Radiative-Convective Equilibrium in Single Column CAM

I-Kuan Hu, Brian Mapes, Richard Neale, and Andrew Gettelman

22nd CESM Workshop
Motivation

The Earth’s atmosphere is an extremely thin sheet of air ...

(NASA, “The Atmosphere”)
Motivation

... within which complex chemical, thermodynamic, and fluid dynamics effects occur.

(Met Office, “Water Cycle for Kids”)
Motivation

... within which complex chemical, thermodynamic, and fluid dynamics effects occur. How do we study it?

(Met Office, “Water Cycle for Kids”)
Motivation

Modeling provides a great tool for understanding and prediction
Motivation

Modeling provides a great tool for understanding and prediction should be a great tool for understanding
Motivation

Issues in a global climate model:
- Processes and feedbacks are mingled together
- External conditions change with time
Motivation

Issues in a global climate model:
• Processes and feedbacks are mingled together
• External conditions change with time

Need frameworks with reduced complexity
→ model hierarchies!

+ full dynamical core
+ surface exchange
+ topography
+ coupling to ocean

1D SCM
Physical Parameterization

3D AGCM
Aquaplanet Simulation

3D AGCM
Full Complexity

3D ESM
Full Complexity in All Components
Motivation

Issues in a global climate model:

• Processes and feedbacks are mingled together
• External conditions change with time

Need frameworks with reduced complexity

→ model hierarchies!

+ full dynamical core
+ surface exchange
+ topography
+ coupling to ocean

This talk:

1D SCM  
Physical Parameterization

3D AGCM  
Aquaplanet Simulation

3D AGCM  
Full Complexity

3D ESM  
Full Complexity in All Components
Introduction

Radiative-Convective Equilibrium (RCE):

• Over the Tropical oceans net radiative cooling $\sim 100-150 \ W/m^2$
Introduction

Radiative-Convective Equilibrium (RCE):

- Over the Tropical oceans

net radiative cooling $\sim 100-150 \, W/m^2$

\begin{tikzpicture}[>=latex, every node/.style={scale=0.7}]
  \draw[ultra thick] (-5,0) -- (5,0) node[above] {TOA};
  \draw[ultra thick] (-5,-3) -- (5,-3) node[above] {SRF};
  \draw[blue, ultra thick, -] (-5,0) -- (-4,0);
  \draw[blue, ultra thick, -] (-4,0) -- (-3,0);
  \draw[blue, ultra thick, -] (-3,0) -- (-2,0);
  \draw[blue, ultra thick, -] (-2,0) -- (-1,0);
  \draw[blue, ultra thick, -] (-1,0) -- (0,0);
  \draw[blue, ultra thick, -] (0,0) -- (1,0);
  \draw[blue, ultra thick, -] (1,0) -- (2,0);
  \draw[blue, ultra thick, -] (2,0) -- (3,0);
  \draw[blue, ultra thick, -] (3,0) -- (4,0);
  \draw[blue, ultra thick, -] (4,0) -- (5,0);
  \draw[orange, ultra thick, -] (-5,-3) -- (-4,-3);
  \draw[orange, ultra thick, -] (-4,-3) -- (-3,-3);
  \draw[orange, ultra thick, -] (-3,-3) -- (-2,-3);
  \draw[orange, ultra thick, -] (-2,-3) -- (-1,-3);
  \draw[orange, ultra thick, -] (-1,-3) -- (0,-3);
  \draw[orange, ultra thick, -] (0,-3) -- (1,-3);
  \draw[orange, ultra thick, -] (1,-3) -- (2,-3);
  \draw[orange, ultra thick, -] (2,-3) -- (3,-3);
  \draw[orange, ultra thick, -] (3,-3) -- (4,-3);
  \draw[orange, ultra thick, -] (4,-3) -- (5,-3);
\end{tikzpicture}

Surface fluxes (LHFLX + SHFLX)
Radiative-Convective Equilibrium (RCE):

- Over the Tropical oceans
  
  **net radiative cooling ~100-150 W/m²**

  ![Diagram](image.png)

  - TOA
  - Energy redistribution by moist convection
  - Surface fluxes (LHFLX + SHFLX)
Introduction

Radiative-Convective Equilibrium (RCE):

• Over the Tropical oceans

net radiative cooling \( \sim 100-150 \, W/m^2 \)

Rad. Cooling \( \approx \) Srf. Fluxes
Precp. \( \approx \) Srf. Evap. (LHFLX)

Energy redistribution by moist convection

Surface fluxes (LHFLX + SHFLX)
Introduction

RCE in Single Column Model:

What we want from a model

\[
\frac{d\tilde{s}}{dt} = \frac{\partial \tilde{s}}{\partial t} + \nabla \cdot \nabla \tilde{s} + \bar{\omega} \frac{\partial \tilde{s}}{\partial \rho} = Q_R + L(c - e) - \nabla \cdot \left( s'v'_h \right) - \frac{\partial (s' \omega')}{\partial \rho}
\]
RCE in Single Column Model:

What we want from a model

\[
\frac{d\tilde{s}}{dt} = \frac{\partial \tilde{s}}{\partial t} + \nu \nabla \tilde{s} + \bar{\omega} \frac{\partial \tilde{s}}{\partial p} = Q_R + L(c - e) - \nabla \cdot (s'v'_h) - \frac{\partial (s'\omega')}{\partial p}
\]

Single column, sorry

• No horizontal dynamics involved
Introduction

RCE in Single Column Model:

What we want from a model

No background vertical motion

No horizontal dynamics involved

No “large-scale” data is fed in, so it does not act like a column at a specific location (current usage of SCAM). Rather, it represents a mean (usually tropical) climate state → 1-D climate model

\[
\frac{d \bar{s}}{dt} = \frac{\partial \bar{s}}{\partial t} + \bar{v}_h \cdot \nabla \bar{s} + \bar{\omega} \frac{\partial \bar{s}}{\partial \rho} = Q_R + L(c - e) - \nabla \cdot \left( s'v'_h \right) - \frac{\partial (s'\omega')}{\partial \rho}
\]

Single column, sorry
Introduction

RCE in Single Column Model:

- No horizontal dynamics involved
- No "large-scale" data is fed in, so it does not act like a column at a specific location (current usage of SCAM). Rather, it represents a mean (usually tropical) climate state → 1-D climate model
- Represent vertical energy transfer only → a purely thermodynamic model

\[
\frac{d\bar{s}}{dt} = \frac{\partial \bar{s}}{\partial t} + \nabla \cdot \bar{s} + \bar{\omega} \frac{\partial \bar{s}}{\partial p} = Q_R + L(c - e) - \nabla \cdot \left( \bar{s} \bar{v}_h \right) - \frac{\partial (s' \omega')}{\partial p}
\]
Introduction

RCE in Single Column CAM, version 5.4 (SCAM5)

\[ \frac{d\bar{s}}{dt} = \frac{\partial \bar{s}}{\partial t} + \bar{v}_n \cdot \bar{s} + \bar{\omega} \cdot \frac{\partial \bar{s}}{\partial p} = Q_R + L(c - e) - \nabla \cdot (s'v'_h) - \frac{\partial (s'\omega')}{\partial p} \]
Introduction

RCE in Single Column CAM, version 5.4 (SCAM5)

\[
\frac{d \bar{s}}{dt} = \frac{\partial \bar{s}}{\partial t} + \bar{\nu} \cdot \bar{v} + \bar{\omega} \frac{\partial \bar{s}}{\partial p} = Q_R + L(c - e) - \nabla \cdot \left( s' v'_h \right) - \frac{\partial (s' \omega')}{\partial p}
\]

- RRTMG (SW+LW)
- Surface LHF, SHF
- Stratiform Micro.
- Stratiform Macro.
- Turbulence BP
- Deep Conv. ZM
- Shallow Conv. PB
- Dynamics
Introduction

RCE in Single Column CAM, version 5.4 (SCAM5)

\[
\frac{d\bar{s}}{dt} = \frac{\partial \bar{s}}{\partial t} + \bar{u} \cdot \nabla \bar{s} + \bar{\omega} \frac{\partial \bar{s}}{\partial p} = Q_R + L(c - e) - \nabla \cdot (s' v'_h) - \frac{\partial (s' \omega')}{\partial p}
\]
Experimental Setup

Basic Setup

• 60 levels, 60-sec. time step
• 29°C SST, 5m/s wind speed
  - For surface fluxes
• No aerosol effects, no rotation
Experimental Setup

Basic Setup

• 60 levels, 60-sec. time step
• 29°C SST, 5m/s wind speed
  - For surface fluxes
• No aerosol effects, no rotation

Initial Conditions

• A moist adiabat appropriate to the SST of 29°C, patched to a 200-K isothermal stratosphere
• RH specified as 70%
  - Sensitivity test: 30%, 50%, 90%
Experimental Setup

Types of Radiative Forcing

• Interactive (RRTMG)
  - Full package
  - No annual cycle of insolation
  - No annual & diurnal cycles of insolation
    (by fixing the zenith angle at 74.5°)

• Prescribed
  - Last 50-day mean of RRTMG w/o annual cycle
  - Idealized
Experimental Setup

Types of Radiative Forcing

• Interactive (RRTMG)
  - Full package
  - No annual cycle of insolation
  - No annual & diurnal cycles of insolation (by fixing the zenith angle at 74.5°)

• Prescribed
  - Last 50-day mean of RRTMG w/o annual cycle
  - Idealized

External Conditions

• SST (which changes the I.C. of T as well)
• Surface wind speed (from vertically uniform zonal wind)
Results
Effects of Radiative Forcing

Interactive Rad. Forcing

Prescribed Rad. Forcing
Effects of Radiative Forcing

Each run reaches to a statistical steady state after 50 days.

Interactive Rad. Forcing

Prescribed Rad. Forcing
Effects of Radiative Forcing

RAD / PRCP / SRFLX (LHFLX)

-111.8 / 102.8 / 110.7 (102.5)

-105.3 / 98.0 / 105.7 (98.4)

-105.3 / 98.2 / 105.9 (98.8)

-105.3 / 97.8 / 105.3 (98.0)

-105.7 / 98.1 / 105.8 (98.4)

Interactive Rad. Forcing

Prescribed Rad. Forcing
"RCE oscillations": Regular oscillations with a period of \( \sim 5-6 \) days.

For all types of radiation forcing considered, RCE oscillations exist, but oscillation patterns differ.
Effects of Radiative Forcing

Interactive Rad. Forcing

Prescribed Rad. Forcing

(a) RRTMG

(b) RRTMG, no annual cycle

(c) RRTMG, no annual & diurnal cycles

(d) Time mean of (b)

(e) IDEAL, 1 K/day
Sensitivity to Initial Moisture Conditions?

(a) RH = 30%
(b) RH = 50%
(c) RH = 70%
(d) RH = 90%

PRCP  LHFLX

Control run → inctvRAD
Sensitivity to Initial Moisture Conditions?

Only in the first 30 days: larger LHFLX and later PRCP onset in the case with drier IC.
Sensitivity to Initial Moisture Conditions?

Only in the first 30 days: larger LHFLX and later PRCP onset in the case with drier IC.

Drier atmosphere imports more q from the ocean for the development of moist conv.

The “fixedRAD” runs show similar results.
# Effects of External Conditions

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>RAD / PRCP / SRFLX (LHFLX) [W/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SST</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25 °C</td>
<td>-95.0</td>
<td>87.2 / 95.6 (87.7)</td>
</tr>
<tr>
<td>27 °C</td>
<td>-102.3</td>
<td>93.4 / 101.6 (93.1)</td>
</tr>
<tr>
<td>29 °C</td>
<td>-105.3</td>
<td>98.2 / 105.9 (98.8)</td>
</tr>
<tr>
<td>31 °C</td>
<td>-111.6</td>
<td>105.2 / 111.5 (105.5)</td>
</tr>
<tr>
<td>U</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 m/s</td>
<td>-93.7</td>
<td>85.5 / 94.1 (85.7)</td>
</tr>
<tr>
<td>5 m/s</td>
<td>-105.3</td>
<td>98.2 / 105.9 (98.8)</td>
</tr>
<tr>
<td>10 m/s</td>
<td>-114.2</td>
<td>109.7 / 113.3 (109.7)</td>
</tr>
<tr>
<td>15 m/s</td>
<td>-119.7</td>
<td>120.7 / 115.6 (120.9)</td>
</tr>
</tbody>
</table>

Larger surface fluxes → larger precip.
Effects of External Conditions

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>RAD / PRCP / SRFLX (LHFLX) [W/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SST</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25 °C</td>
<td>-95.0</td>
<td>87.2 / 95.6 (87.7)</td>
</tr>
<tr>
<td>27 °C</td>
<td>-102.3</td>
<td>93.4 / 101.6 (93.1)</td>
</tr>
<tr>
<td>29 °C</td>
<td>-105.3</td>
<td>98.2 / 105.9 (98.8)</td>
</tr>
<tr>
<td>31 °C</td>
<td>-111.6</td>
<td>105.2 / 111.5 (105.5)</td>
</tr>
</tbody>
</table>

Larger surface fluxes → larger precip.

Consistent period of oscillations
Effects of External Conditions

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>RAD / PRCP / SRFLX (LHFLX) [W/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SST</td>
<td>25 °C</td>
<td>-105.3 / 93.5 / 105.2 (93.8)</td>
</tr>
<tr>
<td></td>
<td>27 °C</td>
<td>-105.3 / 95.7 / 105.2 (95.9)</td>
</tr>
<tr>
<td></td>
<td>29 °C</td>
<td>-105.3 / 97.8 / 105.3 (98.0)</td>
</tr>
<tr>
<td></td>
<td>31 °C</td>
<td>-105.3 / 99.6 / 105.4 (99.8)</td>
</tr>
<tr>
<td>U</td>
<td>2 m/s</td>
<td>-105.3 / 93.8 / 105.2 (93.7)</td>
</tr>
<tr>
<td></td>
<td>5 m/s</td>
<td>-105.3 / 97.8 / 105.3 (98.0)</td>
</tr>
<tr>
<td></td>
<td>10 m/s</td>
<td>-105.3 / 101.9 / 104.5 (102.1)</td>
</tr>
<tr>
<td></td>
<td>15 m/s</td>
<td>-105.3 / 108.3 / 101.2 (108.1)</td>
</tr>
</tbody>
</table>

Larger surface fluxes → larger precip., but not as much as the inctvRAD cases

Period of oscillations increases with higher SST and larger U
### Effects of External Conditions

#### fixedRAD

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>RAD / PRCP/SRFLX (LHFLX)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SST</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25 °C</td>
<td>-105.3</td>
<td></td>
</tr>
<tr>
<td>27 °C</td>
<td>-105.3</td>
<td></td>
</tr>
<tr>
<td>29 °C</td>
<td>-105.3</td>
<td></td>
</tr>
<tr>
<td>31 °C</td>
<td>-105.3</td>
<td></td>
</tr>
<tr>
<td>U</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 m/s</td>
<td>-105.3</td>
<td></td>
</tr>
<tr>
<td>5 m/s</td>
<td>-105.3</td>
<td></td>
</tr>
<tr>
<td>10 m/s</td>
<td>-105.3 / 101.9 / 104.5 (102.1)</td>
<td></td>
</tr>
<tr>
<td>15 m/s</td>
<td>-105.3 / 108.3 / 101.2 (108.1)</td>
<td></td>
</tr>
</tbody>
</table>

#### Fourier Analysis of PRCP (d50 – d200)

Sensitivity to SST

What are the key processes behind these RCE oscillations?

Larger surface fluxes → larger precip., but not as much as the incrvRAD cases

Period of oscillations increases with higher SST and larger U
Precipitation decomposition

Precip. is mainly contributed from the ZM deep convective scheme
Precipitation decomposition

Precip. is mainly contributed from the ZM deep convective scheme.

Oscillations tend to be more irregular; large-scale precip. appears.
Precipitation decomposition

Precip. is mainly contributed from the ZM deep convective scheme.

Oscillations tend to be more irregular; large-scale precip. appears.

No oscillations; weaker total precip.

Interaction between shallow and deep convection may be crucial for RCE oscillations.
Various Convective Schemes

- **Turb** / **ConvSH** / **ConvDP** / Stratiform
- **BP** / **PB** / **ZM** / Park
- **BP** / **PBx2** / none / Park
- **BP** / **PB** / **PB+org** / Park
- **BP** / **UNICON** / **UNICON** / Park
- **CLUBB** / **CLUBB** / **ZM** / **CLUBB**
Various Convective Schemes

Turb / ConvSH / ConvDP / Stratiform
BP / PB / ZM / Park
BP / PBx2 / none / Park
BP / PB / PB+org / Park
BP / UNICON / UNICON / Park
CLUBB / CLUBB / ZM / CLUBB

(a) inctvRAD CTRL
(b) inctvRAD 2UW
(c) inctvRAD ORG
(d) inctvRAD UNICON
(e) inctvRAD CLUBB

RCE oscillations diminish in 2UW and ORG runs

inctvRAD
Summary

RCE-SCAM5

• A 1-D climate model for evaluating column model physics in a clean way
  - Fast runs
  - High temporal and vertical resolution

• Reach a statistically steady state (RCE), but with unexplained fluctuations including multi-day oscillations
  - Insensitive to initial moisture conditions
  - Patterns of RCE oscillations depend on radiative forcing and external conditions
  - The parameterization of deep convection is a key for RCE oscillations; the interaction between shallow and deep convective schemes matters as well
Sensitivity to Numerical Setting?

Control run →

inctvRAD

Vertical Resolution

Temporal Resolution

(a) 30 levels, 60 sec.

(b) 120 levels, 60 sec.

(c) 60 levels, 60 sec.

(d) 60 levels, 30 sec.

(e) 60 levels, 300 sec.
Sensitivity to Numerical Setting?

Control run

The run with lv30 features more irregular oscillations than other runs

(a) 30 levels, 60 sec.
(b) 120 levels, 60 sec.
(c) 60 levels, 60 sec.
(d) 60 levels, 30 sec.
(e) 60 levels, 300 sec.

Vertical Resolution

Temporal Resolution

inctvRAD
Coupling to Parameterized Large-Scale Dynamics

Damped-Gravity-Wave Method (Kuang 2008)

• Let the column “feel” the large-scale vertical motion, and interact with it

\[
\frac{d\bar{s}}{dt} = \frac{\partial \bar{s}}{\partial t} + \nabla \cdot \bar{v} + \frac{\partial \bar{s}}{\partial p} = Q_R + L(c - e) - \nabla \cdot \left( \frac{s' v'_h}{\rho} \right) - \frac{\partial (s' \omega')}{\partial p}
\]

Welcome this guy back!

• Parameterize horizontal divergence (→ vertical motion) in the column by solving 2-D anelastic system with assumed wave solutions. The method involves a damping for controlling wave instability
Effects of Radiative Forcing

Interactive Rad. Forcing

Prescribed Rad. Forcing
Effects of Radiative Forcing

No wave instability.

Resonance between RCE oscillations and the coupled waves?

Interactive Rad. Forcing

Prescribed Rad. Forcing
Various Convective Schemes

- Turb / ConvSH / ConvDP / Stratiform
- BP / PB / ZM / Park
- BP / PBx2 / none / Park
- BP / PB / PB+org / Park
- BP / UNICON / UNICON / Park
- CLUBB / CLUBB / ZM / CLUBB

(a) inctvRAD CTRL
(b) inctvRAD 2UW
(c) inctvRAD ORG
(d) inctvRAD UNICON
(e) inctvRAD CLUBB
Various Convective Schemes

- Turb / ConvSH / ConvDP / Stratiform
- BP / PB / ZM / Park
- BP / PBx2 / none / Park
- BP / PB / PB+org / Park
- BP / UNICON / UNICON / Park
- CLUBB / CLUBB / ZM / CLUBB

The inctvRAD ORG run shows the most prominent wave instability.
PRCP decomposition

(a) SCAM5_{ctrl} — PREC, PRECC_{ZM}, PRECC_{UW}, PRECL

(b) SCAM5_{noUW}

(c) SCAM5_{noZM}

Day

W/m²
The image shows various graphs plotted against pressure levels (hPa) ranging from 1000 to 100, with the x-axis labeled from -2 to 2. The graphs depict different meteorological variables, including temperature (T'), buoyancy (BuoyZM), radiative flux (Rad), moisture flux (MuZM), and cloud fraction (Cld). Each variable is represented by multiple lines of different colors, indicating variations at different pressure levels.
Descending inversion:
$+T'$ results in a buoyancy barrier that suppresses convection at next time step.

Why heating at the cloud top is stronger than heating right below? Detrainment?
Hypothesis

Descending inversion:
$+T'$ results in a buoyancy barrier that suppresses convection at next time step.
Why heating at the cloud top is stronger than heating right below? Detrainment?

"Jump" of deep convection
Convection penetrates the buoyancy barrier atop somehow.
How? Maybe with the feedback from shallow convection?
Similar Phenomena in Nature?

(Courtesy of Prof. Brian Mapes)
Similar Phenomena in Nature?

(Courtesy of Prof. Brian Mapes)
Similar Phenomena in Nature?

(Courtesy of Prof. Brian Mapes)
Similar Phenomena in Nature?

(Courtesy of Prof. Brian Mapes)
Similar Phenomena in Nature?

(Courtesy of Prof. Brian Mapes)
Similar Phenomena in Nature?

(Courtesy of Prof. Brian Mapes)
Similar Phenomena in Nature?

(Courtesy of Prof. Brian Mapes)
Similar Phenomena in Nature?

(Courtesy of Prof. Brian Mapes)
Similar Phenomena in Nature?

(Courtesy of Prof. Brian Mapes)
Similar Phenomena in Nature?

Yes, but may be in different time scales

(Courtesy of Prof. Brian Mapes)
Evaluate Convective Schemes

• 2-plume UW (Mapes & Neale 2011)
  - A new parameter “org” that is meant to parameterize convective organization
  - The 1st plume → shallow convection; the 2nd plume → deep convection
  - Source of org (from the 1st plume): column-integrated rain evaporation
  - Effects of org (for the 2nd plume): +ive org increase the plume mass that reaches the LFC and decrease the entrainment the plume undergoes
Evaluate Convective Schemes

- **2-plume UW** (Mapes & Neale 2011)
  - A new parameter “*org*” that is meant to parameterize convective organization
  - The 1st plume → shallow convection; the 2nd plume → deep convection
  - Source of org (from the 1st plume): column-integrated rain evaporation
  - Effects of org (for the 2nd plume): +ive org increase the plume mass that reaches the LFC and decrease the entrainment the plume undergoes

- **UNICON** (Park 2014 a, b)
  - Diagnoses multiple (default: 1) updraft & downdraft plumes
  - Prognoses sub-grid cold pool & mesoscale organized flow within the PBL
  - Unifies shallow and deep convection
Evaluate Convective Schemes

• **2-plume UW** (Mapes & Neale 2011)
  - A new parameter “org” that is meant to parameterize convective organization
  - The 1\textsuperscript{st} plume $\rightarrow$ shallow convection; the 2\textsuperscript{nd} plume $\rightarrow$ deep convection
  - Source of org (from the 1\textsuperscript{st} plume): column-integrated rain evaporation
  - Effects of org (for the 2\textsuperscript{nd} plume): +ive org increase the plume mass that reaches the LFC and decrease the entrainment the plume undergoes

• **UNICON** (Park 2014 a, b)
  - Diagnoses multiple (default: 1) updraft & downdraft plumes
  - Prognoses sub-grid cold pool & mesoscale organized flow within the PBL
  - Unifies shallow and deep convection

  - Default convective scheme in CAM6
  - Prognoses various sub-grid higher-order moments
  - Consistent modeling of turbulence & microphysics & macrophysics, but may still need the ZM scheme for simulating deep convection
## Effects of External Conditions

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Major Periods [days]</th>
<th>RAD / PRCP / SRFLX (LHFLX) [W/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SST</td>
<td>25 °C</td>
<td>2.0, 3.0, 6.0</td>
<td>-95.0 / 87.2 / 95.6 (87.7)</td>
</tr>
<tr>
<td></td>
<td>27 °C</td>
<td>2.0, 3.0, 5.8</td>
<td>-102.3 / 93.4 / 101.6 (93.1)</td>
</tr>
<tr>
<td></td>
<td>29 °C</td>
<td>1.6, 3.1, 6.3</td>
<td>-105.3 / 98.2 / 105.9 (98.8)</td>
</tr>
<tr>
<td></td>
<td>31 °C</td>
<td>2.0, 3.1, 6.0</td>
<td>-111.6 / 105.2 / 111.5 (105.5)</td>
</tr>
<tr>
<td>U</td>
<td>2 m/s</td>
<td>1.9, 2.6, 5.6</td>
<td>-93.7 / 85.5 / 94.1 (85.7)</td>
</tr>
<tr>
<td></td>
<td>5 m/s</td>
<td>1.6, 3.1, 6.3</td>
<td>-105.3 / 98.2 / 105.9 (98.8)</td>
</tr>
<tr>
<td></td>
<td>10 m/s</td>
<td>1.9, 3.1, 6.3</td>
<td>-114.2 / 109.7 / 113.3 (109.7)</td>
</tr>
<tr>
<td></td>
<td>15 m/s</td>
<td>2.0, 3.0, 6.2</td>
<td>-119.7 / 120.7 / 115.6 (120.9)</td>
</tr>
</tbody>
</table>

Consistent period of oscillations in the cases using interactive radiative forcing.

Negative SHFLX!
## Effects of External Conditions

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Major Periods [days]</th>
<th>RAD / PRCP / SRFLX (LHFLX) [W/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SST</td>
<td>25 °C</td>
<td>1.1, 3.0, 6.0</td>
<td>-105.3 / 93.5 / 105.2 (93.8)</td>
</tr>
<tr>
<td></td>
<td>27 °C</td>
<td>2.4, 3.6, 7.1</td>
<td>-105.3 / 95.7 / 105.2 (95.9)</td>
</tr>
<tr>
<td></td>
<td>29 °C</td>
<td>2.1, 4.3, 8.3</td>
<td>-105.3 / 97.8 / 105.3 (98.0)</td>
</tr>
<tr>
<td></td>
<td>31 °C</td>
<td>5.2, 9.4, 10.7</td>
<td>-105.3 / 99.6 / 105.4 (99.8)</td>
</tr>
<tr>
<td>U</td>
<td>2 m/s</td>
<td>3.5, 6.8, 7.1</td>
<td>-105.3 / 93.8 / 105.2 (93.7)</td>
</tr>
<tr>
<td></td>
<td>5 m/s</td>
<td>2.1, 4.3, 8.3</td>
<td>-105.3 / 97.8 / 105.3 (98.0)</td>
</tr>
<tr>
<td></td>
<td>10 m/s</td>
<td>2.1, 5.0, 10.0</td>
<td>-105.3 / 101.9 / 104.5 (102.1)</td>
</tr>
<tr>
<td></td>
<td>15 m/s</td>
<td>5.4, 9.4, 10.7</td>
<td>-105.3 / 108.3 / 101.2 (108.1)</td>
</tr>
</tbody>
</table>

Period of oscillations increases with higher SST and larger U in the cases using prescribed radiative forcing