The basic effect of cloud/circulation coupling on tropical SSTs

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from Li, Thompson, Olonscheck (JCL in review)
thanks also to Thorsten Mauritsen
Amplification of El Niño by cloud longwave coupling to atmospheric circulation

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Cloud Radiative Feedbacks and El Niño–Southern Oscillation

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interactive clouds -> higher frequency ENSO variability
Two experiments (from MPI)

1. Control simulation run on a coupled AOGCM with interactive clouds

2. Simulation run with “scrambled” cloud radiative effects (cloud “locking”)

(MPI-ESM1.2-LR with preindustrial forcing)
## Scrambling methodology

Clouds are scrambled by reordering the year of the cloud fields at every 2 hour radiation call. EG:

<table>
<thead>
<tr>
<th>Control run</th>
<th>Scrambled run</th>
</tr>
</thead>
<tbody>
<tr>
<td>00Z, Jan 1, Year 1</td>
<td>00Z, Jan 1, Year 100</td>
</tr>
<tr>
<td>02Z, Jan 1, Year 1</td>
<td>02Z, Jan 1, Year 24</td>
</tr>
<tr>
<td>04Z, Jan 1, Year 1</td>
<td>04Z, Jan 1, Year 176</td>
</tr>
<tr>
<td>06Z, Jan 1, Year 1</td>
<td>06Z, Jan 1, Year 87</td>
</tr>
</tbody>
</table>

Method preserves the mean diurnal and seasonal cycles of the cloud fields.
The differences between the control (interactive) and scrambled (locked) runs are due entirely from the effects of clouds on the circulation
Effects on monthly-mean SST variance

\[ \frac{S_{\text{interactive}}^2}{S_{\text{locked}}^2} \]

Figure 1.

- **a**: Variances of monthly-mean SST anomalies from the 200-yr interactive-clouds run.
- **b**: Variances of monthly-mean SST anomalies from the 200-yr locked-clouds run.
- **c**: Ratio of the variances between the interactive and locked runs. Ratios > 1 indicate larger variability in the interactive run, and vice versa. Stippling indicates regions where the ratios are significant at the 95% level. Regions where the SST variance in (a) is less than 0.01 K^2 are masked when calculating the ratios in (c).

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Effects on monthly-mean Z150 variance

\[
\frac{S^2_{\text{interactive}}}{S^2_{\text{locked}}}
\]

Fig. 2. Ratio of the variances between the interactive and locked runs of
(a) atmospheric temperature at 300 hPa,
(b) convective precipitation,
(c) geopotential height at 150 hPa,
and (d) eddy geopotential height at 150 hPa. The black contours superimposed on panel d denote the long-term geopotential height at 150 hPa (contour interval: 14000, 14100, 14110, 14120, 14130 m...). Results are based on monthly-mean anomalies.
Power spectra of SSTs in Nino3.4

FIG. 2. Power spectra of SST anomaly time series for indicated regions. Power spectra of SST anomaly time series averaged over (a) Niño3.4, (b) entire tropics (15°S–15°N), (c) tropical Indian ocean (10°S–10°N, 50°E–100°E), (d) tropical western Pacific (10°S–10°N, 100°E–180°), (e) tropical north Atlantic (0°–15°N, 315°–340°E), and (f) tropical south Atlantic (15°S–0°, 20°W–10°E). Results for the interactive-clouds simulation are indicated by the blue lines, and for the locked-clouds simulation are indicated by the red lines. Regions are indicated by the black boxes in Fig. 1c.
in the tropical Indian ocean

![Graph showing power spectra of SST anomaly time series for different regions.](image)
Large increases in tropical SST variance from days - decades.

averaged over the tropics
The energy budget for the surface mixed layer of the ocean can be expressed in monthly-mean anomaly form as:

\[ C_o \frac{\partial T}{\partial t} = Q_{SW} + Q_{LW} + Q_{LH} + Q_{SH} + Q_{residual}, \]

where primes denote monthly-mean anomalies (departures from the long-term mean seasonal cycle); \( T_0 \) is the anomalous temperature of the mixed layer (assumed proportional to the anomalous SST); \( C_o \) is the effective heat capacity of the mixed layer (\( C_o = C_p r h \), in which \( r \) and \( C_p \) are the density and specific heat capacity at constant pressure of the seawater, i.e., 3850 J kg\(^{-1}\)C\(^{-1}\)), \( h \) is the annual-mean mixed layer depth taken from the ocean model; and the \( Q_0 \) are the heatings due to anomalous surface shortwave radiative flux (\( Q_{SW} \)), longwave radiative flux (\( Q_{LW} \)), latent heat flux (\( Q_{LH} \)), sensible heat flux (\( Q_{SH} \)), advection by the Ekman flow (\( Q_{EK} \)) and advection by the surface geostrophic flow (\( Q_{geo} \)). Here \( Q_{EK} = C_o \sim V_{EK} \cdot T \) and \( Q_{geo} = C_o \sim V_{ geo} \cdot T \), in which \( \sim V_{EK} \) is the Ekman flow induced by the wind stress (\( t \)) and \( \sim V_{geo} \) is the geostrophic currents. We neglect vertical advection and entrainment for simplicity, even though these processes are clearly important along the coastal and equatorial upwelling zones. Following Yu and Boer (2006), Eq. 1 can be manipulated to yield an expression for the temperature variance by a) taking the centered difference of Eq. 1, b) squaring the result, and c) taking the time-mean. As reviewed in Appendix A, the above operation yields the following expression for the temperature variance:

\[ s^2_T = G \cdot s^2_S \cdot e \]

Why?
Variance of shortwave cloud radiative effects: 
Locked clouds
Variance of shortwave cloud radiative effects: Interactive clouds

FIG. 4. Variances in the surface energy fluxes. (a, b) surface shortwave radiative flux, (d, e) longwave radiative flux, (g, h) latent heat flux, (j, k) sensible heat flux, (m, n) heat advection by the meridional Ekman and geostrophic current. Results for (left column) the 200-yr interactive-clouds simulation and (middle column) the 200-yr locked-clouds simulation. The right column is the percentage contribution of each term to the total variance in the interactive-clouds simulation. Results are based on monthly-mean anomalies. The surface radiative flux are based on all-sky radiative flux, the variance in clear-sky radiative flux are of similar amplitude between the control and locked simulations.
Why does the variance in SW CRE increase?

1. Interactive clouds have memory: Their autocorrelation is $\sim r = 0.9$ when sampled on two hourly intervals.

2. The memory comes from the circulation. And it has a strong effect on the variance of clouds and their radiative effects.
Power spectra of random time series

Figure 5: The effect of autocorrelation on cloud fraction power spectra. 

(a) Power spectra for a randomly generated red noise time series with lag-one autocorrelation of $r_1 = 0.9$ (dashed line) and a white noise time series with $r_1 = 0$ (solid line).

(b) Power spectra for time series of cloud fraction at sample tropical grid point ($0^\circ, 180^\circ$) used in the interactive-clouds run (dashed line) and the locked-clouds run (solid). The cloud fraction time series are 50-yr long sampled at two-hourly intervals. The randomly generated time series used to construct the top panel are the same length as the cloud fraction time series.
Power spectra of cloud fraction from the two simulations

Figure 5: The effect of autocorrelation on cloud fraction power spectra. 

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Testing with observations (ERA5)

two-hour lag correlation of SW flux
variance of monthly mean SW flux

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Cloud/circulation coupling acts to “redden” clouds and their shortwave radiative effects.
The reddening leads to increases in the variance of shortwave CRE - and thus SSTs - on timescales from days to decades.
The effect is most pronounced in the tropics

\[ C_0 \frac{\partial T}{\partial t} = Q_{SW} + Q_{LW} + Q_{LH} + Q_{SH} + Q_{\text{residual}} \]

turbulent heat fluxes are dominant in extratropics
cloud/circulation coupling has a pronounced effect on the amplitude of decadal variability

spectra of tropical SSTs with interactive clouds
decoupled clouds