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Workshop Report:

Science of 10-km Resolution L-band Radiometry

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1 Executive Summary

The Science of 10-km Resolution L-band Radiometry Workshop focused on the need for higher spatial resolution spaceborne L-band (1.4 GHz) radiometry in various science disciplines. The message from the workshop was that crossing the 10-km resolution threshold (set for the workshop based on past studies and for pragmatic reasons and purposes) would unlock new science in several disciplines. Key points included the importance of a short revisit interval (daily or sub-daily) and the benefit of combining L-band brightness temperature with higher-frequency radiometer measurements (6-37 GHz) and other satellite data.

Spaceborne L-band radiometry from the ESA SMOS (Soil Moisture Ocean Salinity), NASA/SAC-D Aquarius, and NASA SMAP (Soil Moisture Active Passive) missions launched in 2009, 2011, and 2015, respectively, has furthered our understanding of hydrology, oceanography, cryosphere, ecology, and atmospheric processes. The spatial resolution of these missions ranges from about 40 km to about 100 km. In the future, the ESA CIMR (Copernicus Imaging Microwave Radiometer) mission (launching in 2029) will continue L-band radiometer measurements at about 60 km spatial resolution. While the current L-band radiometer record is invaluable for studying the Earth system, its spatial resolution is insufficient for addressing many critical science questions, improving next-generation global Earth system models, and maximizing the synergistic surface observations at L-band (1.4 GHz) and higher-frequencies (6-37 GHz).

During the workshop, these areas were explored, and the science achievable with next-generation L-band radiometry was evaluated through presentations and discussions. The research question was: "What could be achieved if 10-km resolution L-band brightness temperature records were available with a daily revisit (on the equator) and coincidentally with the higher-frequency brightness temperatures?" The presentations and discussions also included how these observational parameters may need to be revised for what is required or, conversely, may surpass the needs. The following areas emphasized that spatial resolution of 10 km or finer would cross the threshold for achieving new science:

- Oceanography: To uncover land-sea exchanges, ocean-ice interactions, and sea-air interface processes, the spatial scale of the sea surface salinity (SSS) measurement and its ability to get close to the ocean boundary (coastline or sea ice) is vital. A 10-km resolution would allow for capturing these processes.
- Oceanography: In regions with high freshwater variability, such as the coastal, tropical, and Arctic oceans, salinity affects surface density more than temperature, creating density fronts across a broad spectrum of spatial scales. At 10 km and smaller scales, in situ data indicate temperature increasingly compensates salinity's influence, erasing lateral density gradients – a process associated with submesoscale restratification involving frontal slumping, surface-layer instabilities, and subsequent vertical mixing. Determining if this mechanism universally applies or is confined to fronts with compensated temperature and salinity remains a question. A 10-km resolution for salinity observations would advance understanding of these effects, extending beyond major tropical rivers to many smaller river plumes.
- Oceanography: Climate models will not resolve the submesoscales in the near future, so the effects of motions at these scales will need parameterization. However, parameterizations for upper ocean re-stratification by submesoscale, surface-layer eddies require guidance and rigorous evaluation from observational datasets that surpass the 10-km resolution threshold.

- Cryosphere: Understanding sea ice production and growth rates, ice edge processes, and air-ice-sea interactions requires determining the typically thin sea ice thickness. Current capabilities are insufficient, but a 10-km scale would enable effective observation of many of these processes.
- Cryosphere: For accounting for the changing of the refreeze and runoff partitioning across the Greenland ice sheet to understand its mass balance change and contribution to the sea level rise, liquid water content (LWC) is needed at a spatial resolution of at least 10 km twice a day. The 40-km resolution does not adequately capture the requirements for definite modeling of ice sheet processes.
- Atmosphere: To resolve land-atmosphere feedbacks and their impact on the planetary boundary layer, essential for understanding the timing and location of convective storms and tornadoes, the spatial scale of soil moisture (SM) measurement is crucial. The current 40-km scale misses dry-wet boundaries and wet spots that drive these processes, while a 10-km resolution would enable their better monitoring and potentially improve their prediction.
- Hydrology: High-resolution, high-accuracy SM has numerous hydrological uses. The 40-km scale smooths over natural SM variability, but the larger scales of precipitation and atmospheric forcing set a lower limit on SM variability in many regions. Globally, a 10-km scale aligns better with most of these natural forcings. Flash flood prediction, for example, would benefit from identifying areas where soil saturation exceeds critical levels.
- Ecology: Land surface and ecological models continuously push spatial resolution limits, using a mix of resolution scales that does not have to match the model output scale exactly, depending on the parameter. However, lagging too far behind reduces utility and eventually prohibits the effective use of such observables in the models. A 10-km resolution SM and vegetation optical depth (VOD) would better support future models moving toward higher resolution scales.
- Ecology: To track water storage and movement along the soil-plant-atmosphere continuum at ecosystem or ecoregion level, synergistic observations from higher-frequency microwave channels could enhance detection of water movement across soil-vegetation gradients and between woody and leafy biomass. These observables would enable major scientific advances in understanding how vegetation sustains photosynthesis and growth by regulating internal water storage and land-atmosphere exchanges of water, energy, and carbon. Potential applications include drought and wildfire risk assessment and crop management improvements.

The benefit of enhancing the spatial resolution was unequivocally pointed out in many areas, but whether crossing the 10-km resolution threshold alone would enable significant new scientific advances was not fully established. Potential science returns vs resolution were also discussed:

- Cryosphere: The terrestrial cryosphere is primarily defined by the annual freeze-thaw (FT) cycles. L-band radiometry supports observing soil and vegetation FT, but the current 40-km resolution struggles to capture the heterogeneous FT in boreal and sub-arctic landscapes. Higher spatial resolution is needed to more effectively resolve critical FT controls on permafrost stability, vegetation productivity, and water and carbon fluxes.
- Ecology: L-band radiometry-based vegetation optical depth (L-VOD) is valuable for investigating vegetation biomass and water content, including forests. However, current capabilities limit analysis mostly to regional scales. Forest conditions vary globally, and the required resolution thresholds for studying different forest types and processes are still undefined. L-band

radiometry offers unique, complementary information to optical and radar vegetation data, but further research is needed to determine the optimal design for combined observations.

- Agriculture: For agricultural applications, including irrigation, SMAP and SMOS SM and VOD are invaluable at regional to continental scales, with finer resolutions enabling progressively more applications. The open question is how much return each resolution level offers and when it justifies the investment. A 10-km resolution alone is insufficient, so downscaling with higher-resolution data is necessary. Studies show that starting downscaling at 10 km improves the quality of a 1-km downscaled dataset by 50-100 % compared to starting at 40 km
- Wildfire, drought, flood, and other disturbances: L-band radiometer observables like SM, surface inundation, and VOD, are valuable for monitoring disturbances such as drought severity, flood risk, and vegetation recovery, benefiting from the L-band's all-weather capability, vegetation penetration, and sensitivity to standing water and moisture in near-surface soil, snow, and vegetation. New applications could include tracking live fuel moisture, underrepresented in fire models. The utility of these data increases with finer spatial resolution and potentially with up to four daily samples to capture diurnal changes. However, optimal design and cost-benefit tradeoffs for enhanced L-band applications remain undefined.
- Oceanic processes and air-sea interaction: Research on oceanic mesoscale dynamics has highlighted its role in transporting heat, momentum, and tracers via eddies, while studies on sub-1 km scales have explored the effects on mixing and energy dissipation. However, submesoscale processes, bridging meso- and smaller scales, are less understood and have only recently become a focus of research. Characterized by O(1) Rossby number dynamics, these processes challenge traditional quasi-geostrophic theory and are crucial for integrating larger and smaller scale ocean dynamics, uncovering intricate mechanisms just beginning to be understood. L-band observations at 10-km resolution would significantly enhance our capability to observe, model, and forecast these essential processes.

The revisit time for measurements was emphasized across all science cases, with daily or sub-daily observations of geophysical parameters identified as a threshold for achieving new science. The workshop focused on the relevance and potential of next-generation L-band radiometer measurements, especially in light of the upcoming NASA Earth Science Decadal Survey, which will set post-2027 science priorities. The workshop highlighted the cross-disciplinary science potential of 10-km L-band radiometry, emphasizing the need to explore ways to make this capability a reality.

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3 Workshop Scope and Objectives

As the name indicates, the workshop was not about any specific mission but about the science achievable with L-band radiometry were it available at a significantly enhanced (10-km) spatial resolution; this was the workshop's primary objective. The talks covered central disciplinary science and applications in hydrology, oceanography, cryosphere, ecology, and the atmosphere. Because of the high diversity of L-band radiometry applications, each discipline had only a limited amount of time to discuss the benefits of higher resolution observations and other associated needs regarding revisit time, other radiometry measurements, and other data needs. The workshop featured breakout sessions to facilitate additional discipline-specific discussions on priorities and requirements.

The Earth Science community is preparing for the upcoming NASA Earth Science Decadal Survey, expected in the 2027 timeframe, and the workshop was intended to raise awareness of the importance, number, and diversity of science cases enabled through higher resolution L-band radiometry. The workshop was ultimately more about identifying gaps and potential opportunities that could help shape future NASA priorities rather than trying to serve the current ones (established in the last Decadal Survey in 2017).

A specific goal of the workshop was to start developing science traceability matrices (STM) for the different science cases. STM provide a step-by-step outline of the justification of any given observations based on the science needs that the observations serve. The STM developed are shared with the community as part of this summary report, authored by the workshop participants.

3.1 Background

The potential of L-band (~1.4 GHz) radiometer measurements was recognized already in the 1970s with airborne experiments deploying L-band radiometers to measure soil moisture (SM; e.g., Schmugge et al., 1974) and sea surface salinity (SSS; e.g., Blume et al., 1978; Droppelman et al., 1970; Swift, 1974). The L-band radiometer onboard the Skylab was used to acquire the first SM and SSS retrievals from space (Eagleman and Lin, 1976; Jackson et al., 2014; Lerner and Hollinger, 1977), but the problem of deploying a large enough antenna in space to achieve an adequate spatial resolution with the low frequency kept the science community from accessing regularly measured L-band brightness temperatures (TB) from space for decades. Eventually, a new age of satellite L-band radiometry began in 2009 with the launch of the ESA Soil Moisture Ocean Salinity (SMOS) mission (Kerr et al., 2010); in 2011, NASA launched the Aquarius mission (Le Vine et al., 2010; Lagerloef et al., 2008), and in 2015, NASA launched the Soil Moisture Active Passive (SMAP) mission (Entekhabi et al., 2014).

These missions demonstrated an impressive list of science and technology objectives associated with global TB (e.g., Oliva et al., 2013; Peng et al., 2019), SM (e.g., Kerr et al., 2012; 2016; Chan et al., 2016; 2018; Rodriquez-Fernandez et al., 2019; Colliander et al., 2022a; 2023a), SSS (e.g., Font et al., 2012; Tang et al., 2017; Kao et al., 2018; Vinogradova et al., 2019; Reul et al., 2020), freeze/thaw (e.g., Rautiainen et al., 2016; Derksen et al., 2017), and vegetation optical depth (VOD) (e.g., Rodriquez-Fernandez et al., 2018; Wigneron et al., 2021; Chaubell et al., 2022) retrievals; interferometric synthetic aperture radiometry (e.g., Martin-Neira et al., 2016); high-precision radiometry (e.g., Sen et al., 2014); and a large, deployable, spinning reflector (e.g., Piepmeier et al., 2017). Furthermore, radio frequency interference (RFI) sources in the protected 1.4 GHz band were detected, strategies were developed to eliminate them on the ground, and techniques and technologies were implemented to mitigate their impact (Misra and Ruf, 2008; Le Vine et al., 2014; Oliva et al., 2016). But beyond all this, the missions demonstrated a long list of other things, such as the value of SSS retrieval with less-than-optimal noise performance but higher resolution (Aquarius SSS vs SMAP SSS); hurricane winds (e.g., Reul et al., 2012; Yueh et al., 2016); thin sea ice thickness (SIT) retrieval (e.g., Kaleschke et al., 2010); ice sheet parameter retrieval (e.g., Macelloni et al., 2019; Houtz et al., 2019; 2021; Leduc-Leballeur et al., 2020; Mousavi et al., 2021); a range of applications using operational TB, SM, SSS, and VOD data, and many others. L-band radiometry has simply been an absolute success, offering unique capabilities to the suite of Earth observation tools. However, advancing to the next step is extra challenging due to the need for an even larger aperture to enhance spatial resolution, requiring an extra solid scientific foundation for building the next-generation capabilities.

3.2 Why 10 km?

The workshop was scoped to discuss the benefits of 10-km L-band radiometry. The current available resolution is about 40 km with SMAP (Piepmeier et al., 2017) and SMOS (McMullan et al., 2008), and the future has a guaranteed approximately 60 km resolution from ESA's Copernicus Imaging Microwave Radiometer (CIMR) mission (Donlon, 2020). At the same time, several studies have indicated that there are science cases and applications that require much finer resolution (Farahani et al., 2022). However, as the workshop focused on the foreseeable next-generation observations, we must acknowledge certain limitations in available observational approaches. The aperture size required for a 10-km resolution would be about 24 m when matching SMAP's 40° incidence angle and orbit altitude of 685 km and about 40 m when matching CIMR's 55° incidence angle and orbit altitude of 820 km. The incidence angle and orbit altitude determine the swath width and, consequently, the revisit time of the measurements. Considering structures currently in space, these seem feasible, albeit very large, with a non-rotating imaging technique. This could be implemented with a thinned-array synthetic aperture (such as SMOS). However, going substantially past the 40-m size with the technology available for a next-generation instrument does not seem likely. While a 10-km improvement compared to 40 km may not sound that impressive, it corresponds to a 16-fold increase in spatial information content, and it makes a critical difference in observing many physical processes, as concluded from the workshop. There are past studies indicating that a 10-km resolution would exceed a threshold enabling significant new science and applications compared to 40 km (e.g., the user consultation study by Escorihuela and Kerr, 2018; Kerr et al., 2019a; 2019b - the workshop included a presentation on this study).

Some physical parameters retrieved with L-band radiometry can be spatially enhanced by combining them with other higher-resolution measurements, resulting in a higher-resolution retrieval. A prime example is the original SMAP approach, combining the coarse-resolution radiometer data with the high-resolution radar data for SM measurements. The approach takes advantage of the land surface response of both measurements with respect to SM. Other examples include fusing L-band with nested higher frequency retrievals with smaller native footprint sizes. As L-band radiometry provides the essential information content for SM retrieval, the spatial downscaling techniques (Peng et al., 2017) cannot match the accuracy of SM retrieved with equivalent native resolution L-band radiometry. However, the downscaling techniques naturally benefit from a baseline finer resolution L-band TB observation. To manage the workshop's scope and include all science disciplines, the focus was on what can be achieved with 10-km L-band radiometer measurements and not on downscaling techniques, although it is acknowledged that they are related to the broader topic.

3.3 Revisit Time and Other Observational Parameters

The science return of any Earth observation instrument depends on multiple factors. While the workshop's primary focus was on spatial resolution – due to the challenge it poses for low-frequency radiometry – other important observation parameters may decide whether the potential higher resolution measurement is useful. One of the most prominent ones is the revisit time, meaning when and how often any given location is observed. The required revisit time depends on the physical process under observation (Kim and Crow, 2024). The premise of the workshop was that the 10-km L-band brightness temperature would be available from an observation system that would allow daily revisit time on the equator (for typical Earth observation orbits for these kinds of missions, the revisit time depends on the latitude; the revisit time is shorter for higher latitudes). A daily revisit time has been raised in several studies as critical for observing the relevant processes (Escorihuela and Kerr, 2018; Kerr et al., 2019a; 2019b). There are science cases where a shorter revisit time is required, or longer revisits can be tolerated. During the workshop, these requirements were discussed on a case-by-case basis. Generally, the importance of at least a daily revisit was highlighted for most science cases discussed during the workshop.

3.4 Synergistic Observations

In microwave radiometry, the complementary measurements in the 1.4-37 GHz frequency range have been only partially exploited and in variable degrees across science disciplines. In the future, CIMR will guarantee spatially and temporally collocated measurements in the 1.4-37 GHz frequency range and JAXA Advanced Microwave Scanning Radiometer 3 (AMSR3) for the 7-37 GHz frequency ranges. The two missions combined will also provide a range of local overpass times as CIMR will be on a 6 AM/PM orbit (the same as that of SMAP and SMOS), and AMSR3 will be on a 1:30 AM/PM orbit. CIMR will provide the 7 GHz and 37 GHz brightness temperatures at about 15 km and 4 km spatial resolutions, respectively; AMSR3 will provide them at about 60 km and 12 km resolutions, respectively. One of the workshop premises was that the CIMR-type of higher frequency observations would be available with the 10-km L-band observation at the same time, as this will represent state of the art in the future of 7-37 GHz measurements and enable many potential synergistic uses to the point that they help to justify a higher resolution L-band measurement, as discussed during the workshop. Many science observations also require or benefit from multiple other measurements, including radar, passive optical, thermal, and lidar. These were also brought up during the presentations and discussions.

4 Oceanography (Sea Surface Salinity)

Ocean salinity is a vital variable within the Earth's water cycle and a key driver of ocean dynamics (Siedler et al., 2001; Durack, 2015). Sea surface salinity (SSS) and subsurface salinity have been identified as Essential Climate Variables by the Global Climate Observing System (GCOS) and Essential Ocean Variables by the Global Ocean Observing System (GOOS) (Belward et al., 2016). Through the advent of new observing technologies for surface salinity and the efforts to merge salinity measurements with other observations and numerical models, salinity science and applications have significantly advanced over recent years, especially since the launch of SMOS, Aquarius, and SMAP (Vinogradova et al., 2019; Reul et al., 2020). The spatial resolution of these missions' SSS retrievals ranged from about 40 km to about 150 km. The ESA CIMR (Copernicus Imaging Microwave Radiometer) mission, to be launched in the 2028 timeframe, will ensure the continuity of SSS observations at about 60 km resolution. While the current generation of the L-band radiometer record provides an invaluable tool for exploring the Earth system, many critical science questions would benefit from higher-resolution observations of SSS.

4.1 Open Ocean Processes

4.1.1 Science Motivation and Goals

Understanding how oceanic elements of the energy, water, and carbon cycles will evolve in a changing climate and improving related climate model projections is crucial.

4.1.2 Benefit of 10-km Resolution over 40-km Resolution

SSS spatial variability at scales smaller than the footprint of any current SSS satellites (at best ~40 km), called sub-footprint variability (SFV), is very difficult to measure due to the expense and logistical difficulty of deploying instrumentation at that scale in the ocean. However, it is an essential component of the error budget of these satellites. SFV has been estimated using many techniques: thermosalinograph measurements from volunteer observing ships, intensively sampled field campaigns, mooring data (equating time variability with spatial), and high-resolution ocean models (Drushka et al., 2019a; Bingham, 2019; D'Addezio et al., 2019; Bingham and Li, 2020; Bingham and Brodnitz, 2021; Bingham et al., 2021; Thouvenin-Masson et al., 2022). Preliminary calculation of SSS spatial scales supports the obvious conclusion that the observing system limits the observed scales. In other words, a significant portion of the SSS spatial variance spectrum critical for understanding mesoscale and submesoscale processes cannot be observed using today's technology (D'Addezio et al., 2019). The study of SFV has shown that it varies with location and season, generally being largest in the fall in both hemispheres (Bingham et al., 2021). This seasonality is opposite to that of other ocean variables, suggesting that small-scale variability is driven by processes other than mesoscale and submesoscale stirring, which tends to be largest in winter and early spring (Rocha et al., 2016). The most obvious source of variability in SSS is rainfall, which tends to be large in the fall season (Bingham et al., 2021) and usually has a small spatial scale, even in very rainy regions (Chkrebtii and Bingham, 2023). However, a direct connection between rainfall and SFV has not yet been established. Because of the short scales and stochastic nature of rainfall, along with the large spatial scales and steady nature of evaporation, rainfall is a likely source of the spatial variance in small-scale SSS signals because it creates low-density fresh puddles underneath intense rain events (Drushka et al., 2016, 2019b). The impact of this spatial variance on upper ocean dynamics has not yet been studied and could make a fruitful area of research enhanced by high-resolution satellite measurements. Measurements of SSS at a 10 km scale could help tie the surface salinity to the global water cycle by better understanding the exchange of moisture/freshwater.

Variability in sea surface salinity (SSS) at scales of O(10km) is also commonly associated with internal oceanic processes, including eddies, fronts, filaments, and meandering currents (Bingham, 2019). These processes are believed to play a crucial role in connecting the dynamics of the mesoscale flow field, typically spanning 10 to 100 kilometers, to much finer-scale processes, typically ranging from 0.1 to 1 kilometer (Su et al., 2018). They impact dissipation and mixing in the surface layer and have far-reaching implications for a wide array of biological and biogeochemical processes within marine ecosystems, influencing the diverse species that inhabit them (Levy et al., 2012, 2013; Omand et al., 2015).

O(10km) processes exhibit horizontal dimensions smaller than the first baroclinic Rossby deformation radius within latitudes ranging from 60°S to 60°N. As a result, conventional geostrophic and quasi-geostrophic theories, predominantly governing larger and mesoscale ocean circulation, are not applicable. Unlike the smaller-scale phenomena (0.1–100 m), known for their fully three-dimensional and nonhydrostatic nature and their roles in mixing and energy dissipation (Marshall et al. 1997), the understanding of O(10km) processes lags behind. Their significance and dynamics have only begun to be recognized and studied recently (Boccaletti et al. 2007; Thomas et al. 2008; McWilliams 2017). Understanding salinity variations at the O(10km) scale requires bridging mesoscale processes with smaller scales. This linkage is being progressively uncovered through limited yet crucial measurements from modern autonomous in situ platforms (Timmermans and Winsor 2012; Swart et al. 2020) and intensive experiments such as S-MODE (Submesoscale Ocean Dynamics Experiment; Farrar et al., 2020), highlighting the emerging understanding of O(10km) scale processes.

Recent studies utilized satellite and surface forcing data at 25 km resolution, along with saildrone measurements at 300 m resolution, to explore how small-scale salinity and temperature fronts influence surface density and respond to wind and buoyancy forces (Vazquez-Cuervo et al., 2020). These studies reveal density compensation between SST and SSS across scales from submesoscale to basin-wide, achieving full compensation at scales of 10 km or smaller (Ruddick and Ferrari 1999). This compensation neutralizes the individual impacts on density, erasing lateral density gradients and is often associated with submesoscale restratification through mechanisms like frontal slumping and surface-layer instabilities leading to vertical mixing (Ferrari and Ruddick 2000; Hosegood et al. 2006). The universality of this restratification across different frontal conditions remains an open question, as the level of the temperature-salinity compensation can differ based on location, season, and the mixed-layer depth. Given that climate models are unlikely to resolve submesoscale dynamics in the near term, the incorporation of these processes through parameterization becomes essential (Fox-Kemper et al. 2008). Additionally, the recent findings highlight the significant role of heat and freshwater exchanges at the air-sea interface, especially through Ekman convergence near western boundary currents, in the formation of fronts. Saildrone data also show that high winds and increased turbulent heat loss conditions tend to reduce strong density gradients, pointing to the critical influence of surface forcing in modulating salinity/temperature gradients. However, the specific nature and mechanisms of air-sea interaction at scales of O(10km) remain to be fully understood. The intricate submesoscale processes in driving essential ecological and environmental interactions in the ocean have also been discussed (Jaeger and Mahadevan 2018). L-band observations at a 10-km resolution would offer unparalleled insights into submesoscale dynamics, significantly enhancing our capability to observe, model, and forecast these essential processes.

4.1.3 Revisit Time and Other Considerations

Revisit times for current satellite SSS missions are around 3 days over the equatorial ocean, with exact repeats over 7-9 days. Practically, the publication of high level SSS products with 7-9 day cadence from current missions is motivated by sensitivity requirements. For open ocean applications, at 10 km spatial resolution, this frequency is expected to be adequate to characterize the mesoscale surface salinity field. However, it would not be adequate to observe the submesoscale field, which evolves more quickly. This could lead to aliasing of the small-scale, rapid processes into large scale processes. More analysis needs to be done to better understand and define the need for shorter revisit times than what's currently available.

In designing a satellite mission there is always a tradeoff between revisit time and space resolution. Compared to the current missions, an improvement in spatial resolution is expected to be more valuable than improvement in time resolution for studying open ocean processes.

4.2 Coastal Processes

4.2.1 Science Motivation and Goals

There are certain societal needs to understand how coastal watersheds and their ecosystems will evolve in a changing climate and to improve climate model projections for these coastal changes.

4.2.2 Benefit of 10-km Resolution over 40-km Resolution

The move to 10 km spatial resolution for coastal sea surface salinity (SSS) observations would greatly enhance remote sensing science and application capabilities, allowing improved understanding of how coastal waters are influenced by terrestrial freshwater, nutrient, and carbon fluxes as well as by exchange with the adjoining shelf seas and open ocean. Given the ongoing and expected future increases in hydrological cycling (Held and Solden, 2006), coastal communities are already anticipating significant changes in freshwater inflow and sea level with their related impacts on the ecosystem, economy, and coastal hazards. Salinity is an extremely useful passive tracer for these processes in coastal waters at spatial scales of 5-10 km and there have been numerous remote sensing studies using surface salinity proxies such as ocean color and surface temperature to illustrate this point (Decastillo and Miller, 2008; Fournier et al., 2015; Song et al., 2013; Sun et al., 2018). Moreover, because of larger temporal and spatial salinity changes that occur across the coastal zone, the L-band SSS measurement precision requirements can often be relaxed to levels near 0.5 psu even in cold water regions (Grodsky et al., 2018). Data-assimilating coastal ocean circulation models are also calling for higher resolution (2-10 km) SSS observations that can match their increasing resolution and that would provide a much-needed complement to the cloud- and air-sea flux impacted satellite sea surface temperature (SST) data. Adding 10 km SSS data would lead to locally improved ocean current and state predictions and improved global diagnosis of remote water mass advection associated with equatorward freshwater fluxes due to expected changes in pan-Arctic sea ice. In concert with ocean color, SST, and other key NASA coastal datasets, the data would fundamentally alter our ability to monitor land-ocean exchanges of carbon, nutrients, and freshwater from key rivers within the earth system (Fournier and Lee, 2021). Given the close relationship between salinity and ocean carbonate system change in coastal oceans, 10 km resolution SSS data could also help to better identify regions impacted by ocean acidification change due to upwelling or riverine water masses (Salisbury et al., 2015; Schulz et al., 2019). A critical facet of the 'all-weather' multi-frequency microwave radiometer measurements from L- to C- to X-band (cf. Montero et al., 2023) would be the ability to measure coastal SSS and SST in many commonly cloud-covered coastal zone regions. Finally, many coastal applications would benefit, including harmful algal bloom prediction, coastal hazards including tropical cyclone forecasts, ecosystem modeling, local eutrophication, flooding impacts, and fisheries management.

4.2.3 Revisit Time and Other Considerations

The smaller processes that could be observed using salinity observations at the coast occur at time scales larger than inertial (e.g., tides, coastally trapped waves, etc.). A 1-day repeat for SSS satellite observations would satisfy the majority of coastal ocean needs. Weekly observations (similar to the open ocean) would still allow to study most of the coastal ocean processes even if some processes associated with river discharge and upwelling events could benefit from higher revisit time (3 days and shorter).

4.3 Polar Processes

4.3.1 Science Motivation and Goals

There is a need to understand and predict high latitude ocean changes in response to a warming climate and to improve related climate model projections. Brightness temperature measurements have proven to be useful in polar studies, see Chapter 5. In addition, the limited SMAP radar observations demonstrated their utility in polar ice studies. Recent studies (e.g., Long and Miller, 2023; Miller et al., 2023, Long et al., 2023) have demonstrated that when multiple passes are combined, reconstruction techniques can provide enhanced-resolution brightness temperature and backscatter maps with a tradeoff of temporal and spatial resolution. With an effective resolution of ~30 km, the utility of the enhanced resolution SMAP products reinforce the need for finer resolution observations.

4.3.2 Benefit of 10-km Resolution over 40-km Resolution

In the past decades, the high-latitude oceans have undergone dramatic changes that have global implications (Maslanik et al., 2011; Kwok et al., 2009; McPhee et al., 2009). It is, therefore, important to better understand high latitude processes and their forcing mechanisms. Salinity is a key variable in the Arctic Ocean as it controls the stratification and seawater density and might influence sea ice melting and formation (Aagaard et al., 1981; Carmack et al., 2015). Satellite observations of SSS are crucial, especially in the Arctic Ocean, as in situ measurements are particularly sparse there. Even if the sensitivity of L-band brightness temperature to salinity is strongly decreased in cold waters (Swift and McIntosh, 1983; Yueh et al., 2001), satellites can still capture the prominent SSS gradient signals observed in the Arctic Ocean (Fournier et al., 2019). Current SSS observations from SMOS, SMAP, and Aquarius have a large footprint (40-100 km), rendering the retrieval of SSS that close to sea ice edge challenging. Sea ice patches contaminate the brightness temperature signal, making retrieval difficult or impossible. Also, current satellites do not capture the submesoscale salinity gradients observed due to their large footprint. Higher resolution observations would allow retrieving SSS closer to sea ice to minimize the errors due to sea ice contamination within the footprint and to better capture submesoscale signals (fronts and eddies). However, no matter the resolution, SSS retrievals in cold waters at high latitudes are challenging due to the reduced sensitivity of salinity to brightness temperature. Simultaneous C, X, and K-band measurements are therefore necessary to improve the SSS retrieval by better estimating winds (roughness), SST, and sea ice concentration (Kilic et al., 2018).

4.3.3 Revisit Time and Other Considerations

Because of the dynamic nature of the abovementioned processes, a daily to sub-daily revisit time is critical. However, the likeliest orbit configuration for a mission considered here has a polar orbiting satellite, providing an enhanced number of observations for polar areas, likely meeting the requirements.

4.4 SSS Retrieval Considerations

There are several challenges to retrieving SSS from L-band brightness temperature measurements. (1) As mentioned above, there is a drop in sensitivity in cold water at L-band (Swift and McIntosh, 1983), equating to a much lower dynamic range and increasing noise contribution (the sensitivity increases at lower frequency). (2) The measurements can be contaminated by land and sea ice. (3) There are several physical contributors to the L-band brightness temperature signal other than SSS, including ambiguity in temperature, ocean wind roughening, and reflected galactic emission. To retrieve SSS from the current platforms (SMAP and SMOS), it is necessary to use ancillary data, including retrospective analyses and non-collocated observations. The deviations of ancillary parameters from truth introduce errors in the SSS retrieval (Le Vine et al., 2005; Meissner et al., 2014; Le Vine et al., 2007). Additionally, radio frequency interference (RFI) degrades the capacity for SSS measurements in the vicinity of coastal cities. In spite of all these difficulties, SSS can be successfully recovered from satellite observations for most of the ocean at 40 km spatial resolution with 0.1-0.3 psu sensitivity and 7-9 day cadences.

From a sensitivity perspective, improvement in spatial resolution comes at the cost of poorer sensitivity per pixel, assuming a fixed dwell time over a resolved scene. Improvements in spatial resolution at the same sensitivity/revisit cadence, therefore, require improvements in receiver sensitivity. This can be accomplished by careful engineering towards the theoretical noise limits or perhaps incorporating active cooling of critical receiver components. Since radiometer sensitivity improves with the root of observing bandwidth, one option is to employ a wideband radiometer system spanning the microwave P- and L-bands (Johnson et al., 2021). This would have the added benefit of observing at wavelengths where sensitivity to SSS is inherently improved (Le Vine and Dinnat, 2022). However, the impact of RFI on wideband measurements is considerably greater than within the protected 1.400-1427 GHz frequency band. This could be mitigated somewhat by employing highly channelized spectrometer systems and dynamic RFI excision algorithms. If the impact of RFI can be managed, wideband L-band radiometry has the potential to significantly improve SSS retrievals. For missions adhering to conventional aperture designs, the associated improvements in sensitivity would enable 0.1-0.3 psu sensitivity in polar oceans over 7-9 day periods and similar sensitivity over lower-latitude oceans with single looks (Akins et al. 2023). For high-resolution observations, wideband systems could afford the necessary sensitivity/revisit balance with otherwise equivalent receiver noise characteristics.

Another way to overcome the reliance on ancillary data is to concurrently measure SST, SSS, sea-ice concentration, and wind speed. Wind speed is highly variable compared to SSS; therefore, matchups of non-collocated measurements (e.g., using AMSR) likely offer marginal benefit over using forecast/reanalysis ancillary products. Ku- and Ka-band radiometer and scatterometer systems could retrieve wind speed and direction, as well as SST and sea ice concentration, with sufficient accuracy for accurate SSS retrieval. The ESA CIMR mission will be the first platform to collect collocated L-Ka radiometry measurements, demonstrating the impact of reduced ancillary product dependence. By measuring SST, SSS, sea-ice concentration, and wind speed concurrently, CIMR should allow more accurate SSS measurements than current platforms, not only at lower latitudes but also in the polar ocean (Jiménez et al., 2021; Kilic et al., 2018). Wideband L-band systems could also leverage the spectral dependences of SSS and SST/wind signatures to compensate for ancillary biases (Akins et al., 2023), albeit their sensitivity is less than that of higher frequency systems.

5 Cryosphere

5.1 Sea Ice (Sea Ice Thickness)

5.1.1 Science Motivation

The heat exchange between the ocean and the atmosphere in polar regions is mainly controlled by sea ice distribution. Thinner ice, measuring less than half a meter in thickness, plays a dominant role in this heat exchange process, and it has the potential to influence weather and climate. For instance, in Antarctica, polynyas, areas of open water surrounded by sea ice, and thin sea ice, play a crucial role in sea ice production and deep water formation, making them particularly significant for global overturning circulation.

5.1.2 Benefit of 10-km Resolution over 40-km Resolution

The brightness temperature data from SMOS has a footprint size of approximately 35–40 km in diameter. While this resolution is relatively coarse, it already allows for detecting larger polynyas. However, polynyas are often smaller or similar to the size of the SMOS footprint. For more precise observation of coastal polynyas and other mesoscale ocean-ice phenomena, a higher spatial resolution with frequent temporal coverage is required, ideally with measurements taken at least twice daily.

5.1.3 Revisit Time and Other Considerations

Observations once per day are typically sufficient for general monitoring and understanding long-term changes in sea ice thickness. This frequency allows for tracking the sea ice growth, seasonal patterns, and interannual variability of sea ice thickness, aiding in the study of long-term trends and the impact of climate change. However, more frequent observations are necessary for detailed process studies that focus on the dynamics of, e.g., polynya formation, evolution, and disappearance, including the effects of atmospheric and oceanic processes such as winds and tides. Ideally, observations every few hours would provide valuable insights into diurnal variations and short-term changes, offering a more comprehensive understanding of such processes.

5.1.4 Sea Ice Thickness Retrieval Considerations

The uniqueness of the L-band radiometry is that it can resolve the sea ice thickness up to about 1 m in depth based on the increase of TB from the open ocean value when sea ice covers the ocean (Kaleschke et al., 2010). When the ice thickness is more than about 1 m, the TB saturates (the higher frequencies saturate at significantly lower ice depth, which does not allow resolving the thickness). The retrieval is based on relating the TB value to a thickness value under certain assumptions of the sea ice composition. Non-uniformity of the sea ice thickness, sea-ice composition, and sea ice edges all introduce errors to the retrieval. A smaller footprint has an inherent benefit compared to a larger footprint in mitigating these errors. The retrieval can exploit L-band TB measurements at vertical and horizontal polarizations, ranging over 150 K (depending on the polarization). The large TB range makes the retrieval relatively insensitive to the measurement noise, beneficial in reaching for higher spatial resolution because that tends to come with higher measurement noise, all other factors being equal.

5.2 Ice Sheet Melt (Liquid Water Content)

A substantial fraction of the meltwater generated at the surface of the snow/firn layer on ice sheets does not escape. Instead, it is retained after infiltrating into the cold pore space of the underlying snow/firn. The infiltrated meltwater alters the physical density and thermal structure of the firn layer, thereby impacting subsequent infiltration processes. As a result, delineating locations where meltwater either runs off or is retained can be problematic, particularly as the firn layer evolves under changing climate conditions. Satellite retrieval of liquid water content based on L-band radiometry potentially provides much-needed observational constraints on these processes. Widespread and frequent satellite observations of liquid water content have the potential to serve as validation for regional climate model assessments of meltwater generation. Furthermore, observational information may be used to constrain the transformation of the physical structure of firn and its ability to absorb future meltwater. These constraints are particularly important to the processes in Greenland's percolation zone and the ice shelves of Antarctica. The spatial gradients of these processes in both locations are such that a 10 km resolution of liquid water retrievals would improve future satellite microwave radiometer investigations.

5.2.1 Science Motivation and Goals

Successful adaptation and mitigation of rising sea level demands improved constraints on emerging ice sheet processes controlling the magnitude and rate of sea level change in a warming climate. Therefore, it is essential to enhance the confidence in quantitative assessments of present-day ice sheet mass balance arising from meltwater generation and refine the explicit treatment of meltwater refreezing in firn densification models to evaluate the time evolution of runoff/retention and surface elevation change. This calls for an observationally based assessment of the daily to seasonal and 10-km scale distribution of meltwater generation across ice sheets' snow/firn-covered regions. Observations are needed to independently evaluate regional climate model-based meltwater products and to provide an observationally based assessment of in situ liquid water content in snow/firn at a 10-km scale and time scales ranging from hours to days. Observations are also needed to drive models of firn evolution for assessments of surface ice elevation change and subsequent meltwater retention.

Furthermore, meltwater storage and stability analyses need mapping of the location and time evolution of firn aquifers on ice sheets and ice shelves, requiring observations at a 10-km scale at seasonal time scales. Information on the location and time changes of firn aquifers is necessary for improvements in assessments of ice sheet hydrology, mass balance, and the stability of some ice shelves (Miller et al., 2020; 2022a; 2022b; 2023).

5.2.2 Benefit of 10-km Resolution over 40-km Resolution

The melt/refreeze processes in Greenland change across several km scales (forced by atmospheric conditions and altitude changes); the current resolution does not have the fidelity to capture them, while a 10-km resolution would allow their meaningful representation. The firn aquifer sizes vary widely. In general, the 10-km resolution would not be adequate for their exact geographic delineation, but the improved resolution would have two notable benefits. First, obviously, locating firn aquifers with a 10-km resolution is more accurate than with a 40-km resolution. Secondly, the sensitivity of the detection and classification is substantially improved as the presumably sub-footprint aquifer will have a larger relative impact on the measured signal.

5.2.3 Revisit Time and Other Considerations

Total liquid water content in the snow and firn needs to be measured twice a day to identify the diurnal melt/refreeze cycle and at least four times a day to characterize the amplitude and duration of the cycle. The depth distribution of the liquid water content is needed at least daily.

The spatial extent of fully saturated firn is needed at weekly to annual time scales, depending on the context of the aquifer.

5.2.4 Liquid Water Content Retrieval Considerations

Several recent studies have established the capability of L-band radiometry to retrieve liquid water content of ice sheets (Houtz et al., 2019; 2021; Leduc-Leballeur et al., 2020; Mousavi et al., 2021; 2022), while the higher frequencies have been used for ice sheet surface melt detection for decades (e.g., Zwally and Fiegels, 1994; Mote and Anderson, 1995; Abdalati and Steffen, 1995; Das and Alley, 2003; Liu et al., 2005; Fettweis et al., 2006; Tedesco, 2007; 2009; Colosio et al., 2020; Husman et al., 2023). Multi-frequency passive microwave measurements in the 1.4 GHz to 37 GHz range can distinguish seasonal meltwater between the immediate surface and the deeper firn layers (Colliander et al., 2022b). Studies show that the frequency-dependent response is consistent across the ice sheets (Colliander al et., 2023b). The multi-frequency melt indications match with lasting seasonal subsurface meltwater, with delayed refreezing compared to the surface. However, the L-band measurement is the only frequency band that can effectively discriminate between different levels of meltwater, while the higher frequencies lose sensitivity and saturate with more modest meltwater levels (e.g., Colliander et al., 2022b).

5.3 Ice Sheet Temperature (Temperature Profile)

A strong consensus exists among current studies that mass loss from glaciers and ice sheets will continue to raise global mean sea level in upcoming decades-to-centuries under modeled future climate scenarios. Nevertheless, a large degree of uncertainty surrounds potential contributions from ice sheets, with very large and rapid contributions plausible. The uncertainty stems from a lack of comprehensive understanding of ice flow dynamics, partly related to ice sheet interactions with the ocean and partly related to internal and basal ice flow processes. A key component of the latter part is the internal ice sheet temperature that influences the ice rheology and, thus ice deformation rate. Further, the internal ice temperature field can characterize the basal thermal state, thus identifying locations where melted bed conditions can lead to high rates and accelerations of sliding motion. Up to now, in situ measurements of the temperature profile are available from only a few boreholes. Ice sheet flow models that fully couple thermodynamic and mechanical processes thus suffer from a lack of observational constraints. Since the internal ice temperature is a fundamental state variable in models of ice flow dynamics, field observations would transform model assessment and model performance.

5.3.1 Science Motivation and Goals

Successful adaptation and mitigation of rising sea level demands improved constraints on emerging ice sheet processes controlling the magnitude and rate of sea level change in a warming climate; therefore, it is important to incorporate widespread observations of the internal ice temperature into thermo-mechanical modeling of ice flow dynamics. This would be satisfied with an observationally-based assessment of the internal ice temperature field, including depth variability of ice 1-3 km thick at a 10-km resolution. Observed ice temperature information is needed to improve constraints in ice flow models on ice flow by deformation and basal conditions.

5.3.2 Benefit of 10-km Resolution over 40-km Resolution

A higher spatial resolution at L-band (i.e., on the order of 10 km) will allow for a better representation of the effects of the underlying topography or variability across ice shelves, increasing the accuracy in temperature retrieval.

5.3.3 Revisit Time and Other Considerations

The temperature profile of ice sheets is a slow-changing process that needs to be mapped once in decadal scales to answer the science questions above.

5.3.4 Temperature Profile Retrieval Considerations

Recently, Macelloni et al. (2019) performed the first retrieval of the ice sheet temperature in Antarctica by using the L-band observations from the European Space Agency (ESA)'s Soil Moisture and Ocean Salinity (SMOS) and a glaciological model. This is made possible due to the large penetration in the dry snow and ice at the L-band of several hundreds of meters. The retrieval algorithm has been recently improved by using a new minimization method based on Bayesian inference from SMOS observations and microwave emission model simulations and a more advanced glaciological model to represent the temperature profiles (GRISLI, Quiquet et al., 2018). The method was first validated in the available boreholes having different temperature profile types and then temperature maps of whole Antarctica (excluding coastal regions) at different depths were produced. The measurement accuracy typically remains below 2 K for depths up to 2000 m and increases as a function of depth (e.g. ~5 K at 3200 m at Dome C). The methodology was tested in Antarctica and then will be applied to Greenland. The continuity of L-band measurements is fundamental to monitoring possible variability, especially in coastal regions and on ice shelves where the method will be tested in the future.

5.4 Land Surface (Freeze/Thaw and Temperature)

Frozen conditions significantly affect over half of global lands and their eco-hydrology (Kim et al., 2017). However, the annual frozen season is shrinking due to global warming and fundamentally altering ecosystems adapted to colder climates (Kim et al. 2012, Zhu et al. 2019, Li et al. 2021). The rate of frozen season decline is greatest in the high northern latitudes (HNL) where the climate is warming at more than four times the mean global rate (Rantanen et al., 2022). Eco-hydrological impacts from HNL warming and shorter frozen seasons include extensive permafrost thawing, which may reinforce global warming by reducing the northern carbon sink for atmospheric carbon dioxide (CO_2) and methane (CH_4) released from fossil fuel burning (Schuur et al. 2022). Satellite microwave remote sensing is strongly sensitive to landscape freeze-thaw (FT) transitions, while the low to moderate frequencies available from many polar orbiting microwave sensors have the potential for near-daily FT monitoring under day/night and nearly all-weather conditions. However, the current generation of satellite sensors is unable to fully capture FT complexity due to sub-optimal spectral, spatial, or temporal coverage (Podest et al. 2014, Du et al. 2014, Johnston et al. 2021).

5.4.1 Science Motivation and Goals

The feedback between cold regions and the climate system in a warming world must be solved. To accomplish this, we need to understand the CO_2 and CH_4 annual budgets in heterogeneous boreal and Arctic environments with changes in land surface energy/water budgets and boundary layer conditions related to an extended thaw period. The relative stability and rate of thawing and deepening of the active layer overlying permafrost is closely tied to FT timing and the non-frozen season duration (Park et al., 2016). With the enhanced rate of polar warming, the frozen season is rapidly shrinking and promoting widespread permafrost thawing and active layer deepening. The longer and deeper soil thaw season increasingly exposes the vast global reservoir of soil organic carbon (SOC) sequestered over millennia in permafrost soils to enhanced decomposition and greenhouse gas emissions (primarily CO_2 and CH_4), which could reinforce global warming (Schuur et al. 2022). The frozen season effectively bounds the potential growing season and the availability of soil moisture, strongly affecting evapotranspiration, vegetation productivity, soil litter decomposition and respiration, and net ecosystem carbon sequestration (see section 8). Moreover, the unique thermal insulation capacity of snow can effectively decouple soils from the surface and lower atmosphere and enable the persistence of thawed soil conditions (i.e., the zero-curtain) that can sustain microbial SOC decomposition and respiration processes well into the effective winter frozen season (Natali et al, 2019; Mavrovic et al, 2023). The resulting heterogeneity in FT timing and progression along vegetation and soil gradients can lead to asynchronous behavior in photosynthetic carbon uptake and soil decomposition and respiration carbon release, which can alter net carbon sink activity and the seasonal cycle of atmospheric CO_2 (Parazoo et al. 2018, Liu et al. 2019).

There is an urgent need to clarify the nature and complexity of FT cycles and their influence on soil moisture and other ecosystem processes to improve our capacity to fully quantify CO_2 and CH_4 budgets and understand the role of the HNL in the climate system. Global FT environmental data records (EDRs) have been constructed from similar higher frequency (~37 GHz) satellite microwave radiometers, including SMMR, SSM/I, and AMSR-E/2 (Kim et al. 2017). These records span many decades, providing a relatively precise record of FT climate trends. However, the ~12-25 km spatial resolution of these observations is too coarse to resolve the characteristic finer scale FT heterogeneity affecting HNL ecosystem processes (Podest et al. 2014), while the higher frequency retrievals also lack sensitivity to soil conditions. The SMAP mission provides a global operational FT record, with L-band radiometer enhanced FT sensitivity to near-surface soils and 1-3 day repeat sampling, but with a coarse (~40-km) sensor footprint (Derksen et al. 2017). Other available L-band radiometers offer similar capacity and limitations for FT mapping. Moreover, the prevailing coarse footprint and single frequency FT records generally provide a bulk binary classification of the predominant frozen or thawed condition within a grid cell that fails to resolve sub-grid level FT complexity among vegetation, snow, and soil features, or non-linear variations in residual liquid water content and permittivity that occur during FT transitions. The above technical constraints and knowledge gaps could be significantly mitigated by a next-generation L-band radiometer, with additional value gained by the combined use of higher frequency TB, radar, and other complementary observations.

5.4.2 Benefit of 10-km Resolution over 40-km Resolution

HNL environments are highly heterogeneous landscapes composed of forest/tundra, wetlands, and lakes. Lakes and wetlands have strong contrasting microwave emission signatures making it difficult to perform accurate retrievals within 40 km pixels, where the disentanglement of the different contributing features is difficult and brings high uncertainties. A 10-km brightness temperature product will increase the number of pixels where the lake and wetland fractions are low enough to perform reliable retrievals, including in coastal regions. Whereas the current 40-km capability is sufficient to distinguish FT gradients across major biomes, the finer 10-km sampling would provide 16-fold improved information content to distinguish FT differences among individual ecoregions and landforms. Combined observations from L-band and higher frequency TB or active microwave (SAR) retrievals offer the potential for even finer scale FT delineations closer to the level of local landscape variability by exploiting the complimentary FT sensitivity and finer spatial feature information from the higher frequency channels.

5.4.3 Revisit Time and Other Considerations

The FT retrieval would highly benefit from a constant revisit time twice a day with pre-dawn and mid-day passes to capture diurnal patterns in heating and cooling. The daily revisit and diurnal sampling are also needed to capture both the timing of seasonal FT transitions bounding potential growing seasons and transient thaw/refreeze and frost events affecting vegetation growth, surface soil, and snow conditions.

5.4.4 Freeze/Thaw, Vegetation Change, and Temperature Retrieval Considerations

In the last few years, L-band microwave studies have led to the understanding that FT processes, from an ecological point of view, are not strictly binary. For example, in the shoulder season, latent heat release related to freezing or thawing of water in the soil can maintain the presence of unfrozen soil water near 0°C for up to several weeks or more, leading to a gradual FT signal seen by L-Band (Prince et al. 2019). Also, vegetation spring recovery from winter dormancy is not a binary process as well, where trees will generally start a rehydration phase before starting photosynthesis. Temporal lags in FT cycles can also occur between above-ground vegetation and underlying soil conditions due to the insulating capacity of organic soil and snow layers (Roy et al. 2017; Yi et al. 2019; Roy et al. 2020). Hence, the combination of the L-band with other complimentary microwave frequencies and sensors (e.g., SAR, optical, etc.) could help to resolve spatial and vertical FT gradients over the soil-snow-vegetation continuum (Bateni et al. 2013, Podest et al. 2014, Donahue et al. 2023). Spatially nested sampling from the combined observations temporally collocated within narrow early morning and mid-day sampling windows is needed to minimize cross-sensor noise effects stemming from footprint mismatch and diurnal drift in daily heating and cooling.

As dry snow has low impact on L-band signature (Lemmetyinen et al. 2016), there is potential for retrieving other soil characteristics under the snow in winter. Studies using AMSR low frequency have shown the potential of microwave to retrieve soil temperature under snow in Arctic environments (Marchand et al. 2018; Kohn and Royer 2010). Considering that frozen soil permittivity does not change during Arctic cold winter, the main contributor to soil brightness temperature at L-Band should be soil temperature, allowing retrieval of this important variable for winter soil carbon emission.

6 Hydrology (Soil Moisture)

6.1 Science Motivation and Goals

6.1.1 Irrigation

Humans influence their microclimate and regional climate through interventions such as irrigation and land use change which affect landscape water balance and ability to forecast it (Qian et al. 2013; Lawston et al. 2017). Use of remote data to develop crop yield forecasts promotes food security and its management. Irrigation water use is growing worldwide, and agricultural water use is no longer sustainable in a large number of vital agricultural regions. More accurate seasonal crop development forecasts require continuous observations of SM. Observations of the growth in global irrigated agriculture require an observational SM time series.

Only when observational SM at high resolutions is used with statistical governmental census/survey information and other ancillary satellite observations will crop-specific early seasonal and during-season warnings and predictions become possible. Such observational warnings using remote sensing observations will lead to better water use and irrigation scheduling. L-band observations have proven useful in detecting large-scale irrigation patterns (Lawston et al. 2017). Increased spatial resolution will enable monitoring of smaller-scale irrigation, enhancing the utility of remotely sensed SM for water management and data assimilation (DA) and understanding the downwind impacts on precipitation recycling.

6.1.2 Floods and Antecedent Land Surface Conditions

Antecedent land surface controls on short-duration/high-intensity flood events are complex and poorly understood due to existing observational gaps. Pre-storm SM represents the single largest factor determining infiltration of rainfall water and thus the efficiency with which rainfall is translated into streamflow (Koster et al. 2023). As a result, remotely sensed estimates of pre-storm surface SM are highly predictive of subsequent storm-scale runoff efficiency (Crow et al., 2017). Classically, hydrologists have assumed that the importance of pre-storm SM conditions will tend to decrease as rainfall intensively increases. However, recent work has underscored the importance of pre-storm SM as a detectable precursor to even exceptional large-scale flooding events (Tramblay et al., 2021). However, at finer space and time scales associated with flash flood events, the role of pre-storm SM remains poorly understood. This has implications for stormwater management and engineering design.

6.1.3 Land-Atmosphere Flux Rate and its Relation to Soil Moisture

There is a large variation in future water cycle projections. This variation is largely due to how different models treat functional relationships, or their link between model states and fluxes as described in model physics. Remote sensing data can be used to benchmark land surface models and address systematic errors in their representation of land surface state/flux coupling. New and continued satellite records can be optimized to answer the questions: What are the relationships between land surface states (SM and temperature) and surface exchanges with the atmosphere?

How do vegetation, soil texture, and microclimate conditions modulate these limitations? How can we develop observation-based benchmarks of these relationships to validate model outputs?

6.1.4 Soil Moisture and the Planetary Boundary Layer

Extreme events and processes that lead to them are influenced by advection as well as local interactions. The spatial organization of surface boundary conditions modulates how these factors combine to lead to extreme events. Related science questions have spatial resolution requirements that are challenging to meet with current remote sensing systems. How does patchiness of vegetation cover and SM trigger 1) planetary boundary layer growth, 2) mesoscale circulation, and 3) moist convection? To what degree does soil water limitation influence climate variability and extremes? How do land-atmosphere interactions sustain or inhibit extreme events?

6.1.5 Water and Carbon Cycle in Changing Climate

Is the water cycle accelerating? How much of the changes in the Precipitation minus Evapotranspiration (P-E) are due to changes in precipitation (warming and Clausius-Clapeyron), and how much is due to changes in evapotranspiration (greening and CO2 enrichment)? What are the global trends in precipitation extremes?

The water cycle and its links to the carbon cycle over forests are among the influential contributors to the future carbon budget. Do forests change their carbon source/sink due to water limitation? Is there a 'forest drought'? Surface emissivity knowledge afforded by L-band radiometry may significantly help improve the interpretation of SAR data for canopy structure and above-ground biomass (AGB) estimation.

Wildfires are increasingly playing important roles in the carbon budget, air and water quality, and replenishment of water reservoirs. How do soil and vegetation water content dynamics lead to increased wildfire risk? How does landscape hydrology change post-wildfire?

Deforestation is now affecting climate and climate change on a hemispheric scale rather than a regional scale. How does deforestation affect the surface water and energy balance in deforested (and possibly burned) areas, and how does it affect the adjacent non-deforested regions through local atmospheric circulations and advection?

6.1.6 Islands, Sea-level Rise, and Coastal Areas

Sea-level rise will disrupt coastal areas that are among the Earth's most productive and populated regions. What is the landscape hydrology surrounding coastal ecosystems, wetlands, deltas, and mangroves? How will the mean sea level rise and variability influence coastal infrastructure?

Islands play an underestimated role in ocean circulation, and storms that originate over oceans and affect coastal and land communities. How does the hydrology of islands and coastal areas affect oceanic and atmospheric dynamics that influence weather forecast skill?

Increasing the spatial resolution of the L-band will allow for observations closer to the complex land/ocean interface and increase the number of islands with feasible L-band retrievals.

6.1.7 Droughts and Heatwaves

The frequency, intensity, and spatial-temporal evolution of droughts and heatwaves will change with global climate and land cover changes (e.g. Miralles et al., 2019). Mitigation of societal impacts related to droughts and heatwaves requires observations across the drought cascade (meteorological to hydrological, agricultural droughts to societal droughts). These observations should address the question: "How do patterns and dynamics of SM as well as vegetation responses to hydrometeorology drive drought evolution and expansion?", quantify how the lag and intensity of droughts cascade from precipitation to SM to vegetation water content in different vegetation types/in different landscape settings, and test the hypothesis: "stomatal closure in response to increases in VPD has a greater effect on drought evolution than soil type does".

6.2 Benefit of 10-km Resolution over 40-km Resolution

Spatial resolution plays a critical role in a number of the terrestrial hydrology science questions raised above. Critically, due to the nonlinear nature of processes connecting soil moisture and terrestrial water fluxes (e.g., evapotranspiration and runoff), understanding the relationship between terrestrial water states and fluxes requires that we observationally resolve as much underlying SM variability as possible (Vergopolan et al., 2022). A global 10-km SM data product represents a major step in this direction.

Likewise, hydrological hazards are often associated with a particular time/scale. Flash-flood events are commonly defined as having time scales of < 1 hr – roughly corresponding to the hydrologic response time of basins < 100 km^2 in size (Creutin, 2013). Due to the difficulty in issuing adequate warnings at such short time scales, flash flood events in basins of this size are responsible for a significant fraction of total flooding casualties. Improving the spatial resolution of satellite soil moisture products to 10 km would enable an improved understanding of land surface factors contributing to the intensity of such high-impact events.

Likewise, existing land surface models are typically run at a spatial resolution much closer to 10 km than 40 km, and most operational NWP models and their land surface components already run between 1-10 km. For example, NASA GSFC's NLDAS-2 project resolution is run on a ⅛ degree resolution (i.e. slightly coarser than 10 km at mid-latitudes). Matching the spatial resolution of land models, as well as their ancillary (and satellite-driven) datasets including land cover, soil type, and vegetation characteristics, would increase the value of remotely sensed soil moisture for model diagnostic, assimilation, and validation purposes.

Finally, both boundary layer and runoff response are often sensitive to the particular spatial distribution of soil moisture across a landscape. For example, the spatial connectivity of high soil moisture patterns plays a significant role in determining the storm-scale hydrologic response of the land surface (Western et al., 2001). Likewise, the boundary-layer response to soil moisture variations is often sensitive to the heterogeneity and spatial gradients of soil moisture and length-scale of soil moisture anomalies (Huang and Margulis, 2013). In order to examine such sensitivity, explicit spatial mapping of soil moisture anomalies is required at the highest possible spatial resolution.

Furthermore, it is acknowledged that a wide range of applications for which 10-km resolution is insufficient, and downscaling strategies by merging with higher-resolution data will be necessary. However, increasing the native resolution is also essential for these applications because it has been shown that the quality of a 1 km downscaled dataset increases by 50-100 % when starting at a native resolution of 10 km as compared to starting at 40 km (Rodriguez-Fernandez et al., 2024).

6.3 Revisit Time and Other Considerations

One of the most surprising scientific insights provided by the SMAP and SMOS missions has been the degree to which SM retrievals can be used to map large-scale variations in land surface hydrology regimes (e.g., drying stages characterized by nonlinear variations in the dominant soil moisture loss mechanism) - see, e.g., Akbar et al. (2019). Further study of these transitions, and their impact on local hydroclimate, will require a continued commitment to sub-weekly temporal mapping of SM. In addition, improved mapping of rapid regime transitions immediately following rain events would be enabled by the availability of daily data.

In addition, high temporal repetition significantly improves the accuracy of Water Balance Equation (WBE) parameters, which are vital for comprehending terrestrial water cycles and reducing biases in estimates of effective hydrologic depth (ΔZ), as discussed by Kim and Crow (2023). This addresses the challenges arising from limited temporal repeats and the accuracy of satellite-based SM retrieval systems, thereby diminishing uncertainties in hydrologic models. The need for high-frequency SM data aligns with the scientific insights revealed by the SMAP and SMOS missions. Detailed temporal mapping is crucial for enhancing our understanding of hydrological transitions and their effects on local hydroclimates, emphasizing the pivotal role of advanced remote sensing techniques in deepening our understanding of the terrestrial water cycle.

6.4 Soil Moisture Retrieval Considerations

In the decade and a half from the launch of the first L-band sensor there have continued to be developments in retrievals based on higher frequency microwave channels. To optimally leverage L-band radiometry for the applications listed above, it is incumbent on the community to find ways to better utilize these multi-frequency observations within the core of L-band SM retrievals and minimize reliance on modeled or non-coincident information. For example, advances in passive microwave LST retrievals (Prigent et al 2016, Holmes et al 2015, 2018) could be incorporated in SM retrievals to account for separate soil and canopy temperatures. All the temporal information needed to model deeper soil layers needed for effective temperature is contained in a diurnal temperature product. Similarly, advances in VOD retrieval and complementary biomass structure information (see 8.4) will allow the retrieval algorithms to move beyond 0^{th} order tau-omega radiative transfer models by accounting for vegetation height and variations in the single scattering albedo. A more detailed accounting of spatial dynamics in temperature and vegetation within an L-band pixel will in turn facilitate applications that require tracking of temporal variations in soil moisture at the 10 km resolution.

7 Atmosphere: Convective Initiation (Soil Moisture)

Tornadoes occur on spatiotemporal timescales on the order of 100s of m and 10s of s to 10s of min. It is well known that the majority of tornadoes, and particularly the majority of strong to violent tornadoes, are formed by supercell thunderstorms. These storms have unique structures and dynamics that favor tornado production over other storm modes, with both storm-scale and environmental factors impacting the likelihood of tornadogenesis. Past work has found that the lifted condensation level (LCL) height and the magnitude of low-level (0-1 km) convective available potential energy (CAPE) are among several skillful parameters for discriminating between tornadic and non-tornadic environments. However, while these parameters are largely governed by the synoptic-scale environment, localized variations in thermodynamic conditions can and do exist, and these heterogeneities are not typically readily identifiable.

One particular challenge to operational forecasters responsible for warning the public of these events occurs when multiple supercells form in relative proximity, in an overall synoptically similar environment: we still cannot determine with accuracy when and where tornadoes will form and from which parent storms. It is quite possible that localized thermodynamic variations are at least partly responsible for differentiating between tornado producers and non-tornadic storms. One source of thermodynamic variability on scales equivalent to that of the parent storm (i.e., O (~10 km)) is soil moisture content. Latent and sensible heat fluxes from the ground contribute directly to boundary layer temperature and moisture profiles, which impact the available amount of low-level CAPE and the local LCL height and, therefore, the parent storm characteristics. As such, it is quite likely that soil moisture characteristics could influence when and where tornadoes form, given the presence of a parent supercell and an otherwise favorable background environment.

7.1 Science Motivation and Goals

The influence of the land-atmosphere interactions on the planetary boundary layer is a fundamental component of the Earth system. To understand these governing processes and complex feedbacks, we need to quantify the contributions of latent and sensible heat fluxes to changes in the temperature, moisture, and momentum profile within the PBL and determine spatial and temporal variations in the strength of land-atmosphere coupling and the processes that control them.

Convective storms, precipitation, and clouds drive major parts of weather and climate, but we still do not have all the pieces to understand why they occur exactly when and where they do. Therefore, we need to relate land-air processes to the initiation, intensity, and evolution of severe and high-impact weather phenomena, including tornadoes, hail, drought, and extreme rainfall events, and determine spatial and temporal variations in the strength of coupling between land surface and convection/precipitation and the processes that control them.

Improving predictions of precipitation, severe weather, flooding, and droughts (on sub-daily to seasonal timescales and local to global spatial scales) will require leveraging better observations and understanding of land-atmosphere interactions. Community based land-atmosphere coupling metrics (e.g. GEWEX LoCo Project; Santanello et al. 2018) aim to quantify and understand this coupling and can be used to diagnose and develop weather and climate models yet require observations of soil moisture and other process-chain variables (surface fluxes, boundary layer structure and evolution) at similar scales. An essential part of accomplishing this is to identify forecasts of opportunity (i.e., where/when) for which better soil and surface flux initialization improves high-impact weather prediction and determine regions in which improved soil moisture and surface heat flux initialization make the largest improvements in high impact weather prediction skill ("hot spots"), and how those responses vary seasonally ("hot moments").

Finally, the land-atmosphere interactions are subject to anthropogenic changes in climate and land use and understanding them requires improving the skill of climate models for simulating how changes in climate and land use affect the frequency and magnitude of extremes such as droughts and floods.

7.2 Benefit of 10-km Resolution over 40-km Resolution

Because the spatial scale of thunderstorms is on the order of 10 km horizontally, this length scale represents the minimum resolution required to obtain soil moisture values sufficiently to establish a link between tornadoes and soil moisture. Therefore, any product used to study this problem must have at least a 10-km resolution. Understanding of the role of soil moisture in land-atmosphere coupling will also benefit from higher resolution, on par with that of modern NWP systems, in order to tease out the impact of local vs. non-local (large scale, synoptic) forcing.

7.3 Revisit Time and Other Considerations

Because soil moisture characteristics will change on time scales of ~days, having observations available daily would be ideal. Ultimately, due to the tightly coupled nature of soil moisture, surface fluxes, and the boundary layer, considerations for spatial and temporal resolution should be made with respect to corresponding advances in observations of these other components. The strong diurnal nature of land-atmosphere coupling (relative to ocean) also suggests that higher temporal dynamics are critical to capture these complex feedbacks and interactions.

8 Ecology (Vegetation Optical Depth)

L-band radiometry derived vegetation optical depth (VOD) is sensitive to variations in vegetation water content that are driven by plant hydraulics and vegetation structure responses to hydrometeorology. This has been demonstrated from hydro-ecological principles and confirmed over multiple scales ranging from detailed field measurements of individual plants to global satellite observations of diverse ecosystems (Konings et al., 2019). The VOD provides a microwave frequency dependent measure of the vegetation opacity to surface microwave emissions and is therefore sensitive to variations in both above-ground vegetation biomass cover and its water content (Konings et al., 2021; Wigneron et al., 2021). Both of these attributes have strong value for ecosystem science and applications extending from regional to global extents, and over (sub)daily, seasonal, and annual time scales. VOD retrievals have also been successfully derived from higher frequency (C-, X-band) satellite microwave radiometers (Li et al. 2021). However, unlike the higher frequency VOD retrievals, which are primarily sensitive to upper canopy layers, the L-band VOD provides greater sensitivity to a larger canopy volume and maintains sensitivity over a higher level of standing biomass (Rodriguez-Fernandez et al. 2018, Chaparro et al., 2019; Frappart et al., 2020).

Global VOD records derived from existing operational L-band radiometers from SMOS and SMAP have been used in a variety of science applications, including studies on vegetation biomass phenology, disturbance and recovery (Frappart et al., 2020, Schmidt et al., 2023); crop water content and yield estimates (Chaparro et al., 2018; Togliatti et al., 2019); evapotranspiration (Martens et al., 2017), plant trait mapping (Liu et al, 2020), and ecosystem carbon dynamics (Dou et al., 2023, Wigneron et al., 2020; Yang et al., 2023). On daily and weekly timescales, VOD from L-, C-, and X-bands have been used to assess, for instance, plant water uptake (Feldman et al., 2018, Feldman et al. 2021) and live fuel moisture content (Fan et al., 2018, Forkel et al., 2023, Chaparro et al., 2024). Compared with optically-derived vegetation indices, L-band VOD does not saturate in densely vegetated areas and allows capturing information from major terrestrial ecosystem changes (Bueso et al., 2023, Fan et al., 2023).

The combined use of satellite L-band and higher frequency VODs supported by other complimentary satellite data, including L-band soil moisture, offers potential for monitoring the storage and movements of water along the soil-vegetation-atmosphere continuum, which could advance understanding of how plant communities collectively manage scarce water resources to sustain productivity under variable climate, and also how they regulate water, energy and carbon exchange between the land and atmosphere. Key VOD science and technical challenges include disentangling temperature, biomass, and relative water content effects on VOD and interpreting VOD signals from complex ecosystems composed of a diversity of plant functional types and water use strategies.

A 10-km L-band radiometer would provide more than sixteen times finer VOD spatial resolution enhancement over current (~40-km footprint) VOD records from SMAP and SMOS, which could advance new science and understanding of ecosystem-level behavior. For example, a 10 km L-band VOD would achieve a sufficient scale threshold ability to inform individual farm-level management decisions associated with crop water use and critical development stages, tillage, and harvest practices in the US Corn Belt and possibly even in less homogeneous croplands. Global land surface models are rapidly evolving to operate at finer spatial resolutions approaching 10 km while also representing the effects of plant hydraulics on land-atmosphere fluxes (Kennedy et al., 2019; Eller et al., 2020). The model parameterizations and predictions of plant hydraulics currently have very few observational constraints and would benefit from an independent VOD record with similar space-time dimensions (Holtzman et al., 2023).

8.1 Science Motivation and Goals

Several motivating science questions were identified from the workshop that could be more effectively addressed from 10-km L-band radiometer-derived VOD retrievals over the current baseline. One question asked how do vegetation communities control the storage and movement of water/carbon/energy across the soil-vegetation-atmosphere continuum? A major science goal addressing this question involved clarifying how communities of individual plants interact collectively to influence ecosystem-level water use and land-atmosphere fluxes of water, energy, and carbon. An associated science objective identified in this area included quantifying spatial scaling properties linking water storage patterns from individuals to ecosystems.

Another question asked how are natural ecosystems and their associated goods and services responding to climate change? The associated science goals included quantifying the plant water stress response to the changing nature and frequency of droughts; and clarifying how vegetation water deficits influence ecosystem susceptibility to and recovery from drought, wildfire, and other disturbances. Related science objectives included 1) clarifying how diurnal and seasonal changes in vegetation water content respond to increasingly hot droughts and 2) understanding how the drought response of diurnal and seasonal VWC changes is influenced by recent hydroclimatic variability in a given ecosystem. Another question emphasized food security, asking how are agricultural systems and food production responding to changing hydro-climate. An associated science goal is to understand how crop photosynthesis rates will respond to changing climate. Science objectives identified under this theme included: 1) understanding how the timing of crop management and phenology is responding to changing climate and water availability, including more variable precipitation; and 2) understanding how the timing of management and crop phenology is responding to longer growing seasons.

In the field of the global carbon cycle, a key issue is to improve monitoring of the impact of climate (through droughts and associated mortality, windthrow, etc.) and human activities on forest above-ground biomass (AGB). This assessment is based on the spatial relationship between VOD and AGB (Wigneron et al., 2021). However, the quality of this relationship is limited by the within-pixel heterogeneity of the forest cover, due to the coarse spatial resolution of SMOS and SMAP.

8.2 Benefit of 10-km Resolution over 40-km Resolution

A 10-km L-band VOD retrieval for ecosystem applications would greatly improve the delineation of vegetation biomass and water use at the ecosystem or ecoregion level, whereas current capabilities from SMOS and SMAP are largely only able to distinguish broad regional climate and biome level variations.

At 10-km resolution, the impact of forest cover heterogeneity would be greatly attenuated, making estimates of changes in forest AGB much more accurate (Wigneron et al., 2024).

For agricultural applications, the value of a 10 km L-band would provide a significant advance in resolving individual farm and crop-level management practices and water use. A 10-km VOD observable would also be closer to the scale of next-generation land models with sophisticated model representations of plant hydraulics (e.g., CLM, JULES, and Noah-MP), which would have greater utility for land model parameterizations and data assimilation.

8.3 Revisit Time and Other Considerations

The VOD retrievals have ecosystem relevance at daily, weekly, and annual time scales that are associated with respective variations in (sub)daily water use and water storage recovery, phenology and drought recovery, and biomass growth, disturbance, and recovery. A VOD record spanning at least a full annual cycle may be needed to normalize and isolate the water dynamics signal, and to establish baseline conditions to monitor above-ground biomass changes. To fully capture diurnal variability in vegetation water use and recovery, VOD retrievals would have to be consistently sampled at least four times per day. However, finer temporal sampling may provide only limited value (Holtzman et al., 2023). If used, the combination of L-band and higher frequency VOD retrievals would also have to be closely collocated spatially and temporally to ensure similar sampling footprints and similar conditions of surface heating and cooling.

8.4 VOD Retrieval Considerations

Several challenges remain that must be addressed before L-band radiometry can be fully realized for the above applications, including a better understanding of the effects of canopy temperature on the L-band emission signal and the dielectric constant of vegetation; an understanding of how to interpret VOD signals in diverse ecosystems; and the development of better retrieval algorithms to disentangle biomass and relative water content effects on VOD. Significant science value-added could be gained through the additional use of nested higher frequency TB and VOD retrievals, optical retrievals of canopy greenness and solar-induced canopy fluorescence, and Lidar and radar retrievals of vegetation biomass structure. These complementary observations could be applied for further VOD spatial enhancement and partitioning between canopy layers and leafy and woody components, and to clarify relations between vegetation water use and productivity.

9 Science Traceability Matrix Examples

Below are three science traceability matrices (STM) developed at the workshop for the following science motivations:

1. The need to understand how coastal ecosystems will evolve in a changing climate and to improve related climate model projections
2. The importance of understanding how oceanic elements of the energy, water and carbon cycles will evolve in a changing climate and improving related climate model projections
3. The need to understand and predict high latitude ocean changes in response to a warming climate and to improve related climate model projections

The STM show the derivation of the instrument requirements from the science motivation, following the definitions of the science goals, science objectives, and the requirements for the physical and observables.

Science Motivation	Science Goal	Science Objectives	Scientific Measurement Requirements		Instrument
			Physical Parameters	Observables	Requirements
1. The need to understand how coastal ecosystems will evolve in a changing climate and to improve related climate model projections	**G1**. Improve our understanding of land-sea exchanges and their influence on marine ecosystems and biogeochemistry	**O1.1**. Improve our estimation of plume pathway, extent and concentration of freshwater, nutrients, carbon for large and smaller rivers, how it changes over time and its impacts on the coastal ocean METHOD – General: Sea surface salinity is a tracer for riverine runoff. METHOD – Specific: Sea surface salinity observations in conjunction with CDOM, in river measurements of nutrients, ocean currents can trace riverine waters. **O1.2**. Determine the impacts of changes in river discharge caused by human activities on the coastal ocean METHOD – General: The coastal ocean is influenced by land processes via river runoff. Improved ecosystem models for coastal oceans can help understand the impacts affecting the coastal ocean. METHOD – Specific: Sea surface salinity along with ocean color and land observations can help to understand better environmental changes. Eutrophication and acidification in the coastal ocean can be due to human-induced increased mobilization of nutrients and carbon from soils and changes in freshwater discharge.	**PP1**. Sea surface salinity at small scales (1-40 km), daily **PP2**. Sea surface temperature, at small scales (1-40 km), daily **PP3**. Wind speed and direction, at small scales (1-40 km), daily **PP4**. Chlorophyll-a and CDOM, at small scales (1-40 km), daily **PP5**. river discharge, daily **PP6**. land cover, daily	**Obs1**. L band brightness temperatures (SSS) **Obs2.** C-Ka band polarimetric radiometry (WS/dir, SST) **Obs3.** IR(4-12 micron) radiometry (SST) **Obs4.** VIS/NIR imaging (400-900 nm, ocean color/Chl-A, land cover)	**R1**. Frequency/wavelength: L band TB: 1.4 GHz C-Ka band TB: 6.9, 10.7, 18.7, 32 GHz IR: 4-12 micron VisNIR: 400-900 nm **R2:** Spatial resolution: 10 km **R3.** NEDT: L-Ka band TB: 0.2 K **R4.** Radiometric accuracy: L-Ka band TB: 0.5 K **R5.** Radiometric stability: L-Ka band TB: 0.5 K

Science Motivation	Science Goal	Science Objectives	Scientific Measurement Requirements		Instrument
			Physical Parameters	Observables	Requirements
2. The importance of understanding how oceanic elements of the energy, water and carbon cycles will evolve in a changing climate and improving related climate model projections	**G2**. Improve our understanding of salinity processes that influence the energy, water, and carbon cycles	**O2.1**. Improve the estimation of exchanges of carbon at the air-sea interface METHOD – General: Quantifying pCO2 fluxes at the interface between the atmosphere and the ocean would help estimating a branch of the carbon cycle. METHOD – Specific: pCO2 fluxes can be estimated from sea surface salinity, temperature and chlorophyll-a. **O2.2**. Improve our understanding of salinity processes at mesoscales and near land-sea and sea-ice edge METHOD – General: Resolve ocean eddies and fronts as they influence the transport of heat, salt, nutrients, oxygen, and pollutants over long distances. METHOD – Specific: **O2.3**. Improve understanding of evaporation and precipitation fluxes at the ocean-atmosphere interface METHOD – General: Evaporation and precipitation fluxes at the ocean-atmosphere interface can be seen in the sea surface salinity signals. In response to a warming climate, the moisture capacity of the atmosphere increases, so freshwater fluxes at the interface with the ocean are expected to change. METHOD – Specific: Estimate the variance of sea surface salinity is indicative of changes in evaporation minus precipitation minus runoff.	**PP1**. Sea surface salinity at small scales (1-100 km), daily **PP2**. Sea surface temperature, at small scales (1-100 km), daily **PP3**. Wind speed and direction, at small scales (1-100 km), daily **PP4**. Chlorophyll-a and CDOM, at small scales (1-100 km), daily **PP5**. pCO2 fluxes at at small scales (1-100 km) (retrieved from sea surface salinity, chlorophyll-a and sea surface temperature) **PP6**. Sea ice concentration, extent and thickness, at small scales (1-40 km), daily **PP7**. Evaporation and precipitation at the surface of the ocean, at small scales (1-40 km), daily **PP8**. Sea surface salinity gradients at small scales (20 km)	**Obs1**. L band brightness temperatures (SSS) **Obs2.** C-Ka band polarimetric radiometry (WS/dir, SST) **Obs3.** IR(4-12 micron) radiometry (SST) **Obs4.** VIS/NIR imaging (400-900 nm, ocean color/Chl-A, land cover)	**R1**. Frequency/wavelength: L band TB: 1.4 GHz C-Ka band TB: 6.9, 10.7, 18.7, 32 GHz IR: 4-12 micron VisNIR: 400-900 nm **R2:** Spatial resolution: 10 km **R3.** NEDT: L-Ka band TB: 0.2 K **R4.** Radiometric accuracy: L-Ka band TB: 0.5 K **R5.** Radiometric stability: L-Ka band TB: 0.5 K

Science Motivation	Science Goal	Science Objectives	Scientific Measurement Requirements		Instrument
			Physical Parameters	Observables	Requirements
3. The need to understand and predict high latitude ocean changes in response to a warming climate and to improve related climate model projections	**G3**. Improve our understanding of ocean-ice and ocean-atmosphere interactions in high-latitude oceans	**O3.1**. Improve our understanding of how ocean state in one season preconditions sea-ice evolution in the subsequent season METHOD – General: Salinity is the dominant driver of stratification in the Arctic Ocean and plays a key role in sea ice formation. METHOD – Specific: Stratification in the Arctic Ocean, driven by salinity, can trap heat subsurface, allowing sea ice to form more rapidly. When the stratification is disrupted by winds or waves, heat is released to the surface and could slow down sea ice formation. **O3.2**. How does ice melt water influence air-sea exchanges of heat and momentum METHOD – General: The Arctic open water season is becoming longer. The ocean surface, normally covered by sea ice, now allows exchanges between the ocean and the atmosphere. METHOD – Specific: The stratification of the growing open ocean at high latitudes (driven by salinity) can have an impact on the exchanges of heat and momentum between the ocean and the atmosphere.	**PP1**. Sea surface salinity at small scales (1-40 km), daily, close to the marginal ice zone, icebergs, ice shelves, and coasts **PP2**. Sea surface temperature, at small scales (1-40 km), daily **PP3**. Wind speed and direction, at small scales (1-40 km), daily **PP4**. Sea ice concentration, extent and thickness, at small scales (1-40 km), daily **PP5**. Heat and momentum fluxes at the ocean surface, at small scales (1-40 km), daily	**Obs1**. L band brightness temperatures (SSS) **Obs2.** C-Ka band polarimetric radiometry (WS/dir, SST) **Obs3.** IR(4-12 micron) radiometry (SST) **Obs4.** VIS/NIR imaging (400-900 nm, ocean color/Chl-A, land cover)	**R1**. Frequency/wavelength: L band TB: 1.4 GHz C-Ka band TB: 6.9, 10.7, 18.7, 32 GHz IR: 4-12 micron VisNIR: 400-900 nm **R2:** Spatial resolution: 10 km **R3.** NEDT: L-Ka band TB: 0.2 K **R4.** Radiometric accuracy: L-Ka band TB: 0.5 K **R5.** Radiometric stability: L-Ka band TB: 0.5 K

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Appendix: Workshop Agenda

Science of 10-km Resolution L-band Radiometry

Jet Propulsion Laboratory - Meeting Room: 180-101

October 10-12, 2023

Day 1

Setting the Stage (Chair: Andreas Colliander)

8:00	Registration	
8:30	Opening Remarks	Duane Waliser
8:40	Welcome and Introductions	Andreas Colliander
8:55	Meeting Objectives	Andreas Colliander
9:15	Current State of L-band Radiometry	Dara Entekhabi
9:35	Outlook of L-band Radiometry	Andreas Colliander
9:50	ESA User Consultation Study on the Need of L-band Radiometry	Matthias Drusch (remote)
10:10	***Break***	
10:25	Feasibility of 10-km Resolution L-band radiometry	Andreas Colliander
10:45	Discussion	

Cryosphere: Sea Ice (Chair: Ted Maksym)

11:00	On Sea Ice and Its Importance in the Climate System and Processes Observable with 10 km L-band Radiometry	Ted Maksym
11:30	Sea Ice Thickness Retrieval	Lars Kaleschke (remote)
11:45	***Lunch***	

Cryosphere: Ice Sheets (Chair: Joel Harper)

12:45	Overview of Science Problem, Value of Liquid Water Retrieval, and Treatment of Spatial Scales	Joel Harper
13:25	Ice Sheet LWC Retrieval (L-band and multi-freq.)	Andreas Colliander
13:40	Firn Aquifer Detection and Monitoring (L-band)	Julie Miller
13:55	Ice Sheet Temperature Retrieval	Giovanni Macelloni (remote)

Cryosphere: Land Surface and Freeze/Thaw (Chair: Alexandre Roy)

14:10	Importance of Vegetation Growth Processes and Methane Release to Earth System and Linkage of F/T Spatial Scales to the Processes	Alexandre Roy
14:50	***Break***	
15:05	Retrieval of F/T with L-band Radiometry	Xiaolan Xu
15:25	Enhancement with C- to Ka-band Radiometry	John Kimball

Atmosphere: Convective Initiation (Chair: Steven Quiring)

15:40	Significance of Convective Processes in INCUS	Kristen Rasmussen
16:00	Soil Moisture-Precipitation Interactions in the Central United States	Trent Ford
16:20	Investigating Spatial Relationships Between Soil Moisture and Tornado Events using SMAP	Jana Houser
17:00	***Adjourn Day 1***	

Day 2

Oceanography (Chair: Severine Fournier/Tony Lee)

8:00	*Preparation for day 2*	
8:30	Operational Implications of Higher Resolution Sea Surface Salinity (NOAA)	Eric Bayler (remote)
8:45	Sea Surface Salinity and Open Ocean Processes	Fred Bingham
9:00	Sea Surface Salinity and Coastal Processes	Doug Vandemark
9:15	Sea Surface Salinity and Polar Processes	Julian Schanze
9:30	Air/Sea Fluxes and Impact of Sea Surface Salinity at Small Scales	Lisan Yu
9:45	SSS Retrieval with 1.4 GHz and Wide-Band Measurements	Sidharth Misra
10:00	SSS Enhancement with C- to Ka-band Radiometer Measurements	Alex Akins
10:15	***Break***	

Hydrology: Water and Energy Cycle (Chair: Dara Entekhabi/Wade Crow)

10:45	Soil Moisture and Land-Atmosphere Coupling with Higher Resolution Soil Moisture	Josh Roundy
11:00	Soil Moisture Heterogeneity and Triggering of Atmospheric Convection	Paul Dirmeyer (remote)
11:15	Global Estimates of L-band Vegetation Optical Depth and Soil Permittivity over Snow-covered Boreal Forests and Permafrost using SMAP Satellite	Ardeshir Ebtehaj

Hydrology: Land Surface Models (Chair: Wade Crow)

11:30	Issues and Challenges in Soil Moisture Data Assimilation	Sujay Kumar (remote)
11:45	NWP/Hydrologic Forecasting Implications	Stephane Belair (remote)
12:00	Issues In Soil Moisture Assimilation with LSM	Wade Crow
12:15	**Lunch**	

Hydrology: Soil Moisture Applications and Retrieval (Chair: Thomas Holmes)

13:30	Surface Soil Moisture and Plant Water Uptake	Andrew Feldman (remote)
13:45	SM Retrieval with L-band Radiometry	Rajat Bindlish
14:00	Multichannel PMW for soil moisture and Evapotranspiration	Thomas Holmes

Breakouts (Chair: Andreas Colliander)

14:15	Organize to Breakouts	
14:30	**BREAKOUT 1 (including break)**	
16:30	Breakout Summaries	
17:15	***Adjourn Day 2***	

Day 3

Ecology (Chair: John Kimball)

8:00	*Preparation for day 3*	
8:30	Importance of Biomass and Plant Hydrology to Earth System	Paul Siqueira
9:00	L-band VOD biomass Applications	Maria Piles (remote)
9:15	VOD Applications for Plant Hydrology	Alex Konings
9:30	Review of Measuring VOD Dynamics with L through X-band Radiometry	JP Wigneron (remote)
9:45	VOD Linkage to Biomass and Vegetation Water Content over Croplands	Brian Hornbuckle

Breakouts (Chair: Andreas Colliander)

10:00	**BREAKOUT 2 (including brake)**	
11:15	Breakout Summaries and Inputs to Science Traceability Matrices	
12:00	Closing and Future Activities	
12:30	***Adjourn Day 3***	