Time Scales in Soil Moisture Data Assimilation

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Background/Outline

• Assimilated obs are typically closer to the surface (and have faster time scales) than the land model variables of greatest interest
  • e.g., assimilate surface soil moisture to constrain root-zone (and surface) soil moisture

• Which model time-scales benefit from the assimilating surface soil moisture?
• Can we manipulate the obs to improve analysis to slower states?
  • Improvements in assimilation of faster states to constrain slower states from assimilating time-averaged obs (Huntley and Hakim, 2010; Steiger et al, 2014; Tardif et al, 2014, 2015)
Decomposition of Soil Moisture DA time scales

- Assimilated 9 years of AMSR-E soil moisture into NASA’s Catchment model using an EnKF
- At four USDA ARS sites with dense networks giving grid-scale surface soil moisture observations
- Harmonic decomposition of each soil moisture time series into:
  - Long (inter-annual)
  - Seasonal (mean seasonal)
  - Short (sub-seasonal)
- Estimated impact of DA on ubMSE (c.f. ARS obs) at each time scale

Draper and Reichle, 2015
Model vs. Obs

- Model and remotely sensed obs have different distribution of variance across each time scale
- Remotely sensed obs generally have more variance at the fast time scales than the model
- Bulk rescaling for bias correction will cause errors in one time scale to effect other time scales (e.g., enhanced seasonal cycle reduces variance in other time scales):
  - Consider separating time scales when rescaling
    - Exclude seasonal cycle: De Lannoy and Reichle (2016)
    - Rescale each time-scale separately: Su and Ryu (2015)
Assimilation Results

- Assimilation reduces the error variance (ubMSE) in the surface soil moisture at all time scales.
- Similar absolute magnitude of improvement in short and long time scales (larger relative reduction in long time scales errors).
- Can improve model representation of sub-seasonal (individual synoptic events) and inter-annual errors (persistent drought).
- Evaluation that does not capture inter-annual variability likely underestimating potential improvements.

Surface soil moisture error variance by timescale, at four locations

Equivalent to RMSE = 0.04 m3/m3

M: Model Openloop
Ac: Assimilation
Toy DA study: Consequences of assimilating obs of a fast state to update a slow model state?

- Test with synthetic experiment using a simple force-restore soil moisture model (Noilhan and Mahfouf, 1996)
- Assimilate surface soil moisture ($X_1$) to update both soil layers ($SM_1$, $SM_2$) using the EnSqrtKF (Whitaker and Hamill, 2002)
- Evaluate impact at 2 time scales:
  - slow (seasonal, and longer)***
  - fast (sub-seasonal) time scales

\[
\begin{bmatrix}
  x_1(t+1) \\
  x_2(t+2)
\end{bmatrix} =
\begin{bmatrix}
  x_1(t) + \frac{1}{\delta_1}(P - E_1) - \max\left(\frac{1}{\tau}(x_1(t) - x_2(t)), 0\right) \\
  x_2(t) + \frac{1}{\delta_2}(P - E_1 - E_2)
\end{bmatrix}
\]

\[
E_i = D_i \left(1 - e^{(-x_i(t)/c_i)}\right), i \in 1, 2
\]

P = Precip
E1 = bare soil evap,
E2 = transpiration,
D = evaporative demand
tau = drainage time scale,
di = depth layer i
Synthetic Experiments

- Generate truth: force model with USCRN obs over 12 years.
- Generate obs: add random perturbations (fast and slow t’scales) to the truth
- Model: force with MERRA output in place of obs
  - SM1(2) - 70% (99%) error variance is slow
    (DR15: 50% model SM1 error slow)
- Assimilation:
  - R - specify same magnitude of Q(1,1)
  - Q - perturb P (fast) and E (slow) with perturbations representative of errors (diff USCRN and MERRA) in each
    - (HBHT+R)/(y-Hx)**2 > 1
  - Repeat each experiment 5X, report mean

- Presented results are robust: hold with model parameter errors, very large R, mis-specification or R, Q (magnitude, and off diagonal correlations)
Time scale of observation errors

- Experiments adding fast time scale error to the observations show DA performs well even with large amounts of observation noise.
- Assimilating fast state (with fast errors) to update a slow state does not appear to be problematic.
- Experiments adding slow time-scale errors show DA sensitive to persistent errors in the observations (DA algorithm assumes no obs bias).

![Graphs showing RMSE in SM1 and SM2 with different line styles representing different error variances.](image-url)
Assimilating time-averaged observations

• Assimilate time-averaged obs, following Huntley and Hakim (2010)
• No advantage in layer 2 from assimilating time-averages (since EnKF is a more efficient filter)
• Degradation in layer 1 from assimilating time-averages
Time-averaging of assimilated obs

• If have more obs error at longer time scales, time-averaging of the obs can marginally improve the deep layer, while degrading the shallow layer.

~equivalent to AMSR-E study

<table>
<thead>
<tr>
<th>Fraction of R at slow time scales</th>
<th>RMSE in SM1</th>
<th>RMSE in SM2</th>
<th>RMSE in SM1</th>
<th>RMSE in SM2</th>
<th>RMSE in SM1</th>
<th>RMSE in SM2</th>
</tr>
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<tbody>
<tr>
<td>0.05</td>
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<td>0.2</td>
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<td>0.4</td>
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Changes in DA performance from assimilating time-averaged obs is due to the reduced assimilation frequency (reducing serial correlation in the assimilated observation errors)

Contrast to ocean/paleo. studies with much larger time-scale separation, for which improvements are from increased error covariances
Summary and Conclusions

• Modeled and remotely sensed surface soil moisture estimates have differing distribution of variance across different time scales -> time-scale specific errors present
• Assimilation of remotely sensed surface soil moisture corrected model at inter-annual and sub-seasonal time scales
• Synthetic study demonstrates that assimilating faster time-scale obs to update slower states is not particularly problematic for soil moisture DA
• Assimilation of observations with slow (systematic) errors is problematic
  • Land DA examples? Sensor drift, errors in vegetation & temperature used in retrieval
• [not shown:] Assimilating fast time scale obs to update only slow time scale model state is problematic
  • Land DA examples?
• In above cases, assimilating time-average observations marginally improves slow time scale model variable, while degrading the fast time scale
  • Improvements are associated with less frequent DA
  • Contrast to Tardif et al (2014): assimilating (one year) time-averaged atmos obs into coupled ocean/atmos. System beneficial to slow ocean processes -> due to increased error covariances.
• Caveat: single case, suitability of force-restore model?
Thanks for Listening.

Time-averaging obs: updating only slow time scales

- If DA only updates the slow layer, can degrade the slow layer (due to addition of fast time scale noise)
- Can be partially ameliorated by assimilating time-averaged obs
- Again DA impact in slow layer limited, and averaging degrades fast layer
- Effect of time-average again due to temporal sampling