Land-surface-BL-cloud coupling & the diurnal cycle

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Diurnal Cycle

- The surface diurnal cycle over land is the "climate signal" that is important to us
- $T_{\text{max}}, T_{\text{min}}$ and $\text{DTR} = T_{\text{max}} - T_{\text{min}}$
- Surely we understand it? Surely we can model it? We observe it every day and forecast centers work hard to reduce their biases!
- As climate warms, some evidence $T_{\text{min}}$ increasing faster than $T_{\text{max}}$
- **Result of fully coupled system**: soil, surface layer, BL, clouds, precipitation…
State of our Models: CMIP5

“The diurnal temperature range is found to vary substantially between different CMIP5 models, in particular in the subtropics, and is in general underestimated by the models. In future projections with the high emission scenario, the models disagree on both sign and the magnitude of the change of the diurnal temperature range over land.”

[Lindvall and Svensson, 2012, submitted]
Diurnal Cycle: ERA40

- $T_{sc}$: scaled by $LW_{net24}/4\sigma T^3$
- Rise: $SW_{net}$ & Bowen Ratio
- Fall: $LW_{net}$
- Asymmetry
- Both satisfied in coupled system?

Betts (JGR 2006)
Diurnal Temperature Range

- *Increasing cloud*: DTR falls
  - $T_{rise} > T_{fall}$
    - *(DTR Scaled)*
  - $T_{mean} < (T_{max} + T_{min})/2$
  - *(Zeng & Wang, 2012)*

*ERA-40 Madeira River basin*
Diurnal Temperature Range

- *Increasing cloud*: DTR falls
- $T_{\text{rise}}$ and $T_{\text{fall}}$ from $T_{\text{mean}}$ become asymmetric
- Scaled $T_{\text{rise}} > T_{\text{fall}}$

*ERA-40 JJA BERMS-SK site*
Surface Energy Balance

\[ R_{\text{net}} = SW_{\text{net}} + LW_{\text{net}} = H + \lambda E + G \]

- Surface processes and atmospheric processes
- SW (day) and LW (night) dominate
- Partition between clear-sky and cloud processes in the atmosphere ['cloud forcing']
- Partition of the surface \( R_{\text{net}} \) into \( H \) and \( \lambda E \): availability of water for evapotranspiration
ERA40: $T_{\text{max}}$, $T_{\text{min}}$, DTR

“Night”

- $T_{\text{max}}$, DTR decrease as LW$_{\text{net}}$ gets smaller (moist, cloudy)
- $T_{\text{min}}$ increases

“Day”

- $T_{\text{max}}$, DTR increase with SW$_{\text{net}}$ (dry, sunny)
- $T_{\text{min}}$ flat
ERA40: $T_{\text{max}}, T_{\text{min}}, \text{DTR}$

“Night”

- $T_{\text{max}}$, DTR decrease as $LW_{\text{net}}$ gets smaller (moist, cloudy)
- $T_{\text{min}}$ increases

“Day”

- $T_{\text{max}}$, DTR increase with $H$ (dry, sunny)
- $T_{\text{min}}$ flat
Partition by BR = H/λE

- BR impacts $T_{\text{max}}$ most
- BR impacts $T_{\text{max}}$, $T_{\text{min}}$ and DTR most
My view of SEB

$SW_{net}$ (or $H$) dominates $T_{max}$

$LW_{net}$ dominates DTR, $T_{min}$
Clouds & Surface $SW_{\text{net}}$

$SW_{\text{net}} = SW_{\text{down}} - SW_{\text{up}} = (1 - \alpha_{\text{surf}})(1 - \alpha_{\text{cloud}}) SW_{\text{down}}(\text{clear})$

- **surface albedo**
  
  $$\alpha_{\text{surf}} = \frac{SW_{\text{up}}}{SW_{\text{down}}}$$

- **effective cloud albedo** [per unit area surface]
  
  - scaled surface short-wave cloud forcing, SWCF

  $$SWCF = SW_{\text{down}} - SW_{\text{down}}(\text{clear})$$

  $$ECA = \alpha_{\text{cloud}} = -\frac{SWCF}{SW_{\text{down}}(\text{clear})}$$

[Betts and Viterbo, 2005; Betts, 2007]
Surface $LW_{\text{net}}$

- Point comparison: stratified by RH (LCL) & $\alpha_{\text{cloud}}$ (ECA)
- Quasilinear clear-sky and cloud greenhouse effects
- Drives DTR and $T_{\text{min}}$
\( \text{LW}_{\text{net}} \) - Diurnal Temperature Range
ERA-40 & Monthly Flux Tower data

- Mean \( \text{LW}_{\text{net}} \), DTR well correlated

[Betts: JGR, 2006; Betts and Silva Dias, 2010]
Seasonal cycle of Diurnal Temperature Range (DTR)

- DTR linked to phenology and transpiration
  - 5 April: melt, BR high, RH low, clear sky, DTR ↑
  - 5 May: forest leaf-out, transpiration, RH, cloud ↑, DTR ↓
  - 2 Oct: frost signals forest senescence

[Image of line graph showing Diurnal Temperature Range (°C) over the year from 5 April to 2 October. The graph indicates a peak in DTR on 5 May and a decline on 2 October. The location is Rutland, Vermont, 43°36.7'N, 72°57.4'W, 2000-2009.]

[Betts, 2010]
- H warms NBL, merges residual BL, forms first cumulus
- Shallow cloud transports lock LCL to ML depth
- Deep dry BL, large LW cooling gives large DTR (& NBL)
- LW cooling of ML balances surface H over 24h

[Betts, 2003]
Modeling Issues

- Fully coupled system
- Must solve over sequential diurnal cycles with coupled radiation clouds and BL
- Even non-precipitating case poorly modeled
- Critical measurable parameters are cloud-base, $f(\theta,q)$, and cloud-fraction/optical depth, which determine SWCF/ECA
Forced SCM – All Model Physics (Amazon)

ECMWF SCM

*Initial conditions:*
Grid-point in Rondônia

*Forcing*
Idealized Diurnal Omega, single tropospheric mode

Φ=0 : subsidence at midnight
M=0 : zero mean ascent
A=2 : 2x 0.05 Pa/sec

Forced SCM run of 15 days
Average day 2-15
Quasi-equilibrium diurnal cycle, all model processes, specified vertical advection, no horizontal advection

[Betts and Jakob, JGR 2002b]
14-day Coupling: Fluxes and Precip.

14-day mean fluxes and cloud cover against precipitation

For $M=0$ (no mean ascent)
Amplitude $A=0, 1, 2, 4$
Phase $\Phi$ from 0 to 21

$LH (\lambda E)$ determines precip - 1:1 line shown

Cloud cover determines $SW_{net}$, $R_{net}$ and LH

Diurnal phase of omega forcing determines SW cloud forcing
Impose Mean Ascent

Banded data as mean ascent forcing $M = 0, 1, 2$ increases

For $M=2$, split modes

- daytime ascent gives stratiform precipitation, high cloud cover
- daytime subsidence gives convective precipitation, low cloud cover
Split Modes - Phase of Forcing

Daily Means: M=2, A=4

Daytime subsidence: Φ= 6 to 18 gives High $R_{\text{net}}$ and Daytime convective rain

Daytime ascent: Φ= 21, 0 and 3 gives Low $R_{\text{net}}$ and Daytime stratiform rain
DTR on $LW_{net}$

- ERA-40 basin means
- Non-equil. SCM
Complex Diurnal Modes

- Quasi-2day precipitation modes reflected in DTR (and other variables) \([\text{for } M=\Phi=0; A=4]\)
Modeling Issues

- Fully coupled system
- Must solve over sequential diurnal cycles with coupled radiation, clouds and microphysics
- Precipitation, cloud and surface radiation sensitive to forcing and its phase
- Critical measurable parameters are cloud-base, cloud-fraction, cloud forcing, incoming radiation and precipitation

- “CMIP5 models disagree on both sign and the magnitude of the change of the diurnal temperature range over land”