[Coupling metrics to diagnose land-atmosphere interactions]

Generalized Equilibrium Feedback Assessment (GEFA)

- References:
  - Liu, Z., N. Wen, and Y. Liu, 2008: On the assessment of nonlocal climate feedback. Part I: The generalized equilibrium feedback assessment. *J. Climate*, **21**, 134–148, doi: 10.1175/2007JCLI1826.1.
  - Wang, F., M. Notaro, Z. Liu, and G. Chen, 2014: Observed local and remote influences of vegetation on the atmosphere across North America using a model-validated statistical technique that first excludes oceanic forcings. *J. Climate*, **27**, 362–382, doi: 10.1175/JCLI-D-13-00080.1.
  - Yu, Y., M. Notaro, F. Wang, J. Mao, X. Shi, and Y. Wei, 2018: Validation of a Statistical Methodology for Extracting Vegetation Feedbacks: Focus on North African Ecosystems in the Community Earth System Model. *J. Climate*, **31**, 1565–1586, doi: 10.1175/JCLI-D-17-0220.1.
- Principle:
  - Variability of an atmospheric variable A over time is presumed to have a forced component from multiple slowly-evolving boundary conditions $\boldsymbol{O}$ and internal variability N: $A(t) = \boldsymbol{B}\boldsymbol{O}(t) + N(t)$ where $\boldsymbol{B}$ is a vector of feedback weights. $\boldsymbol{O}$ can be local land factors or from remote land or ocean. Mean annual cycles and long-term trends are first removed from all fields.
  - For a time scale τ there is a time series of trailing boundary forcings $\boldsymbol{O}(t-\tau)$. Lagged covariance matrices can be estimated by applying the transpose:

$$\boldsymbol{C_{AO}}(\tau) = A(t)\boldsymbol{O}^T(t-\tau)/L$$
$$\boldsymbol{C_{OO}}(\tau) = \boldsymbol{O}(t)\boldsymbol{O}^T(t-\tau)/L$$
$$\boldsymbol{C_{NO}}(\tau) = N(t)\boldsymbol{O}^T(t-\tau)/L \ = 0 \text{ by assumption}$$

  - The feedback vector is then estimated as: $\boldsymbol{B} = \boldsymbol{C_{AO}}(\tau)\boldsymbol{C_{OO}^{-1}}(\tau)$
  - There exists a variant called Stepwise GEFA (SGEFA) applicable to short data sets (see: Yu et al. 2018).
- Data needs:
  - Both local and nonlocal feedbacks can be assessed, depending on source (locations) of forcing time series used to assess of atmospheric variability.
  - Forcings $\boldsymbol{O}$ should have a much redder spectrum than the atmospheric variables examined, appropriate to the chosen time scale.
  - Well suited to a wide range of data sets including model output, particularly if time series are long (multiple years).
- Observational data sources:
  - The slow manifold of $\boldsymbol{O}$ makes this well suited to forcing variable data sets that have incomplete, frequent missing or irregularly sampled data, such as polar-orbiting satellite measurements that have a multi-day repeat cycle, or occasional cloud obscuration.
- Caveats:
  - GEFA metric is intrinsically linear, so may not detect nonlinear or threshold-triggered forcings well.
  - As with other correlation metrics, causality is not assured.

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