Land Atmosphere Interactions: What is needed to improve their representation in Land Surface Models

Paul Dirmeyer

Center for Ocean-Land-Atmosphere Studies
George Mason University
Fairfax, Virginia, USA

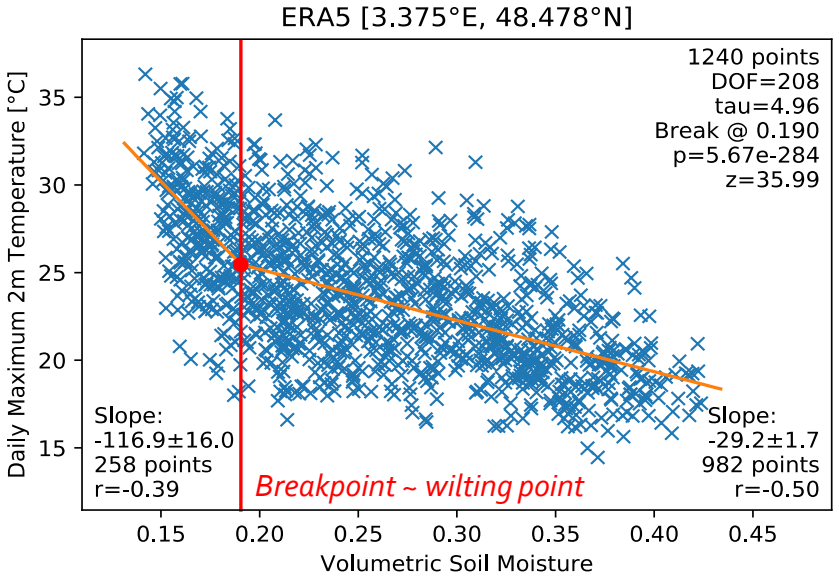
One Word… *Breakpoints*


Dustin Hoffman and Walter Brooke in “The Graduate” – 1967.

- Models are imperfect.
- Models have errors.
- Models have biases.
- Couple two models together…
  - Errors and biases propagate
  - Model equilibria are unrealistic
- For the land-atmosphere system, the key to a good coupled model is accurate representation of the transitions between different regimes (where coupled behaviors are consistent).
  - Whether physical, biogeochemical, ecological…
  - On scales from weather to climate

Definition of Breakpoint

- A breakpoint is where a change in functional relationship occurs between purported cause and effec
- Often represented by a piecewise linear relationship / regression.
- Example on the right: daily maximum summer temperature as a function of surface soil moisture.
  - This breakpoint occurs at the wilting point: surface evaporation shuts down, ground heating, sensible heat flux and radiative heating compound.
- Breakpoints exist because of underlying physical processes.

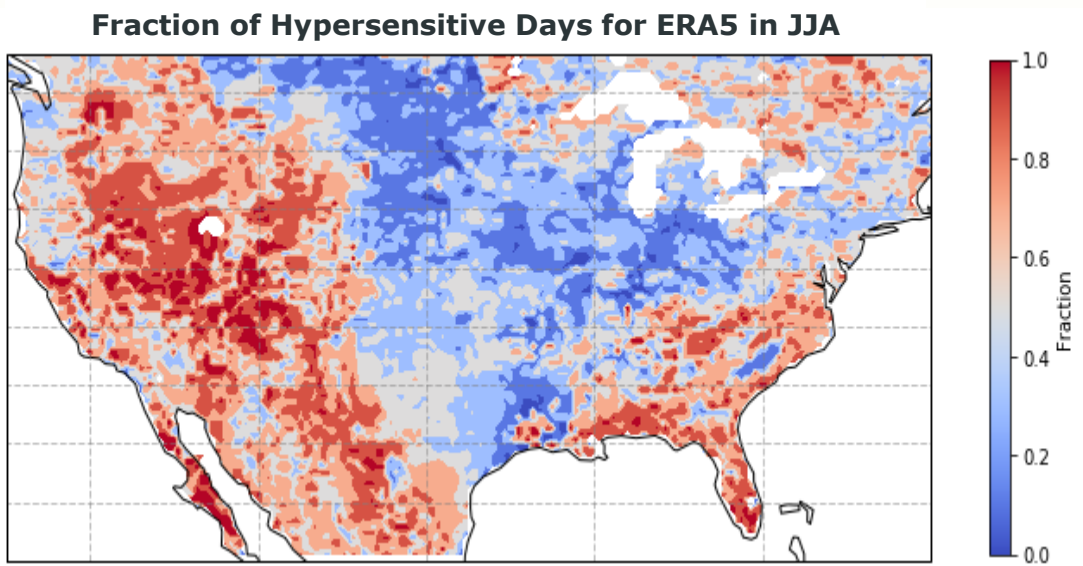


Grid cell in France – ERA5 data from July 1979-2018

Dirmeyer et al., (2021: AGU Advances; 10.1029/2020AV000283)

Example: Soil Moisture & Extreme Heat

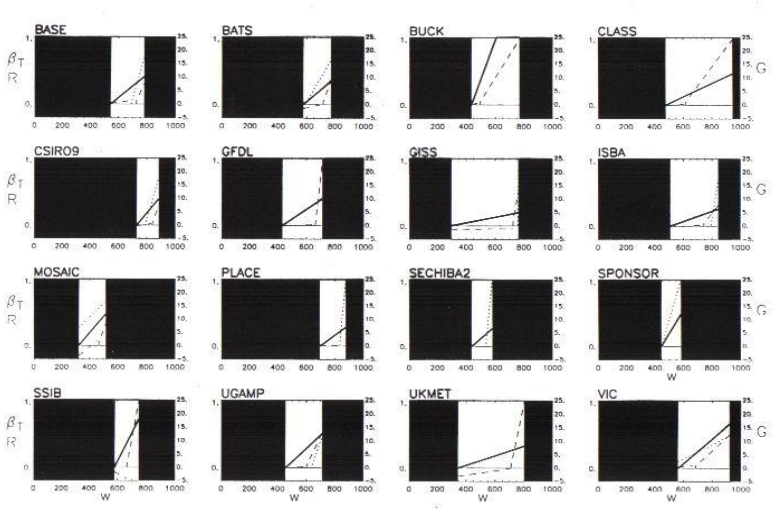
- "Hypersensitive" days are those when soil moisture is below its breakpoint for increased sensitivity of T_{max} to soil moisture.
- Verified with observed data from FLUXNET, SCAN.
- An effective coupled L-A model will:
  - Be on the correct side of breakpoints in the right places at the right times.
  - Can simulate the transitions across breakpoints realistically.



Benson & Dirmeyer (2021: JHM,110.1175/JCLI-D-20-0440.1)

Changes in Paradigms

- Historically, the focus on model performance has, first and foremost, been on simulation of the *mean* (i.e., reduction of bias), and secondarily, variability (e.g., *standard deviation*).
- For forecasts and hindcasts, skill metrics including RMSE, correlation, and various skill scores are typically used.
- These performance metrics are all univariate – processes are multivariate – relationships between variables determine coupled behavior.
- Koster et al. (2009) advocated for normalization (for soil moisture). Biases are meaningless; ultimately variability and co-variability are important.

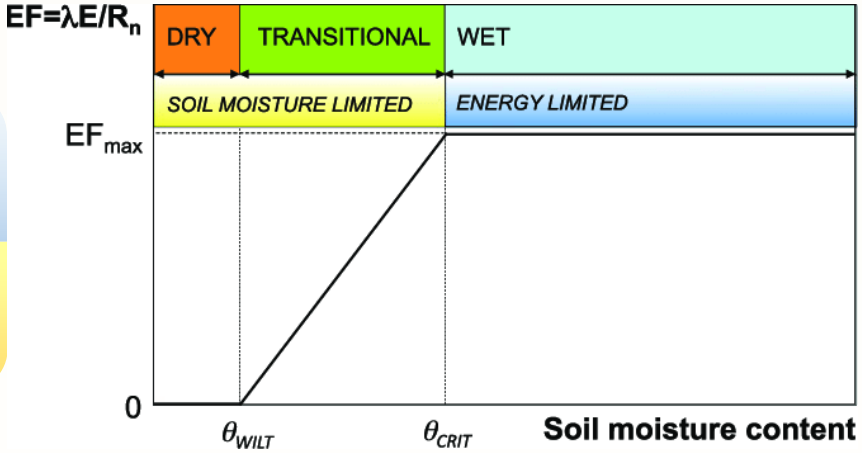


Koster & Milly (1997: J Climate)

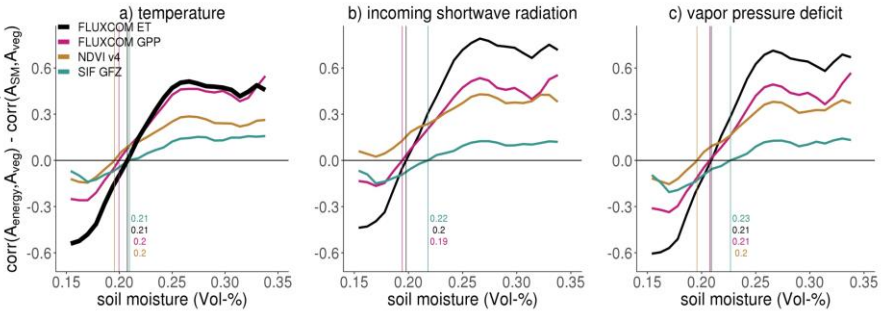
Koster et al. (2009: J Climate, 10.1175/2009JCLI2832.1)

Soil Moisture's "Three Regime" Paradigm

- For soil moisture:
  - Above a critical point, wet (energy availability limits evapotranspiration)
  - Below the wilting point: dry
  - Transitional: soil moisture regulates ET
- More complex statistical methods can be used to detect critical soil moisture θ_{CRIT}.
- A combination of satellite and *in situ* data can be used to establish global fields for model validation.



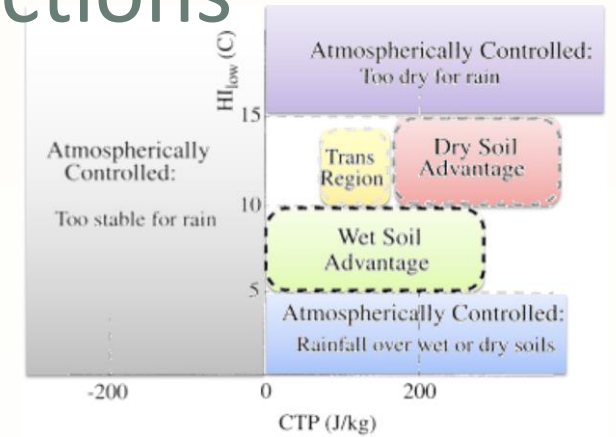
Seneviratne et al. (2010: Earth Sci. Rev., 10.1016/j.earscirev.2010.02.004)



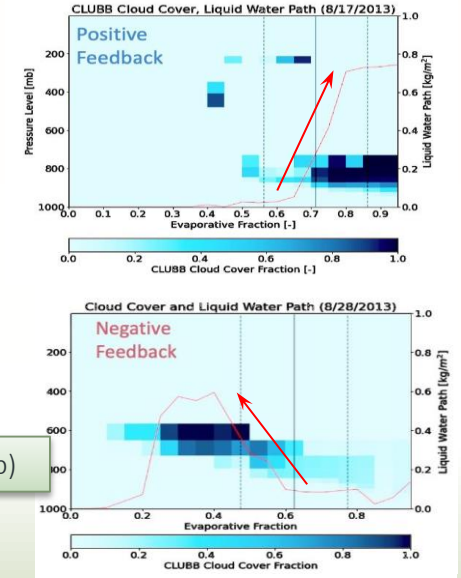
Denissen et al. (2020: J. Geophys. Res., 10.1029/2019JD031672)

More Complex Coupled Interactions

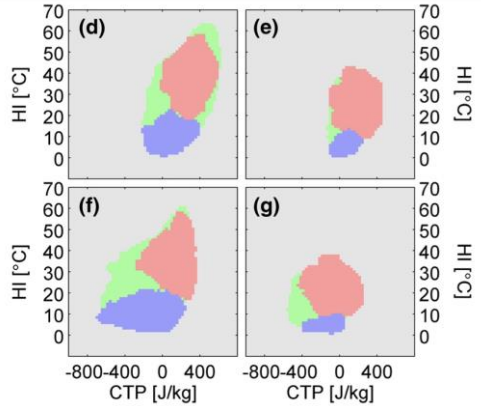
- In the land-atmosphere system, interplay between components can create complex regime transitions and interactions.
- Depending on soil moisture regime, surface fluxes and atmospheric profiles, the formation of clouds may be favored over either drier or wetter ground.
- Spatial patterns over the land surface can drive atmospheric circulations that further alter feedbacks.



Findell & Eltahir, 2003a,b: J. Hydrometeor., 552-



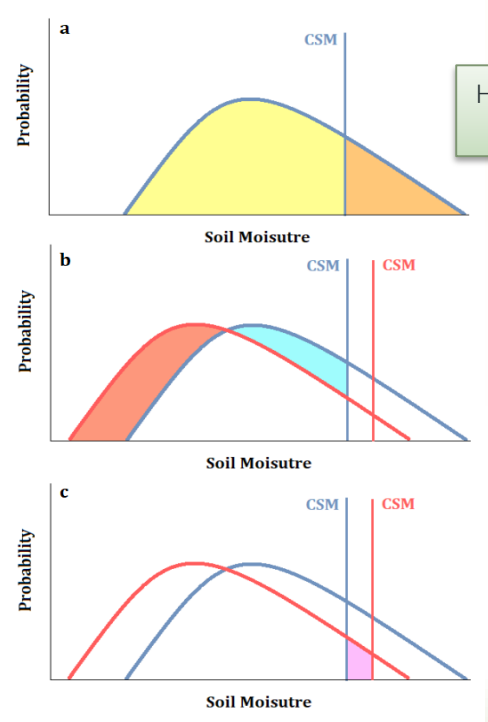
Hay-Chapman & Dirmeyer (in prep)



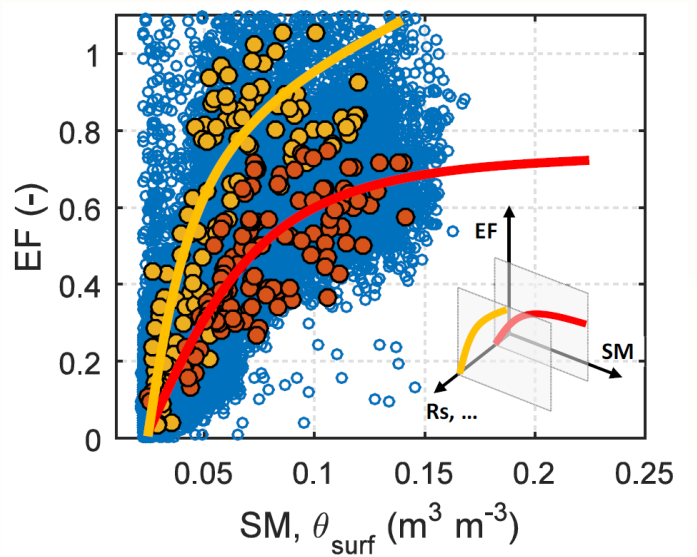
Roundy et al. (2014: Clim. Dyn., 10.1007/s00382-013-1982-7)

The Critical Point Is Fluid

- While the wilting point is a robust function of soil and vegetation types, the critical point depends on environmental factors.



Hsu & Dirmeyer (2022; Earth's Future, in prep)

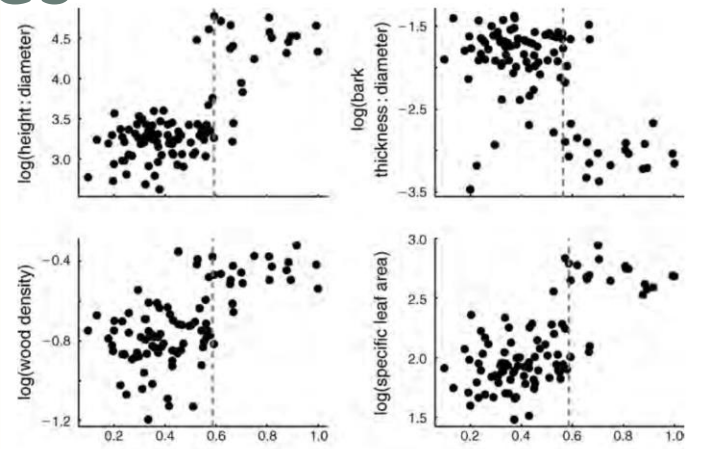


Haghighi et al.(2018: WRR., 10.1002/2017WR021729)

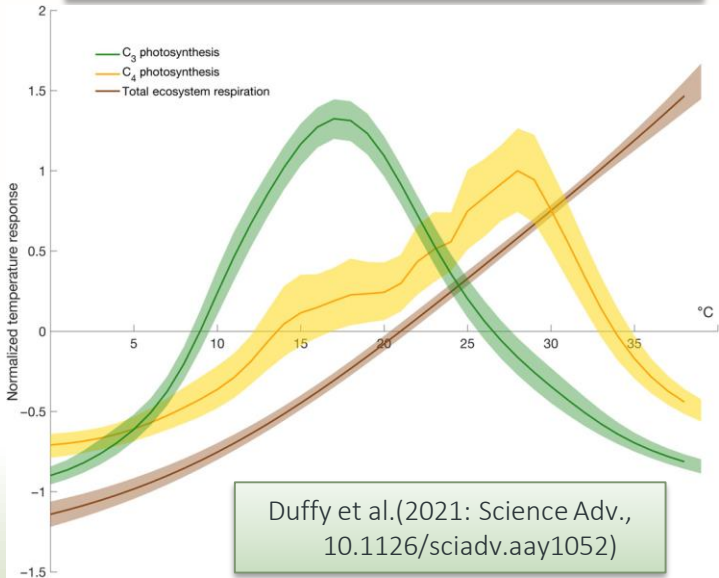
- In a changing climate, the time a location spends in a water-limited regime depends on both changes in soil moisture distributions and shifts in the critical soil moisture value, and not soil moisture alone.

Ecological Modeling Examples

- Transition between tropical forest and savannah marks a breakpoint between two quasi-stable regimes, determined mainly by fire dynamics.
- Perhaps the most important breakpoint in ecosystems is that between GPP-dominant and TER-dominant conditions that determine the sign of NEP.
  - Locally, depends on many environmental, chemical (nutrient) and biological factors.
  - Integration to any scale beyond point-scale compounds complexity.



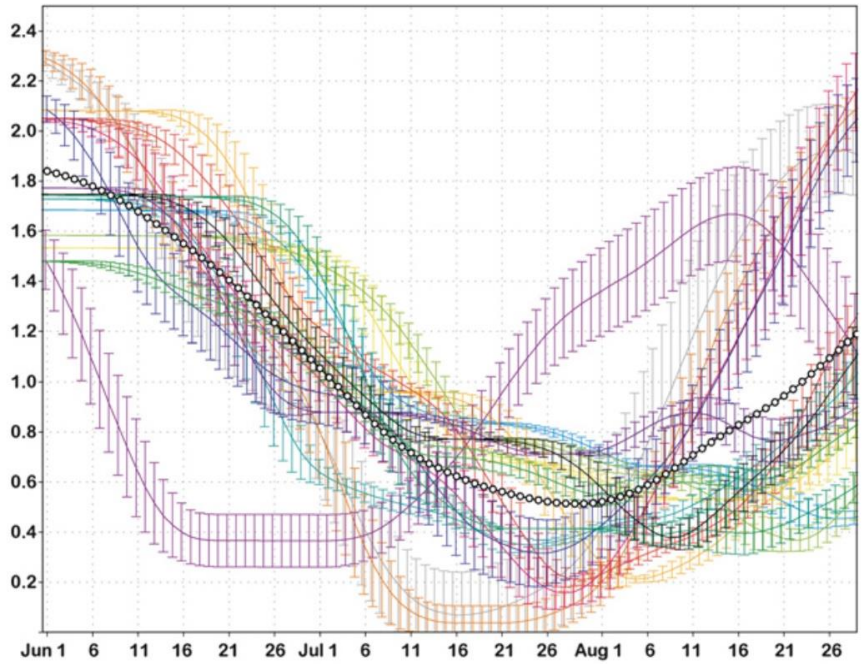
Dantas et al.(2013: Ecology, 10.1890/12-1629.1)



Duffy et al.(2021: Science Adv., 10.1126/sciadv.aay1052)

Cautionary Tale

- An example of unintended consequences when modeling breakpoint behaviors…
- To prevent "stomatal suicide" in tropical C4 grasslands after dry-season onset, a recovery timer was implemented in CLM4.
- This caused 30-60 day oscillations in LAI that introduced bogus sub-seasonal predictability into CCSM4.

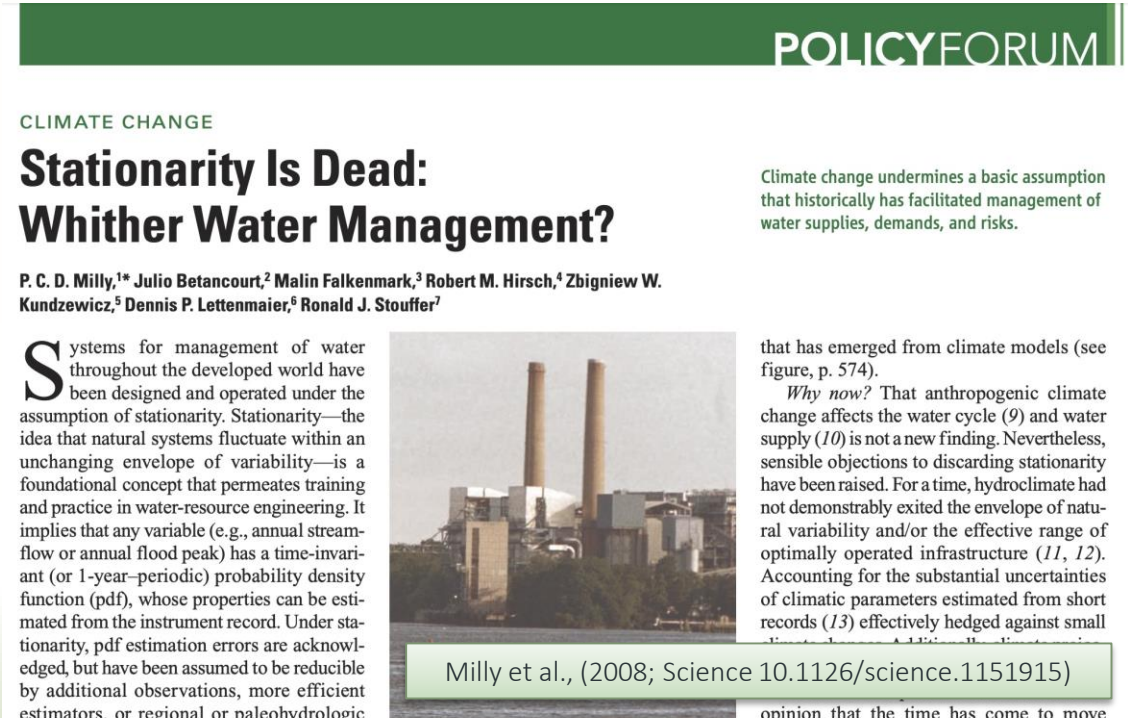


Dirmeyer et al., (2013; J. Climate; 10.1175/JCLI-D-13-00029.1)

- Lesson: quick fixes in coupled models will usually cause side effects, often far from the fix. It is best to have a model do things for the right (physical) reasons….

Statistics Finds Breakpoints

- As shown, various statistical methods can be used to identify breakpoints in observational and model data sets.
- But statistics alone does not explain them… this is a danger for those who view machine learning techniques as a panacea.
- Statistical models trained on past data cannot *guarantee future returns*. Models must represent physical processes that define breakpoints (and their changes).



POLICYFORUM

CLIMATE CHANGE

Stationarity Is Dead: Whither Water Management?

Climate change undermines a basic assumption that historically has facilitated management of water supplies, demands, and risks.

P. C. D. Milly,[1]* Julio Betancourt,[2] Malin Falkenmark,[3] Robert M. Hirsch,[4] Zbigniew W. Kundzewicz,[5] Dennis P. Lettenmaier,[6] Ronald J. Stouffer[7]

Systems for management of water throughout the developed world have been designed and operated under the assumption of stationarity. Stationarity—the idea that natural systems fluctuate within an unchanging envelope of variability—is a foundational concept that permeates training and practice in water-resource engineering. It implies that any variable (e.g., annual streamflow or annual flood peak) has a time-invariant (or 1-year–periodic) probability density function (pdf), whose properties can be estimated from the instrument record. Under stationarity, pdf estimation errors are acknowledged, but have been assumed to be reducible by additional observations, more efficient estimators, or regional or paleohydrologic

that has emerged from climate models (see figure, p. 574).

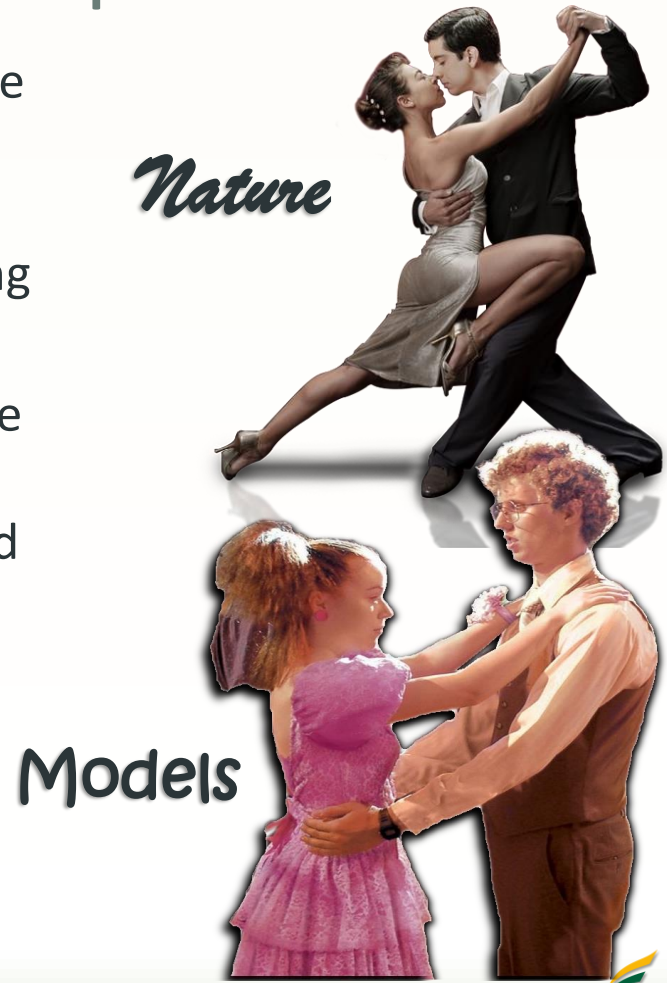
Why now? That anthropogenic climate change affects the water cycle (*9*) and water supply (*10*) is not a new finding. Nevertheless, sensible objections to discarding stationarity have been raised. For a time, hydroclimate had not demonstrably exited the envelope of natural variability and/or the effective range of optimally operated infrastructure (*11*, *12*). Accounting for the substantial uncertainties of climatic parameters estimated from short records (*13*) effectively hedged against small

opinion that the time has come to move

Milly et al., (2008; Science 10.1126/science.1151915)

Coupled L-A Model Development

- Land models and atmosphere models have been developed separately (in isolation), then plugged together without much coupled validation. Not good for simulating L-A interactions.
- Until recently, it was not feasible to pursue model development and validation in a coupled way. With new understanding and data, now we can, and we are!
- We have a chance to model nature much better and improve weather predictions and climate projections including breakpoints: the critical thresholds and transitions – it's a coupled system.



Katharine Ross and Dustin Hoffman in “The Graduate” – 1967.