Holocene hydroclimate of the Volga Basin recorded in speleothems from the Central and Southern Ural Mountains, Russia

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Volga River Basin: Area Overview and Project Motivation

Opportunities and limitations within a speleothem-based approach

- Largest watershed in Europe; discharge to the Caspian Sea
- Major source of agricultural production; large exports
- Highly susceptible to drought (3 out of 5 years)
- No ‘time-continuous data’ on Holocene Volga discharge (Ward et al., 2007)

Volga River Basin: Area Overview and Project Motivation

Opportunities and limitations within a speleothem-based approach

- Karst terrain is common in the SE sector and along the Ural range, which delineates eastern border

Tash-Astiy, Bashkortostan, Russia

View south from Kinderlinskaya Cave

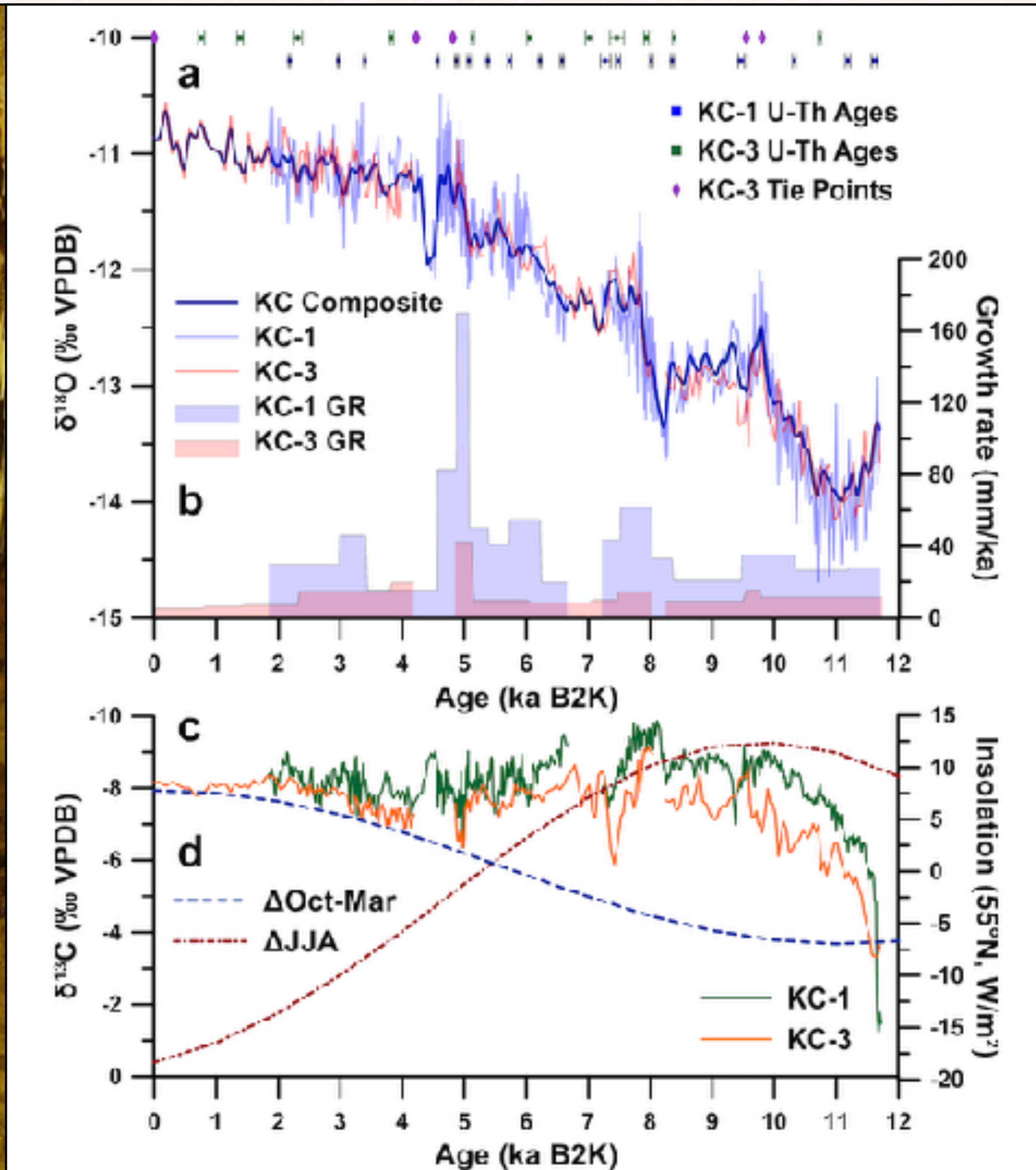
Volga River Basin: Area Overview and Project Motivation

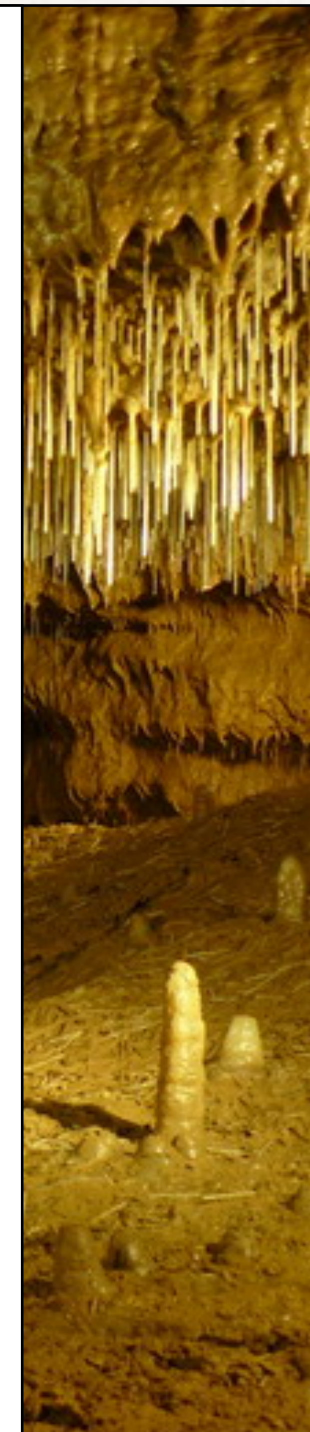
Opportunities and limitations within a speleothem-based approach

- Karst terrain is common in the SE sector and along the Ural range, which delineates eastern border
- Well monitored cave sites, sample replication, high-precision age constraints
- Can we isolate hydroclimate signals from speleothem proxies?
- To what extent can cave records provide a proxy for basin-wide hydroclimate?

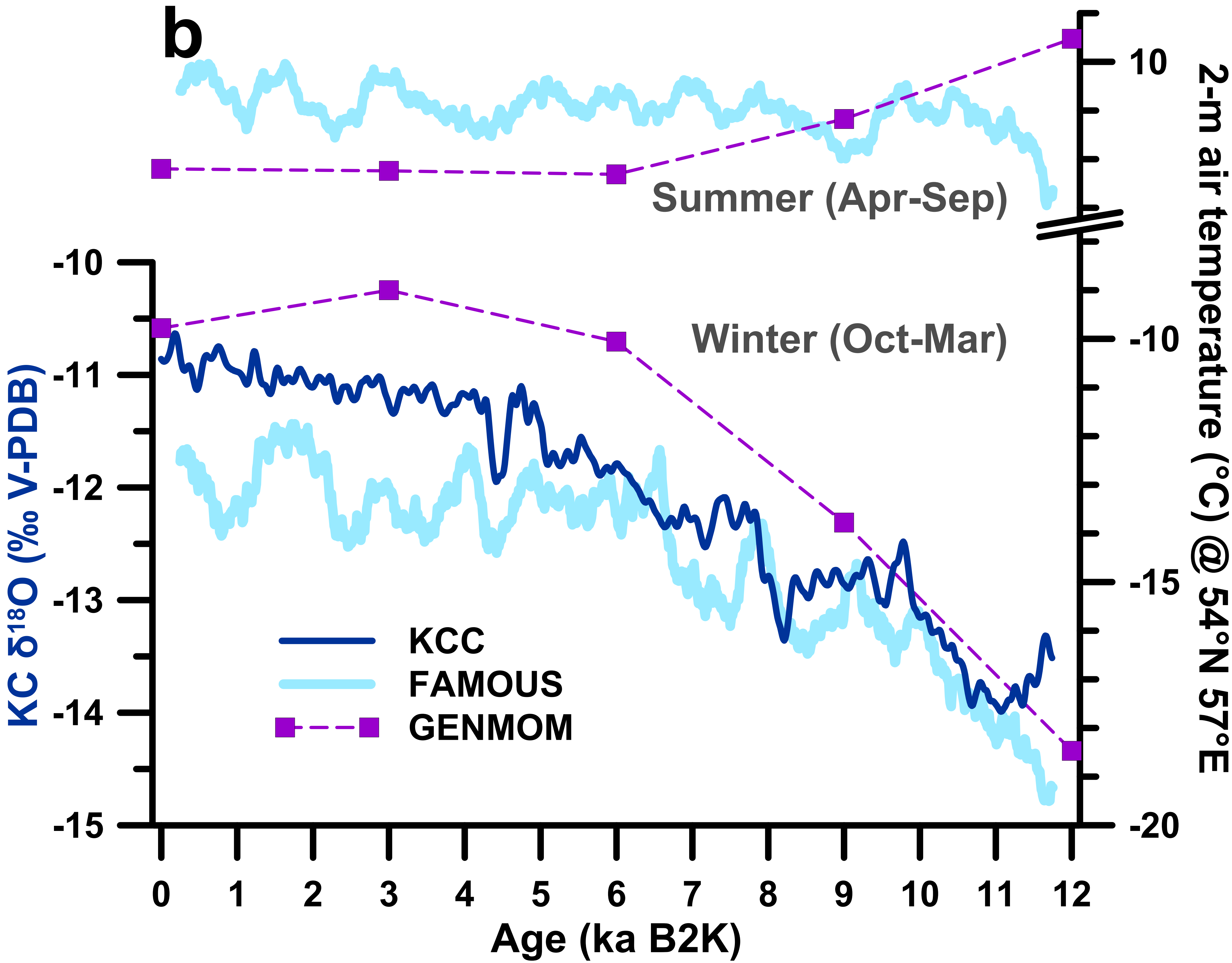
Kinderlinskaya Cave

- Longest cave in the region (>9 km), well decorated dead-end room
- Stable microclimate, monitored over a 6-year interval





Continental Climate Dominated by Winter Trends



Working hypotheses and research goal

- Winter (Oct-Mar) climate inferred from speleothem $\delta^{18}O$, positive correlation with T/P
- Warm-season climate and aquifer dynamics can be inferred from $\delta^{13}C$ and Mg/Ca, respectively; Sr/Ca compared to test for PCP control
- Inferred trends should be replicable between samples/caves, not site-specific noise

GE3 – Geologov-3 Cave

KC – Kinderlinskaya Cave

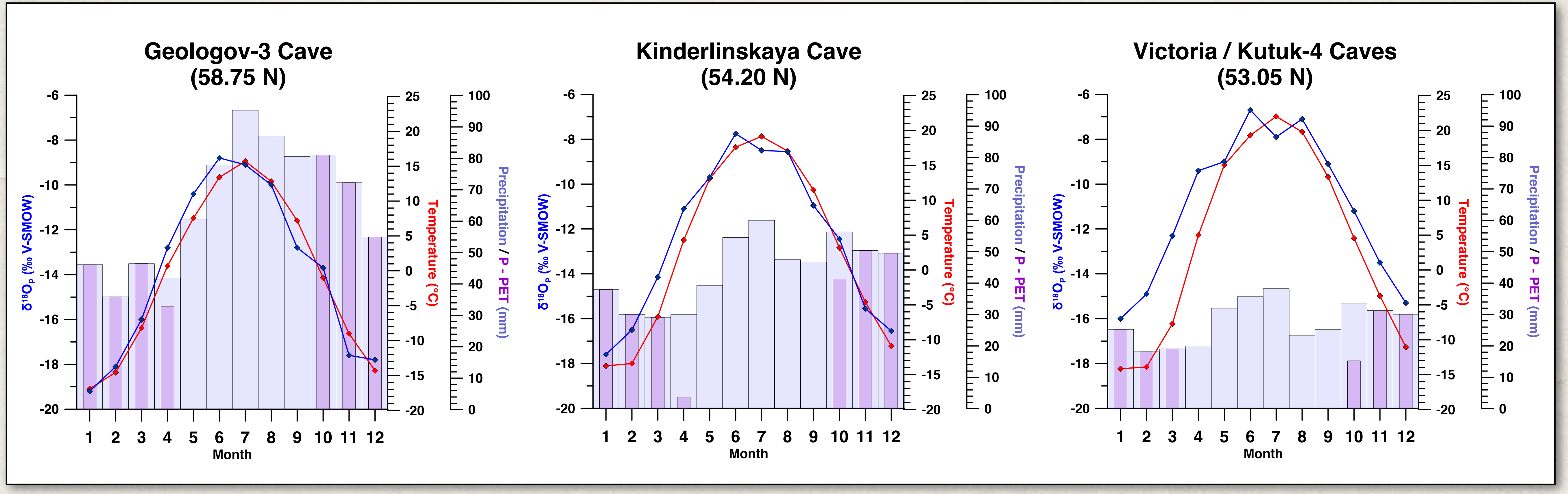
KT-4 – Kutuk-4 Cave

VC – Victoria Cave

Cave Climates, Seasonal Infiltration Bias

Regional context for record interpretation

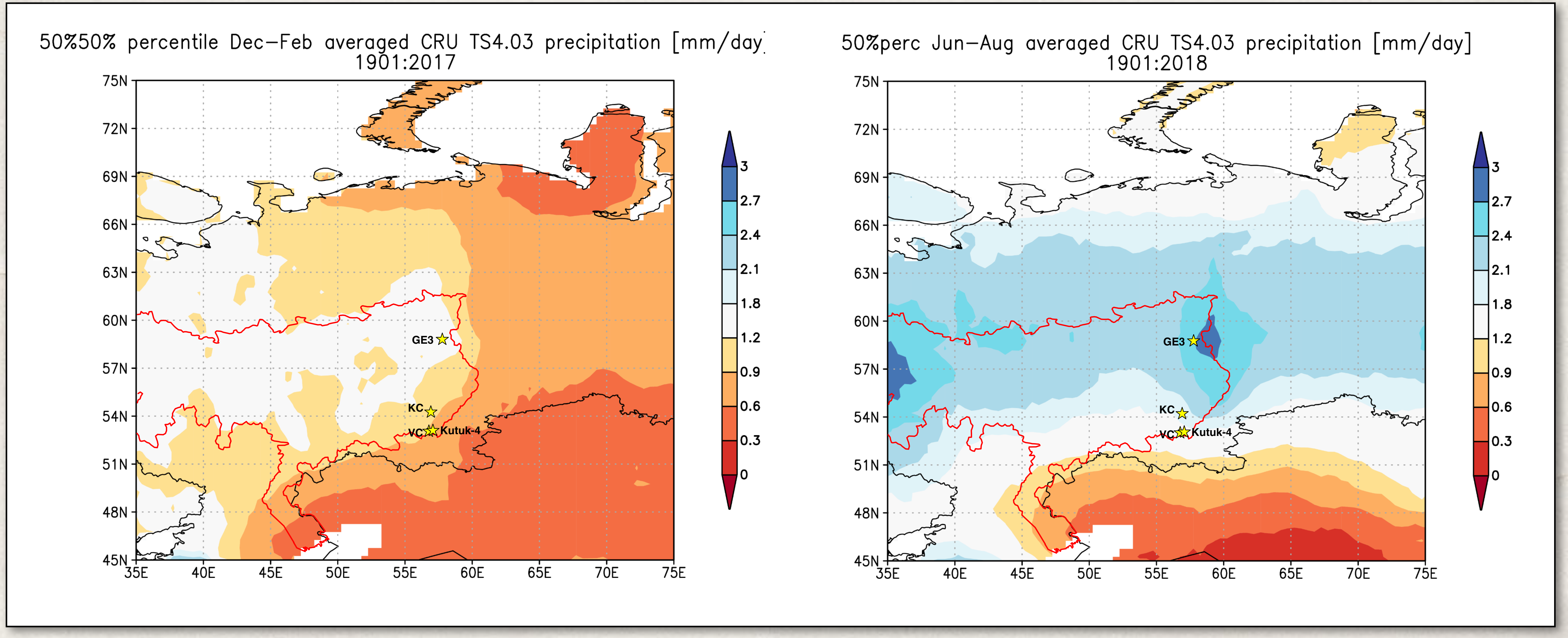
- Winter (Oct-Mar) precipitation contributes the vast majority of infiltration at all cave sites, due to high potential evapotranspiration from Apr–Sep
- Cave-water $\delta^{18}O$ values are within ~0.5‰ of recharge-weighted precipitation
- Trend toward higher summer T and lower summer P from north to south



Watershed Precipitation, Signal Heterogeneity

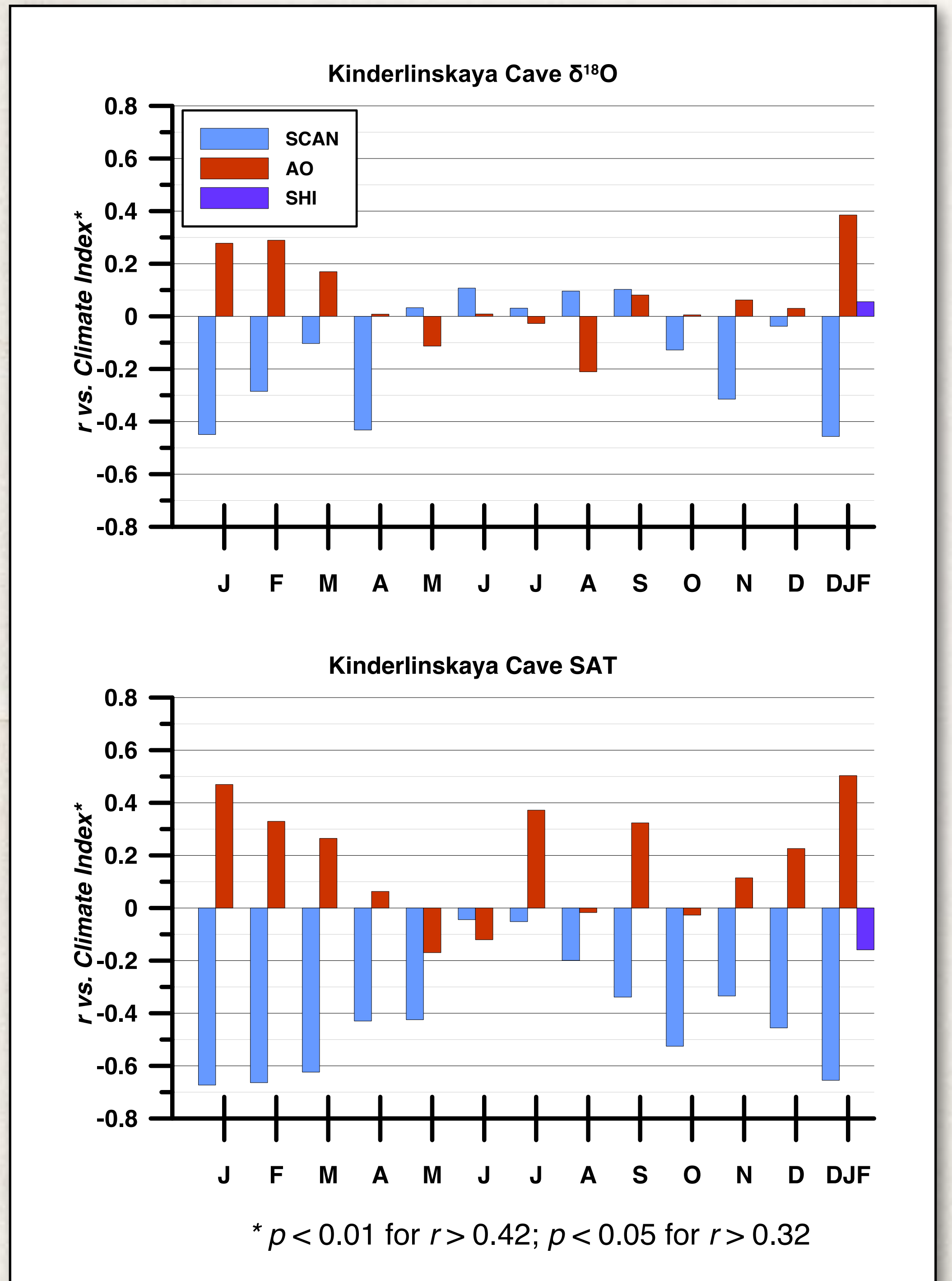
Regional context for record interpretation

- Cave transect spans areas of highest to lowest precipitation in both winter and summer
- Crosses the modern Köppen-Geiger boundaries (Dfc-Dfb-Dfa), based on JJA T



Atmospheric Controls on Winter $\delta^{18}O_P$ and SAT

Regional context for record interpretation

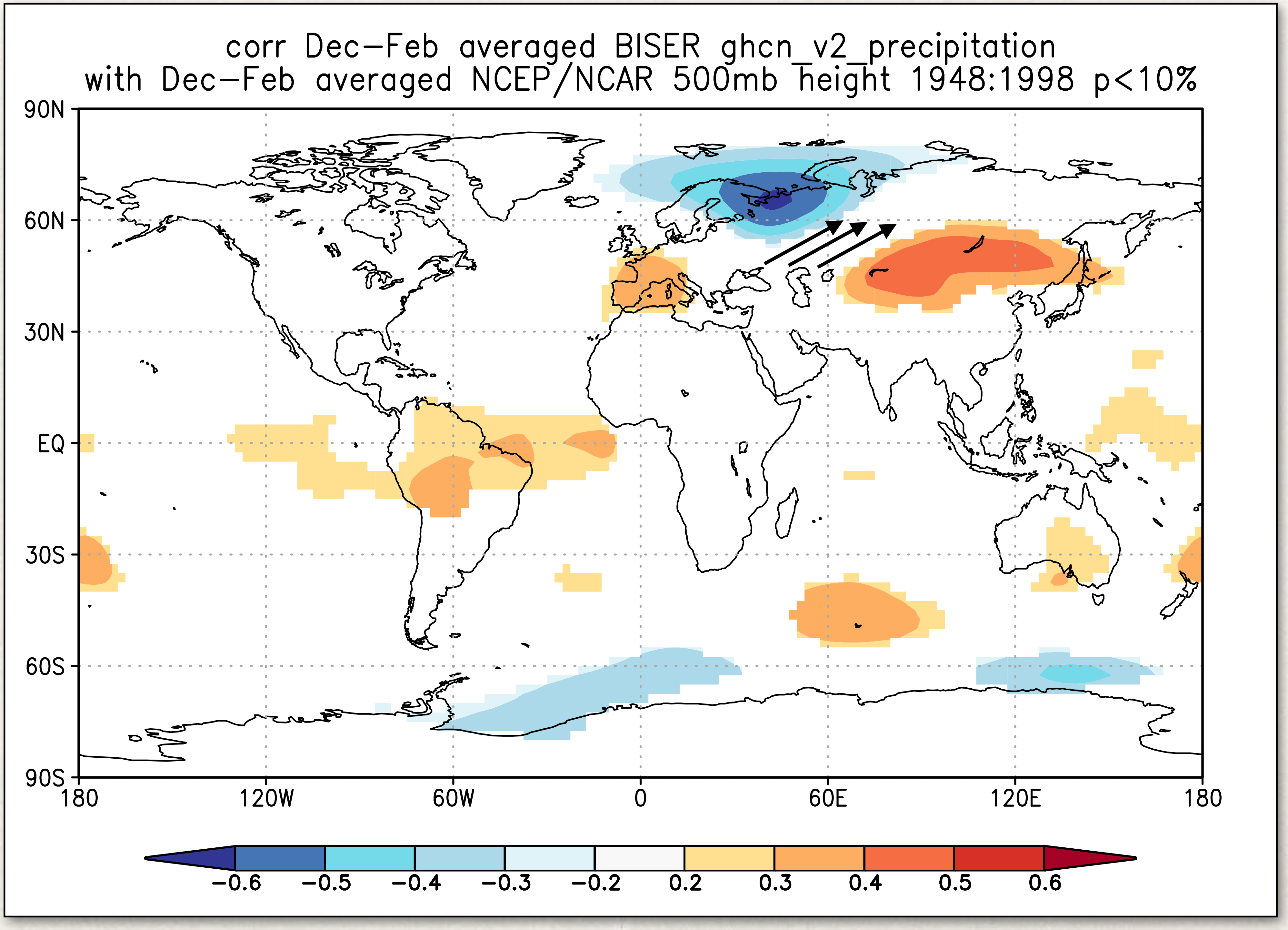


- Winter T and $\delta^{18}O_P$ (anti)correlated with Arctic Oscillation (Scandinavian pattern)
- Lack of correlation during summer is inconsequential, due to seasonal bias in $\delta^{18}O$ signal
- Stronger continental westerlies: milder winter T, higher P, higher $\delta^{18}O$

*Historical $\delta^{18}O_P$ data (1979–2016) from **IsoGSM2** database (Yoshimura et al., 2008); monthly correlations are corroborated by nearby GNIP data (Baker et al., 2017; see SI)

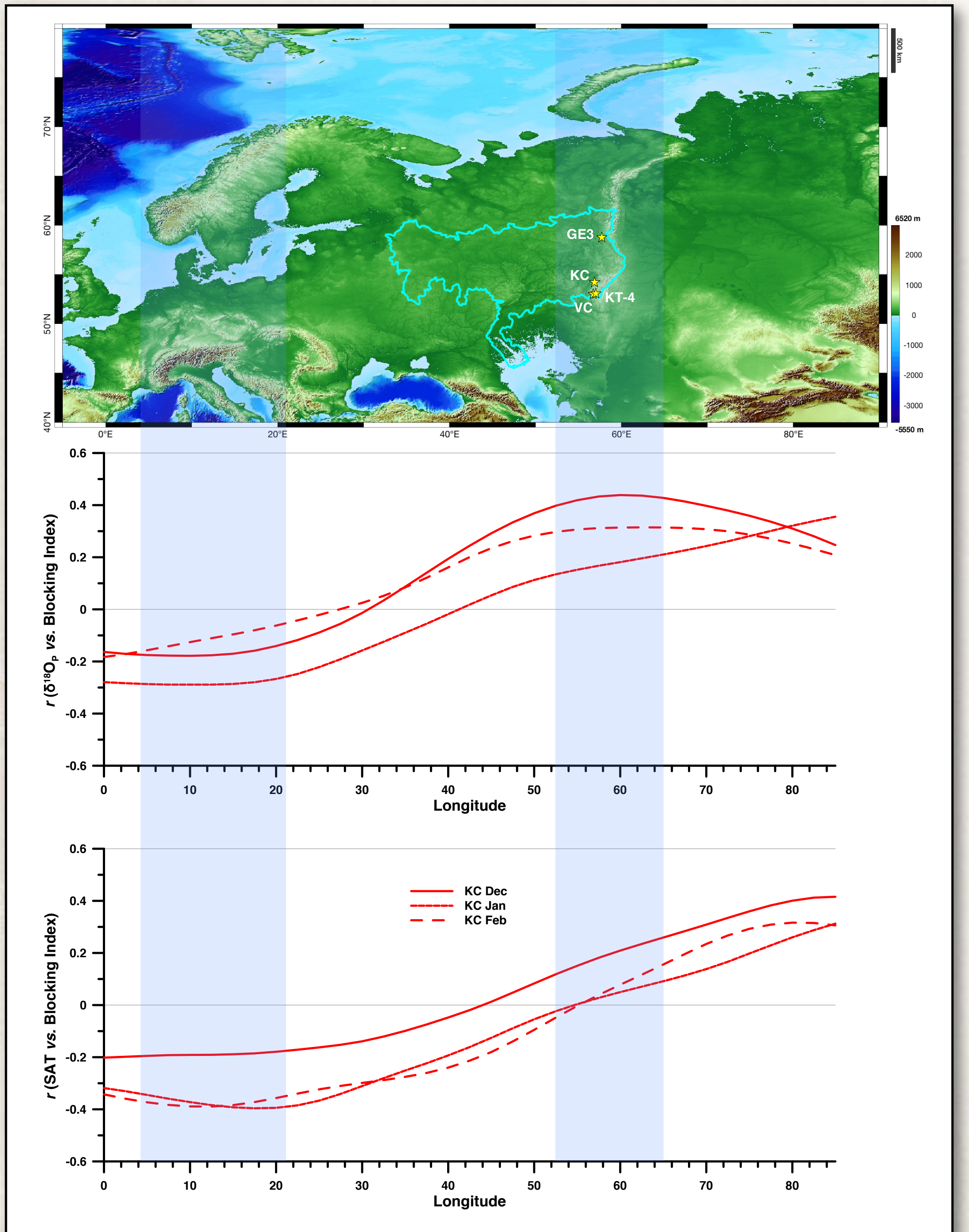
Atmospheric Controls on Winter $\delta^{18}O_P$ and SAT

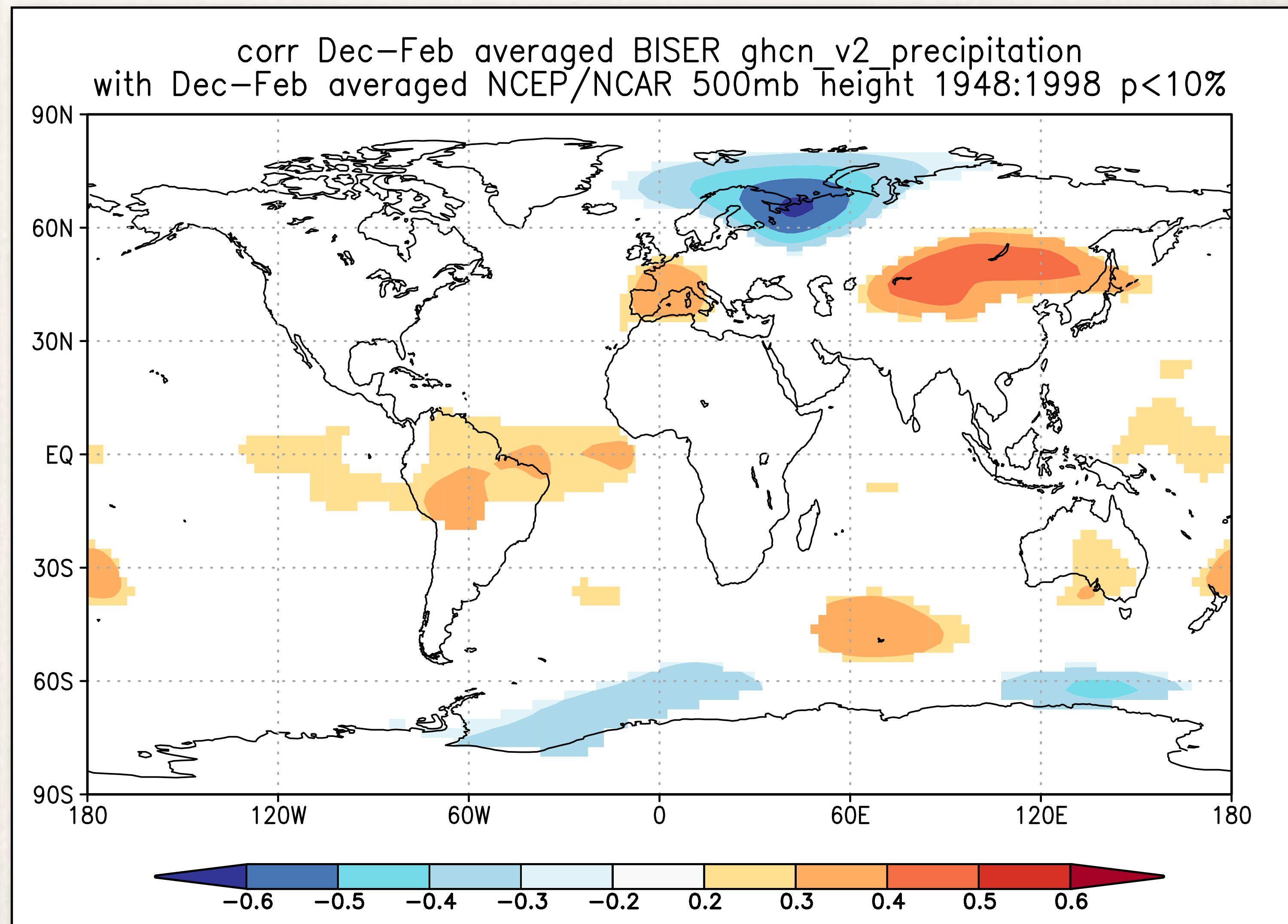
Station data: Biser, Russia (near Geologov-3 Cave)



Midlatitude blocking influence on Ural speleothem δ¹⁸O

Opposite phasing from Scandinavian and Ural blocking

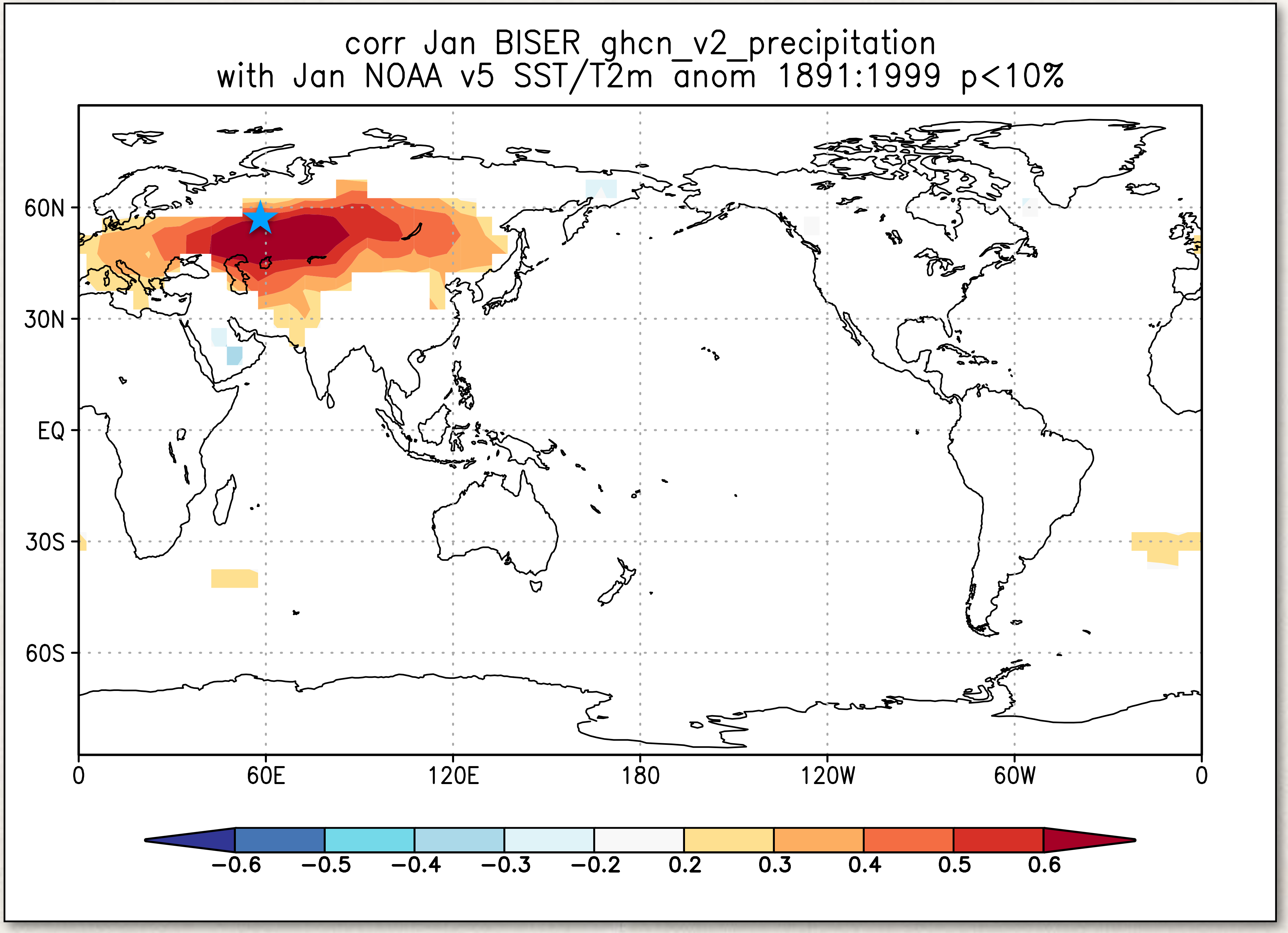




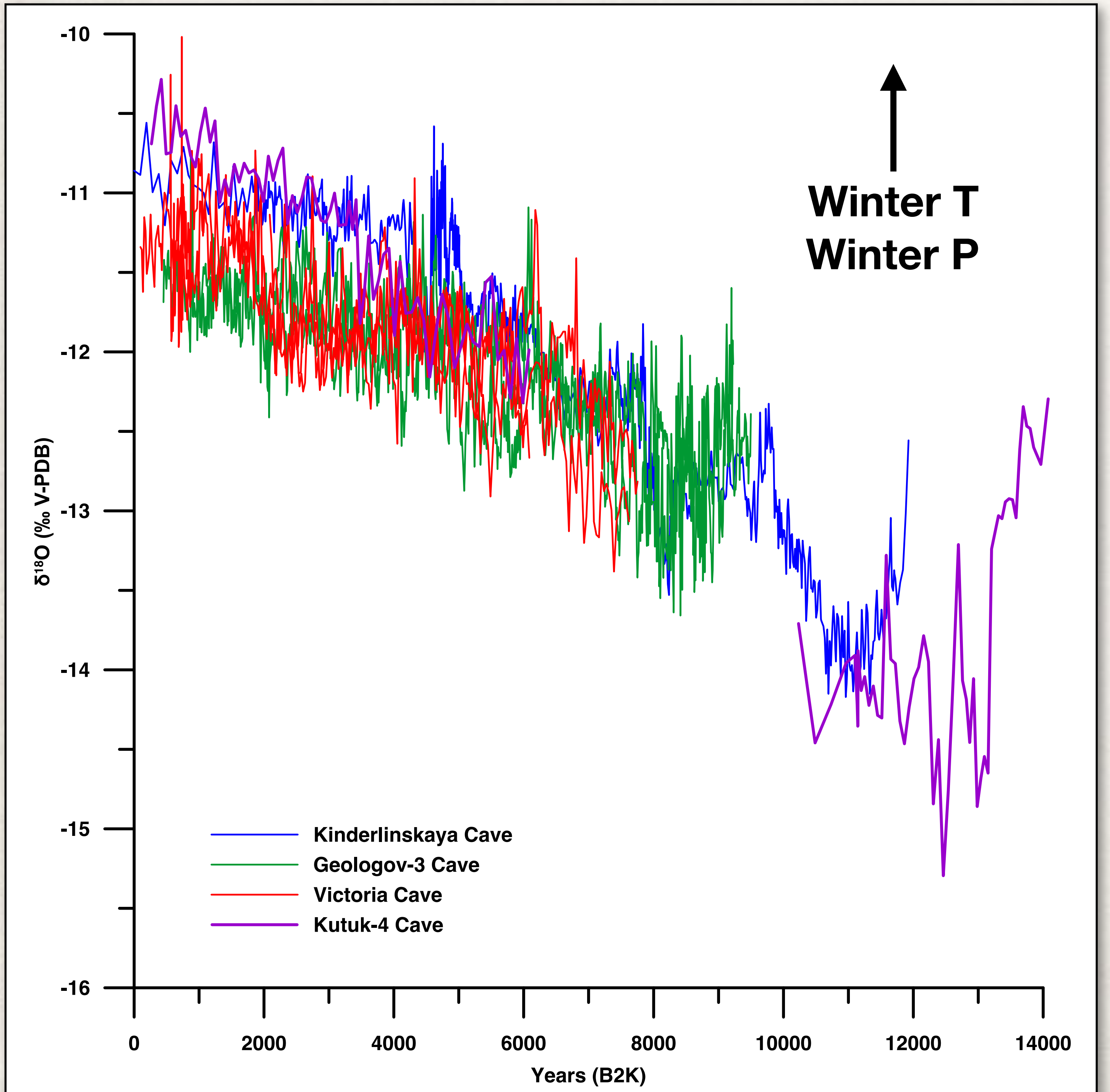
***Blocking index:** ΔGPH_{500} from 40–60°N + 80–60°N

Correlation of January Precipitation with T

Station data: Biser, Russia (near Geologov-3 Cave)



The Winter Hydroclimate Story from Ural Caves

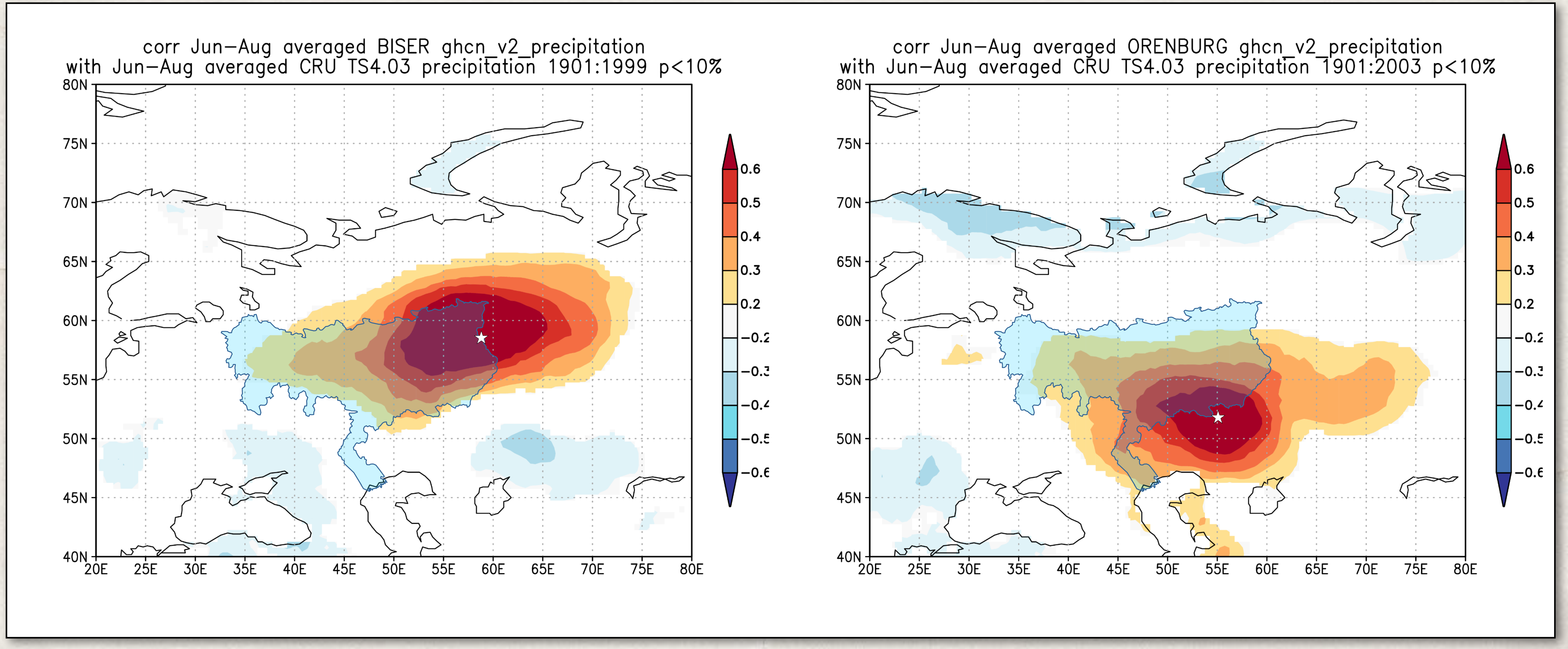


- Long-term increase in speleothem $\delta^{18}O$
- Replicated well across the Ural transect
- Holocene increase in winter T, P
- Consistent with model outputs, suggesting EH winter aridity

Watershed JJA Climate, Signal Heterogeneity

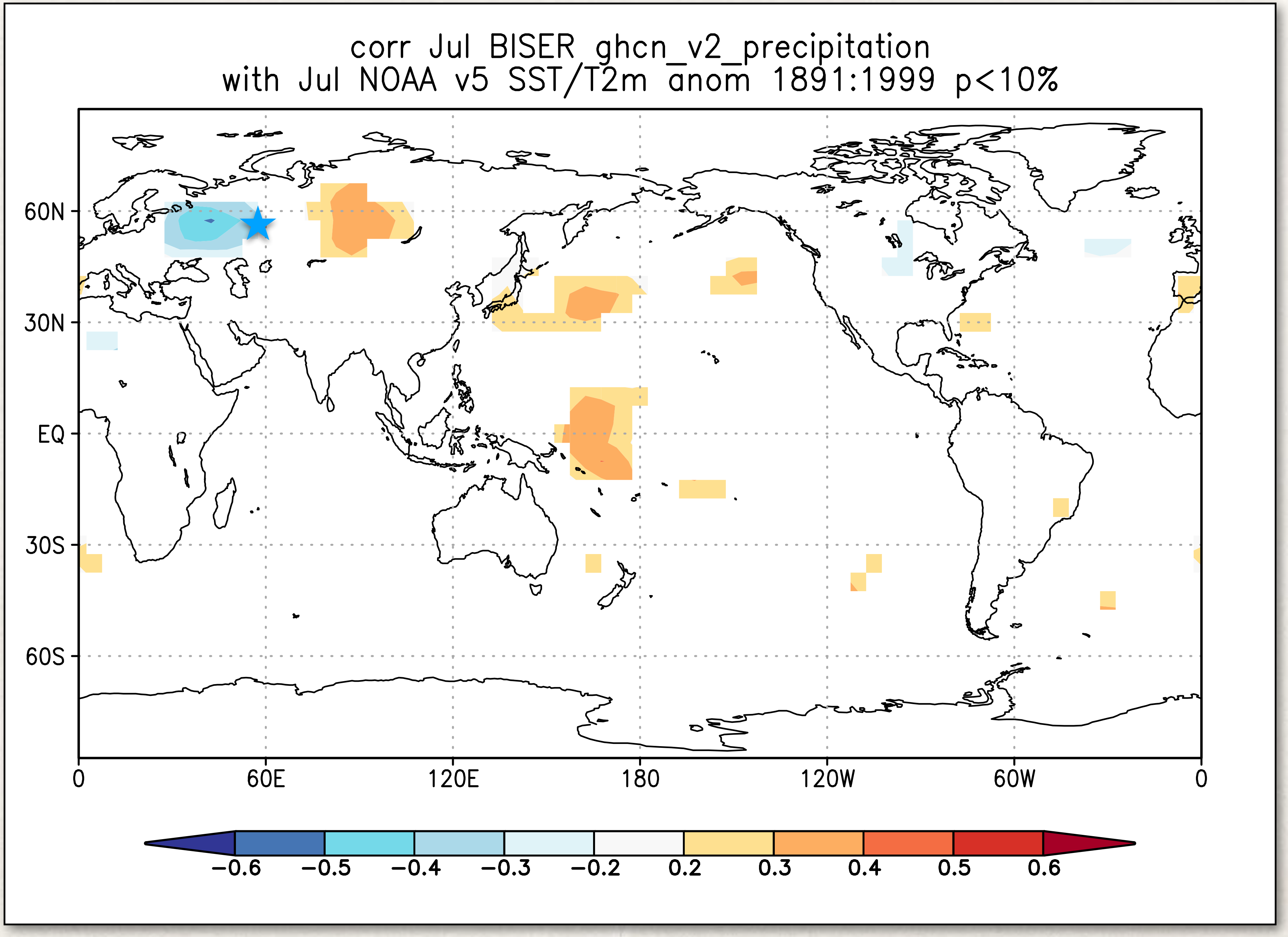
Regional context for record interpretation

- How reflective of basin-wide precipitation patterns can each site be?
- Single-point correlation of 20th-century station JJA P vs. gridded JJA P:



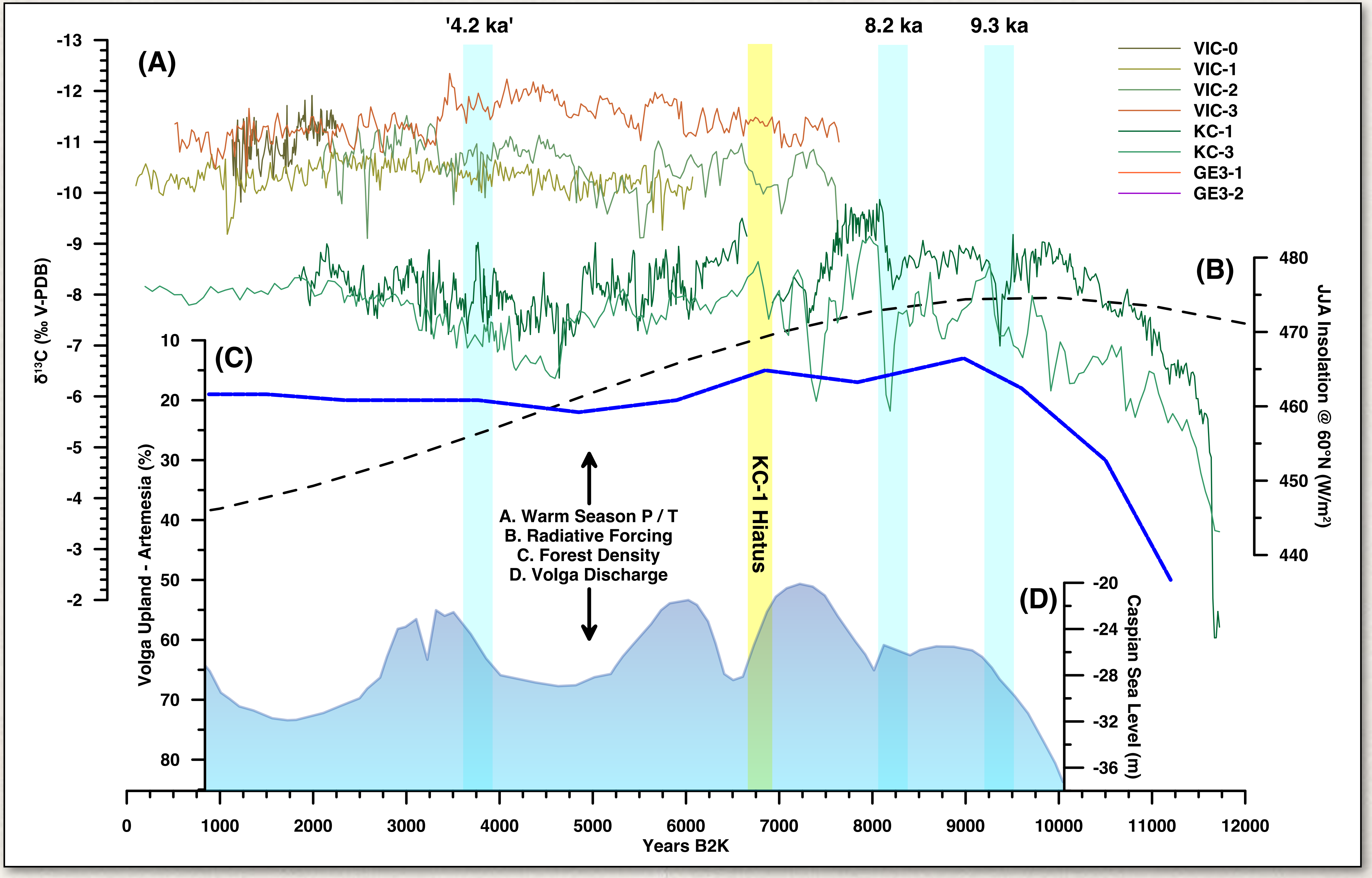
Correlation of July Precipitation with T

Station data: Biser, Russia (near Geologov-3 Cave)



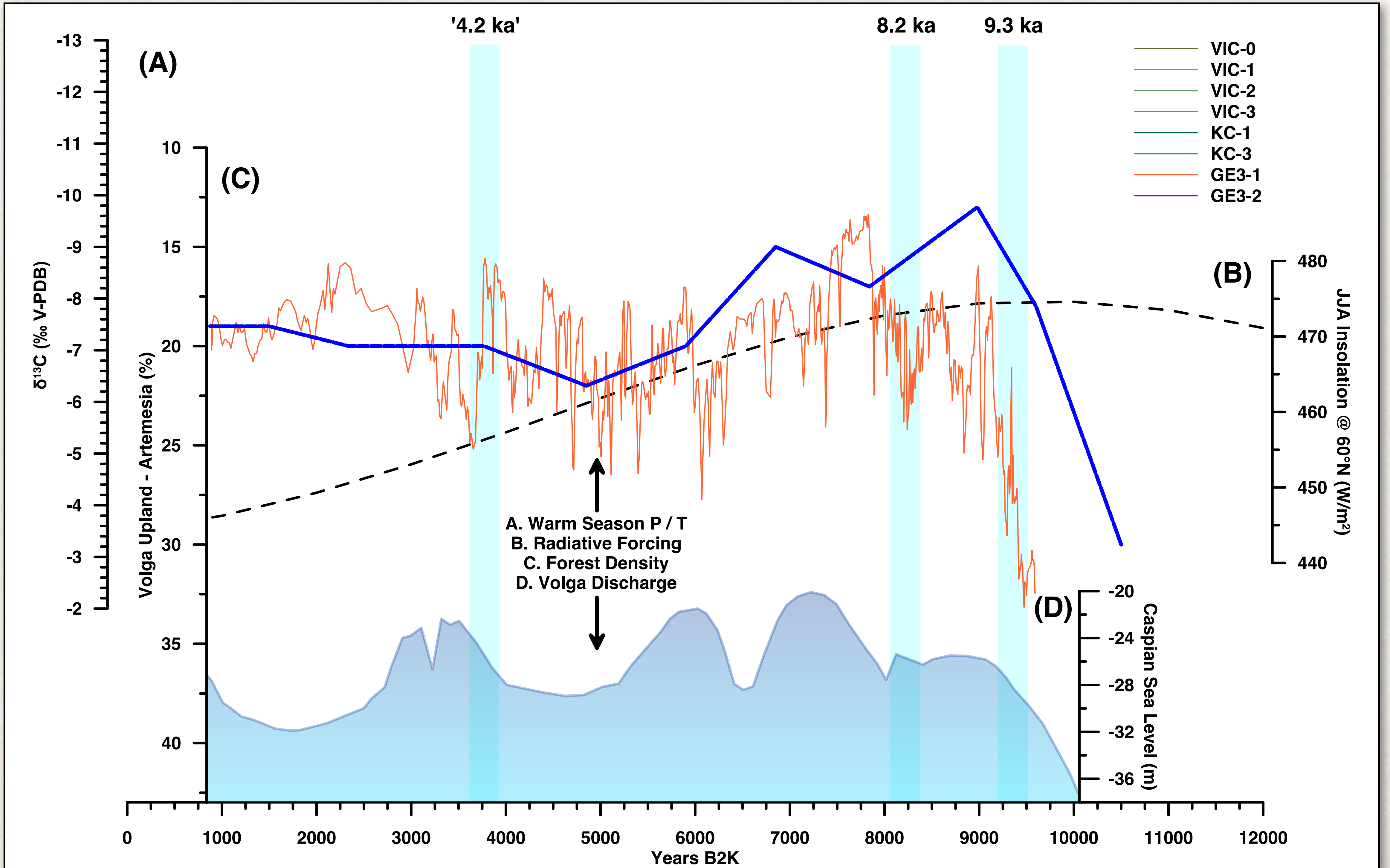
Southern Ural δ¹³C Results & Interpretation

Kinderlinskaya and Victoria caves



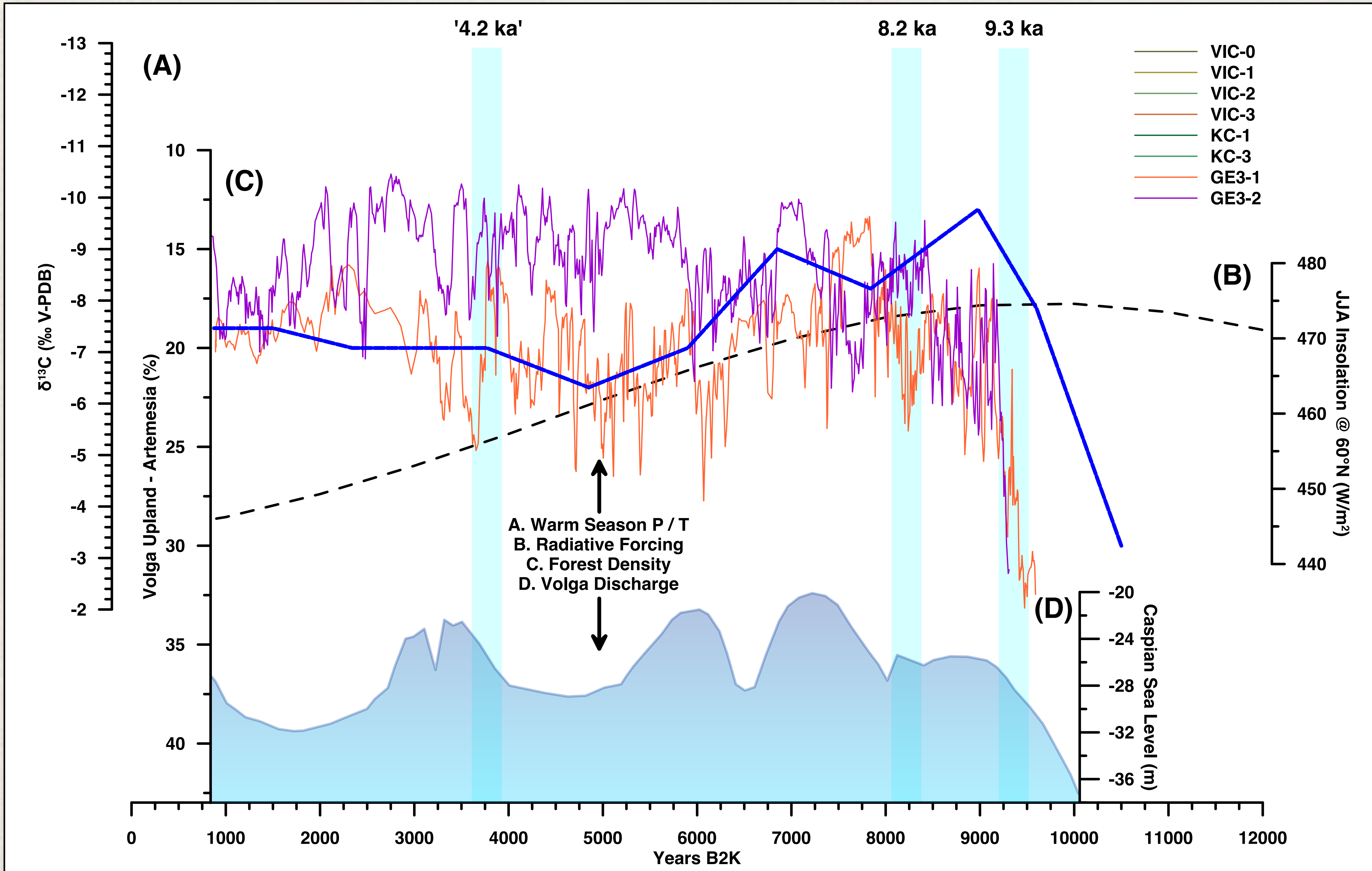
Central Ural δ13C Results & Interpretation

Geologov-3 Cave



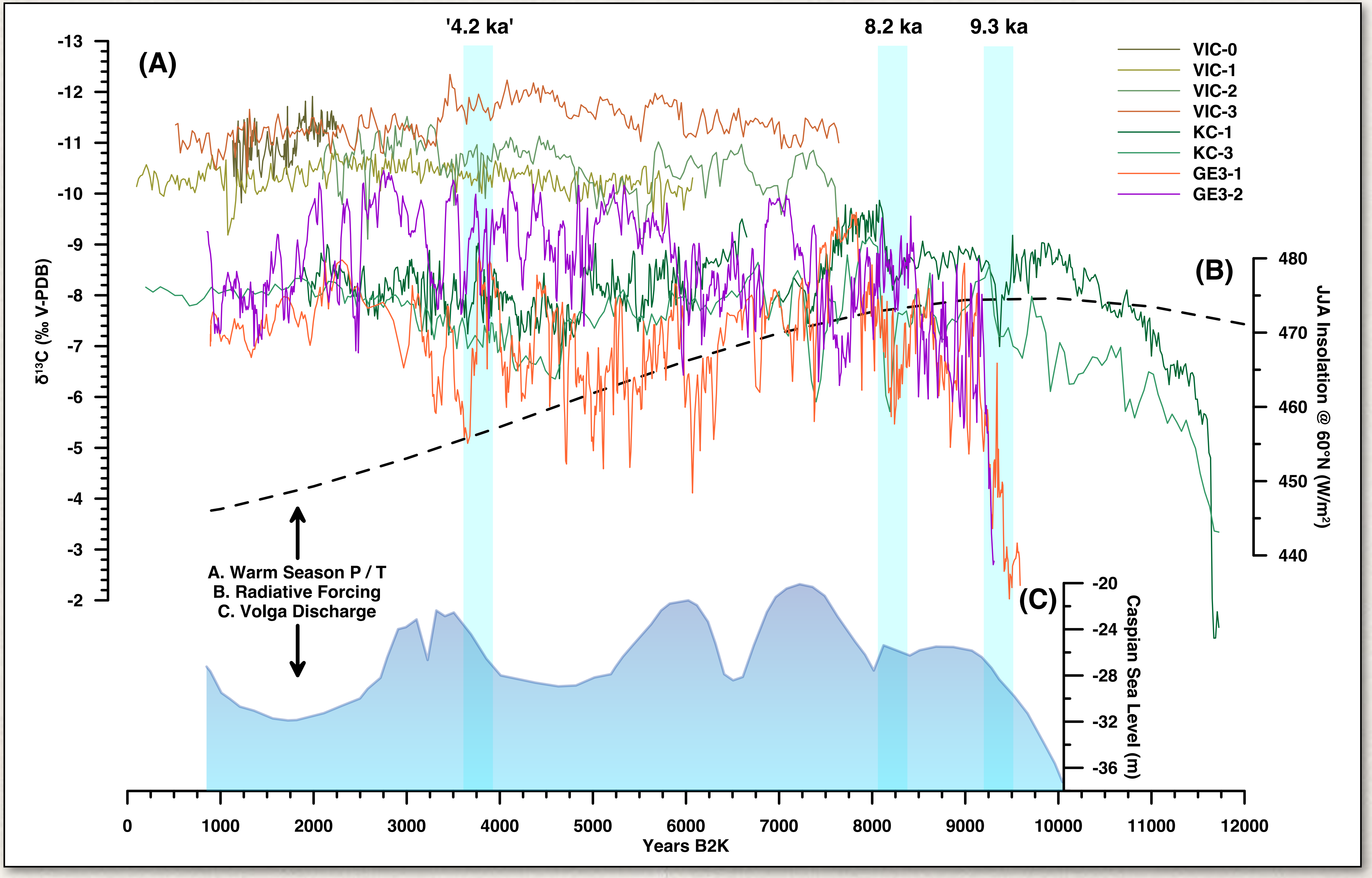
Central Ural δ13C Results & Interpretation

Geologov-3 Cave – Stalagmite GE3-2 discordance?



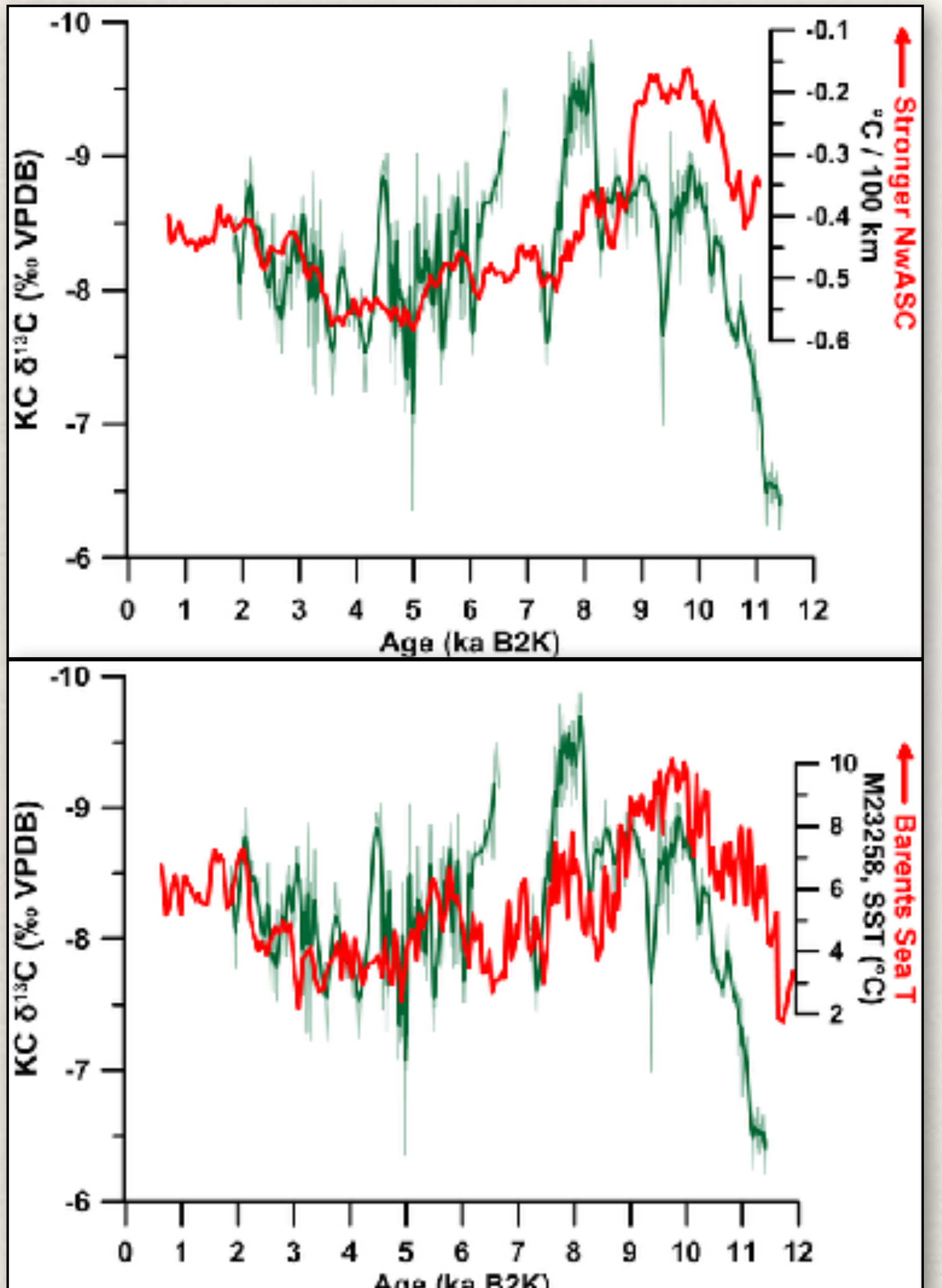
S. and C. Ural $\delta^{13}C$ Results & Interpretation

All cave sites



Dynamic controls on δ¹³C and regional hydroclimate

Coherent portrait from instrumental, modeled, and ocean-core data



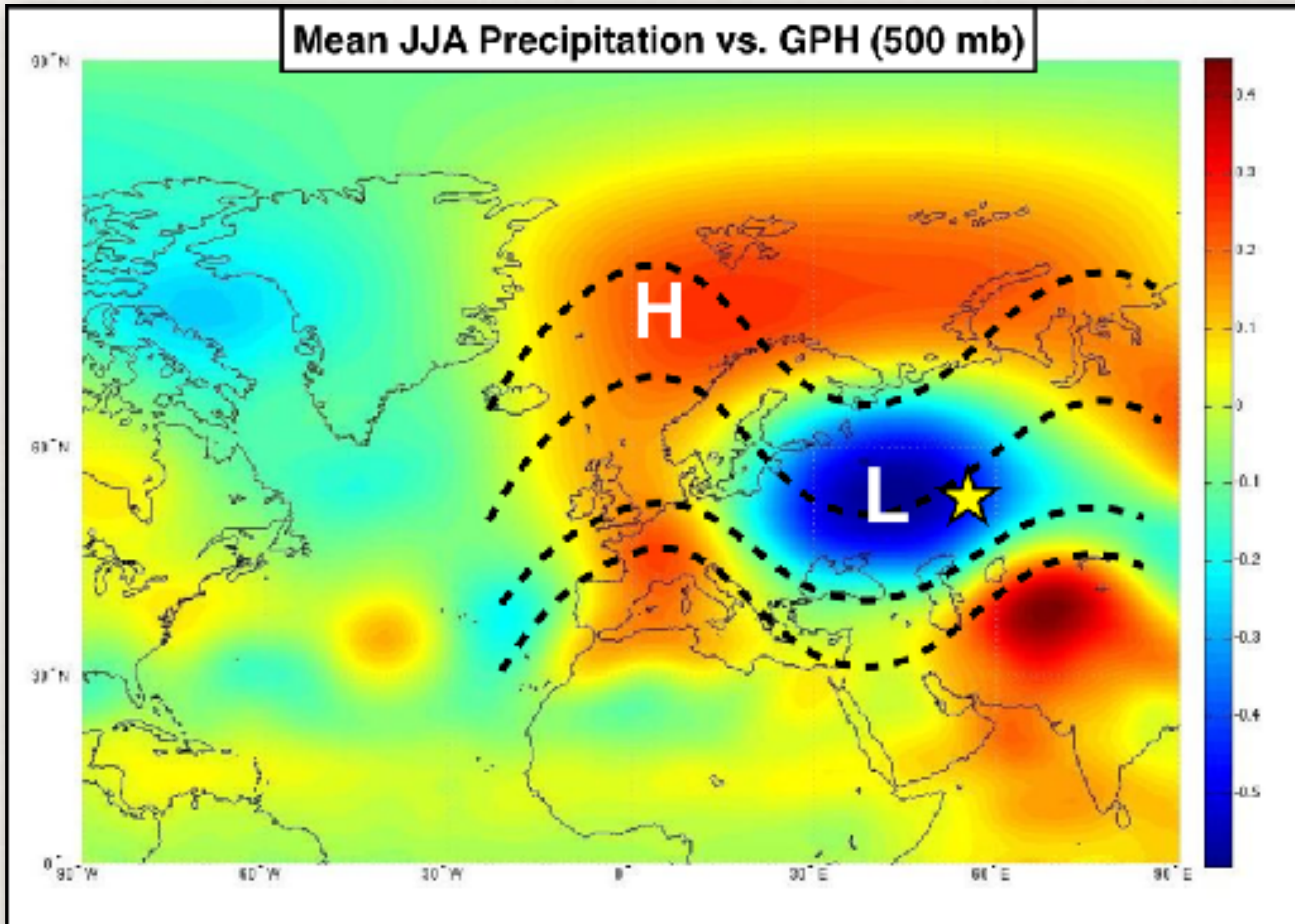
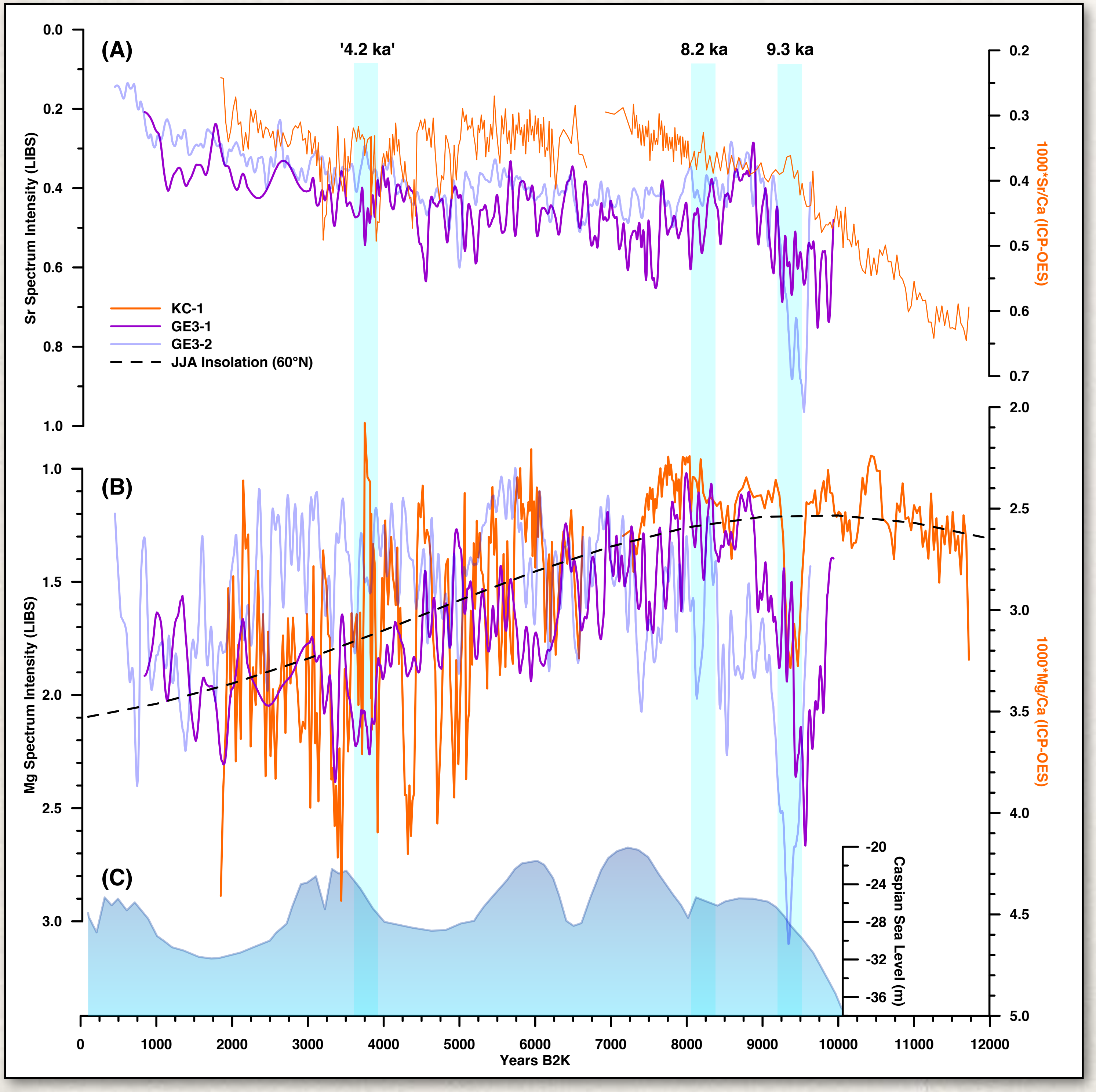


Figure Upper: Historical precipitation (JJA) at Ufa station vs. mean geopotential height (500 mb), based on NCAR/NCEP reanalysis (1948–2016). Dashed lines show inferred wave structure.

Figure Left: KC δ¹³C vs. (top) SST gradient along the Norwegian–West Spitsbergen Current, and (bottom) Barents Sea SST (Hald et al., 2007)

Trace Element Results & Interpretation

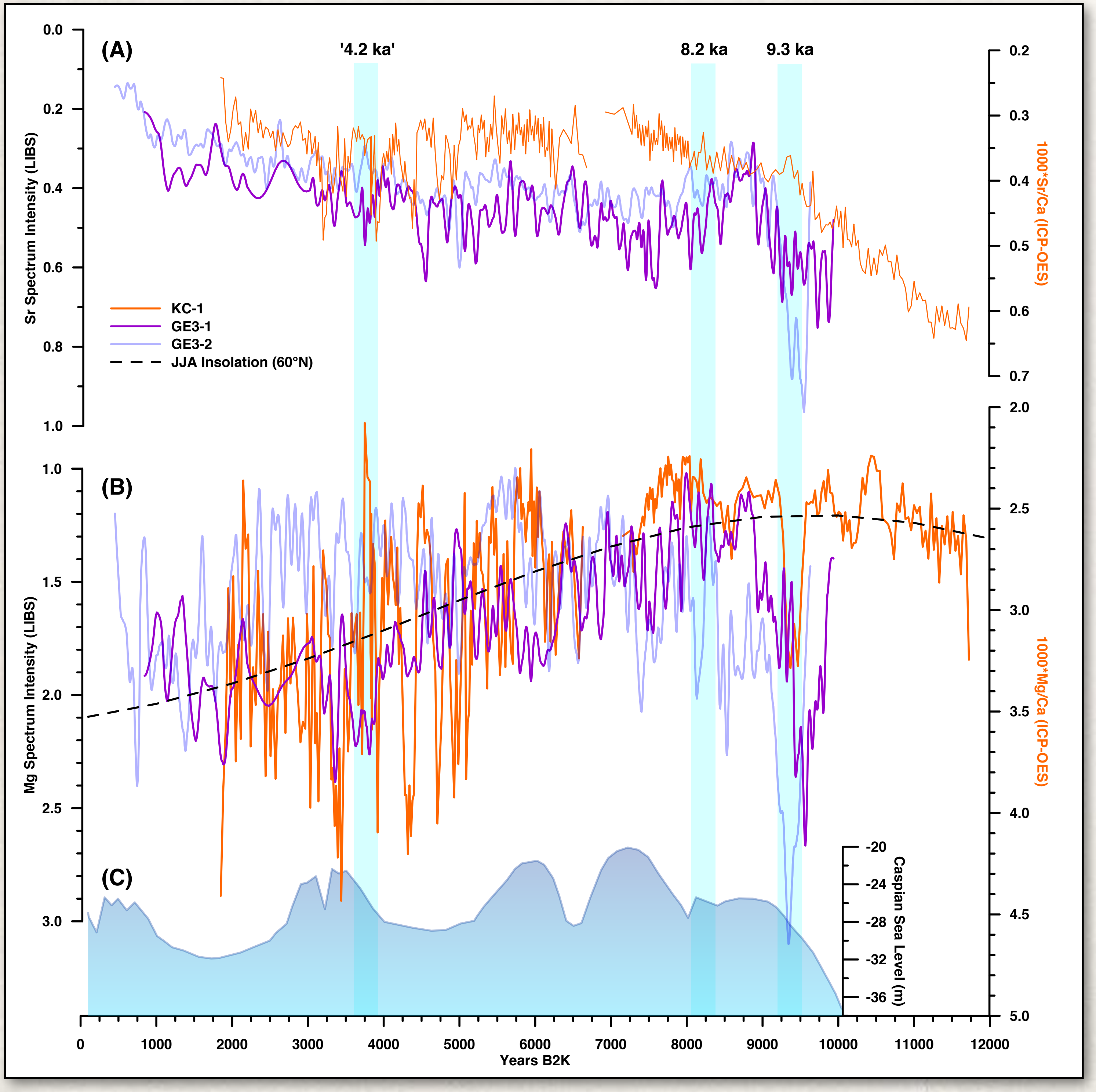
Geologov-3 and Kinderlinskaya caves

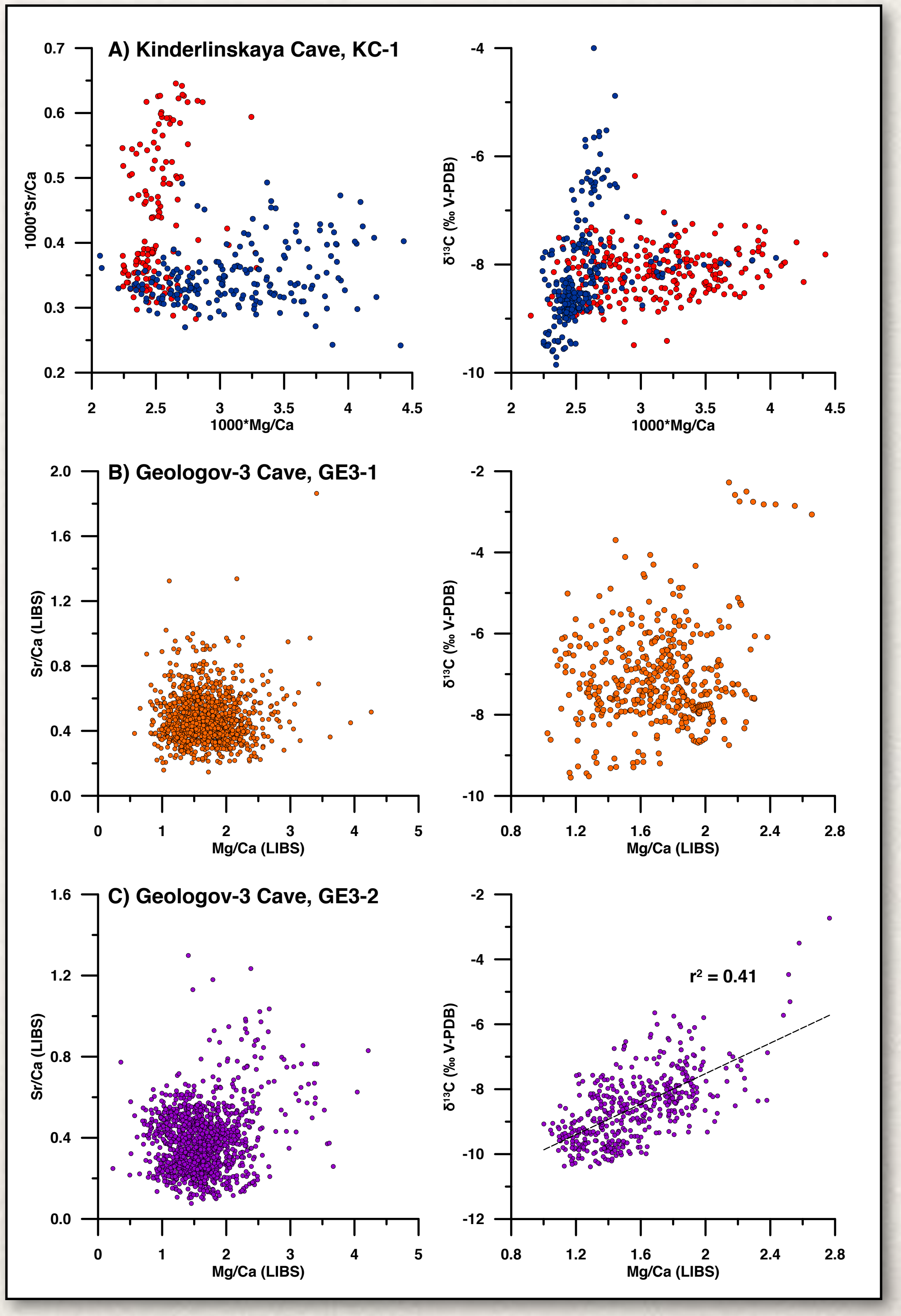


- General decrease in Sr/Ca over the Holocene, opposite the trend in Mg/Ca
- Mg/Ca broadly replicates between S. and C. Ural sites and is paced by JJA insolation
- PCP is not the primary control on Mg and Sr abundance—what causes the decoupling?
- Sr and Mg are coupled in GE3 stals during '9.3 ka' cooling

Trace Element Results & Interpretation

Geologov-3 and Kinderlinskaya caves

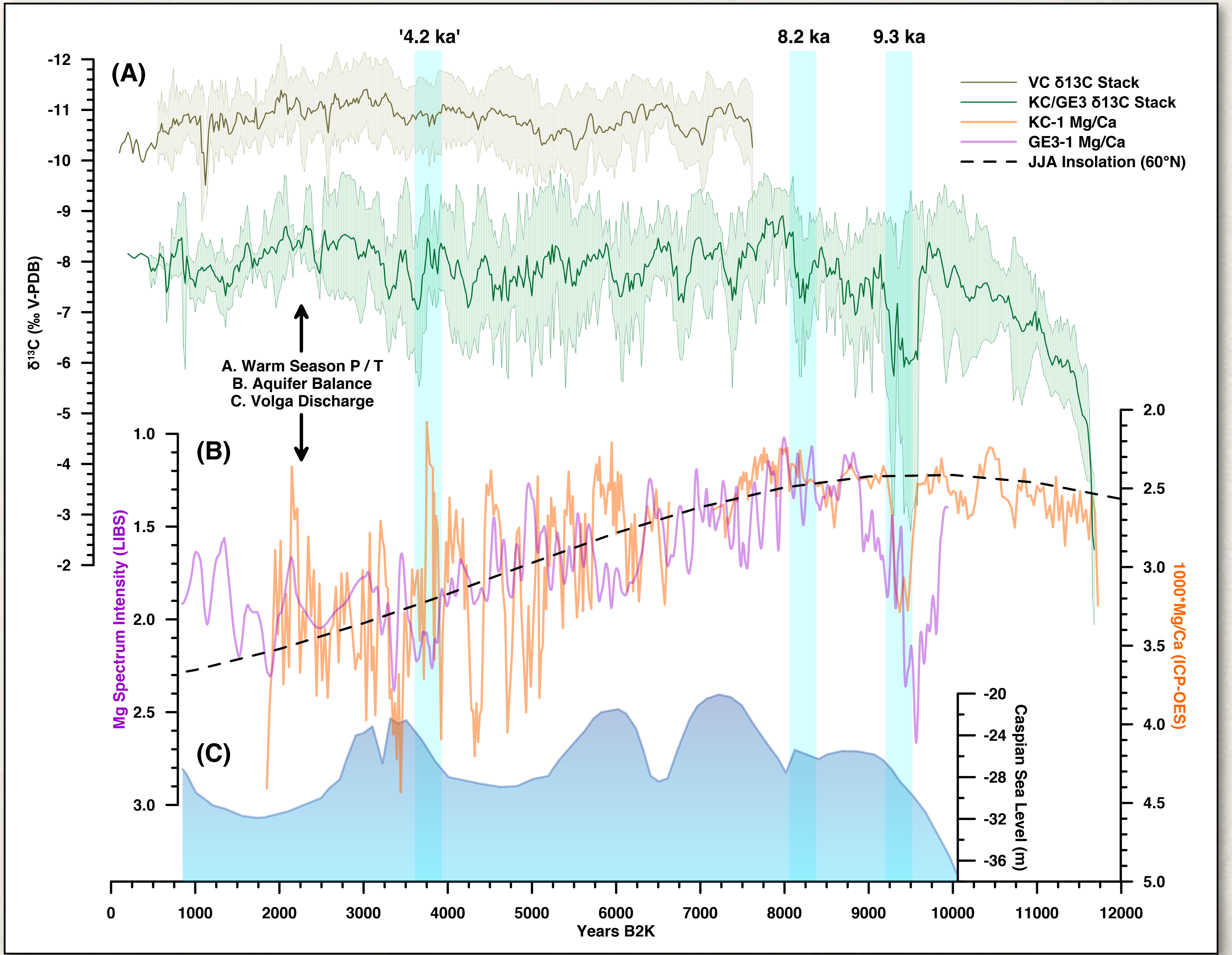




Holocene Hydroclimate of the Volga Basin

Data summary and conclusions

- Initial decrease in δ¹³C from near bedrock values to Holocene mean: afforestation
- Stable δ¹³C; centennial perturbations during known cold events
- Mg/Ca follows JJA insolation; EH summer P was likely higher than modern, & offset winter aridity
- Consistent with, but no specific correlation to Holocene Caspian SL (Rychagov, 1997)



Conclusions

- Speleothem $\delta^{18}O$ is strongly coherent across the 640-km transect from the Central to Southern Ural Mountains, suggesting a common winter climate signal: Holocene warming, increased precipitation, associated with stronger westerlies

- Speleothem $\delta^{13}C$ is broadly coherent, especially between KC and GE3 caves, and shows relatively stable soil-vegetation dynamics since ~10 ka; millennial-scale trends paced by Barents Sea SST, likely due to influence on atmospheric ridge structure

- Speleothem Mg/Ca, not driven by PCP, likely reflects long-term water balance and is paced by JJA insolation; suggests Holocene optimum near ~8 ka and subsequent reduction in water balance

- Cave data generally support reconstructions of Caspian Sea level and Volga vegetation (pollen-based), and to some extent time-slice studies of river regime and soil moisture

- Composite speleothem records provide a first-order estimate on Volga Basin hydroclimate across the Holocene, can be utilized in modeling studies and model-data comparisons