Exploration of Hemispheric Asymmetry in the Surface Energy Budget using CERES and Reanalysis Data

Norman G. Loeb¹, Hailan Wang², Anning Chen², Kuan-Man Xu¹

¹NASA Langley Research Center, Hampton, VA
²Science Systems and Applications, Inc. (SSAI)

CERES Science Team Meeting, October 6-10, 2014
Toulouse, France
Introduction

- The large-scale tropical circulation and precipitation is constrained by the regional distribution of energy.
- The hemispheric asymmetry in energy into the Earth-Atmosphere system determines the cross-equatorial heat transport in the atmosphere and ocean.
- This in turn constrains the mean position of the ITCZ.

Objective

- Use CERES EBAF (TOA & SFC) Ed 2.8 and ERA-Interim to determine the implied atmospheric and ocean cross-equatorial heat transports.
- Further decompose the implied cross-equatorial heat transport into radiative and non-radiative contributions.
- Evaluate how climate models (CMIP5 & MMF) represent the cross-equatorial heat transport.
Observations

- CERES EBAF Ed2.8 (TOA and SFC).
- ERA-Interim total energy tendency and column-integrated divergence of total energy \((c_p T + gz + Lq + k)\).
  - Version of ERA-Interim used obtained from NCAR: The climate data guide: ERA-Interim: Derived components.
  - In this version, a mass flux correction has been applied to the divergence terms.
- GPCP V2.2
# CMIP5 Models

<table>
<thead>
<tr>
<th>Model #</th>
<th>Model</th>
<th>Country</th>
<th>Nx*ny</th>
<th>Lon*lat</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ACCESS1-3</td>
<td>Australia</td>
<td>192x145</td>
<td>1.875x1.25</td>
</tr>
<tr>
<td>2</td>
<td>bcc-csm1-1-m</td>
<td>China</td>
<td>320x160</td>
<td>1.125x1.12</td>
</tr>
<tr>
<td>3</td>
<td>CanESM2</td>
<td>Canada</td>
<td>128x64</td>
<td>2.8x2.8</td>
</tr>
<tr>
<td>4</td>
<td>CCSM4</td>
<td>USA</td>
<td>288x192</td>
<td>1.25x0.94</td>
</tr>
<tr>
<td>5</td>
<td>CNRM-CM5-2</td>
<td>France</td>
<td>256x128</td>
<td>1.4x1.4</td>
</tr>
<tr>
<td>6</td>
<td>CSIRO-Mk3-6-0</td>
<td>Australia</td>
<td>192x96</td>
<td>1.875x1.86</td>
</tr>
<tr>
<td>7</td>
<td>FGOALS-g2</td>
<td>China</td>
<td>128x60</td>
<td>2.8125x3.05</td>
</tr>
<tr>
<td>8</td>
<td>GFDL-CM3</td>
<td>USA</td>
<td>144x90</td>
<td>2.5x2.0</td>
</tr>
<tr>
<td>9</td>
<td>HadGEM2-ES</td>
<td>UK</td>
<td>192x145</td>
<td>1.875x1.25</td>
</tr>
<tr>
<td>10</td>
<td>inmcm4</td>
<td>Russia</td>
<td>180x120</td>
<td>2x1.5</td>
</tr>
<tr>
<td>11</td>
<td>IPSL-CM5B-LR</td>
<td>France</td>
<td>96x96</td>
<td>3.75x1.9</td>
</tr>
<tr>
<td>12</td>
<td>MIROC-ESM</td>
<td>Japan</td>
<td>128x64</td>
<td>2.8x2.8</td>
</tr>
<tr>
<td>13</td>
<td>MPI-ESM-MR</td>
<td>Germany</td>
<td>192x96</td>
<td>1.875x1.86</td>
</tr>
<tr>
<td>14</td>
<td>MRI-CGCM3</td>
<td>Japan</td>
<td>320x160</td>
<td>1.125x1.12</td>
</tr>
<tr>
<td>15</td>
<td>NorESM1-ME</td>
<td>Norway</td>
<td>144x96</td>
<td>2.5x1.9</td>
</tr>
</tbody>
</table>
Multiscale Modeling Framework (Grabowski 2001; Khairoutdinov and Randall 2001)

- A CRM is embedded at each grid column (~100s km) of the host GCM to represent cloud physical processes
- The CRM explicitly simulates cloud-scale dynamics (~1s km) and processes
- Periodic lateral boundary condition for CRM (not extend to the edges)

Upgraded CRM with a third-order turbulence closure (IPHOC):

- Double-Gaussian distribution of liquid-water potential temperature, total water mixing ratio and vertical velocity
- Skewnesses, i.e., the three third-order moments, predicted
- All first-, second-, third- and fourth-order moments, subgrid-scale condensation and buoyancy based on the same PDF
Atmospheric & Surface Energy Budgets from CERES and Reanalysis

\[ \frac{\partial A_E}{\partial t} = R_T - F_S - \nabla . F_A \quad (1) \]

\[ F_S = R_S + LE + S \quad (2) \]

\[ F_A = \frac{1}{g} \int_{0}^{p_s} (h + k) \bar{u} \, dp \]

\[ A_E = c_p T + gz + Lq + k = h + k \]

\[ \frac{\partial A_E}{\partial t} & \nabla . F_A => ERA-Interim \]

\[ R_T & R_S => CERES EBAF Ed2.8 \]

\[ F_S & (LE + S) => Residual Terms in (1) & (2) \]
Surface Fluxes Inferred from CERES EBAF $R_T$ and $R_S$ & ERA-Interim Div($F_A$)

$R_S$ (CERES SFC)

$\text{LE + S (}F_S - R_S\text{)}$

$F_S$ (CERES TOA, ERA-Int. TETEN, Div)
Comparison of Surface Flux ($F_s = R_s + LE + S$)

CERES TOA & ERA-I TETEN, Div(TOT)

CMIP5 (15 Model Mean; $R_s + LE + S$)
Comparison of Turbulent Heat Fluxes (LE + S)

CERES TOA, SFC, & ERA-I TETEN, Div(TOT)

Global Mean
-108 Wm\(^{-2}\)

CMIP5 (15 Model Mean; LE + S)

Global Mean
-104 Wm\(^{-2}\)
Implied Cross-Eq. Heat Transports in Atmos. & Ocean from Energetic Constraints

- Determine cross-equatorial heat transports in atmosphere and ocean from hemispheric contrast in energy fluxes.

<table>
<thead>
<tr>
<th>Southern Hemisphere</th>
<th>Northern Hemisphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_T ) = 1.4 Wm(^{-2} )</td>
<td>( R_T ) = -0.18 Wm(^{-2} )</td>
</tr>
<tr>
<td>( \nabla . F_A ) = -0.98 Wm(^{-2} )</td>
<td>( \nabla . F_A ) = 0.89 Wm(^{-2} )</td>
</tr>
<tr>
<td>( \frac{\partial A_E}{\partial t} ) = 0.03 Wm(^{-2} )</td>
<td>( \frac{\partial A_E}{\partial t} ) = 0.0 Wm(^{-2} )</td>
</tr>
<tr>
<td>( F_S ) = 2.3 Wm(^{-2} )</td>
<td>( F_S ) = -1.1 Wm(^{-2} )</td>
</tr>
</tbody>
</table>

\( R_s = 113 \text{ Wm}^{-2} \)
LE+S = -110 Wm\(^{-2} \)

\( R_s = 105 \text{ Wm}^{-2} \)
LE+S = -107 Wm\(^{-2} \)
In order to transport energy from warmer atmosphere in NH to cooler atmosphere in SH, mean position of ITCZ needs to be in NH (Frierson et al. 2013; Marshall et al. 2013).

- Transport of DSE in upper branch of Hadley circulation exceeds latent heat transport in lower branch by 0.2 PW.
Radiative & Non-Radiative Contributions to Cross-Equatorial Heat Transports

- Hemis. contrasts in SFC & ATM radiation determine direction of atm. & ocean heat transports.
- Hemis. contrast in turbulent heat fluxes imply heat transport in opposite direction.
- Assumes hemis. symmetry in ocean heat storage.
Hemispheric Asymmetry

Mean Values
All Surfaces; All-Sky

TOA Alb
Atm Abs
Atm Tran
Sfc Alb

NH: 160.4
SH: 164.1
\(\Delta: -3.8\)

NH - SH Difference
All Surfaces; All-Sky

All-Surfaces; Clear-Sky

TOA Alb
Atm Abs
Atm Tran
Sfc Alb

NH: 219.5
SH: 208.9
\(\Delta: -10.6\)
Comparisons with CMIP5 Models
- All models show SH -> NH Cross-Eq. Heat Transport.
- Large spread amongst models.
- Only half the models show NH -> SH AHT$_{EQ}$ seen in obs.
- Models with strong \( SH \rightarrow NH \) AHT\(_{EQ} \) show more precip in SH (double ITCZ).
- Only 2 models provide correct sign of precip. asymmetry.
Comparisons with High-Resolution Multi-Model Framework Results (Xu and A. Cheng, 2013)
- Models overestimate SH TOA and surface energy gain relative to NH.
- SPCAM-IPHOC provides better representation of net SW asymmetry (TOA & SFC).
- Models yield SH -> NH OHT$_{EQ}$ and NH -> NH AHT$_{EQ}$ consistent with obs.
- However, Implied cross-equatorial heat transport in models is factor of 2 larger than observations, both in atmosphere and ocean.
Conclusions (1/3)

- Mean position of ITCZ north of the equator is a direct consequence of hemispheric asymmetry in surface heating.

- Observations imply 0.4 PW SH -> NH OHT$_{EQ}$ and 0.2 PW NH -> SH AHT$_{EQ}$.

- Clouds reduce hemispheric asymmetry in radiative fluxes both at TOA and SFC.
Conclusions (2/3)

- CERES EBAF-TOA and SFC combined with ERA-I TETEN enable decomposition of cross-equatorial heat transport into radiative and non-radiative (turbulent heat flux) components.

- Regional patterns of surface fluxes (radiation + turbulent) inferred as residual of CERES EBAF TOA minus ERA-Interim TETEN appear quite reasonable.

- Hemispheric contrasts in SFC & ATM radiation determine direction of atmospheric & oceanic heat transports, while turbulent heat fluxes act to transport heat in opposite direction.
Conclusions (3/3)

- All CMIP5 models show SH -> NH OHT$_{EQ}$ (consistent with obs), but only half show the observed NH -> SH AHT$_{EQ}$.

- Models with stronger SH -> NH AHT$_{EQ}$ show more precip in SH (double ITCZ).

- Only 2 CMIP5 models provide consistent sign of precip. asymmetry compared to GPCP.

- MMF models capture direction of cross-equatorial heat transports but magnitude is twice as large as observations.