity. The ability to better measure warm SST PLs and wakes thanks to the X/C band combination for SST and L-band wind retrievals, will also help in better characterizing feedbacks of PLs on sea-ice formation.

NASA's CYGNSS mission used GNSS Reflectometry to detect high winds for the tropics and mid-latitudes, but not at higher latitudes. CIMR will help to extend the L-band measurements of high winds, especially over the polar oceans.

Sea Ice Properties – see the report from the cryosphere team.

2. What enhanced or new products can you develop with simultaneous multi-frequency microwave measurements?

SST

The CIMR will significantly enhance the spatial resolution and temporal sampling of PMW SST as well as improve PMW SST retrieval quality. These advantages will help improve the quality of blended SST products.

CIMR's 15-km PMW SST spatial resolution (before any re-gridding where a gridded spatial resolution of 5-10km is anticipated) is a dramatic improvement from the 55-km resolution (typically reduced to 25 km after gridding) of current PMW SST measurements. This increased resolution is important for operational ocean forecasts, mesoscale air-sea interaction, and monitoring capability for the coastal oceans and near sea-ice edges.

In terms of temporal sampling, CIMR provides up to eight measurements of PMW SST for the same location at high-latitude oceans for one satellite (CIMIR-A or CIMR-B). CIMR-A and -B together will provide the unprecedented capability to resolve the diurnal cycle of SST. This represents a major improvement over the current capability, which is important for science and applications related to ocean-sea ice interaction and air-sea interaction.

Further enhancement of the low-frequency bandwidth (e.g., by including a spectrometer that covers up to 3 GHz) is expected to further improve the sensitivity to polar ocean SST, thus improving the quality of SST in these regions.

SSS

The CIMR will improve the temporal sampling and retrieval quality of L-band SSS. SSS has been measured by L-band radiometers onboard ESA SMOS (2010-present), NASA Aquarius (2011-2015), and NASA SMAP (2015-present) missions. Although all satellite SSS missions have nearly-global coverage, SSS observations have different temporal coverage. The SMOS has an 18-day repeat and a 3-day sub-cycle [*Boutin et al.,* 2018], Aquarius has a 7-day repeat [*Lee et al*., 2012], and SMAP has an 8-day repeat with a 2-3-day sub-cycle [Fore et al., 2016, *Meissner et al.,* 2018]. The temporal resolution of the CIMR will be 1.5 days globally with an increased sub-daily resolution above 60°N. A daily temporal resolution will bring important information on ocean dynamics and ecology especially in the coastal ocean and at high latitudes. Moreover, daily SSS observations will be valuable to the operational ocean and ecological forecasting and climate prediction systems that generate information about the past, current, and future ocean state [*Boukabara et al.,* 2016].

To retrieve SSS from brightness temperatures measured by an L-band radiometer, it is necessary to remove various contributions, including from surface roughness and thermal effects. While the L-band radar on Aquarius was used to correct the surface roughness effect, this correction in both SMOS and SMAP SSS retrievals relies on ancillary wind data. Moreover, all three L-band missions use ancillary SST measurements to remove thermal effects on brightness temperature measurements. The adequacy and accuracy of ancillary wind and SST measurements are very important for SSS retrieval uncertainties [e.g. *Vinogradova et al*., 2019]. Therefore the CIMR, by allowing simultaneous measurements of SST and winds, will improve SSS retrievals especially at high latitudes where the surface roughness effects are strong.

While L-band radiometry is relatively sensitive to SSS variations in tropical and subtropical oceans, it has poor sensitivity at high-latitude oceans (for SST<5ºC). Inclusion of a low-frequency spectrometer (0.5-3GHz) is expected to significantly improve the sensitivity to SSS in polar oceans and thus the retrieval accuracy of SSS. Given the essential roles of salinity in polar ocean dynamics and the interaction of the polar ocean with the lower-latitude ocean as well as with the atmosphere, such an enhancement has a great potential to revolutionize polar oceanography, especially in light of the paucity of in-situ SSS measurements in the Arctic Ocean (e.g., Figure 1).

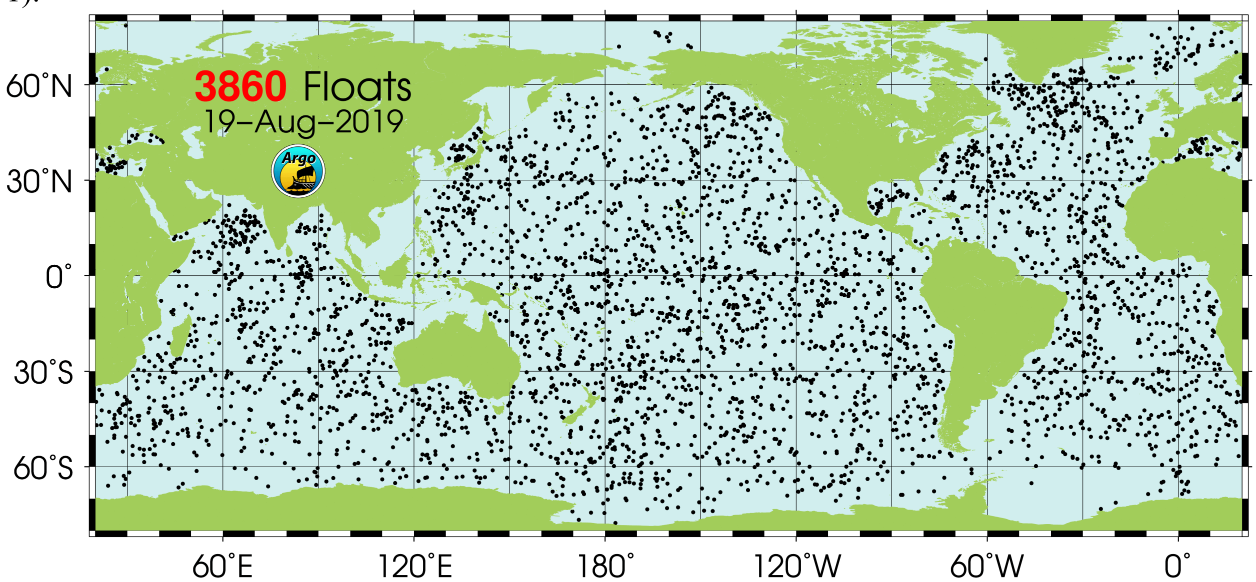

Figure 1. Current distribution of Argo floats in the global ocean, showing few floats in the Arctic Ocean and sparse distribution in the Southern Ocean.

<u>Density</u>

The CIMR will provide an unprecedented sea surface density (SSD) retrieval, as the instrument is capable of independently measuring SST and SSS simultaneously without relying on ancillary datasets. This provides perfect collocations of all input variables required to derive SSD without introducing uncertainty due to spatial and temporal mis-match of co-location for SST and SSS.

Due to the wider swath width compared to the SMOS or SMAP, all areas of the globe will be sampled more frequently, which will provide a crucial advantage in observing dynamic ocean areas. The relatively small footprint size of SST observations that the CIMR will provide will directly translate into better SSD estimates at high latitudes, where large SST gradients are present. The improvements in reflector performance in providing SSS and SST measurements closer to the coast and sea-ice edge will increase the observable area.

The CIMR will improve studies of intermediate-water and deep-water formation, which require accurate estimates of SSD. These estimates are crucial in understanding the pathways and changes in the overturning circulation, one of the largest drivers of global climate. Estimates of SSD in areas of isopycnal outcropping can be used to estimate one component of the oceanic mixing budget (Marshall & Speer, 2012). Daily, collocated SST and SSS measurements will also provide a valuable constraint for ocean forecast models, as SSD is a pivotal element of estimating ocean surface currents.

Air-sea turbulent heat and moisture fluxes

Air-sea turbulent heat and moisture fluxes are computed from bulk aerodynamic parameterizations that use air-sea variables (e.g. wind, SST, air temperature and specific humidity (Ta and Qa)) as input (Fairall et al. 2003). CIMR provides simultaneous multiple low-frequency (1.4 (L-band), 6.9 (C-band), 10.65, 18.7 (Ku-band), 36.5 (Ka band) GHz) microwave measurements that allow direct retrievals of SST (6.9GHz), wind speed (36.5GHz), SSS (L-band), SIC (Ku and Ka bands), rain rate, integrated cloud liquid water, etc. Retrievals of Ta and Qa can be obtained from microwave brightness temperature at Ku and Ka bands. Although the two channels are not exactly near the peak frequency channel of water vapor absorption at 22.2 GHz (Jackson et al. 2006; Yu and Jin 2018), the CMIR is configured with lower noise, better accuracy, more frequent revisits, and higher spatial resolution which deems to be promising in improving turbulent heat and moisture flux estimates in the Arctic ocean and adjacent seas. Furthermore, coincident mesoscale measurements of SST and wind help minimize space/time sampling mis-matches, which can improve the quantification of air-sea coupling and feedback over mesoscale eddies, fronts, and the marginal ice zone.

Ocean surface winds

The CIMR's abilities to (1) enhance the spatial resolution and temporal sampling of radiometer-derived wind speeds and (2) measure high winds will significantly improve the blended wind products. These improvements are important for improving ocean model simulations, initialization of ocean and climate forecasts, and estimates of air-sea fluxes, including biogeochemical fluxes (e.g. CO_2) across the air-sea interface.

3. What science and applications questions can you address with simultaneous CIMR products on land, ocean and cryosphere?

Polar oceans and interactions across different Earth system elements

Owing to the improved sampling and lower noise level of the radiometric measurements, CIMR will help advance sciences and applications across different elements of the Earth system, especially in the polar (Arctic and Antarctic) regions. For both the Arctic Ocean and the Southern Ocean, an important contribution of the CIMR is to improve ocean-sea ice interaction and sea ice forecasts. This is due to the simultaneous measurements of SSS and sea ice properties as well as SST and winds. In particular, sea ice properties and SSS near the sea-ice edge, especially with CIMR's frequent sampling in polar regions, will provide important measurements to constrain models used for studying ocean-sea ice interaction as well as to improve the initialization of sea ice forecast.

Currently, the uncertainties of satellite SSS in the polar ocean regions from all L-band satellites (SMOS, Aquarius, and SMAP) are much larger than those in lower-latitude oceans. This is due to the relative lack of sensitivity of L-band to SSS in the cold-water environment ($<5^oC$). This is compounded by the fact that the radiometers on these satellites operate on relatively narrow allocated bandwidth (~24-27 MHz). The currently envisioned bandwidth for CIMR's L-band radiometer is also 27 MHz. While CIMR's low noise level, coincident SST and wind measurements, and frequent temporal sampling at high latitudes will improve polar-ocean SSS retrieval, microwave radiometry over a broader frequency near L-band or including P-band have great potential to revolutionize polar-ocean salinity remote sensing by improving the SSS retrieval quality. Moreover, broader frequency radiometry also has the potential to improve the measurements of thin (seasonal) ice.

For the Arctic system, CIMR measurements of SSS, SST, winds, precipitation, as well as other variables that can be derived from these measurements (e.g., ocean surface currents) will also help improve: (1) the characterization of synoptic variability in the Arctic (e.g. the polar vortex); (2) the depiction of the Arctic and midlatitude connection on climate and weather time scales; (3) the assessment of the impacts of hydrological, atmospheric, and cryospheric (sea ice) forcing on Arctic Ocean freshwater, ocean circulation, and marine biogeochemistry; (4) the understanding about the roles of Arctic Ocean and sea ice on Arctic terrestrial changes (e.g., soil moisture). For the Antarctic/Southern-Ocean system, CIMR measurements will also enhance the understanding of sea ice changes, ocean water mass formation, ocean circulation and marine biogeochemistry.

Air-sea interaction and forecasts of weather and climate events

The expected improvement of SST and air-sea flux estimates by the CIMR will significantly enhance the understanding of air-sea interaction processes such as mesoscale SST-wind coupling. The higher temporal resolution of SSS & SST together with simultaneous measurements of SST, SSS, and wind improves studies of ocean response to synoptic weather and can better constrain coupled modeling for hurricanes as well as tropical/extratropical cyclones, including forecast and impact studies. On intraseasonal timescales, the Madden-Julian Oscillation (MJO) is a phenomenon that has important societal relevance. MJO has typical periods of 30-60 days with 8 phases, each lasting for about 3-4 days. CIMR's ability to resolve daily SSS and all-weather SST in tropical oceans will provide important measurements to constrain MJO coupled models and has the potential to improve MJO forecast. Salinity has been found to play an important role in triggering El Niňo-Southern Oscillation (ENSO) (Zhu et al. 2014). Recent studies have demonstrated the usefulness of satellite SSS in improving seasonal/interannual forecasts (e.g., Hackert et al. 2014). CIMR's ability to extend the satellite SSS record to cover multiple ENSO events can thus improve ENSO forecast capabilities in climate prediction centers.

Land-ocean linkages

CIMR's ability to improve the temporal resolution of SSS will improve the monitoring of river plume impacts and inverse constraint of river discharge associated with synoptic storms, in synergy with upcoming measurements such as river water-height slope measurements from the Surface Water Ocean Topography (SWOT) mission. Daily simultaneous measurements of SSS and winds from the CIMR will also enhance the research on processes associated with the dispersal of river-plume induced freshwater as well as the associated redistributions of nutrients and contaminants. Simultaneous measurements of soil moisture, surface inundation, and SSS will also improve the assessment of flooding impacts across the land-sea interface.

Ocean sciences

CIMR's enhanced all-weather SST measurements will improve the detection of SST fronts and related applications for marine biogeochemistry. The simultaneous measurements of SST and SSS will also improve the tracking of horizontal surface density fronts and the related studies of ocean dynamics on mesoscales. Ocean circulation at horizontal density fronts on scales of tens of kilometers is considered to be responsible for transporting much of the heat and carbon from the ocean surface to deeper layers. However, our capability to observe these small-scale density fronts is currently limited. The daily, high-resolution CIMR measurements will enable quantification of density fronts on scales of tens of kilometers, particularly in regions where temperature dominates the density variability (for instance, in the western boundary currents and in upwelling regions). CIMR measurements and science will complement the upcoming NASA Surface Water and Ocean Topography (SWOT) mission, which will measure sea surface height on 5-10 km horizontal resolution. CIMR measurements will also improve the studies of marine ecosystem dynamics and ecology forecasts as well as ocean acidification and air-sea CO_2 flux, especially for processes associated with mesoscale variability.

CIMR's higher resolution and lower noise SST estimates (compared to past C-band MW radiometers), combined with the dense temporal sampling at high latitudes, should allow a new capability to estimate daily gridded upper ocean vector currents. These currents would be derived as for ice and atmospheric motion, using cross-correlation analysis of features (Maximum Cross Correlation , MCC; Emery et al., 1986). While perhaps most valuable in the Arctic, the estimation can also be made globally and will benefit from blended IR-MW SST when the IR sensor data are available. Additionally, such MCC-derived current products would be available to complement or enhance existing geostrophic- and Ekman-driven current estimates from satellite-derived SSHA and wind products such as GlobCurrent and OSCAR.

The continuity and enhancement of data products for ocean variables (including SST, SSS, sea ice parameters, ocean surface winds, and precipitation) will further benefit ocean forecasts and ocean state estimation and research on marine biogeochemistry.

4. What Highest and High Importance measurements in the 2017 Decadal Survey will be done with CIMR measurements?

The CIMR will contribute to addressing the following societal/science goals/questions identified in the 2017 Decadal Survey on Earth observation from space. The assessed significance of the Earth science application/objective is noted as: Most Important (MI), Very Important (VI), and Important (I).

Hydrological Cycles and Water Resources

- ***H1 Coupling the Water and Energy Cycle.*** *How is the water cycle changing? Are changes in evapotranspiration and precipitation accelerating, with greater rates of evapotranspiration and thereby precipitation, and how are these changes expressed in the space-time distribution of rainfall, snowfall, evapotranspiration, and the frequency and magnitude of extremes such as droughts and floods?*

- Addressing the science objective (MI) for developing and evaluating components of the water and energy cycles and their interactions, CIMR's simultaneous observations (SSS and SST) contribute to assessing the water cycle's evaporation-precipitation balance over the ocean, while, in conjunction with its sea-ice observations, capture aspects of the water cycle's critical and variable cryospheric component.

Weather and Air Quality

- ***W1 Planetary Boundary Layer Dynamics.*** *What planetary boundary layer (PBL) processes are integral to the air-surface (land, ocean and sea ice) exchanges of energy, momentum, and mass, and how do these impact weather forecasts and air quality simulations?*
- ***W2 Larger-Range Environmental Predictions.*** *How can environmental predictions of weather and air quality be extended to seamlessly forecast Earth system conditions at lead times of 1 week to 2 months?*
- ***W3 Surface Spatial Variations Impacts on Mass and Energy Transfers.*** *How do spatial variations in surface characteristics (influencing ocean and atmospheric dynamics, thermal inertia, and water) modify transfer between domains (air, ocean, land, cryosphere) and thereby influence weather and air quality?*
- Considering the Decadal Survey's listed challenges in 1) planetary boundary layer dynamics (W1, MI), 2) mass and energy transfers (W3, VI), and 3) extended-range environmental predictions (W2, MI), CIMR's simultaneous observations will notably contribute to developing the relevant science and facilitate exploitation in numerous applications. The CIMR mission will provide necessary observations for assessing heat, moisture, and momentum flux between the ocean, atmosphere, and sea-ice domains, directly facilitating the evaluation of mass and energy transfers and planetary boundary layer dynamics. These observations directly facilitate longer-range environmental predictions, particularly for coupled systems and for the Arctic, where sea ice has a significant role in altering the coupling of oceanic and atmospheric processes.

Climate Variability and Change

- ***C4 Atmosphere-Ocean Flux Quantifications.*** *How will the Earth system respond to changes in air-sea interactions?*
- ***C6 Seasonal to Decadal Predictions, Including Changes and Extremes (C-6 and C-7).*** *Can we significantly improve seasonal to decadal forecasts of societally relevant climate variables?*
- *C7 How are decadal-scale global atmospheric and ocean circulation patterns changing, and what are the effects of these changes on seasonal climate processes, extreme events, and longer term environmental change?*
- ***C8 Causes and Effects of Polar Amplification.*** *What will be the consequences of amplified climate change already observed in the Arctic and projected for Antarctica on global trends of sea-level rise, atmospheric circulation, extreme weather events, global ocean circulation, and carbon fluxes?*
- Examining climate variability, change, and effects requires improved initialization for modeling and prediction (C6,VI), as well as enhanced understanding of coupled processes and rates (C4, VI) and relevant observations for driving/constraining those processes and associated changes (C7, VI), including polar amplification and its consequences (C8, VI). CIMR's simultaneous observations of multiple relevant parameters will serve to 1) reveal processes and dependencies; 2) highlight variability, evolution, change, and trends; and 3) coherently constrain assessments and predictions.

5. Emerging science and applications

In the past few years, there have been emerging science and applications related to the linkages of ocean salinity and the water cycle (e.g., Yu 2011, Vinogradova et al. 2013, 2017). Moreover, satellite SSS data have been used to evaluate oceanic evaporation-precipitation (E-P) products from atmospheric reanalyses using satellite SSS (e.g., Yu et al. 2017) and to inversely constrain E-P estimates in the context of ocean state estimation (e.g., Köhl et al. 2014). Recently, SSS has been identified as a skillful predictor for sub-seasonal to seasonal prediction of terrestrial precipitation (e.g., Li et al. 2016a and 2016b, Li et al. 2018). The method demonstrated its real-time prediction skill, winning the first price for year-long, real-time sub-seasonal rainfall forecasts of U.S. west "Sub-seasonal Climate Forecast Rodeo", sponsored by The Bureau of Reclamation in partnership with the National Oceanic and Atmospheric Administration (NOAA), U.S. Geological Survey, U.S. Army Corps of Engineers, and California Department of Water Resources (https://www.whoi.edu/oceanus/feature/a-rainfall-forecast-worth-its-salt/, https://www.drought.gov/drought/news/sub-seasonal-climate-forecast-rodeo-winners-announced-0).

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3.3 Terrestrial Hydrology Panel Report

For land surface hydrology in general and soil moisture in particular, L-band frequencies have long been considered the most sensitive to surface soil moisture through moderate amounts of vegetation. While SMOS and SMAP continue to produce high quality L-band soil moisture retrievals during their extended missions, there are no current plans by either NASA or Europe to build an L-band follow-on mission (Figure 1).

CIMR will have many new qualities that will be extremely useful in addressing some important NASA science priorities, particularly in the cryosphere and ocean communities (see Table 1). These qualities include making simultaneous measurements in multiple microwave channels, daily revisit resulting from a large swath, and the potential with CIMR A/B for a ~14-year data stream. However, the native or 3-dB spatial resolution of the CIMR L-band channel is coarser than SMOS/SMAP.

SMAP/SMOS are single frequency instruments offering only L-band. They require ancillary land surface temperature data to enable soil moisture retrieval. SMOS has a range of spatial resolution from 35 km to > 60 km depending on the incidence angle. SMAP (following the same definition of spatial resolution as CIMR) has a constant spatial resolution of 41 km. CIMR has a constant resolution of ~ 60 km but will provide L-band products on a 36-40 km grid (to be consistent with SMAP) by exploiting the large oversampling characteristics of this channel.

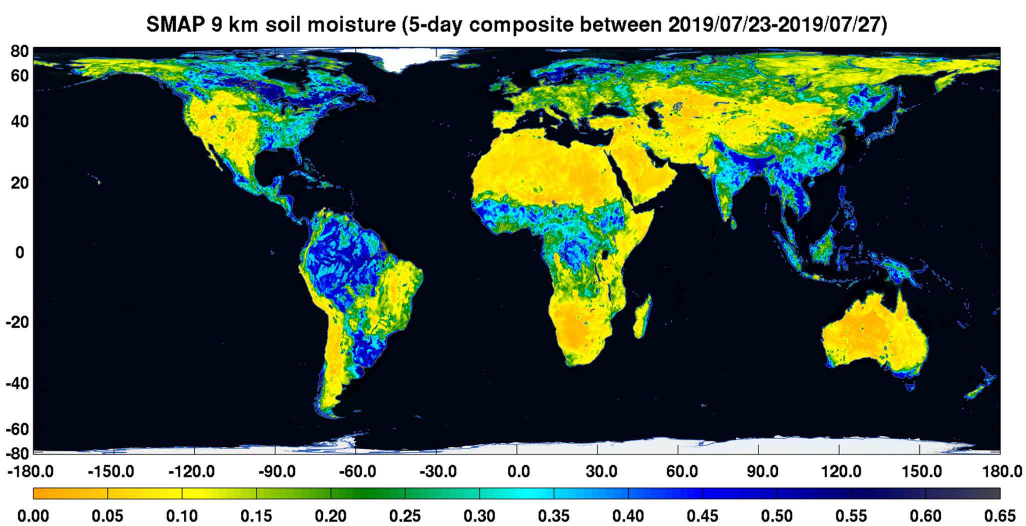

Figure 1: Example global map of surface soil moisture from the SMAP observatory.

The Terrestrial Hydrology panel discussions emphasized the science and applications value of CIMR L-band and multi-channel microwave measurements. The assessments here are made in the context of building on the heritage of SMAP and SMOS L-band science and applications, and finding a way to continue the soil moisture and freeze-thaw information data streams into the future in the short-term. We did not directly consider science and application activities that are enabled by using the higher (higher than L-band) CIMR frequencies alone. There are many such applications but their assessment would require a much broader participation from the science community.

Attribute	SMAP	CIMR
L-Band Spatial Resolution (at -3dB)	40 km	L-band:<60 km (40 km after data processing)
Data Refresh Rate	2-3 days	95% in one day (daily with two satellites)
L-Band Measurements Precision (NEDT)	1.1 K for one sample and 0.55 K on 36 km grid	<0.3 K for L1B product
Spectral Resolution	L-band	L-, C-, X-, Ka- and Ku-bands
Other band Spatial Resolution (at -3 dB)	None	C/X-band: <15 km Ku-band: <5 km Ka-band: <5 km
RFI Detection	Yes	Yes
Data Latency	<12 Hours (80% of data in 3hours actual)	<3 Hours

Table 1: Comparison of CIMR (one satellite) and SMAP instrument main science attributes. Values for main attributes are listed. Improvements in capability and relative advantages are shaded in green.

1. How will CIMR ensure continuity of important data records in your field?

Soil moisture demonstrates relatively high levels of temporal memory and significant seasonal variability. In addition, soil moisture extremes (associated with drought and floods) are often driven by processes that vary regionally – which precludes the effective use of ergodic sampling techniques that leverage spatial coverage for improved temporal sampling. Finally, soil moisture's role in the climate system is commonly characterized via the use of (seasonally varying) 2nd-order statistics (e.g., to establish its time/space autocorrelation and coupling versus water/energy/carbon fluxes) which often vary seasonally. These factors all work to degrade the value of short-term soil moisture data sets. Instead, consistent, long-term records are required to adequately quantify soil moisture's role in determining interannual climate variability and driving regional water resource availability.

The value of such long-term soil moisture data records is also enhanced by the specific availability of L-band data products. The ability of C- and X-band soil moisture retrievals to detect interannual soil moisture variability is compromised by their relative lack of sensitivity to soil moisture. Likewise, they struggle to describe the phase and amplitude of soil moisture seasonality due to the increased difficulty of compensating X- and C-band retrievals for seasonal temperature and vegetation variations (see Figure 2). Strong evidence exists that L-band soil moisture products overcome these limitations for a majority of the global land area. CIMR provides simultaneous measurements from all three of these bands, enabling systematic and synergistic applications.

Longer data records would also allow application users to comprehensively test the impact of soil moisture information in their decision-support systems and complete the research-to-operations transition. In many cases, this transition requires soil moisture climatology information that cannot be accurately obtained from short-term data records. End users queried by the SMAP Applications Surveys have consistently listed long-term data continuity as the single most critical factor impacting their plans to integrate soil moisture into their operational decision support systems. The CIMR-A and CIMR-B satellites will provide a minimum of 10-years on orbit (assuming a 7-year design life for each satellite and a staggering of launch dates).

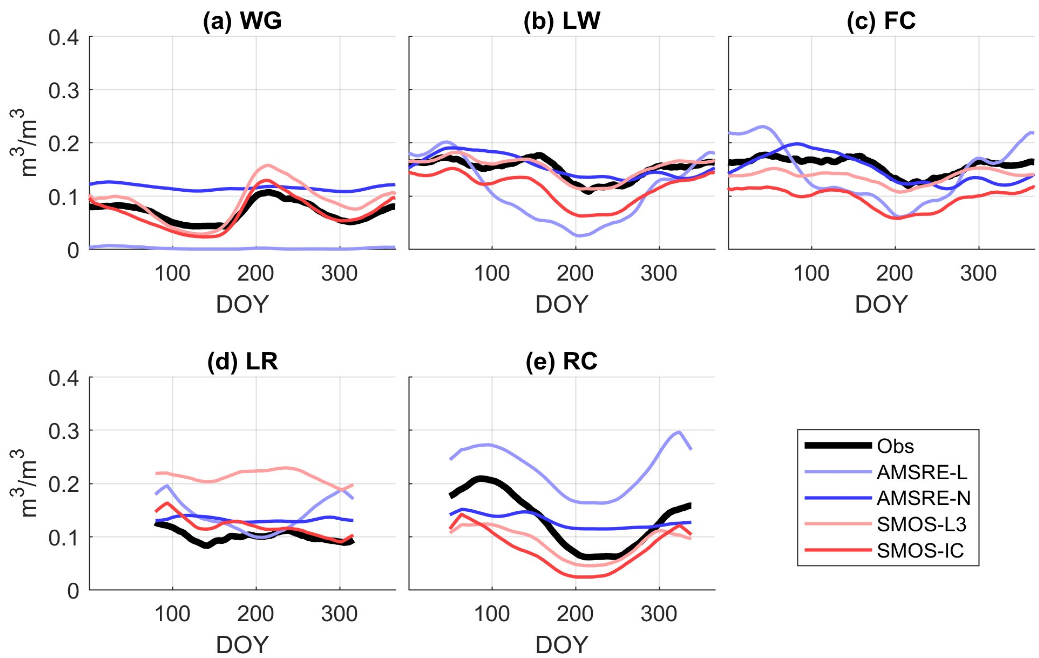

Figure 2: Soil moisture climatology information derived from the C/X-band AMSR-E retrievals (blue) and L-band SMOS retrievals (red) versus analogous information based on averaging of high-resolution ground observations at USDA ARS watershed sites. WG: Walnut Gulch, LW: Little Washita, FC: Fort Cobb, LR: Little River, RC: Reynolds Creek

2. What enhanced products can you develop with simultaneous multi-frequency microwave measurements?

<u>Surface Soil Moisture Information</u>
Several spectral and orbital attributes of the CIMR have made it a promising opportunity to extend and enhance the long-term availability of a global surface soil moisture record.

The space-time coincident availability of the L-band observations (1.41 GHz) and higher-frequency observations (e.g. 6.9 GHz, 10.7 GHz, 18 GHz and 37.0 GHz) onboard the CIMR will enable estimation of a number of confounding factors that are essential to accurate soil moisture retrieval from space. These factors include land surface temperature, fractional surface water inundation extent, and vegetation contributions (microwave scattering, absorption, and emission). The availability of these coincident estimates reduces the dependence, latency, and uncertainty of external static and dynamic ancillary data, leading to a faster and more robust operational delivery of soil moisture data to the end users. Besides its prime use in soil moisture remote sensing, CIMR's L-band will also contribute to freeze/thaw state transition (seasonal and diurnal) monitoring, which is an important constraint on water availability and mobility.

According to the current mission operation design, CIMR will fly in tandem as instruments A and B on a sun-synchronous orbit with LTDN (local time descending node) and LTAN (local time ascending node) of 6:00 am and 6:00 pm, respectively. Compared with past and current radiometers operating at similar frequencies, one distinguishing strength of CIMR is its wide swath. At ~1900 km, it is 33% wider than GCOM-W/AMSR2 and 90% wider than SMAP and SMOS. CIMR will not only achieve complete polar coverage (i.e. without the so-called 'pole holes') but also an unprecedentedly high global revisit frequency of 95% global coverage in one day, and 99% in 1.5 days with just one instrument. Temporal frequency of observations will be even greater (sub-daily) at the higher latitudes (≥60˚N/S) due to converging polar orbits and a wide sensor swath width. Once operational, the combination of CIMR A and CIMR B will enable L-band sub-daily gapless global coverage.

CIMR-A will fly in coordination with MetOp-SG(B1) providing access to scatterometer data within 10 minutes above 55°N/S. CIMR-B will fly in coordination with MetOp-SG(A1) providing access to high-resolution (0.5-1 km at nadir) MetImage visible and thermal infrared data within 10 minutes above 55°N/S. At the equator, the separation of CIMR and MetOp-SG data is 3 hours.

The boost in revisit frequency compared with SMAP or SMOS will allow CIMR adequate temporal resolution to capture rapid dynamic soil moisture processes previously unattainable by existing L-band sensors. The corresponding CIMR soil moisture retrievals will allow assessments of rapid dry-downs from storm events when much of the drainage and runoff occurs. The daily fidelity of CIMR observations will improve the characterization of soil moisture preconditions and wetting from severe rainfall events, which are key variables affecting soil water storage capacity and flood risk. Sub-daily soil moisture estimates will also help in reducing estimation bias of the marginal probability distribution function of surface soil moisture and enhance its utility in science applications such as estimation of precipitation and evapotranspiration from space. CIMR's L-band soil moisture potentially may lead to enhanced hydroclimatological applications.

In many numerical weather prediction applications as well as monitoring and forecast of flash floods, severe storms, and agricultural crop yields, surface soil moisture estimation at a spatial scale of 10 km or less is essential in order to provide relevant information to the stakeholders. Even though CIMR's current native resolution (constant <60 km, potentially 40 km after data processing), as is the case for SMOS and SMAP, is not adequate for these applications, there is a possibility that the Sentinel-1 radar backscatter data or CIMR's C-, X-, and Ka-band higher-frequency channels and their associated FOV dimensions (11 km x 19 km at 6.9 GHz, 7 km x 13 km at 10.7 GHz, and 3 km x 5 km at 37.0 GHz) can be utilized in conjunction with its L-band channels to produce surface soil moisture estimates at a spatial scale of 10-15 km. At present, CIMR has a wore spatial resolution than SMAP or SMOS, the synergic use of other CIMR's frequency channels with L-band can possibly mitigate this issue. SMAP science objectives in its Science Traceability Matrix include Hydroclimatology and Hydrometeorology requirements at 40 and 10 km resolutions respectively. CIMR will ensure science continuity of the Hydroclimatology requirement and with possible multi-channel algorithms approach the Hydrometeorology requirement (see Table 1).

Vegetation Information

The CIMR observations at L-, C- and X-bands enable derivation of vegetation information that 1) can be used for improving the CIMR soil moisture retrieval, and 2) is critical for answering important ecological, eco-hydrological and hydrologic science questions.

Past studies have shown that dual polarized L-band measurements, and also C- and X-band measurements, can be used to retrieve vegetation opacity. Vegetation opacity information obtained simultaneously with the soil moisture retrieval can improve the soil moisture retrieval. In particular, the multi-frequency approach can better account for the different electromagnetic interactions in the canopy. This will also improve how exactly the vegetation is compensated for in the soil moisture retrieval. The simultaneous and microwave-based accounting of vegetation avoids many of the issues that the conventionally used ancillary data sets face. This concerns all vegetation types, but in particular it is critical for denser canopies such as forests.

The microwave vegetation opacity can be related to other important vegetation characteristics such as vegetation water content (VWC) and above-ground biomass. VWC is a dynamic variable with short time-scale variability; its application for answering key science questions regarding plant water-carbon-energy relations and plant-atmosphere interactions will benefit from the high revisit time of CIMR, especially at higher latitudes. Furthermore, water relations in the soil-plant continuum can be studied with CIMR using the combined retrieval of VWC and SM, and the multi-frequency measurements potentially enable isolation of the different components of the canopy. The multi-channel capability of CIMR will be particularly helpful for these applications. This is a new variable for global ecology; the Terrestrial Ecosystems section includes more information on this topic and other vegetation monitoring capabilities of CIMR, which were identified as a high priority by the Ecosystems panel, while the Land Hydrology panel had greater emphasis on soil moisture.

As compared to SMAP, CIMR has a higher incidence angle (55° vs 40°). Overall, this higher incidence angle reduces sensitivity to SM. However, as it provides a longer path through canopy, it helps in derivation of the vegetation related parameters, especially at L-band.

Many of the features described above require a lot of work to develop the multi-frequency approaches to a mature state in which they can be applied to retrieval algorithms to produce science quality data. This work is expected to include OSSE analyses and field experiments where a development of a new OSSE and collection of new field experiment data are needed. There is recent progress in developing electromagnetic models for vegetation that have the potential to significantly improve the representation of vegetation in the forward models and retrieval algorithms. These approaches need to be included in the development work.

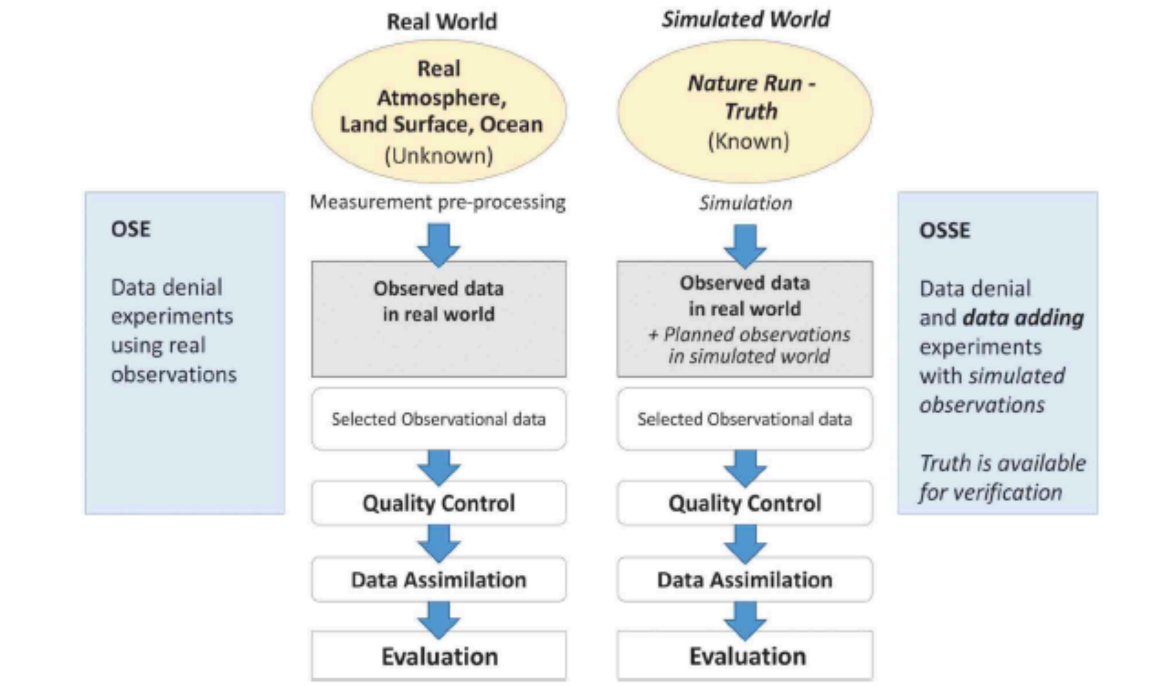

FIGURE 5 | Schematic of an observing system experiment, OSE (left-hand flow diagram), and an observing system simulation experiment, OSSE (right-hand flow diagram). See text for an explanation of the terms in the figure. Based on material in Masutani et al. (2013).

From https://www.frontiersin.org/articles/10.3389/fenvs.2014.00016/full

3. What science and applications questions can you address with simultaneous CIMR products on land, ocean and cryosphere?

With near global daily data refresh rate, multi-channel microwave and good measurements precision, CIMR data will allow new cross-disciplinary science applications in the geosciences. In the workshop we identified two examples of cross-discipline applications that are enabled by CIMR measurements. In the first, observing the exchange of water in the soil-plant continuum can be made possible by the multi-channel CIMR measurements. Simultaneous surface soil moisture and vegetation information can be derived from the multi-channel and simultaneous CIMR measurements. The vegetation information from the different channels may also address important science questions about how and where water is stored in the above-ground plant structure. Also, the pulse-response of different components of the plant to intermittent soil moisture availability can be addressed. The daily global coverage by CIMR (95% in one day global coverage by one satellite and better than daily with two satellites) allow detection of short time-scale water uptake by plants.

In a second example, the link between the water cycle over land and over oceans is the subject of a cross-discipline science application. Over land, soil moisture is a state variable of the water cycle and its dynamics are strongly influenced by precipitation-minus-evaporation or P-E. Over the ocean, surface salinity is a state variable of the water cycle and its dynamics are strongly influenced by evaporation-minus-precipitation or E-P. Globally E-P (or P-E) must integrate to zero. Locally, discharge of fresh-water into the saline oceans causes density gradients that drive flow. Also, river and direct groundwater discharge into the oceans carry nutrients which can lead to algal blooms and oxygen reductions ('dead zones'). With daily CIMR data availability, the time-change of the two water cycle state variables (surface soil moisture and surface sea salinity) can be estimated robustly in order to constrain P-E (or E-P) fields globally. Seasonal and weather-related shifts in the fields and their integral over the globe will be possible for the first time. This would be an important milestone in the study of the water cycle.

4. What Most and Very Importance measurements (MI & VI) in the 2017 Decadal Survey will be done with CIMR measurements?

The Most Important (MI) science goal of the ESAS 2017 Global Hydrological Cycles and Water Resources Panel is a fundamental and yet still not wholly resolved question with important science implications and societal consequences. It asks *how is the water cycle changing*? The H-1 science goal builds on the premise that in a warming climate, we would expect an accelerated water cycle because the air water holding capacity is expected to scale with temperature (Clausius-Clapeyron relation). This could lead to more extreme precipitation and droughts or dry periods.

Listed below are four use-cases of surface soil moisture information with anticipated attributes of CIMR (long duration record and 1- to 2-days refresh rate global) to address the H-1 MI Science goal of the 2017 Earth Science and Application Decadal Survey.

Case # 1 (H-1 Science Goal)
Evapotranspiration and precipitation should scale as Clausius-Clapeyron as the world warms. But observations and models show that the rate of increase is less than what Clausius-Clapeyon dictates (see Figure 3). There are a number of constraints on both precipitation and evapotranspiration. One major constraint on evapotranspiration is soil moisture and water availability limitation in the soil. How much soil moisture limits evapotranspiration, how often regional evapotranspiration is in the water-limited regime, are frequency of days in this regime increasing or decreasing, where and under what conditions, etc. are all questions about the central role of the state variable of the water cycle over land – soil moisture – on how the water cycle responds in a warming climate.

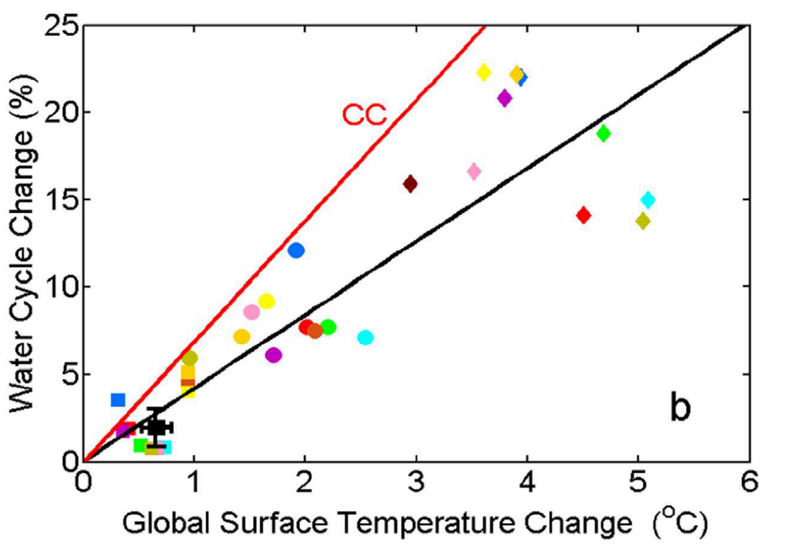

Figure 3: Change in water cycle as a percentage of historical mean versus change in global mean surface temperature. Black line has the slope 4.2%/°C and Clausius-Clapeyron is red line. Squares show historical, circles show Representative Concentration Pathways (RCP) 4.5, and diamonds show RCP8.5 simulations (Skliris, 2016).

Case # 2 (H-1 Science Goal)

Evapotranspiration flux at the land-atmosphere boundary is the flux that conveys all three main cycles of the Earth System. It is an exchange of water, energy and carbon at the interface. One of the major factors controlling the rate of evapotranspiration is available soil moisture (see Figure 4). Evapotranspiration transitions between energy- and water-limited regimes over land. The two regimes lead to different coupling with the atmosphere and they are associated with different feedback mechanisms (two-way coupling with atmosphere and convective potential). Transition between the two regimes and the percent of time in each regime depends on the soil moisture separating the two regimes. Establishing the value of this soil moisture threshold during different seasons and under different physiographic conditions needs to be established. The values of this threshold and shifts in the marginal probability distribution of soil moisture together determine how the water, carbon and energy cycles will shift in the future. This line of investigation to be enabled by CIMR's long-term and frequent refresh surface soil moisture product is necessary to address the ESAS MI Science Goal H-1.

Case # 3 (H-1 Science Goal)

In climate change and global warming, higher air temperature leads to increases in climatic precipitation (leading to more wetting of soil moisture) and increases in atmospheric evaporative demand (increased available energy leading to more drying of soil moisture). At the land surface the soil moisture state variable of the water cycle - the variable that determines how atmospheric forcings (precipitation and net radiation) are partitioned into individual flux components of the surface water and energy balance- is being pulled in opposite directions. How runoff shifts and how regional water availability changes, how evapotranspiration responds and affects food crops and ecosystem services depend on which direction the soil moisture marginal distribution at a region shifts to the right or left. CIMR soil moisture retrievals with 1- to 2-day refresh allow estimation of the marginal probability density function that is not possible with lower sample sizes. The wet regime has fast dynamics and without close to daily sampling we would get bias in the probability density function estimation and poorer statistical robustness.

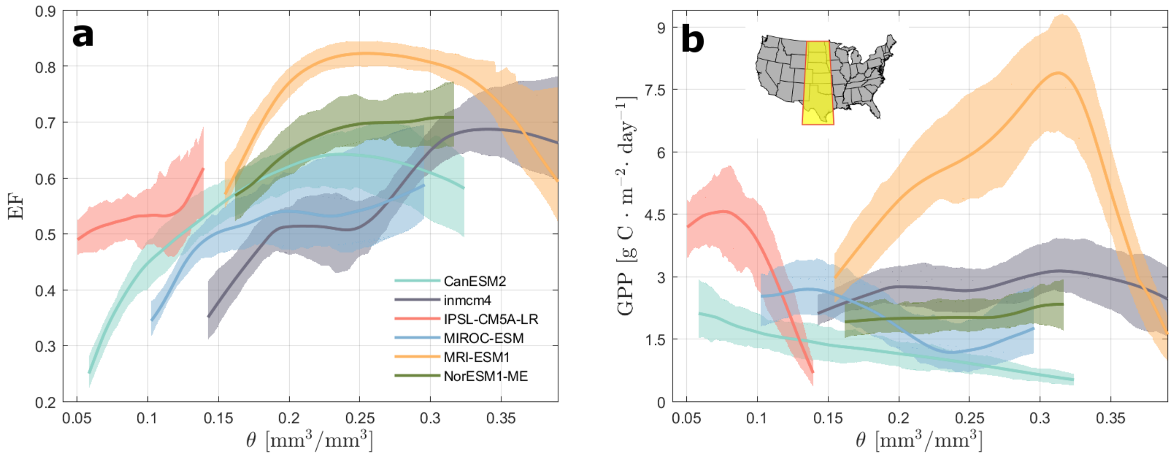

Figure 4: Evaporative Fraction (EF) is evapotranspiration and associated latent heat flux normalized by available energy. Gross Primary Productivity (GPP) is the rate of Carbon exchange between the surface and atmosphere during the process of photosynthesis and plant growth. These fluxes affect the rate of the energy and carbon cycles over land and link these cycles with the water cycle. How Earth System models represent these fluxes is indicative of how they capture these three important cycles and how robustly they can produce climate change projections. Both EF and GPP depend on soil moisture. But their functional dependence is widely varying among models (several CMIP models and the domain of evaluation are shown). To reduce the uncertainty of Earth System models, the EF-soil moisture and EF-GPP relationships need to be developed that serve as benchmarks for the models. Global and daily mapping of soil moisture is needed to firmly establish these figures for different physiographic conditions, biomes and seasons (see Gianotti et al., 2019).

H-2 Science Goal

Surface soil moisture information can also be used to make significant advances in addressing how changes in land use affect the water cycle (Science Goal H-2c). Global change can be defined as environmental change due to human activities that include atmospheric composition change (greenhouse gases) as well as land use/land cover change. Significant land use change is a global change that has happened already and at local rates often surpassing atmospheric composition change. A change in land use/land cover modifies the water cycle by affecting the partitioning of precipitation into runoff and infiltration and impacting soil moisture storage, which in turn influences later evapotranspiration (ET). In this context soil moisture is an integrator variable in land use global change. In addition, a change in land use/land cover at various spatial scales can also impact the rate of water recharge and carbon cycling in the system.

H-3 Science Goal

Addressing the 2017 Earth Science and Application Decadal Survey Science Goal H-3c requires simultaneous information of water storage in the soil and vegetation canopy. The CIMR capabilities in addressing these requirements represent a major advance in the fundamental understanding of how the structure, productivity and health of the terrestrial vegetation affects the water cycle. Vegetation opacity information can be considered as the counterpart to soil moisture storage, but in the form of water storage in vegetation biomass. Since opacity at microwave frequencies is directly related to the amount of water contained within the vegetation, vegetation opacity can also be seen as an indicator of plant water stress (e.g. Rao et al, 2019). Vegetation characteristics such as opacity also provide information about linkages between the water, carbon, and energy cycles owing to strong stomatal controls on canopy gas exchange, particularly during times of plant water stress. Lessons learned from SMAP & SMOS suggest that soil moisture and vegetation opacity (vegetation water) are linked in the plant-soil continuum and should be retrieved together simultaneously which CIMR will be able to accomplish. This should improve our knowledge of plant responses to water stress, components of which are still largely unknown even though such information is critical to food security issues and carbon balance in ecosystems. CIMR's daily revisit will also enable critical measurements to be made of the fast-changing elements of the soil-plant coupling in diurnal to inter-storm to post-storm time frames.

H-4 Science Goal

Soil moisture is a key variable in water-related natural disasters including floods and droughts. Accurate information concerning antecedent soil moisture conditions is a key source of hydrologic forecasting skill for regional-scale flooding events occurring over time scales of days to weeks. Soil moisture controls the proportion of rainfall that infiltrates, runs off, or evaporates from the land surface. Soil moisture also integrates precipitation and evaporation over periods of days to weeks and introduces a significant element of memory into the land–atmosphere system. Consequently, the availability of reliable information about surface saturation is widely regarded as an important component of accurately forecasting the onset and evolution of flooding events. A portion of this predictability is based on land–atmosphere coupling and on the potential for improving precipitation forecasts through the improved initialization of surface wetness in numerical weather forecasting and climate models. Remotely sensed surface soil moisture observations have been shown to improve both the timing and the magnitude of the flood forecast in a land surface hydrology model (Crow et al., 2017). These estimates can be used in early warning systems and to mitigate the flood damage. Increased frequency and severity of floods is commonly cited as one of the potential risks of climate and land-use change (IPCC report). Accurate soil moisture observations from passive microwave instruments are especially useful for intermediate to large watersheds where most flood damage occurs.

Agricultural drought is determined based on deficit in soil moisture. An agricultural drought is considered to have set in when the soil moisture availability to plants has dropped to such a level that it adversely affects the crop yield and hence agricultural productivity. The soil moisture dynamics given by the change in soil moisture between two time periods can provide information on the intensification or improvement of drought conditions. A major characteristic of droughts is the presence of extremely low soil moisture, either due to reduced precipitation and/or increased evapotranspiration. Soil moisture can thus provide a vital precursor signal about drought conditions and its severity (e.g., Jencso et al., 2017). Antecedent precipitation alone is insufficient as a leading indicator of drought, as not all meteorological droughts transition to agricultural drought. Long-term soil moisture data records are critical to understand the impact of changing climate on the duration and severity of droughts.

Path Forward

After priority measurements have been identified, both numerical modeling and field experiments will be performed. There is a need for improved forward modeling of multi-channel microwave data, which can be undertaken in collaboration with European colleagues already conducting synergistic activities in preparation for the CIMR mission. In particular, the role of radiative transfer frameworks and their ability to adequately model observed data has been subject to debate within the community, and an investigation in this regard is warranted to benefit both CIMR as well as other future satellite radiometer missions. In terms of field experiments, a CIMR airborne simulator is needed, as knowledge of how best to combine multi-frequency microwave data and the sensitivity of the different frequencies to soil and vegetation parameters is currently unknown. Existing satellite microwave datasets of different frequencies (e.g., AMSR2 and SMAP/SMOS) can also be combined to test resulting algorithms. There is a strong push from the community for a multi-channel forward simulation test-bed to assess the value of multi-channel microwave measurements and new retrieval algorithms, and be an organizing mechanism within both the US and European communities. It is expected that a test-bed will be able to assess whether multi-channel data can produce higher resolution passive microwave data than is currently possible, quantify the brightness temperature accuracy and define sampling requirements, and determine what additional ancillary information is needed to complement the multi-channel observations.

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3.4 Terrestrial Ecosystem Panel Report

Introduction

The global water, energy, and carbon cycles are important elements of the Earth's ecosystems. These three cycles are strongly coupled in space and time, and exert important controls on evaporation, transpiration and carbon exchange over most of the global land surface (see previous chapter from the Terrestrial Hydrology Panel). Not surprisingly, accurate and precise knowledge of soil moisture provides a strong constraint on establishing the rates of these cycles, how they covary and their subsequent impact on the evolution of weather and climate. Of greater importance is the full vertical profile of water transport and storage in the soil-plant continuum (Figure 1). While global observations of surface soil moisture have become available in recent years from low frequency (L-band) microwave satellite missions, including SMOS and SMAP (Entekhabi et al. 2010; Kerr et al. 2010), establishing the vertical water profile from root zone in soil to leaves in the canopy along different ecosystem and environmental gradients remains a high-priority for the hydrological, ecological and carbon cycle science communities.

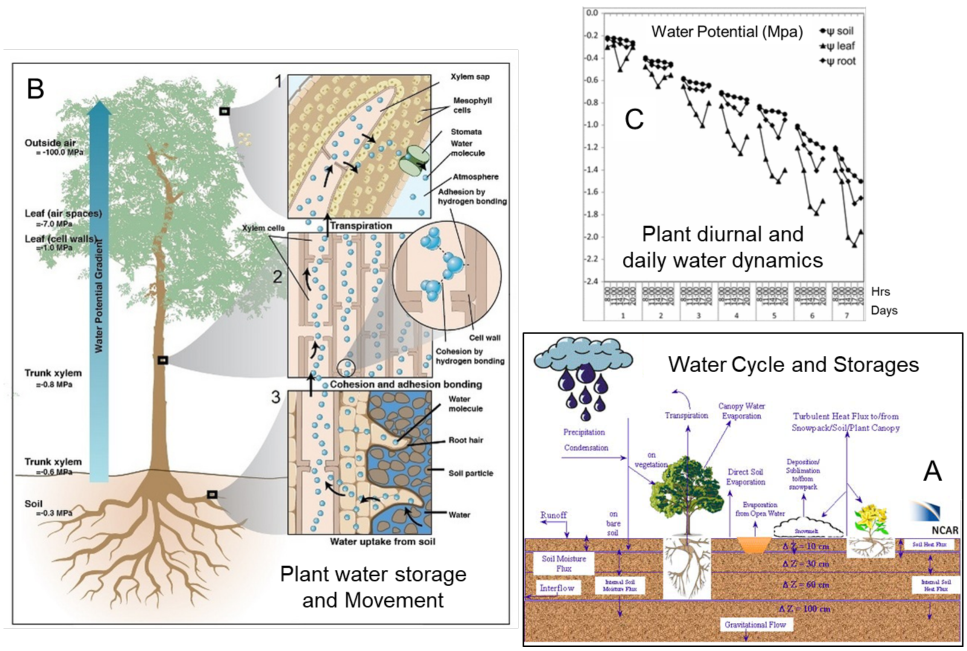


Figure 1. (A) Water cycle and storages across various land and ecosystem components, and the important role played by soil moisture; (B) Representation of the water transport pathway along the soil-plant-atmosphere continuum with further details in the inset about the movement of water through leaves (inset #1), xylem (inset #2) and out of the roots to the soil (inset #3). (C) Diurnal and daily water dynamics in plants during a drying cycle for three different components of the soil-plant-atmosphere continuum. As drying continues, typically leaves have the largest dynamic response followed by roots and soil. ***CIMR will provide new information to partition terrestrial water storages, enabling new understanding of the central role of plants in regulating the water, carbon and energy cycles****. Images courtesy of: (A) NCAR - https://ral.ucar.edu/projects/watercycles/components/task4.php; (B) McElrone et al, 2013, available at - https://www.nature.com/scitable/knowledge/library/water-uptake-and-transport-in-vascular-plants-103016037; (C) Grzesiak et al., 2016.*

A primary reason for developing a quantitative understanding of water stores in plant, litter, and soil compartments, as well as representing transport from the soil to the canopy, is to better understand the response of ecosystems to climate extremes and disturbance, especially events related to water-stress and droughts (Parmesan et al. 2006; Choat et al. 2012; Anderegg et al. 2015) . With increasing climate variability and higher probability of more persistent and more severe water stress, plant mortality may increase to a level that tips regional ecosystems from a robust sink to a source of carbon, leading to a significant positive climate feedback and exacerbating climate warming trends (Friedlingstein et al. 2015; Schimel et al. 2015). Knowing the behavior and potential response of ecosystems to water stress events requires concomitant observations at multiple microwave frequencies to retrieve water status in soil and in vegetation layers, with sub-daily to weekly sampling over ecosystems globally (see Figure 1 inset).

In addition, profound environmental changes are happening over northern permafrost landscapes, including boreal forest and tundra ecosystems encompassing more than 27 million km^2 and 20% of Earth's land area. The Arctic-Boreal Zone (ABZ) is being subjected to both gradual "press" disturbances (i.e., due to changes in temperature and precipitation) as well as abrupt "pulse" disturbances (i.e., due to insect outbreaks, fire, soil subsidence and erosion) (Schuur et al. 2018). However, our fundamental understanding of the magnitude and behavior of the evolution of carbon fluxes (both CO_2 and CH_4) remain rudimentary, with several issues (e.g., impacts on ecosystem carbon balance during different stages of permafrost thaw, interannual and seasonal variability, impacts of extended decomposition, potential changes in carbon-water cycle coupling under future climate) that are not well quantified or understood (Koven et al. 2011, Schuur et al. 2015, McGuire et al. 2018). Furthermore, if current warming trends continue, northern ecosystems may switch from being primarily energy-limited to being water-limited, thus heralding stronger coupling between the carbon and water cycles. To detect and better understand these changes, and represent them in Earth System models requires simultaneous and temporally high-frequency observations of freeze/thaw, permafrost and active layer thickness and soil moisture state – requirements that are only possible from a multi-channel microwave sensor that includes low-frequency (L-, P-band) capabilities. Currently, none of the missions that are active are designed or configured to deliver such detailed information about the Northern high-latitudes.

The CIMR mission will potentially provide enabling observations to improve process understanding, monitoring and model predictions of environmental change. From the Ecosystems perspective, CIMR offers three very attractive features: (a) high temporal frequency of observations, particularly in data sparse regions such as the Northern high latitudes, (b) the prospect of retrieving concomitant observations at multiple microwave frequencies, both higher frequencies useful for multi-component vegetation water content discrimination and extending to L-band for surface retrievals, and (c) long mission duration (10+) years. The following sections of this chapter provide a more detailed description on how CIMR can advance terrestrial ecosystem science and applications. A science algorithm and data testbed is also recommended for developing and testing the advanced microwave retrieval algorithms and modeling approaches needed to quantify and fully exploit the potential benefits of CIMR for the land and ecosystems communities.

1. How CIMR can ensure continuity of important ecological data records

In a changing climate, multi-decadal records of microwave satellite observations are critical for identifying long-term changes in ecosystems. For example, long-term monitoring of carbon stored in tropical rainforests with L-band microwave retrievals (Chapparo et al., 2019; Fan et al., 2019) is critical as the climate changes; carbon releases into the atmosphere triggered by forest disturbance would significantly amplify the effects of climate change. At high latitudes, polar amplification magnifies the effects of climate change, leading to a long-term increasing trend in the length of the non-frozen season (Kim et al., 2012), with potential implications for methane emissions from thawing permafrost, and consequent global warming feedbacks.

With both SMAP and SMOS in extended mission phase, there is a critical need for follow-on L-band observations. **CIMR is a viable option for extending the L-band record into the future over the next 15 years. These observations alone enable analysis of ecosystem variability from sub-daily to seasonal and interannual timescales.** In addition, CIMR provides a critical link to past satellite records at higher microwave frequencies. Historical observations at higher frequencies measure related but distinct ecosystem properties compared with L-band. It is difficult to evaluate long-term trends in ecosystem properties due to potentially confounding changes in observation frequencies over time. CIMR's collocated multi-frequency observations can be used to quantify how L-band observations covary with higher-frequency microwave observations. This information can be used to standardize new L-band observations with historical higher frequency observations, allowing for multi-decadal trend detection (e.g. Figure 2). CIMR is the essential link in exploiting the full potential of the historical record.

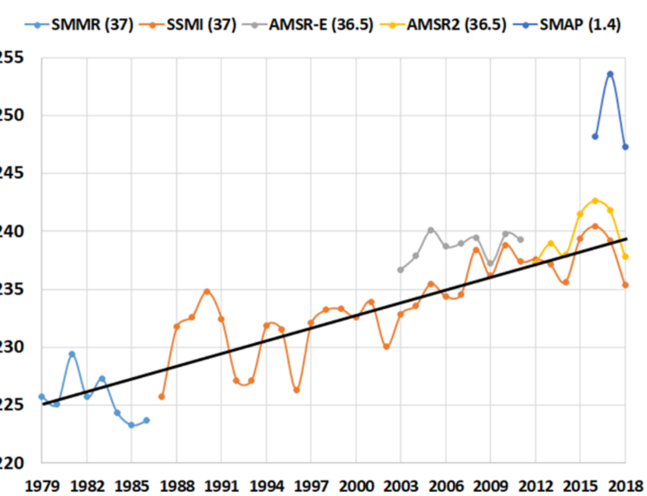


Figure 2: Global mean annual non-frozen season trend detected from satellite microwave radiometry from overlapping sensor records (Kim et al. 2017, 2019). The non-frozen season has increased by ~3.6 days per decade since 1979. L-band (1.4 GHz) observations from SMAP measure deeper in the soil profile compared with higher-frequency (~37 GHz) observations from SMMR, SSM/I, and AMSR. Collocated multi-frequency observations from CIMR will provide L-band continuity and allow future and historical multi-frequency observations to be compared, enhancing long-term trend detection. CIMR will also enable improved detection and delineation of lake ice and freeze-thaw dynamics in snow, soil and vegetation.

2. New, improved, or enhanced science products enabled from simultaneous multi-frequency microwave measurements

CIMR's multi-frequency observations are sensitive to variations in water content across multiple layers of the vegetation canopy, and in the surface soil. Since different plant components take up and lose water at different rates, they differ in water status at any given time (Bohrer et al., 2005). Although uncertainties remain in linking microwave vegetation observations (e.g. optical depth) to soil conditions and plant physiology (e.g. water potential), these uncertainties are largely driven by a historical lack of data (Konings et al., 2019). Because diurnal variations in plant water content can be as large as day-to-day variations, multi-frequency retrievals of plant water content from a shared footprint and overpass time are needed to capture the water gradient across different soil and canopy elements at the same stage in the diurnal curve. Spatially consistent, multi-temporal sampling of water status changes during a 24-hour cycle are also needed to capture the diurnal drawdown and recovery of soil and plant water storages. **CIMR's simultaneous, single-platform measurements would potentially for the first time enable mapping of plant water content variations along the entire soil-plant-atmosphere continuum.** The potential addition of lower frequency P-band channels into CIMR would enable the detection of root zone (0-1m depth) soil moisture, which is expected to have a more direct control on vegetation. The Multi-layer soil and plant water content retrievals from CIMR would enable major advances in understanding ecosystem responses to water stress, particularly if linked with synergistic canopy structural information from other satellites including Lidar or Radar (e.g. ICESat2, GEDI, NISAR, ROSE-L), and foliar chemistry and trait information from hyperspectral sensors (e.g. ESA CHIME or NASA SBG).

CIMR's orbit further enhances the potential for sub-daily observations, particularly at the higher latitudes (>45^o), for enhanced delineation of the diurnal cycle of plant water dynamics. Additionally, because of the relationship between plant water content and both phenology and biomass (Tian et al., 2018; Fig. 3a), CIMR-enabled multi-component plant water content retrievals, together with its frequent revisit, could enable new understanding of how ecosystems respond to and recover from environmental disturbances including drought.

CIMR's multi-frequency measurements, including lower frequency L-band, enable enhanced detection and monitoring of dynamic changes in surface water extent and wetlands. L-band is synergistic with the higher frequencies, providing enhanced sensitivity to surface water even under clouds and low to moderate vegetation cover, which are a significant improvement in this area over current capabilities available from optical-IR and higher frequency microwave satellites (Du et al., 2018; Fig 3b). CIMR's frequent revisit would enable such mapping at greater temporal resolution than SMOS or SMAP, potentially enhancing applications for monitoring surface flooding and rapid moisture responses to precipitation events. Synergistic information from planned L-band SAR missions (e.g. NISAR, ROSE-L) combined with the global coverage and near-daily fidelity of CIMR observations could enable further enhancements in delineating wetland inundation and vegetation structure, while the addition of satellite altimetry (e.g. SWOT) and gravimetry (GRACE-FO) information could enhance the partitioning and quantification of terrestrial water storages and their linkages.

Lastly, CIMR's multifrequency capabilities will improve the delineation of freeze-thaw conditions in soil and vegetation, which are key environmental constraints to water mobility and energy and carbon exchange in seasonally frozen environments. The potential addition of CIMR P-band capabilities, in addition to L-band, may improve estimation and monitoring of permafrost extent stability and active layer thickness. CIMR's multi-frequency observations could also be used to enable greater accuracy of these retrievals under snow cover and vegetation.

The greater incidence angle of CIMR compared to SMAP (55 vs 40 degrees) might improve vegetation sensitivity at the expense of surface sensitivity; thus, additional studies are needed to understand this tradeoff. Indeed, further (simulation) studies will be necessary to fully understand the potential of CIMR for many ecological science applications, as discussed in more detail in the Testbed section of this document

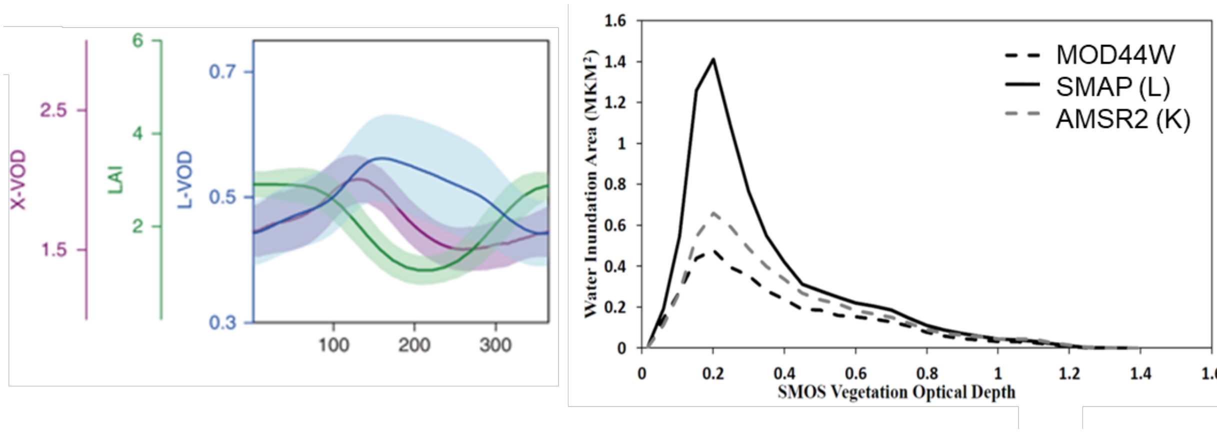


Figure 3. (Left) Dynamics of microwave vegetation optical depth (VOD) phenology at different frequencies (X-, L-band) relative to canopy leaf area (LAI) from optical remote sensing in Southeastern US forests (Tian et al., 2018); here, the different observations show unique phenology cycles in canopy greenness and biomass water content. (Right) Global satellite retrievals of surface water extent across different vegetation (VOD) density layers derived from L-band (SMAP) and X-band (AMSR) passive microwave frequencies; here, the lower frequency L-band retrievals indicate greater global water coverage attributed to more effective vegetation penetration and surface water sensitivity than from X-band or optical (MOD44W) remote sensing approaches (Du et al., 2018).

3. Science and applications questions enabled from simultaneous CIMR products on land, ocean and cryosphere

From the perspective of ecosystem dynamics, the CIMR mission offers four very attractive features. First, CIMR will provide **high temporal frequency** of observations, particularly at high latitudes (>45˚), enabling new observations of ecosystem dynamics and sub-daily behavior. In addition, the dawn and dusk overpass times of CIMR complement the after midnight and early afternoon overpass times of other microwave radiometers, potentially increasing the number of sub-daily observations at higher frequencies. Second, the **long duration** of the planned CIMR mission, nominally 15 years, enables better characterization of both interannual variation and secular trends, both of which are important to ecosystem dynamics that respond over a spectrum of time scales, especially following major disturbances. Third, through the concomitant observation at multiple frequencies—including L-band and possibly lower frequencies—the CIMR mission offers the prospect of determining both **soil and vegetation water storage changes**, which are key ecosystem attributes interconnecting carbon, water, and energy pathways and linking to processes in land, ocean, and cryosphere. Fourth, the CIMR mission offers the prospect of improving retrievals of **surface water inundation**, including high latitude surface water dynamics associated with changing permafrost and detection of seasonally flooded forests in the tropics. These CIMR attributes are expected enable or enhance a range of ecological applications (e.g. Figure 4).

Cross-cutting science and applications questions that CIMR data streams could advance include:

- How do variable and changing environmental conditions at high latitudes, e.g., **polar amplification**, **climate oscillation modes**, or **changing snow seasonalities**, affect water-carbon-energy dynamics and their consequences for ecological services and societal impacts (Hernández-Henríquez et al. 2015; Vavrus 2018; Smith et al. 2019)?
- How can monitoring **seasonal agricultural progress** in food and water insecure regions be advanced, particularly in cloud-obscured regions at risk, such as sub-Saharan Africa, using vegetation optical depth, soil moisture, precipitable water vapor, and sea surface salinity data streams (Sheffield et al. 2014; Enenkel et al. 2016; Li et al. 2016; Alemu and Henebry 2017; Crow 2019)?
- How can improved characterization of soil moisture profiles, surface inundation, and vegetation optical depth aid **human health risk assessments** (Chuang et al. 2012; Oliver et al. 2015)?
- How can **changes in permafrost affecting land surface integrity** be monitored effectively over the vast and remote polar regions, characterized by sparse ground monitoring stations, long periods of seasonal darkness and extensive cloud cover, to map areas of risk from infrastructure degradation (Liljedahl et al. 2016; Shiklomanov et al. 2017; Hjort et al. 2018)?
- Can ephemeral phenomena important to biomass production, such as **flash droughts** and **plant water recovery after storms**, be effectively monitored (Velpuri et al. 2016; Xu et al. 2018)?
- Can the **seasonality of Northern Hemisphere lake ice** as an essential climate variable and the timing of ice-off associated with methane releases detected by atmospheric methane sensors (e.g. ESA Tropomi and Merlin, NASA GEOCARB) be effectively captured and monitored? (Karlsson et al. 2013; Du et al. 2017; Sharma et al. 2019).

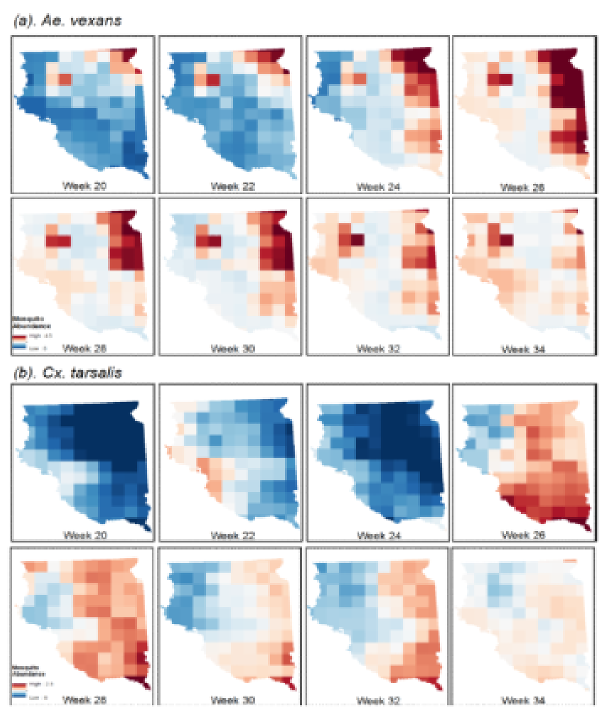


Figure 4 Time series of maps showing the predicted habitat suitability for Aedes vexans*, a flood-water mosquito, and* Culex tarsalis*, a vector of West Nile Virus, in eastern South Dakota during 2010 based on AMSR-E land parameters and ancillary data from Chuang et al. 2012. The L-band of CIMR will improve characterization of soil moisture and surface inundation dynamics and the collocated observations at higher frequencies will also enable better discrimination of vegetation and temperature effects on ephemeral habitats of these and other human disease vector species.*

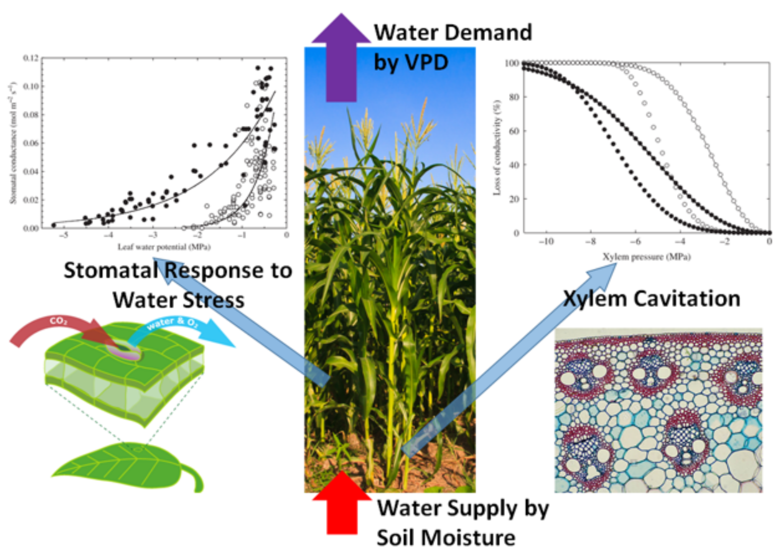
4. Highest and High Importance measurements in the 2017 Decadal Survey that can be addressed with CIMR measurements

A potential revolutionary advance of CIMR lies in the improved capabilities to partition water storage components, quantify water-carbon-energy linkages, and soil-vegetation-atmosphere coupling. CIMR is expected to significantly contribute to the following ecosystem science and applications questions ranked as most important (MI) from the recent Decadal Survey (DS 2017): **E-1** Ecosystem Structure, Function, Biodiversity; **E-2** Fluxes Between Ecosystem, Atmosphere, Oceans, and Solid Earth; **E-3** Fluxes Within Ecosystems. The following CIMR derived measurements are closely aligned with these high importance measurement objectives for Ecosystems.

(MI) E-1b/c. *Quantify 3D structure and physiology of vegetation.*

CIMR's multi-frequency capability provides for improved estimation of vegetation biomass and water storage in different canopy levels or components (e.g. leaf, branch, stem), which are expected to have different storage magnitudes and temporal characteristics. This enhanced information will enable new understanding of plant-water relations. Further understanding derived from layer-specific plant water content information may be achieved with the addition of other synergistic observations of vegetation structure and foliar chemistry from satellite Lidar (e.g. GEDI) and hyperspectral (e.g. SBG) retrievals. CIMR's high temporal resolution (up to multiple visits per day) enables the **tracking of dynamic plant water storage variations and use strategies**, including diurnal and day-to-day changes, which allow for advancing the understanding of plant water use strategies and ecosystem responses to water stress (Figure 5).

Figure 5: Depiction of different plant water use strategies: anisohydric (closed circles) vs isohydric behavior (open circles) (McDowell et al., 2008; Konings et al., 2016). CIMR will improve temporal sampling and understanding of these critical strategies affecting global water, carbon, energy cycles and linkages.



(MI) E-2a. *Quantify fluxes of CO2 and CH4 globally at 100-500 km scales monthly between land ecosystems and atmosphere.*

CIMR's ability for surface water and soil moisture estimation enables better quantification of the carbon budget at global and especially high-latitude regions**.** This is particularly relevant for improving understanding and quantification of methane (CH4) release in high-latitude regions and wetlands. For example, CIMR's improved capacity to monitor freeze-thaw state and permafrost extent could significantly advance carbon budget modeling in the Arctic Boreal Region (ABR). The L-band observations from CIMR offer enhanced sensitivity to surface water and soil moisture influencing CH_4 emissions from uplands and wetlands (Watts et al., 2014). The potential addition of lower frequency (P+L-band) observations will enable improved characterizations of surface and root zone soil moisture (more directly accessible to vegetation), as well as moisture controls to soil litter decomposition and heterotrophic respiration processes throughout the soil column which influences greenhouse gas exchange. These CIMR observations and potential applications have strong synergies with planned satellite missions focusing on atmospheric carbon (e.g. OCO3, TROPOMI).

(MI) E-3a. *Quantify flows of energy, carbon, water, nutrients sustaining life cycle of terrestrial and marine ecosystems, and partitioning into functional types.*

CIMR is potentially a game changer in regards to monitoring water storage variations throughout the soil-vegetation continuum. Vegetation is a primary conduit and control on water, carbon and energy exchange between the land and atmosphere due to strong canopy stomatal regulation on gas exchange required for photosynthesis. Improved estimation of water storages and flow throughout the soil-plant continuum will improve understanding of the water, carbon and energy cycles, and their linkages through an improved ability to characterize plant water uptake and vegetation stress factors affecting photosynthesis and respiration, evapotranspiration, and latent and sensible energy partitioning. CIMR thus has synergy with other satellite missions related to the water cycle (e.g. ECOSTRESS, GRACE-FO), which may provide new understanding of terrestrial water storage dynamics and partitioning.

Ecosystems Justification and Requirements for an OSSE testbed

<u>The need for a testbed</u>:

A land and ecosystem OSSE (Observation System Simulation Experiment) or testbed is recommended for implementing and assessing the design and outcomes of a multifrequency satellite observing system. The OSSE would be designed to understand the physics of observations at multiple frequencies (in isolation and in combination), sensitivities of each observation to system parameters such as frequency and incidence angle, as well as sensitivities to ecosystem variables defining vegetation and soils. The OSSE would also serve to clarify the effects of spatial scales and heterogeneities, as well as that of temporal variability on potential retrievals. The OSSE could also be used to develop and test new geophysical retrieval algorithms for ecosystem and land variables that are needed for process modeling. The OSSE would potentially (and in the longer term) implement process models in a closed loop with microwave observing system simulations, somewhat similar to data assimilation approaches.

<u>Properties of a proposed OSSE testbed</u>:

The proposed OSSE will include first-principles-based emission (passive, radiometer) and scattering (active, radar) models that enable more accurate predictions of the observed data at multiple target frequencies (P, L, C, X, Ku, potentially Ka) compared to current models in use. Greater levels of sophistication and realism can be added in successive stages to better capture landscape details and their interactions with microwaves at various frequencies through the use of full-wave Maxwell's equations where appropriate and feasible. We envision that, depending on the frequency of interest, a combination of full-wave Maxwell-based and approximate models will be used for an optimum balance of accuracy and computational efficiency. As such, we will avoid many of the inaccuracies introduced by using overly simplified models (such as some based on the radiative transfer equations), and ensure consistent treatment and a uniform set of assumptions across the frequency bands. The microwave models could also include provisions for reflectometry (both L-band GNSS-R and P-band MUOS-R), since these observations are proving to be highly valuable with respect to both spatial scaling and temporal gap-filling.

OSSE Approach:

Initial OSSE development would involve defining the building blocks of diverse landscapes through the use of discrete canonical scatterers representing vegetation and soils. As the passive microwave observations are at multi-km (if not multi-tens of kilometers) scale, we will build such coarse resolution representations and observation predictions from the fine-resolution landscape units (plot level). This approach would enable a built-in capability to investigate landscape heterogeneity. It would also allow for computational aggregation of the fundamental building blocks of vegetation and soils into science-driven quantities (e.g., VOD, VWC, biomass), and mapping of frequency-dependent properties such as VOD to more specific quantities pertaining to vegetation structure and moisture content. The OSSE should include a comprehensive treatment of the soil moisture and structure profile, using full-wave soil scattering models of layered rough surfaces, for root-zone soil moisture (RZSM). Realistic inputs should also be used to simulate temporal dynamics, such as atmospheric forcing and seasons.

OSSE Implementation and Validation:

The proposed OSSE is an ambitious undertaking that needs the involvement of a large community of remote sensing and process modelers. The OSSE should have a modular construction, with increasing sophistication over time to incorporate accurate microwave models at multiple frequencies, relevant vegetation and soil modules at each frequency, and ultimately, process models that can ingest products retrieved from remote-sensing (e.g. Figure 6). To properly test and validate the OSSE, a comprehensive set of in-situ and remote-sensing-analog (i.e, airborne campaigns) data should be used. Available meaurements from ground-based networks (e.g., NEON, COSMOS, SoilSCAPE, and new deployments) should be utilized along with airborne instruments that can provide the multi-frequency observations. Collaborations with other technology development efforts to develop such multi-frequency airborne observing systems should be encouraged. All of these efforts are not only relevant to CIMR, but are also excellent opportunities for synergies with other missions such as NISAR, BIOMASS, and Sentinel-1.

OSSE Use-Case Examples:

The OSSE can be used to investigate numerous scenarios. For example, it can address the following questions:

- Can L-, C-, and X-band data combine to produce reliable high resolution (10-20 km) passive microwave information for surface soil moisture retrieval? What are the vegetation effects and impacts?
- What is the accuracy and sampling requirements for microwave brightness temperature at each of the above frequencies for a given retrieval algorithm and accuracy requirements? What are the impacts of different spatial correlation features and heterogeneity?

- How do simultaneous multi-channel microwave measurements allow estimation of emission/scattering parameters with less reliance on ancillary data?

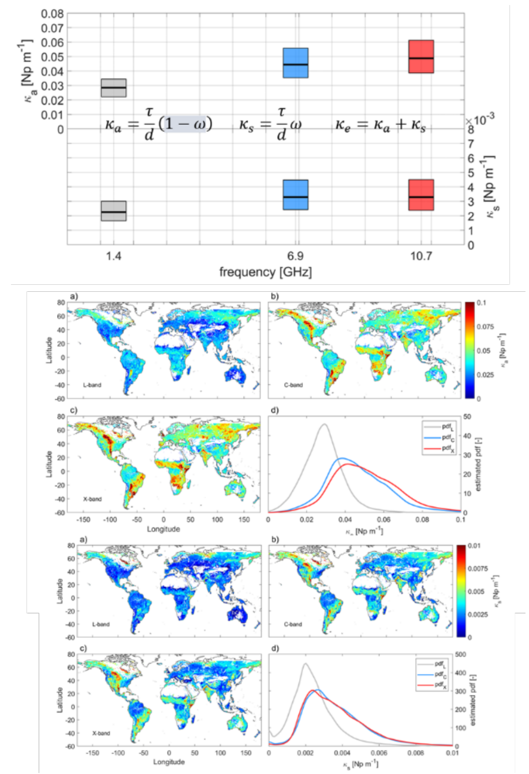


Figure 6. All panels taken from Baur et al., 2018. Analysis from SMAP and AMSR-2, showing frequency-dependent estimates of global vegetation absorption (k_a) and scattering (k_s) coefficients. Together, these quantities form the extinction coefficient (k_e). The proposed OSSE will be able to predict these, or similar, vegetation properties globally at different frequencies, different spatial scales, seasonally, etc.

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