Rising subsurface water storage in North American Arctic and Subarctic river basins inferred from baseflow recession

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Streamflow trends indicate that subsurface water storage is increasing ~3 mm per decade in Arctic and Subarctic river basins

Overview

Permafrost is thawing as the climate warms[1,2], which affects surface hydrology[3], but direct measurements of permafrost active layer thickness (ALT) are limited to a few hundred sites located primarily in the Northern Hemisphere supported by the Circumpolar Active Layer Monitoring (CALM) program[1]. To address the sparsity of direct ALT measurements, we developed a method to estimate ALT trends from streamflow measurements[3], which integrate changes in active layer water storage over broad areas and in regions that lack direct ALT measurements. We applied the method to river basins located along a permafrost extent gradient in North America (Figure 2) and compared predicted trends in soil water storage with Gravity Recovery and Climate Experiment (GRACE) terrestrial water storage.

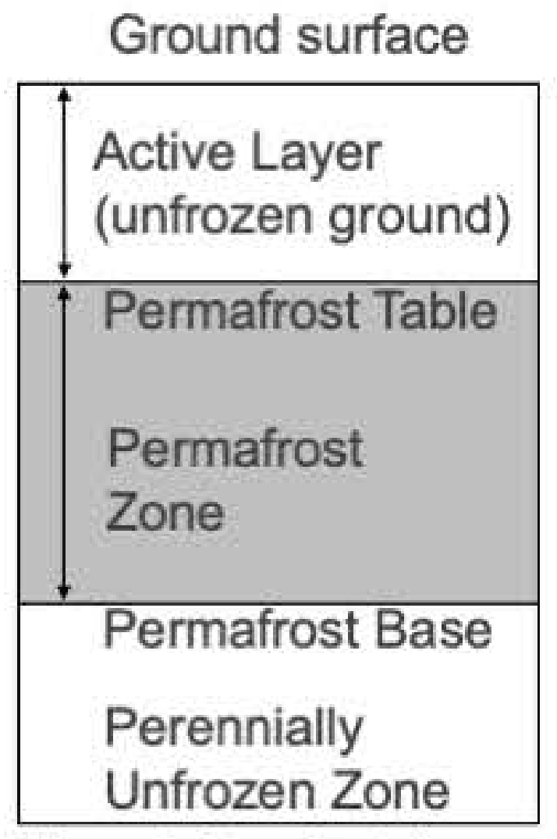


Figure 1. Permafrost diagram (after Kurylyk *et al* 2014).

Estimating soil water storage from baseflow

The rate of change of streamflow is fundamentally linked to the amount of water stored in catchment soils[4]. As permafrost thaws, the "active layer" of thawed soil thickens, which increases its water storage capacity (Figure 3). We estimated changes in permafrost active layer water storage using baseflow recession analysis, which is an inverse method that solves the groundwater flow equation by curve-fitting to streamflow recession events[3,4] (Figure 3b). Streamflow data for ten gaged river basins in the Northwest American Arctic and Subarctic with at least one CALM site were used in the analysis (Figure 2).

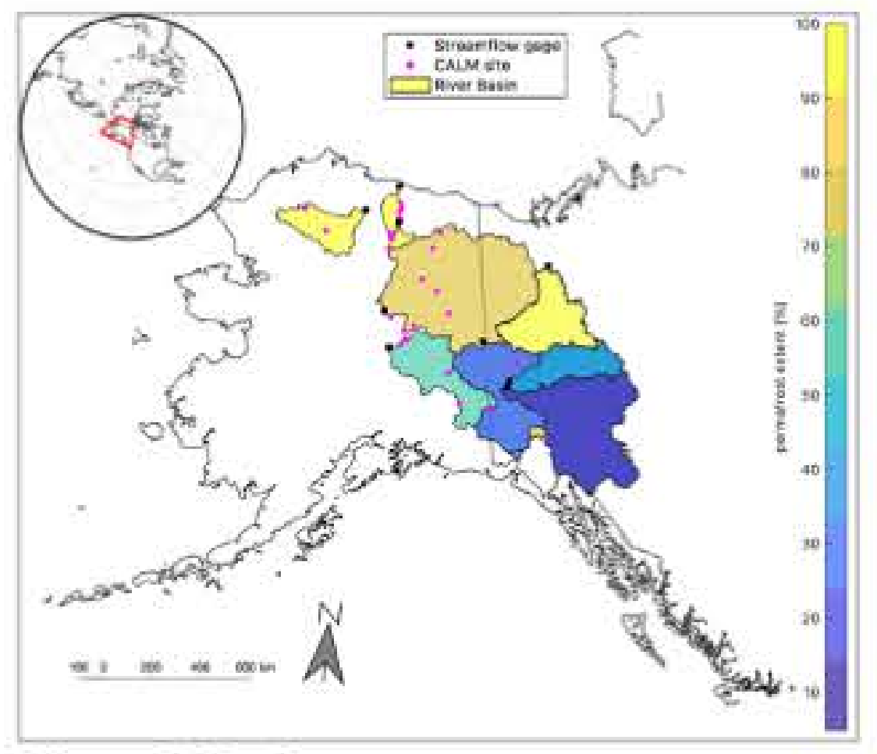


Figure 2. Study area map.

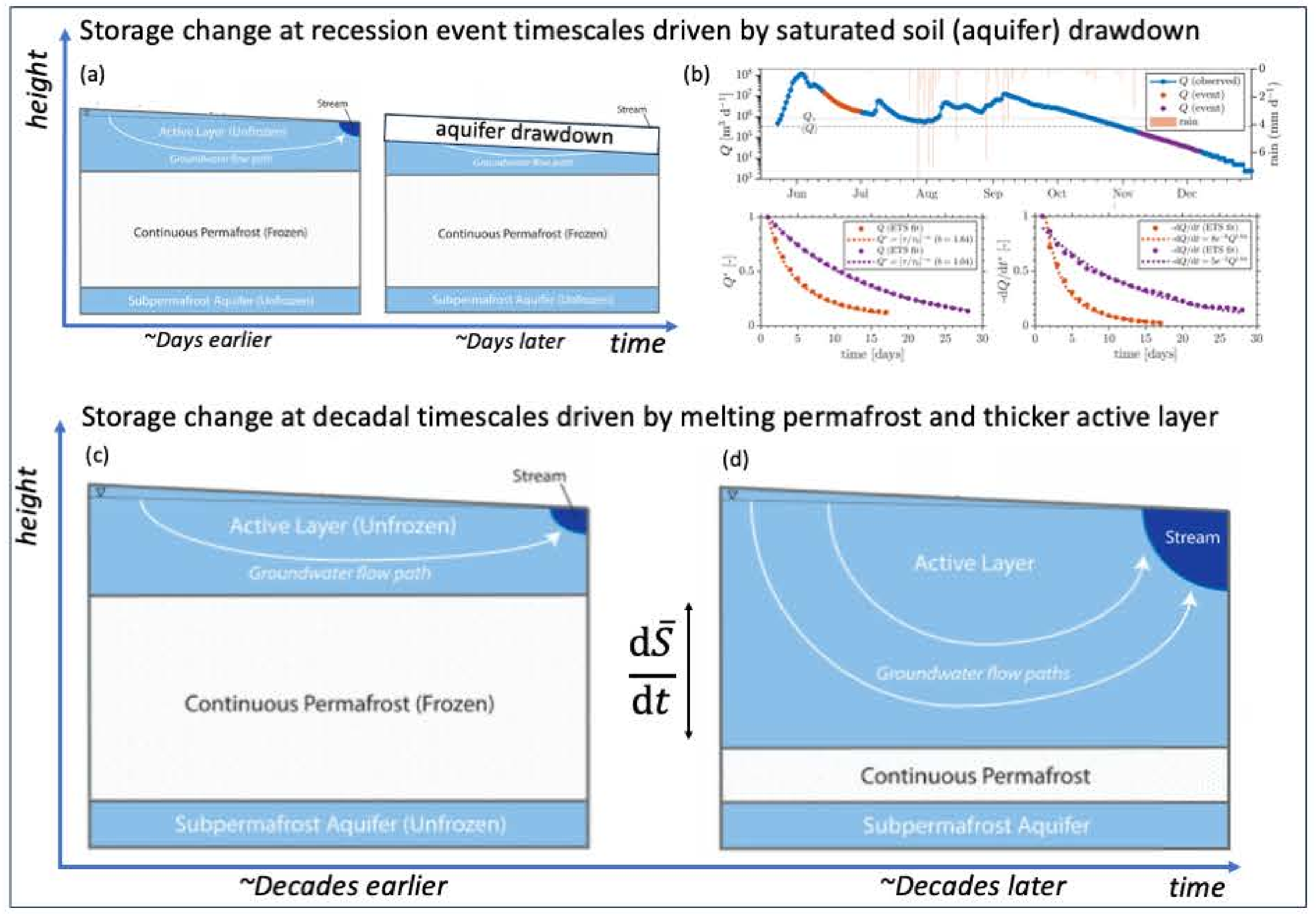


Figure 3. Conceptual model of water storage changes in melting permafrost soils (after *Evans et al. 2020)*. (a) Saturated soil thickness drawdown at recession event timescales (~daily to weekly) driven by baseflow delivery to streams. (b) Example baseflow recession analysis used to estimate saturated aquifer thickness. (c-d) Saturated soil thickness over ~decadal timescales driven by melting permafrost and thickening active layer. Parameters estimated from populations of curve fits to recession events measured over multi-decadal periods were used to estimate trends in soil water storage $d\bar{S}/dt$. These baseflow-inferred trends were compared with change in soil water storage capacity inferred from active layer thickness measured at CALM sites, and to trends in GRACE terrestrial water storage.

Storage trends from baseflow analysis compared with ALT trends from CALM sites (1990–2020)

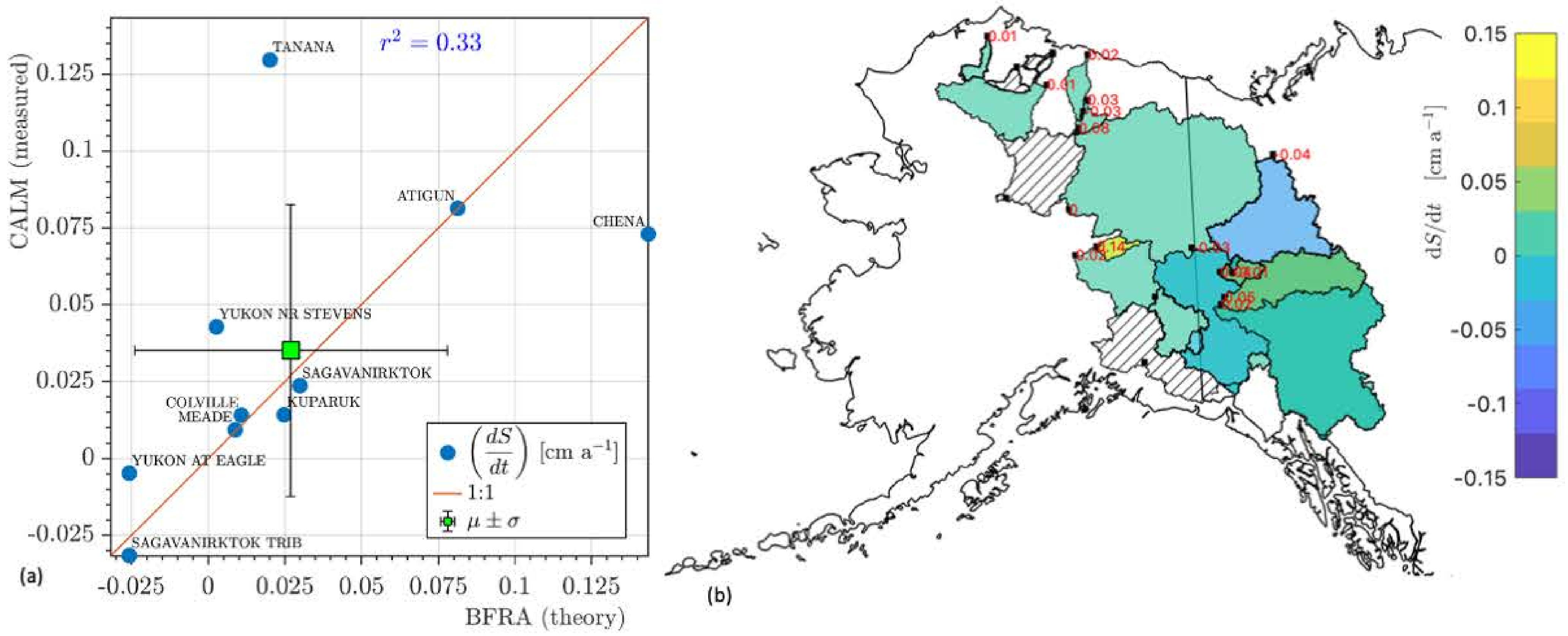


Figure 4. (a) Linear trends in active groundwater layer storage predicted with baseflow recession analysis (BFRA) compared with trends in active layer thickness (ALT) storage capacity from field measurements at Circumpolar Active Layer Monitoring (CALM)[1] sites for ten river basins with >10 years of overlapping streamflow and ALT data. Correlation coefficient (r^2) is printed in upper right. The mean (± one standard deviation) (green square) is 0.03±0.05 cm per year (cm a^{-1}) for basin-scale BFRA predictions and 0.04±0.05 cm a^{-1} for plot-scale CALM measurements. (b) Linear trends in active groundwater layer storage estimated from baseflow recession analysis during the period of available CALM measurements (1990–2020) mapped on fifteen river basin outlines (trend values are also printed in red text). Five basins with <10 years of overlapping streamflow and ALT data omitted from the comparison in (a) are included in (b). Five basins with <10 years of streamflow data are omitted from trend analysis (hatched outlines).

Storage trends from baseflow analysis during the GRACE period (2002–2021)

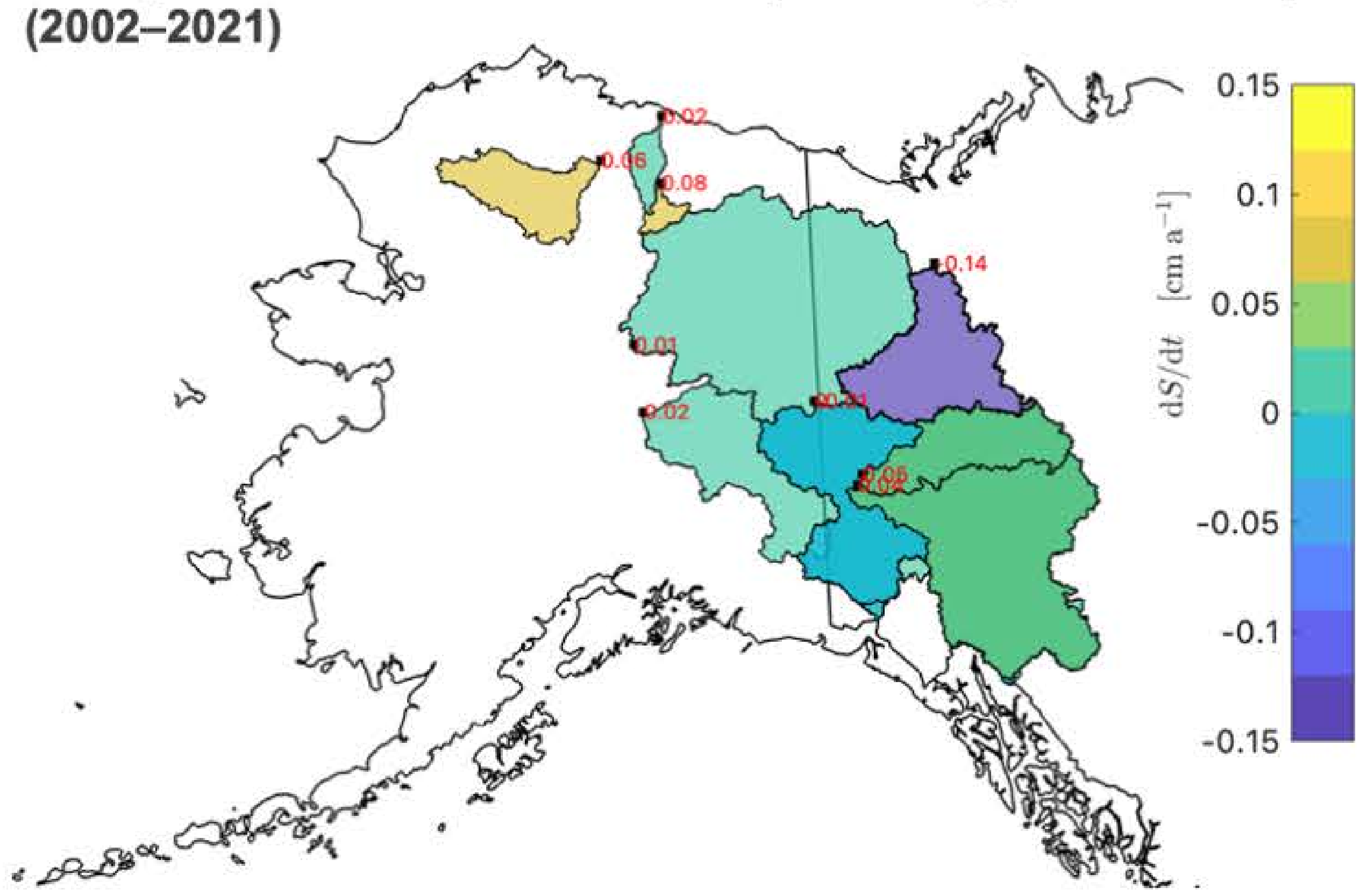
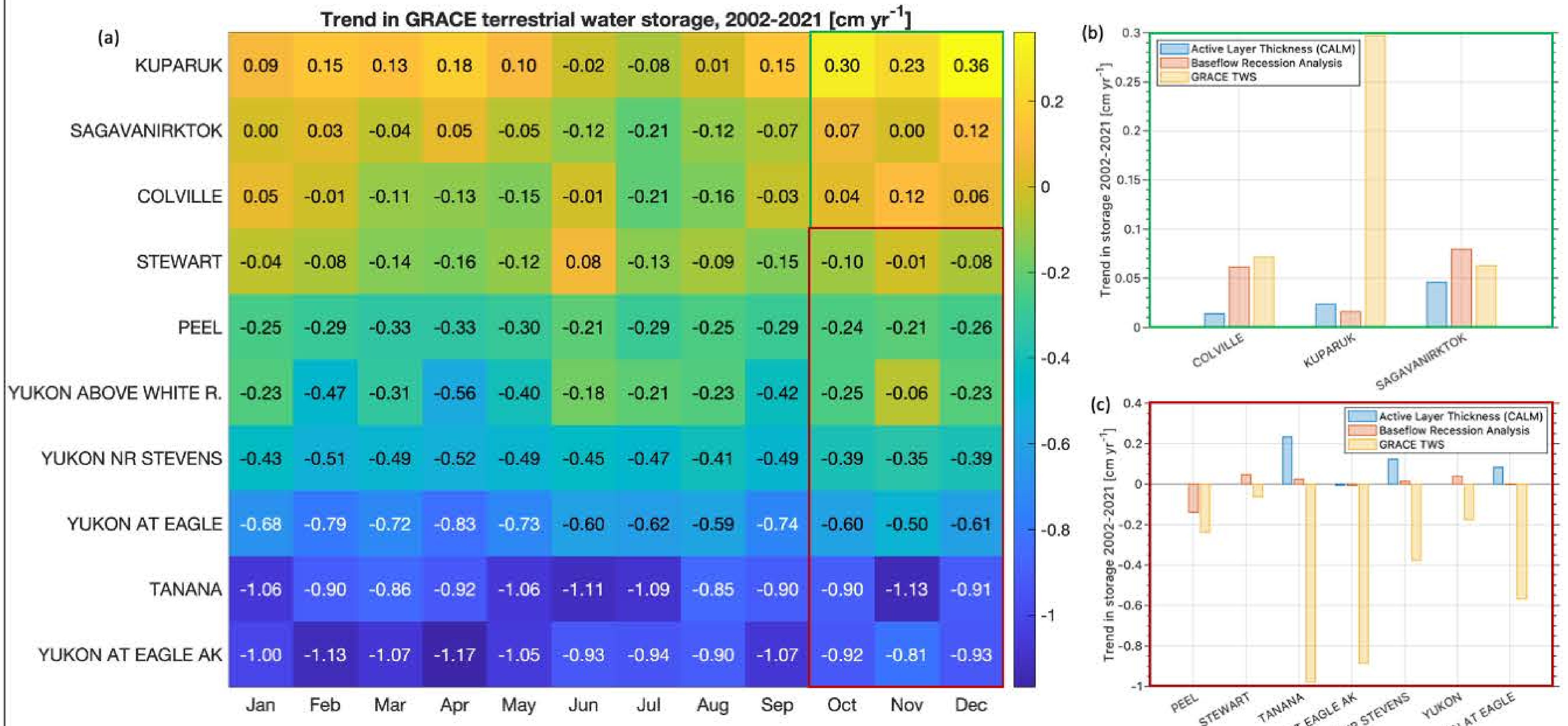


Figure 5. (a) Linear trends in active groundwater layer storage estimated from baseflow recession analysis for the period of available GRACE data (2002–2021) mapped on river basin outlines. The mean (± one standard deviation) dS/dt is 0.03 ±0.03 cm a^{-1} for basin-scale BFRA predictions and 0.07 ±0.08 cm a^{-1} for plot-scale CALM measurements (not shown). Relative to the 1990–2020 period (Figure 4), CALM data indicate an acceleration of active layer thickening and associated storage capacity. In contrast, BFRA predicts no acceleration in active layer water storage, suggesting that increased soil water associated with melted ground ice was lost to evaporation and/or runoff rather than stored in thicker active layer during this time period.



Trend in GRACE terrestrial water storage, 2002-2021 [cm yr^{-1}]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
KUPARUK	0.09	0.15	0.13	0.18	0.10	-0.02	-0.08	0.01	0.15	0.30	0.23	0.36
SAGAVANIRKTOK	0.00	0.03	-0.04	0.05	-0.05	-0.12	-0.21	-0.12	-0.07	0.07	0.00	0.12
COLVILLE	0.05	-0.01	-0.11	-0.13	-0.15	-0.01	-0.21	-0.16	-0.03	0.04	0.12	0.06
STEWART	-0.04	-0.08	-0.14	-0.16	-0.12	0.08	-0.13	-0.09	-0.15	-0.10	-0.01	-0.08
PEEL	-0.25	-0.29	-0.33	-0.33	-0.30	-0.21	-0.29	-0.25	-0.29	-0.24	-0.21	-0.26
YUKON ABOVE WHITE R.	-0.23	-0.47	-0.31	-0.56	-0.40	-0.18	-0.21	-0.23	-0.42	-0.25	-0.06	-0.23
YUKON NR STEVENS	-0.43	-0.51	-0.49	-0.52	-0.49	-0.45	-0.47	-0.41	-0.49	-0.39	-0.35	-0.39
YUKON AT EAGLE	-0.68	-0.79	-0.72	-0.83	-0.73	-0.60	-0.62	-0.59	-0.74	-0.60	-0.50	-0.61
TANANA	-1.06	-0.90	-0.86	-0.92	-1.06	-1.11	-1.09	-0.85	-0.90	-0.90	-1.13	-0.91
YUKON AT EAGLE AK	-1.00	-1.13	-1.07	-1.17	-1.05	-0.93	-0.94	-0.90	-1.07	-0.92	-0.81	-0.93

Figure 6. (a) Trend in monthly GRACE terrestrial water storage anomalies for ten river basins shown in Figure 5 during the period 2002–2021. Basins are ordered from high to low average monthly trend slope (top to bottom). (b-c) Average October–December GRACE trend slope for (b) three river basins on the North Slope of Alaska and (c) seven river basins located south of the North Slope of Alaska, compared with baseflow recession predictions and CALM ALT measurements. Monthly GRACE values averaged in (b) and (c) are indicated by green box and red box in (a), respectively.

Conclusions

- We estimated soil water storage trends using recession analysis of baseflow in river basins located along a permafrost gradient in Northwest America (Figure 2).
- Recession analysis indicates that soil water storage increased about 3 mm per decade between 1990–2020, while field measurements at CALM sites indicate the permafrost active layer increased about 3 cm per decade (Figure 4), corresponding to an average drainable porosity of 10%.
- During 2002–2021 (Figure 5), measurements at CALM sites indicate active layer thickening accelerated to ~7 cm per decade, whereas recession analysis indicates no acceleration in soil water storage, suggesting melted ground ice contributed to increased runoff or evaporation rather than soil water storage.
- GRACE observations indicate terrestrial water storage increased during October–December at three sites on the North Slope of Alaska, consistent with recession analysis predictions and CALM measurements (Figure 6b). At all other sites, GRACE data indicates terrestrial water storage decreased, which is inconsistent with recession analysis predictions and measurements at CALM sites.
- Overall, baseflow recession analysis can provide cost-effective estimates of permafrost thaw rate at broad spatial scales and for regions or times lacking direct field measurements of active layer using available streamflow measurements.

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