Understanding Hydrometeorology using global models

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Preamble

- Not a review talk
- Title is meant to be a paradox
- Simple models for understanding?
  Hydrometeorology is too complex
- Climate interactions of water
  [phase changes and radiation interactions] are central to climate
- Let us confront the challenge
Climate is both global and local

• Need coupled earth system models
• Need them locally to warn us of the first frost [local diurnal cycle in September]
• Improving our global models is central
• Global models can be used as tools to understand interacting processes
• Contrast our model world, which we dimly understand, and the real world, where we only understand fragments of a complex, living system.
What controls evapotranspiration?

• “Equilibrium evaporation”.
  *Raupach (BLM, 2000, QJRMS 2001)*

• Models for the *growing daytime “dry BL”*

• Fascinating but simplified by ignoring some key real-world physics, which control evaporation for climate equilibrium.
What is this ignored physics?

• Cloud fields control cloud base, the surface net radiation, and dominate the cooling rate of the CBL
  
  *It is not the dry BL solutions that are relevant*

• Climate problem is a 24-hr mean problem, with a superimposed diurnal cycle
  
  *It is not just a growing daytime BL problem*

• First-order atmospheric constraints on evaporation. Global models with coupled cloud fields include these processes, so they can help us understand the coupling
Outline

a) Global scale feedbacks – seasonal forecasts

Idealized global soil moisture simulations and evaporation-precipitation feedback over continents

b) Land-surface coupling at daily timescale – 30 years of ERA40 river basin time-series

Coupling of soil moisture, cloud-base, cloud cover, radiation fields, sensible, latent heat; TCWV, precipitation and omega
a) Global scale feedbacks - Idealized soil moisture simulations and evaporation-precipitation feedback

- Serendipity, and great flood on the Mississippi of July 1993
- Parallel ECMWF suite with a 4-layer soil model to better represent soil moisture memory
- Soil moisture sensitivity experiments for July, 1993
July 1993: wet-dry soil initialization

- Increase of monthly forecast precipitation: peaking at over 4 mm/day or >125 mm/month [Beljaars et al. 1996]
Seasonal forecasts with idealized soil moisture

- ERA40 model: 120-day forecasts at T-95 L60 from May 1, 1987 (DOY=121)
- Identical except
  a) Soil moisture initialized at 100% field capacity for vegetated areas
  b) Soil moisture initialized at 25%

Soil Moisture Index

\[ 0 < SMI < 1 \text{ as PWP} < \text{SM} < \text{FC} \]
P, E, P-E and SMI for Eastern US

- Reduction of SMI reduces precipitation, evaporation
- has little impact on P-E which averages to small values over summer
- Memory of soil moisture lasts all summer
Monsoon India

Only in monsoon regions where P-E is large is memory of SMI reduced
Evaporation over land linked to precipitation: [away from monsoons]

- So what controls evaporation?
- Not classic “equilibrium evaporation”
- Recast equilibrium evaporation as as a diurnally averaged problem, linked to cloud-base and cloud fields

[Betts, JHM 2000; Betts et al., JGR 2004, in press]
Surface energy balance, and ML “equilibrium”

- 3 Americas regions
- 5-day means: of wet and dry simulations

- Latent heat $\lambda E$ against SMI: weak relation: sensitive to $R_{\text{net}}$
- Sensible heat $H$ against SMI: tight relation
- linked to dependence of depth to cloud-base on SMI
Sensible heat flux: $H$

- $H$ against $P_{\text{LCL}}$: linear with slope related to cooling processes in ML
- $H$ is constrained by ML cooling, constrained by cloud-base
- Net long-wave has similar behavior: coupled to $P_{\text{LCL}}$
Amazon basin in more detail

- $H$, $8E$ quasi-linear with $P_{LCL}$: 2-m $Q$ and $T$ quasi-linear with $P_{LCL}$
- Over wetter soils, $E$ increases; $T$ decreases and $Q$ increases in ML
- *New coupled state* has lower LCL, with cooler, moister ML; reduced $H$ and larger $E$
Conclusions-1

• Climate and climate change over land depends critically on getting evaporation-precipitation feedback right

• ERA-40 model has large E, P feedback over continents  [Is it right?]

• The change in surface energy budget over dry and wet soils is consistent with a shift of the mean sub-cloud layer equilibrium
b) ERA40 river basin budgets

- Basin averages: hourly archive
- Daily averages: 1972-2002 [11000 days]

- Madeira : Amazon
- Arkansas-Red : Mississippi
- Athabasca : Mackenzie

- [ERA40 biases: see Betts et al. 2003a,b]
ERA40 for Madeira River basin compared with LBA Rondonia pasture site: 1999

- Large seasonal change of diurnal amplitude
- ERA-40 basin ranges smaller than at pasture site
ERA40 Annual means
1957-2001

P: precipitation
E: evaporation
R: runoff
CSM: Column soil water
Annual means

TCWV: Total column water vapor
P: precipitation
P-bias from observations

Regression on TCWV

P: precipitation
R: runoff
P-bias
**ERA40**

*Annual means corrected*

Mean is ± 10%, but

Little signal in interannual variability

Data for P uncertain
Monthly precipitation and P-bias from observations against TCWV

P against TCWV:
[similar to annual]

Bias against data
ERA40 is
wet in dry season
dry in wet season
[if P-data is correct]
T control by precipitation
Coupling of soil moisture index, cloud-base height and Evaporative fraction

- Mean cloud-base height increases over drier soils and with larger surface $R_{\text{net}}$
- Evaporative fraction increases with soil moisture, and decreases with $R_{\text{net}}$
- 3 basins similar: with additional dependence on unstressed resistance
Madeira basin for July and November

- July: dry season
- Nov: wet season

- Surface fluxes as function of cloud-base and cloud cover
$LW_{\text{net}}$ dependencies

- Soil moisture index
- Cloud-base
- Total cloud cover
- Diurnal range: $T_s$
- 2 months merge to single quasi-linear distribution
SW_{net} dependencies

- Tight coupling to LW_{net}
- Cloud-base
- Total cloud cover
- Sensible heat flux H

- Distinct distributions except for H
Sensible heat flux $H$

- Diurnal range: $T_s$
- Maximum $T_s$
- Cloud-base
- $SW_{net}$
- Distinct distributions except where coupled to $SW_{net}$
- Subcloud heating rates
- 3K/day in July
- 6K/day in November
Latent heat flux $\lambda E$ and $H$

- Coupling of $H$ to SMI through $P_{LCL}$ stronger than coupling of $\lambda E$
- $\lambda E$ has more variation with $R_{\text{net}}$ in rainy season
- $H$ splits into 2 branches as function of $R_{\text{net}}$ [contrast $SW_{\text{net}}$]
LW coupling for other basins

- $LW_{\text{net}}$ tightly coupled to cloud cover and cloud-base
- Madeira has 50hPa lower cloud-base
- Red-Arkansas has 0.25 lower cloud cover
**Surface-coupled physics**

*Daily Means* (Madeira River)

Soil moisture index against $P_{LCL}$: LCL of cloud-base
EF: Evaporative fraction

Soil moisture index against LCC: Low cloud cover
$LW_{net}$: surface net longwave
Tropospheric-coupled physics

Daily means

$\Omega_{\text{mid}}$: mid-tropospheric omega against TCWV and TCC

TCWV against Precipitation and TCC

[Linear regression]
**Coupling of ascent with precipitation**

**Daily means**

P and E against

$\Omega_{\text{mid}}$: mid-tropospheric omega

Note P $\Rightarrow$ 0 at $\Omega_{\text{mid}} \sim 40$ hPa/day

“Moist circulation” and precipitation
Conclusions-2

• Model data such as reanalyses can be used to understand coupling of processes.
• Coupling of surface processes in ERA-40, though complex, is comprehensible.
• Soil moisture, cloud-base, cloud cover, the radiation fields and evaporative fraction are coupled quite tightly [sub-seasonally].
• Mid-tropospheric omega, TCWV and TCC coupled.
  Mid-tropospheric omega and precipitation closely linked on daily time-scale.
Conclusions-3

- Evaporation is controlled somewhat indirectly by the controls on net radiation and sensible heat flux
- The long-wave flux control by cloud-base height and cloud cover is particularly tight across all basins
- The sensible heat flux is coupled to cloud-base height, cooling processes in the sub-cloud layer, as well as directly to the shortwave flux [in ERA-40]
Conclusions-4

- Proposing a framework for analyzing model data for land-surface feedbacks
- Proposing analysis framework for comparing global models and climate observations

- RH, cloud-base and cloud cover need to be measured with the radiation fields as *climate variables*
- Climate modeling with interchangeable plug-in modules is fraught with peril, as the feedbacks change
Comparisons with data

ERA-40 ‘point’ Harvard forest tower
SW-cloud coupling to $P_{LCL}$

- Total cloud cover: ERA40
- Transmitted fraction SW
- Transmitted fraction PAR

-compare LW coupling