Appendix 3. Near-Surface Geophysics Science Questions Compiled from the Survey and Workshop 1

Anthropogenic Activities (Archeology, Forensics, Environmental Remediation, Engineering, Energy and Mineral Resources)

Material characterization and methods standardization in NSG

- What are the geophysical signatures of critical elements and/or their host rocks?
- Can we understand and generalize repeatability standards and best practices for conducting NSG surveys, particularly for monitoring processes or landscapes over time?

Infrastructure and urban environments

- **How can infrastructure and urban areas use shallow geophysical information to keep pace with rapid urbanization and changing energy systems?**
- **How can Earth Science guide urban development to minimize hazards and risks?**

Culture and Heritage, Humanitarian, Environmental and Social justice

- How can a better understanding of historical land use and changes enable environmental and climate justice efforts?
- How can we improve soil conservation and restoration by leveraging the spatial resolution, repeatability, and scalability of NSG techniques?

Pollutants, changing earth system, and human activities

- What are the coupling mechanisms, stresses, and feedbacks between a changing climate with a changing critical zone and human activities (e.g. logging, farming practices, pollution)?
- How do near surface processes drive human activities (water, food, health, hazards,...)?
- How can NSG improve detection, monitoring, and management of **pollutants** in the critical zone?
- How can NSG aid in understanding the effects of soil degradation from human activities (e.g., deforestation, monoculture cropping) and remediation efforts?

Energy and geothermal resources

- How can critical elements be extracted from the Earth surface, both sustainably and with minimal environmental impact, to support the production and storage of **alternative energy?**
- How can improved mapping of permafrost, heat, and permeability assist in understanding and characterizing geothermal energy resources?
- How can NSG improve safety in sequestration of critical materials (carbon, radioactive waste)?
- How is the critical zone geothermal regime changing and can we understand/predict heat flow fluctuations?

Improving mineral exploration

- How can we improve resolution in geophysical methods to identify lower concentrations of critical minerals at greater depths and better understand mineral distribution?
- How do we locate and access economic deposits of critical minerals without excessive environmental damage at any stage of the process (exploration, extraction, transportation, processing)?
- Can conductors and breaks in seismic reflectors map former fluid flow channels where critical metals became concentrated?

Element cycling, chemical processes, and formation of deposits

- What controls the fluid flow pathways and groundwater influence that lead to the formation and distribution of mineral deposits
- How large of an effect do hydrothermal vents have on global element distribution and circulation?
- What are the spatial and temporal scales of critical element/mineral cycling and redistribution due to tectonic, magmatic, and hydrologic processes?
- How does near surface geologic structure affect the distribution of critical element **deposition**?
- How does human activity such as mining and remediation impact groundwater composition, ecosystem balances, ground stability, and other various critical zone processes?
- What is the architecture of magmatic, hydrothermal, brine, groundwater, or other fluid flow systems that transport and sometimes concentrate critical elements and minerals?

Biogeochemistry, Ecology, and Coastal Processes

Carbon cycling

- How is carbon sequestered and cycled in the shallow subsurface? At what rate is carbon stored in, and released from, near-surface deposits and soils?
- How do emerging soils (e.g. following deglaciation or melting permafrost) and the processes they host affect the carbon cycle?
- What are mechanisms and timescales for carbon sequestration and how effective are methods over short, medium and long time frames? Specifically, how likely/quickly is return of CO_2 to the atmosphere?
- How does wetland drainage or reclamation influence local carbon consumption, water quality, erosion rates and habitat change?
- How do changes in temperature and rainfall patterns affect soil organic carbon?
- How do human-driven processes (e.g., farming) influence soil chemistry (e.g., carbon sink or source) or the water cycle?
- How do management practices, species composition, and parent material affect a soil's ability to store carbon in mountainous forests?
- What are the dynamics of coupled transport of carbon and water over daily to annual time frames in peatlands?

Nutrient cycling

- How can time-lapse geophysical monitoring reveal the complex nonlinear feedback systems between geo, hydro, chemo and bio cycles/systems?
- How will the loss or alteration of vegetation due to climate change (changing drought/precipitation regimes, changing wildfire regimes) influence rock weathering, nutrient/element cycling, sediment transport, mass wasting, and climate over both small and large spatial and temporal scales?
- How do geophysical processes affect the cycling of elements through the critical zone; which in turn influences biodiversity?
- How do water and nutrient availability correspond in soils?
- How do geological processes influence biodiversity and how are critical elements distributed and cycled?
- What is the influence of temperature on near-surface physical, mechanical and biological systems?
- "How are biogeochemical cycles of bioactive elements (e.g., iron) linked across land surface, atmosphere, and hydrosphere?"
- Can we remotely monitor nitrate transport and degradation in the subsurface?
- How can we use NSG to constrain coupled hydrological and biogeochemical state and fluxes?
- How do earthquakes affect biohydrochemical processes in the shallow crust and in soils?

Subsurface controls on microbial activity and vegetation dynamics

- How does geologic parent material constrain vegetation shifts in response to changing climate?
- How does subsurface structure influence the distribution and function of terrestrial and aquatic ecosystems?

- How do soil structures affect soil microorganism activities resulting in gas production and emission hotspots in soils?
- How does surface lithology affect vegetation growth?
- How do extreme climate events (drought/flood cycling) affect the underlying lithology and influence the distribution of hot spots and hot moments of microbial activity?
- What is the role of soil, in particular the upper 2 m of the earth's surface in biogeochemical cycles and climate change?
- How do we better estimate mass balance exchanges between the atmosphere and the shallow (say <10M depth) subaerial biosphere? What is the role of structure, porosity, and vertical permeability on fluxes from these different locations?

Coastal Processes

- What is the effect of sea-land interaction on biogeochemical cycles, i.e. how does sea level rise affect nutrient cycling in the coastal zone?
- How can we identify prehistoric tsunamis and superstorms in stratigraphic records so that we can better constrain their recurrence intervals and magnitudes?
- How does the coastal zone respond to increased storminess and rising sea levels associated with climate change?
- How do local, regional, and global changes alter carbon and nitrogen cycling at the terrestrial-aquatic/marine interface?
- How do sea-level change, sediment supply, land cover, and diagenesis interact to affect carbon sequestration in deltas?

Critical Zone and Surface Processes

Simplified out of 94 CZ/SP-related questions from the survey

1) CZ factor/mechanism-related (climate, topo, lithology, biological activity, anthropogenic): i.e. how does XX influence the CZ?

- *How does the thickness and degree of weathering in the critical zone vary across the Earth's surface and how are they modulated by factors such as climate, topography, and lithology.*
- *How will global climate change impact bio/hydro/geochemical processes occurring in the critical zone*
- *How do pollutants and anthropogenic activities (like development practices) affect critical zone processes?*
- *How does the shallow structure of the critical zone influence water cycling and vegetation distribution?*
- *What's the critical zone response to short term events and/or extreme weather?*
- *How does long-term drought affect critical zone water cycling?*
- *What are the interactions, and specifically the fluxes of energy and matter along the atmosphere-vegetation-critical zone continuum?*
- How are changes in the earth's snowpacks affecting mountain forests and carbon stocks?
- *How do changing surface temperatures affect carbon storage in wetlands, especially wetland forests?*
- *Which mechanisms of heat and mass transfer are most important at the soil surface?*
- *How do the geofluids (0-300 C) affect the rock alteration on or near earth's surface?*

2) CZ architecture-related (regolith/soil thickness, degree of weathering, groundwater/hydro): i.e. how does XX vary across the CZ?

- *How does the thickness and degree of weathering in the critical zone vary across the Earth's surface and how are they modulated by factors such as climate, topography, and lithology.*
- *How does heterogeneity that can be imaged deep in the CZ (10s to 100s of m) impact the biodiversity at the surface?*
- *How does groundwater quality change in the critical zone?*
- *How can groundwater storage (including the unsaturated zone), a critical component of the water cycle, be properly monitored?*
- *How do variations in subsurface weathering influence hydrologic partitioning in the critical zone?*
- *How does the 3D soil architecture control the critical zone development, function and service?*
- *How does near-surface heterogeneity affect inferences of deeper Earth structure?*

3) Surface Processes/Geomorphology related: i.e. scale/methods integration, controls on topographic change

- *How do deep Earth, deep crust, shallow crust, and critical zone processes couple with hydrosphere and atmosphere processes to shape Earth surface conditions through time?*
- *How do climate, hydrology, tectonics, and geological structure and lithology combine to control landscape and soilscape evolution?*
- *How do lithology, tectonics, climate, and biota drive critical structure across hilly and mountainous landscapes?*
- *How do fractures and characteristics of bedrock influence topographic change?*
- *How can integration of diverse geophysical datasets with high-resolution computer models of landscape evolution, mantle dynamics, and climate be implemented efficiently to enable a process-based understanding of the causes and consequences of topographic change, including human-induced?*
- *And how can different scales of topographic change be integrated?*
- *How does land surface change affect atmospheric processes?*
- *What are the relative differences between anthropogenic activities and natural erosion processes in terms of rates, consequences and qualitative results?*
- *What impacts do topographic changes have on the water cycle and do changes in the water cycle lead to changes in the long-term evolution of topography?*
- *What is the relationship between geomorphology and water storage/flow in changing regional climates?*
- *What are the processes driving vertical land motion and soil loss/accretion at the land-coast interface, what are their relative contributions to relative sea level rise, and how can the land loss be mitigated?*
- *To what extent are processes of erosion and sediment transport, which affect stream ecology, influenced by changes in baseflow and stormflow given different subsurface materials?*

4) <u>Generic: relation NS-CZ; modelization,</u>

- *How can NSG play a pivotal role in building a digital twin for critical zone observatories?*
- *How can NSG provide efficient mapping of the critical zone?*
- *How can NSG provide real-time imaging of active processes in the critical zone?*
- *What controls the structure and dynamics of the near-surface, which in turn controls carbon and water fluxes in the critical zone?*
- *What is the quantified response of geophysical field measurements to changes in sediment properties, i.e. how to build quantitative ground models from geophysical measurements*

Cryosphere

Permafrost

1. How is permafrost loss occurring as climate changes?
2. How do observations of permafrost changes inform predictive models?
3. How does permafrost affect climate (e.g. methane), creating a feedback?
4. What are the consequences of permafrost changes (for the planet, groundwater flow, biology, humanity)?
5. How does near-surface geology affect permafrost?

Ice sheets/glaciers

6. How rapidly are ice sheets and glaciers collapsing?
7. How do observations of ice sheets inform predictive models?
8. How do ice sheets affect climate (e.g. albedo, topography), creating a feedback?
9. How do ice sheets, oceans and atmosphere interact?
10. How does near-surface geophysics help predict sea level rise?
11. What are the consequences of sea level rise for coastal communities?
12. How do ice sheet changes (isostatic, sea level, …) affect rivers and erosion?
13. What are the material properties at the beds of ice sheets and glaciers?

Sea ice

14. How does sea ice respond to climate change?
15. How do observations of sea ice inform predictive models?
16. How does sea ice affect climate (e.g. albedo), creating a feedback?

Seasonal snow

17. How does the changing seasonal snow cycle/glaciers affect freshwater availability?
18. How will agriculture be affected by changing snow pack?

General, Miscellaneous

19. How is near-surface geophysics important for reconstructing cryosphere dynamics?
20. What are the planetary implications for ice cover?
21. How do changes in solar radiation, orbital parameters, geochemical cycles affect planetary ice cover?
22. Is there frozen water in the lunar subsurface?
23. How does the cryosphere interact with the other areas of focus (hydrology, CZ, …)?

Geohazards (Volcanoes, Earthquakes)

Earthquakes

Characterization of near-surface effects, fault structures and seismic processes to understand earthquakes

- What are the mechanics of the shallow crust during the various phases of the seismic cycle?
- How do near-surface structure and processes affect seismic data intended for examining deeper targets? How can we remove these near-surface effects?
- What is the relationship between near surface expression of faults and near surface activity and deeper tectonic processes?
- How can shallow seismic surveys provide additional 3D data for earthquake evaluation on a regional or continental scale?
- How are deeper fault zones imaged by seismicity and/or crustal scale imaging connected to the surface?
- How does mapping of faults reveal specific active features?
- How can we visualize fault activity and tsunami deposition history to understand the cyclic occurrence of large earthquakes?

Seismic hazard and risk assessment

- How does the variability in poroelastic parameters from variations in lithology and overburden stress affect earthquake ground motions?
- What are the physical mechanisms and models that link near-surface geologic structure to earthquake ground-motion site effects, and their implications for hazard and risk?
- Granular materials can deform as if they were fluids, yet are generally analysed as frictional materials. What are the consequences of ignoring viscous behavior in geohazard risk?
- How can our knowledge of subsurface structures and (changing) water content help to mitigate the seismic risk in cities?
- How can the understanding of earthquake and fault rupture mechanisms help to better understand associated risks with long time fluid injections?
- How can studies of near-surface geophysics benefit from the development of early-warning systems?
- How can near-surface geophysics be used to predict natural geohazards by monitoring stress distribution within a target area?
- Can hydrogen production in active fault zones be efficiently monitored and used to predict fault activity?

Volcanism

- How can dissolved gases (CH4, CO2, H2S) be mitigated before supersaturation (and explosive outgassing) in "killer lakes" (Lake Kivu)?
- How can integrating multiparametric measurements lead to short-term warning of volcanic eruptions having slight or ambiguous precursors? How do those signals differ between episodes of unrest that result in eruption versus those that do not?
- What controls phreatic explosions? Can we detect precursors to these using near-surface geophysics?

- How can high resolution, long offset 3D seismic surveys help understand volcanic systems?
- Can near-surface geophysics detection of changes in the hydrothermal system at volcanoes help us forecast the onset and style of volcanic eruptions?
- How does the near surface environment influence locations of volcanic vents, mass discharge during volcanism, frequency and intensity of eruptions, persistence of degassing, and types of hazards?
- How can near-surface geophysics be better used to characterize deposits of past volcanic eruptions to improve forecasting of future unrest?

Volcanic/seismic interactions

- How does magmatism affect aftershock distribution and earthquake hazard assessment?
- How does the presence of magmatic bodies affect earthquakes and strain localization?
- How does the constitution of the critical zone and underlying crust affect volcanism and seismicity?

Ground deformation (subsidence), mass movements, infrastructure failure

- Can we make the local and regional contributions of soils explicit for geohazards evaluation, including subsidence?
- How can we measure the state of landslide material and predict catastrophic landslides?
- How do we better monitor aging dams and levees for potential catastrophic failure?

Impact of a near-surface center/hub in integrating research, improving outreach and education and lowering entry barriers

- How can we leverage new technology to better understand near-surface geophysics?
- How can seismic, geodetic, electromagnetic methods together constrain mixtures of solids, gases, and liquids?
- For a typical volcano, earthquake fault and landslide site, can we draw some “Global Standard stratotype section and point” as an example to help uniformly cope with these problems all over the world?
- How can we use drone technology to map UXO and geohazards to 10 meters depth?
- To what degree can near-surface geophysics assist city planners and state governments seeking to mitigate hazards to society?
- What approaches can be used to help Earth Science research combat misinformation and disinformation with respect to geohazards?
- How will the proposed center/hub break down the barriers to get entrenched communities to define and consider geohazards in integrated approaches?

Hydrology and Hydrogeophysics

Groundwater

- How do we protect groundwater aquifers from depletion, seawater intrusion, and contamination?
- Improve techniques for refining identification of sedimentary changes and stratigraphic mapping within shallow aquifers.
- How is subsurface water storage changing?
- Support sequence stratigraphy for better aquifer modeling and definition
- Architecture of the subsurface related to pathways for fluids and elements.
- Location of mineral and groundwater resources in the upper 1 km of the crust
- How can we better manage groundwater resources from aquifer to basin scale?
- groundwater exploration, mapping and monitoring
- Deriving hydrogeological parameters from geophysical data.
- Role of faulting on hydrologic flow barriers, partitioning land subsidence, and controlling occurrence of GDEs
- Can we effectively implement continental scale groundwater store monitoring with mobile gravitometers?
- The groundwater component of the water cycle is often taken as the shallowest occurrence as a surface (the water table) and needs to address the vastness of this resource across (thickness, internal variability in quality and quantity, transmissivity and storage) across the continents, as this represents 99% of the available (liquid) freshwater on the planet and has much to do with biodiversity, human and ecosystem health, mineral cycling, geohazards, etc. - akin to understanding the vastness and variability within the oceans.
- How is water stored and accessed beyond the typical soil depths--over large spatial scales?
- NSG can help us understand and monitor aquifer recharge and groundwater flow more generally.
- How are pathways for lateral runoff activated in variable media and how can we model them using ground-penetrating radar (GPR)?
- How can improvements to near-surfacegeophysics be incorporated into a better understanding of the saturated unconsolidated and upper consolidated earth materials.
- How can minivibe seismic combined with micro seismic and PBO GPS networks better define subsurface hydrologic flow barriers?
- How can near-surface geophysics better inform groundwater flow processes?
- How can we create hydrogeological models directly from borehole information and geophysical resistivity models using the known uncertainties.
- How can we use geophysical imaging methods to efficiently and cost-effectively assess and monitor potable aquifers?
- How do changes in groundwater affect the water cycle and extreme events?
- Where is groundwater distributed and what are the sources of recharge and discharge rates?
- How does groundwater flow and inter-connectedness relate to subsurface properties?
- How does groundwater use impact saltwater intrusion, and are offshore groundwater resources exploitable?
- How much are our groundwater resources being depleted?
- How does water circulate within the Earth?
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Climate Change

- Better coordination could greatly help studies of how groundwater is changing in response to climate change. Many such surveys are undertaken by scientists who are not primarily geophysicists and so could benefit from better training and equipment.

- can near surface geophysical methods be used to determine anthropogenic effects on soil/ ground water & climate change? What aspect of geophysical methods can we apply?
- Areas in high latitudes are warming at faster rates than many other parts of the world. Freshwater chemistry is influenced significantly by terrestrial drainage. Permafrost thaw will impact the routing and residence time of infiltrating precipitation in turn influencing surface water chemistry. How will thawing of permafrost change freshwater systems in the high latitudes?
- As lands become more arid how does it impact the water and CO2 cycle.
- Does fresh water input from melting ice stop the ocean thermohaline circulation?
- How can we use NSG to understand new patterns and predict water cycle behaviors such as new flood hydrographs, as climate change drives changes in temperature and precipitation regimes, compounded by changes in land surfaces (e.g., increased impermeable surfaces due to development, different vegetation communities), etc
- How are hydrologic systems changing and what are the impacts to the distribution of water within the subsurface and it's influence on biogeochemical reactions related to greenhouse gas emissions, carbon cycling, mineralization, metal transport, and nutrient availability.
- changing pressure from glaciers, meltwater and hydrology filling local reservoirs and irrigation interacting with local climate through evaporation/precipitation
- How can hazards to human populations due to future changes in water distribution be mitigated, if possible at all?
- How do changes in climate (temperature, precipitation, timing of precipitation) on in-stream water availability? How can such changes in surface and groundwater be identified for better water use/rights planning?
- How do changes in climate process affect access to clean water sources?
- How do climate-related changes in uppermost soil layers change the partitioning of water infiltration vs run-off?
- How do fluids cycle through the near surface and what are the implications for strategies to deal with climate change?
- How do geological processes contrast water reservoir storage shortness owing to climate changes?
- How does global hydrologic cycle affect climate change?
- How does the water cycle and water vapor in the atmosphere factor in to any potential climate?
- How moisture is "transported" between the earth and the atmosphere and how this effects the climate in the long term, yet also the weather in the short term.
- How will global warming change the distribution of water compared to mankind's needs?
- How does changes in the NS affect climate change specifically hydro-geology?
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GW-SW

- Understanding groundwater and surface-water exchange dynamics
- Identification of near surface anomalies and unsaturated/saturated zone boundaries
- Can passive electrical geophysical methods map and quantify net streamflow gains and losses.
- How does a changing climate modify runoff processes and surface-groundwater exchange, particularly in high-latitude/cold environments where snow and permafrost have been historically prevalent?
- How does groundwater / surface water interaction impact riparian and coastal environments.

Recharge

- How severely will changes in annual precipitation/snow pack impact groundwater levels in overdrafted aquifers?

- How can groundwater recharge practices be optimized?
- How do changes in the distribution and timing of recharge impact headwater streams, biodiversity and downstream ecosystems.
- How do changing precipitation patterns modify the distribution of near-surface soil moisture and its feedback into the overall water cycle?
- What factors determine the locations and quantities of natural recharge.
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Water Quality/Contamination

- how do we detect contaminant plumes
- groundwater contamination issues. human-induced hazards (pollution, engineering) in addition to geohazards.
- How groundwater movements along fault are affected water pollution
- How increase on e.g. sea level or erosion (due to e.g.: intense fires, deforestation, human control on surface currents, among others) influence good quality surface water availability?
- How do geologic structures control groundwater susceptibility to anthropogenic contaminants?
- How can groundwater contaminant plumes be traced without expensive methods like coring and groundwater sampling?
- How does underlying lithology influence the distribution of hot spots and hot moments of contaminated groundwater?

Ecohydrology

- How can we monitor underground interactions between plants, soil, and soil organisms, and how do these interactions affect biogeochemical cycles and biodiversity?
- How do plant-driven portions of the hydrologic cycle feed back to climate under global change?
- How do the atmosphere, shallow soil layer, and vegetation interact under conditions of rapid change to/from drought or flood conditions?

Topography/Geomorphology

- how does near surface geophysical structure buffer or exacerbate drought impacts on ecosystems?
- How topographic change affects water level.
- How does the water cycle relate to topographic change?
- Subsidence due to fluid withdraw.
- Are there predictable tipping points associated with the changing water cycle that will result in rapid and significant change in hillslope and fluvial geomorphic processes with concurrent implications to biogeochemical cycles and biodiversity?
- How do temporal changes in streambed morphology affect the water cycle over time?

Earth System/Interdisciplinary

- How do Earth processes (fluids, heat, chemistry) interact between atmosphere/hydrosphere/critical zone/deep Earth?
- How does the energy budget and water cycle integrate on the land surface?
- How dominant are the roles of water, energy and carbon cycles in near-surface geophysics?
- How do changes in water cycles affect water-related hazards at both local and global scales?
- How does the water cycle affect seismicity and how does seismicity affect the the flow and level of groundwater?
- A lack of adequate information about and resolution of ocean mixed layer, PBL, and air-sea flux characteristics is a significant limiting factor in the simulation and prediction of most weather and climate variations that originate over the ocean, ranging from the MJO, ENSO, and cyclonic

storms in the tropics to sea ice formation and distribution at high latitudes, yet there has been no organized effort to create a sustained global observing system. What characteristics would such a system require, and how does the lack of such a system impact science?

- How are the sources of Earth's water cycle changing?
- How do changes in the Earth's water cycle affect local water cycles?
- How do different cycles, e.g. water and biogeochemical, interact and drive each other?
- What are the observable effects of changes in Earth's water cycle?
- How do we measure Global changes in the Water Cycle from short time scales to decade time scales?

Land use change

- How can we better predict and monitor the impacts of land use, development, and climate change on hydrological systems at a range of scales.

Soil Science, Agriculture, and Geosphere-Atmosphere Interactions

Soil Science

- How can we monitor underground interactions between plants, soil, and soil organisms, and how do these interactions affect biogeochemical cycles and biodiversity?
- How can NSG methods be best used to determine anthropogenic effects on soil/ ground water & climate change?
- How do microbial processes influence climate?
- What are the effects of climate change on soil sustainability?
- What are the most critical elements of interplay between greenhouse gasses (CH4, CO2, N2O, etc), soil properties, and surface hydrology, in the context of climate change?
- How do wildfires change soil properties making areas more prone to mudslides? How can we predict those changes?
- How do climate-related changes in uppermost soil layers change the partitioning of water infiltration vs run-off?

Agriculture

- How can we quantify the consequences of drought hazards (rainfall deficits, temperature-enhanced evapotranspiration) on the exposure (rainfed crops, irrigated areas) and societal vulnerability (decrease in crop productivity) in unfavorable zones such as the Mediterranean region?
- How does the near-surface soil moisture be precisely estimated on a regional scale, so that water use for crop production can be optimized/reduced/managed?

Geosphere-Atmosphere Interactions

- What are changes within the shallow subsurface telling us about regional and/or global climate change?
- How do air-sea exchange processes influence climate?
- What is the response of coastal margins to climate change and land use change - with implication to coastal ecosystems and communities?
- How do feedbacks and connectivity among the biosphere, atmosphere/climate, critical zone and surface processes moderate these systems' responses to perturbation?
- How do the atmosphere, shallow soil layer, and vegetation interact under conditions of rapid change to/from drought or flood conditions?

- How do near-surface processes influence atmospheric chemistry and how does climate change accelerate or slow-down such interactions?

- How do changing precipitation patterns modify the distribution of near-surface soil moisture and its feedback into the overall water cycle?