Does deep subsurface water increase rainfall at monthly to inter-annual time scales in the Sahel and Congo?

Masters Thesis Proposal   by Alpha Lo   2/26

General topic

This research investigates whether deep subsurface water can influence precipitation, trigger wet season onset, and prolong monsoons. The mechanism for this to happen is via vegetation that brings subsurface water to the surface and transpires it to create precipitation, and via supplying water to upper soil moisture layers which then evaporate to create precipitation.

If deep surface water affects precipitation, this suggests a potential climate intervention point: humans can alter deep subsurface water through soil management, groundwater extraction, and managed recharge, which may in turn influence regional and global precipitation patterns, affecting agriculture and urban water resources.

Traditionally, precipitation has been understood as arising from coupled interactions among the atmosphere, land surface, and ocean, with rainfall patterns largely shaped by oceanic forcing and surface soil moisture. Observational and modeling studies have shown that soil moisture in the top few centimeters to tens of centimeters influences rainfall, acting as a feedback that preconditions convective activity. For example, Tuttle (2016) demonstrated using Granger causality that fluctuations in surface soil moisture can help predict subsequent precipitation events. Similarly, Dirmeyer (2011) have shown both observationally and in land–atmosphere model experiments that soil moisture correlates with rainfall on weeks-to-months timescales, highlighting the role of the land surface as a memory and modulator of the hydrological cycle. These studies collectively support the idea that upper soil layers act as a fast-to-medium memory in the coupled system, but they leave open the question of whether deeper layers of soil and groundwater contribute to precipitation variability.

While surface soil moisture is well established as a modulator of precipitation, the deeper subsurface - extending below one meter and into groundwater reservoirs - may provide additional memory and influence over multi-month to multi-year rainfall patterns. Modeling studies by Barlage (2017), Anyah (2008), Martinez (2016) indicate that groundwater dynamics can impact precipitation, suggesting a terrestrial pathway for medium- and slow-mode feedbacks in the land–atmosphere system. However, these models rely on assumptions about hydrogeological water storage and flow that may not fully reflect actual subsurface conditions. Observationally, stable isotope analyses (Evaristo 2016) provide evidence that groundwater contributes to evapotranspiration and, indirectly, to precipitation, but isotope methods can struggle to distinguish between pathways and typically integrate over all vegetation, limiting their resolution for specific subsurface layers. There are a lot of uncertainties in the modelling and stable isotope analysis. These limitations highlight the need for additional observationally constrained approaches to verify the influence of deep subsurface water, and to lower the uncertainty levels.

To address this gap, we take a statistical approach to our data from observations and observationally constrained models. We ask of the data: does knowing the past state of one variable help predict the future state of another, beyond what we could already predict from that variable's own history? This approach is the Vector AutoRegression (VAR) framework, a statistical approach that leverages time series data to capture dynamic relationships. The VAR, has several parts to it - Granger causality, Impulse Response Functions (IRFs), and Forecast Error Variance Decomposition (FEVD). Each tool takes the same regressions equations and extracts different information from it.

If deep terrestrial water storage in month t carries information that improves our forecast of precipitation in month t plus 3, information that the precipitation record alone does not contain, then storage is said to Granger-cause precipitation. This is not causation in the mechanistic sense, but it is meaningful evidence of directional predictive influence flowing from one part of the system to another.

Applying the VAR framework of Granger causality, FEVD, and IRFs to multi-layer soil moisture and groundwater observations allows us to determine whether layers beneath the top 5 cm, including those deeper than 1 m, have predictive power for rainfall and wet season onset. FEVD helps quantify the relative contribution of each subsurface layer to precipitation variability, while IRFs provide a complementary view of the timing and persistence of responses.

Climate components operate on different intrinsic timescales: the atmosphere acts as a fast mode (hours to weeks), land surface processes as a medium mode (days to months), and the ocean as a slow mode (seasons to decades). The timescales at which deep subsurface water impacts rain may function at medium-mode component with multi-week to multi-month memory and as a slow-mode component with multi-year memory. Granger causality, FEVD, and IRFs together allow us to see how much deep subsurface water impacts the rain at different lag times ranging from one month to two years.

Land water may not only modulate rainfall but also help trigger the onset of the wet season, as evidenced by vegetation greening that often precedes the first rains in Sahel. (Adole 2018). Model-based studies of the Congo (Wright 2017) suggest that early-season soil moisture and vegetation feedbacks precondition rainfall, accelerate monsoon onset, and influence larger-scale circulation to bring in ocean moisture earlier. While observational analyses provide some support for these model findings, direct evidence linking deep subsurface water to wet season initiation and circulation changes remains limited. Impulse response functions (IRF) introduce a hypothetical perturbation, a single anomalous pulse, to one variable and trace how that disturbance propagates through the system over subsequent months. If we see in the IRF that there is an acceleration of the rainfall from a change in the deep subsurface water, this is one extra piece of supporting evidence that evapotranspiration from the land is able to trigger the wet season.

Research Question

Does subsurface water, including layers below 5 cm and deeper layers below 1 m, influence precipitation variability, wet season onset, and wet season duration across medium and multi year timescales?

Hypotheses

1. Subsurface water influences rainfall - both shallow (below 5 cm) and deep (below 1 m)
2. Deep subsurface water impacts rainfall at monthly and inter-annual scales.
3. Deep subsurface water can trigger the onset of the wet season

Methodology

Data: Shallow subsurface water, below 5 centimeters, is obtained from total water storage from the GRACE JPL mascon product. GRACE mascons provide data at roughly 300 kilometer spatial resolution and monthly temporal resolution. This means that our analysis examines whether the subsurface water within each 300 km grid cell has a predictive effect on rainfall over the course of a month, rather than daily variability. To isolate the water below the very top soil layer, we subtract SMAP surface soil moisture, which measures approximately the top 5 centimeters. By subtracting SMAP from GRACE TWS, we obtain a shallow subsurface water signal beneath the top 5 centimeters.

Deeper subsurface water, below 1 meter, is obtained from the GRACE-constrained GLDAS2.2 product. GLDAS2.2 integrates land surface modeling with GRACE TWS observations to estimate deeper soil and groundwater storage. This product provides monthly estimates over the same spatial resolution as GRACE.

Locations: I will look at 5 places at the 13.5N latitude line in the Sahel, in Burkina Faso, Chad, Guinea, Nigeria and Mali. And look at 2 places in Congo. Each place will be a 300km sq cell.

Linking Analysis to Hypotheses

H1 - Subsurface water influences rainfall: Using the shallow GRACE minus SMAP signal and the deeper GLDAS2.2 estimates, we test whether subsurface water improves precipitation prediction beyond rainfall's own autoregressive history. Granger causality within the VAR framework identifies directional predictive influence. The F-stat and p value give us whether there is a significant influence of the deep subsurface water on rain at a lag time of n months. FEVD quantifies the relative contribution of shallow and deep storage to rainfall variability.

H2 – Deep subsurface water impacts rainfall at monthly and inter-annual scales.
We examine the lag structure in Granger tests and IRFs. Monthly data allow detection of short-term impacts for shallow subsurface water and multi-month to multi-year persistence for deeper storage. IRFs reveal the duration and shape of responses, indicating how many months the impact is felt.

H3 – Deep subsurface water triggers onset of wet season: By examining IRFs during pre-onset and early wet season months, we test whether deep water storage anomalies accelerate rainfall at beginning of wet season.

Confounding Factors and Robustness:

Vector autoregression and Granger causality are susceptible to confounding factors. A confounder is a variable that influences both the predictor and the outcome, creating the appearance of a causal relationship where none exists. For example, a large-scale climate oscillation may affect both deep subsurface water and rainfall, producing a predictive relationship even if there is no direct causal link. Long-term trends such as global warming could also generate spurious correlations. To address these confounders, we take several steps.

Seasonal cycles are handled in two ways. First, we deseasonalize each time series by removing the long-term monthly mean for each calendar month. Second, we construct a continuous seasonal function, a sum of sine waves with different frequencies and phases, and include it directly as a covariate in the VAR framework.

Multiyear climate oscillations are quantified within the VAR framework, allowing evaluation of how much of rainfall variance is attributable to these oscillations relative to deep subsurface water. Atlantic sea surface temperature time series are also included as predictors in Granger tests.

Long-term trends are removed through detrending, ensuring that predictive relationships reflect directional influence rather than spurious correlations from secular changes.

Shuffle tests provide a non-parametric baseline. The rainfall time series is randomly reassigned from a different year, breaking temporal alignment with storage variables while preserving each series' internal statistics. Granger causality should disappear in the shuffled data, confirming that observed predictive influence reflects true directional coupling.

Wet season subsetting VAR and Granger analyses are repeated on wet season months alone.

Timeline

March – I've built up a number of datasets which I have analyzed for different countries already. I will be continuing getting analysis of the data. Checking VAR results to see if they are correct. Is the confounding factors of seasonality, trending, and multiyear land-sea oscillations taken properly into account? Is the linear Granger causality sufficient to show proper predictive ability? Are there tests properly showing the rain acceleration? Is it okay to use the CLSM Gldas2.2 model for this VAR? Then I will write up paper, and at end of March of beginning of April, submit paper to journal.

Apr- Work on a global map of groundwater to rain, to see how significant each place is in how groundwater affects rain. Also an intriguing resulted from the VAR showing that with rain, sst, and deep subsurface water as variables, that the deep subsurface water affected ocean temperatures. Will explore if this means subsurface water affects African Nino.

May - defend thesis

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