Theme 6
Aerosol-cloud-precipitation interactions and radiative feedbacks

Julia Schmale, EPFL, Switzerland
Martin Radenz, TROPOS, Germany
Nina Maherndl, TU Delft, Netherlands
Jessie Creamean, CSU, USA
Markus Frey, BAS, UK
and the whole Theme 6 team

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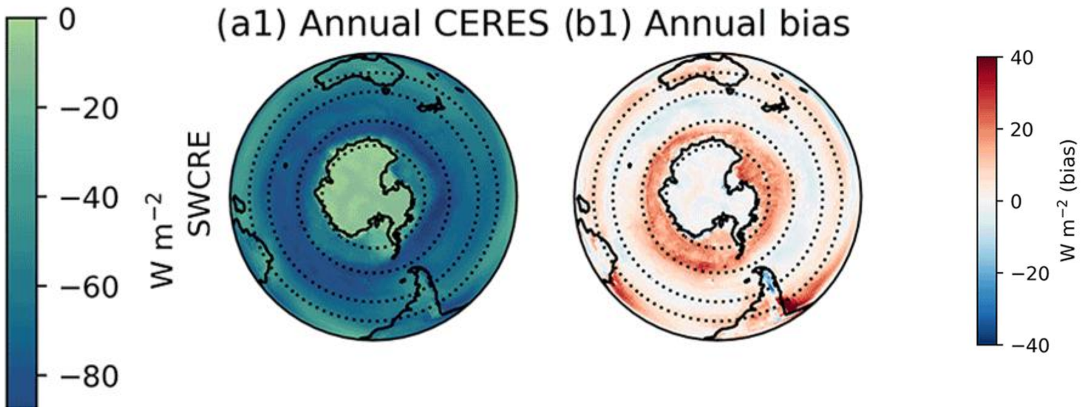
Motivation
Aerosol-cloud-precipitation interactions and radiative feedbacks?

- Significant **variability and uncertainty in climate predictions** originates from the simulated cloud cover over the Southern Ocean.
- Clouds have a marked impact on the **surface energy balance.**
- Clouds and precipitation have a marked influence on **the surface mass balance**

Short-wave cloud radiative effect



ACCESS-AM2 radiation and cloud biases against CERES and MODIS

- SW radiative forcing up to 20 W/m^2
- Liquid water path bias up to -100 g/m^2 **(Low bias)**
- Ice water path bias up to + 100 g/m^2 **(High bias)**

Fiddes et al., 2022, ACP

Research needs - Knowledge Gaps (KG)

KG1 - Quantifying aerosol sources, properties and processes

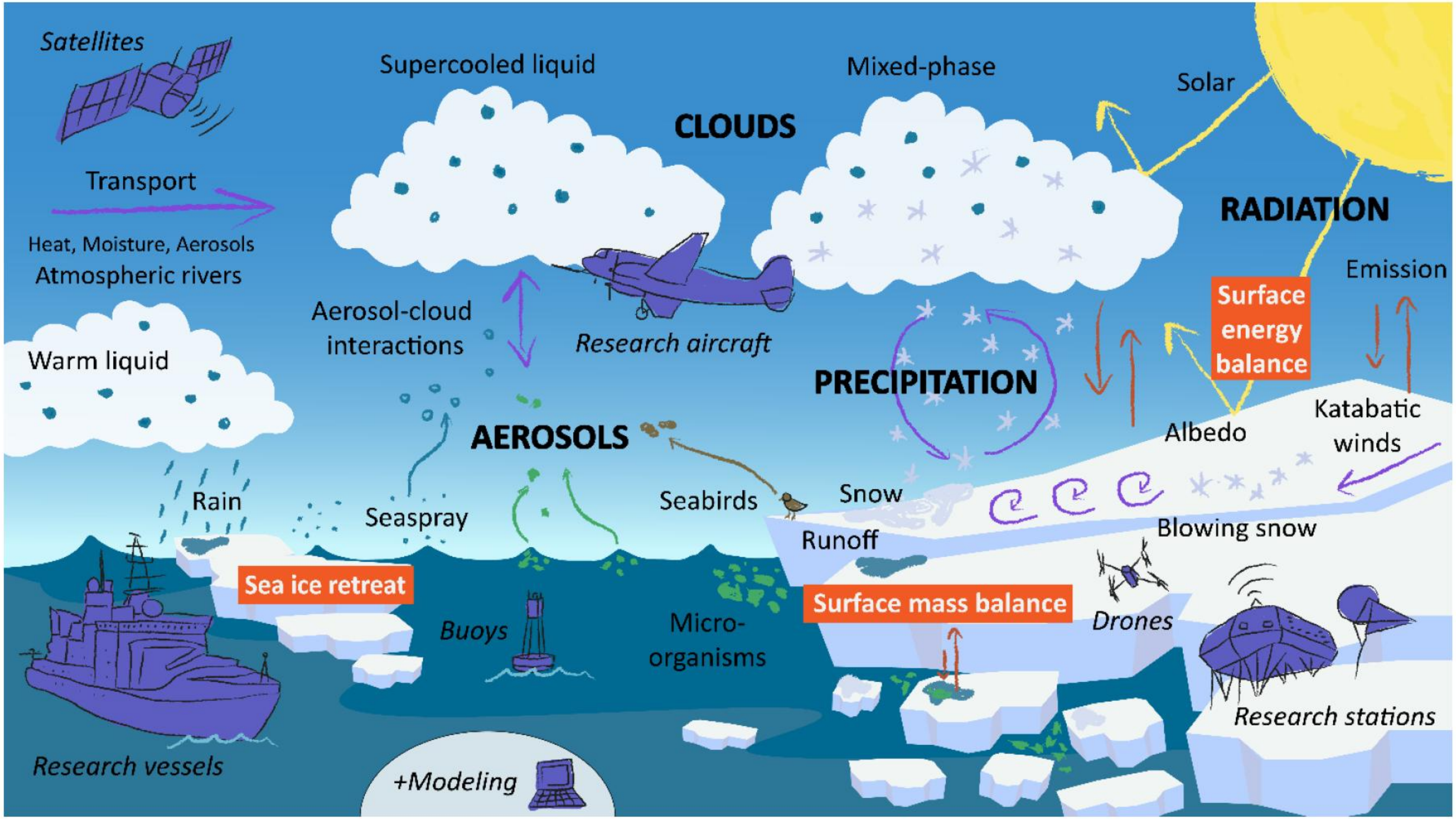
KG2 - Characterizing cloud and precipitation properties

KG3 - Understanding the surface energy budget and boundary layer structure

KG4 - Constraining cloud-circulation coupling

KG5 - Advancing the modelling of clouds and aerosols in the Southern Ocean Antarctic Continent region

Coupled atmosphere ocean ice climate system



Observing strategies and essential variables
Supported by modeling

- **Synchronized year-round** observations on
  - Research vessels, stations, from satellites
- Multilevel approach to collected variables
  - **Priority 1**: baseline, year-round, across all platforms and locations
  - **Priority 2**: more details, particularly in the vertical dimension (fewer sites, potentially during IOPs)
  - **Priority 3**: high impact observations at dedicated supersites (expeditions, voyages, research flights)
- Modeling activities: validate models, intercompare models; case studies for process understanding; interpret observations

Recommendations / Summary

- integrated ensemble of in situ and remote sensing observations targeted specifically at improving numerical representation and constraining model uncertainties
- We emphasize the need specifically for vertical observations at low-level cloud altitude along latitudinal gradients
- covering East and West Antarctica as well as the peninsula
- Theme 6 will mitigate the fact that at present structured data to constrain aerosol-cloud-precipitation processes and radiative impacts are virtually non-existent.

For break out

KG1 Quantifying aerosol sources, properties and processes

- Aerosol observations across multiple platforms spanning the full SOAC annual cycle are vital for assessing the aerosol-cloud-precipitation interactions and radiative feedbacks affecting Antarctic ice-sheet mass loss and recent dramatic sea-ice decline.
- Key open questions are
  - The sources of aerosols
  - How the aerosol and specifically CCN and INP populations are responding to changes in the SOAC system through shifts in aerosol precursors and processes (e.g., open ocean and sea-ice biological activity, long range transport, snow and ice loss, precipitation).
  - Vertical distribution of aerosols
- Systematic observations of both primary and secondary aerosol properties, their formation, and transport processes from ground-based stations, shipborne and airborne platforms, and remote sensing are urgently needed to improve their spatiotemporal representation in models.

KG2 Characterizing cloud and precipitation properties

- A better understanding of the interplay of INPs, SIP, and dynamics in the formation of ice in clouds is urgently needed to constrain the impact on the radiative budget.
- To improve models, the microphysical pathways leading to precipitation need to be characterised and the amount and phase reaching the surface quantified.
- This regional variability resulting from distant versus local moisture transport and orography must be quantitatively understood.
- Hence, quantifying liquid precipitation and its location is extremely important, especially for its effects on snow and ice-covered surfaces.

KG3 Understanding the surface energy budget and boundary layer structure

- Improving cloud and atmosphere representations in models remains central to advancing predictions of energetic processes essential to SOAC climate evolution.
- The scarcity of year-round SEB and ABL observations representing the diverse conditions of the SOAC severely limits the ability to constrain these interacting processes and hinders model validation.
- Overall, improved representations of interacting energy and mass budget processes that are intimately tied to aerosol-cloud-precipitation interactions is critical for advancing predictive capabilities of Antarctic ice sheets and sea ice.

KG4 Constraining cloud-circulation coupling

- Cloud-circulation coupling processes are especially critical during extreme weather events, and specifically if these occur in close succession.
- Major open questions remain on how clouds interact with circulation patterns and influence ARs, WCBs and heat waves, as well as how cloud-circulation coupling processes will evolve with global warming.

KG5 Advancing the modelling of clouds and aerosols over the Southern Ocean and Antarctic Continent (SOAC)

- Targeted modeling studies using a hierarchy of models, ranging from Large Eddy Simulation models to Earth System Models, are essential for reducing persistent cloud and aerosol biases over the SOAC and for increasing confidence in Earth system model projections over the region.
- Key research gaps
  - representation of mixed-phase and ice clouds.
  - insufficient parameterisations of aerosol sources and processes in this region.
- Research is needed to identify the most critical processes that must be represented in models as well as to set up modeling frameworks and intercomparison exercises to robustly evaluate models and tune free parameters against observational references of SOAC clouds.

Essential variables

Theme 6: Essential variables

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Topic	Priority 1	Priority 2	Priority 3	Knowledge gap
Aerosol	**Physical properties** Total particle number concentration (> 10 nm) Particle number size distribution (10 nm to 10 µm)	Particle number concentration (> 3 nm) Particle number size distribution (3 nm to 20 µm) Optical properties CCN number concentration and hygroscopicity INP number concentration (-10, -15, -20°C)	Particle number size distribution (1 to 20 nm) INP number concentration (online) Hygroscopicity (sub-saturated) Cloud residual number size distribution Particle fluxes (at the surface and airborne)	**Quantifying aerosol sources, properties and processes (KG 1, 3, 4)**
	Chemical composition on total suspended particle (TSP) including major ions, organic carbon/elemental carbon	**Chemical composition** Size-resolved composition Major inorganics (TSP or PM10, PM2.5, PM1) Methane sulfonic acid (TSP or PM10, PM2.5, PM1) **Vertical distribution from surface to above first cloud layer** in situ particle number concentration in situ particle number size distribution in situ particle chemical composition Optical properties (remote sensing)	**Aerosol chemical composition** Organics and marine carbohydrates (TSP or PM10, PM2.5, PM1) Online aerosol, trace gas and ion chemical composition Fluxes of sea spray aerosols and VOCs	
Gases	Water vapour	**gases** Sulfur species Volatile organic compounds Iodine oxide Ozone (at the surface) ammonia, sulfuric acid, methane sulfonic acid	stable water isoptopes (ground and vertical profile) ozone (vertical profiles) Nitrogen species (amines, amides...)	
Blowing Snow		particle size distribution	images, velocity, habit	
Biology	In situ sea-surface Chlorophyll-a General description of nearby animal population (e.g. bird colonies)	particulate organic carbon and total organic carbon of surface sea water taxonomic groups of phytoplankton	Sea-surface microlayer samples Ocean surface mixed-layer samples(<1 m depth)	

Theme 6: Essential variables

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Biology	General description of nearby animal population (e.g. bird colonies)	organic carbon of surface sea water taxonomic groups of phytoplankton	Ocean surface mixed-layer samples(<1 m depth)	
Clouds	**Remote Sensing** Cloud cover Fog identification Cloud base height Vertical profile of backscatter	**Remote sensing** Cloud phase, LWC, LWP, IWC, IWP (radar, lidar, radiometer) Cloud particle vertical velocity	**Remote sensing** Multi-frequency / dual-polarisatioon cloud radar **In situ (balloons, aircraft)** Cloud particle size distribution Cloud particle images	**Determining cloud and precipitation properties and moisture sources (KG 2, 4)**
Precipitation	**At surface** daily total, hourly rate, phase	Vertical profile Size distribution	**Sampling** chemical composition, INP and stable water isotopes of falling rain and snow, chemical composition, INP, salinity, pH of surface snow	
Meteorology	**At 2 m height** Barometric pressure Air temperature Air relative humidity	**Daily in situ vertical profile of** Barometric pressure Temperature Relative humidity Horizontal wind speed Wind direction	**In situ vertical profiles with high spatial and temporal coverage of** Barometric pressure Temperature Relative humidity 3D wind	**Understanding the surface energy budget and boundary layer structure (KG 3)** **Constraining cloud-circulation coupling (KG4)**
	At 10 m height Horizontal wind speed Wind direction	**At surface** 3D wind speed Turbulent fluxes (momentum, sensible and latent heat) **Remote sensing** Vertical profiles of horizontal and vertical wind	**At multiple heights on mast** 3D wind speed Turbulent fluxes (momentum, sensible and latent heat)	
Radiation	**At surface** Total and diffuse	**At surface** Longwave up-/downward Shortwave up-/downward Direct Spectral	**Vertical profiles** Longwave up-/downward Shortwave up-/downward	