The "Pattern Effect": Conceptual Frameworks

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Roadmap

• Global feedback framework and it’s failure

• A refined view of the radiative response

• Open Questions
  • Radiative response
  • Forcing and heat uptake
  • Patterns
Energy Budget

\[ \overline{N} = \overline{F} + \overline{R} \]

Energy Input (radiative forcing)

\[ \overline{F} \]

Radiative damping

\[ \overline{R} \]

Energy Budget Diagram:

- Energy Input \( \overline{F} \)
- Radiative damping \( \overline{R} \)
- Net Energy \( \overline{N} \)
Radiative feedback $\lambda$

Energy Input (radiative forcing) $\overline{F}$
Radiative damping $\overline{R} = \lambda \overline{T}$

\[ \overline{N} = \overline{F} + \lambda \overline{T} \]
If you know $\lambda$ you know ECS

Energy Input (radiative forcing) $\bar{F}$

Radiative damping $\bar{R} = \lambda \bar{T}$

$\bar{N} = \bar{F} + \lambda \bar{T}$

Equilibrium: $\bar{N} = 0$

$\bar{T}_{eq} = \frac{\bar{F}}{\lambda}$

Estimates of ECS

NOAA ERSST 1979-2020

Turns out radiative response is complicated

\[ \bar{N} = \bar{F} + \bar{R}(T(x)) \]

The big questions:

\[ \bar{N} = \bar{F} + \bar{R}(T(x)) \]

- \(\bar{R}(T(x))\)
- \(\bar{N}, F, T(x)\)
Roadmap

• Global feedback framework and it’s failure

• A refined view of the radiative response

• Open Questions
  • Radiative response
  • Forcing and heat uptake
  • Patterns
General energy budget equation

\[ \bar{N} = \bar{F} + \bar{R} \left( T(x) \right) \]
Feedbacks are just Taylor series in disguise

\[ \bar{N} = \bar{F} + \bar{R}(T(x)) \]

Global temperature expansion

\[ \bar{R} \approx \lambda \left[ \frac{\partial \bar{R}}{\partial T} T \right] \]

Soden and Held 2008, Roe 2008
Feedbacks are just Taylor series in disguise

\[ \bar{N} = \bar{F} + \bar{R}(T(x)) \]

Global temperature expansion

\[ \bar{R} \approx \lambda \frac{\partial \bar{R}}{\partial \bar{T}} \bar{T} \]

Regional temperatures expansion (WRONG)

\[ \bar{R} \approx \sum_x \frac{\partial R(x)}{\partial T(x)} T(x) \]

Nonlocal effects matter

\[ \bar{N} = \bar{F} + \bar{R}(T(x)) \]

Global temperature expansion

Regional temperatures expansion (Correct)

\[ \bar{R} \approx \lambda \left[ \frac{\partial \bar{R}}{\partial \bar{T}} \right] \bar{T} \]

\[ \bar{R} \approx \sum_{x,y} \frac{\partial R(y)}{\partial T(x)} T(x) \]

Zhou et al 2017, Dong et al 2019
Nonlocal effects matter

\[ \bar{N} = \bar{F} + \bar{R}(T(x)) \]

Global temperature expansion

Regional temperatures expansion (Correct)

\[ \bar{R} \approx \lambda \left\{ \frac{\partial \bar{R}}{\partial T} \right\} T \]

\[ \bar{R} \approx \sum_{x} \frac{\partial \bar{R}}{\partial T(x)} T(x) \]

Zhou et al 2017, Dong et al 2019
Nonlocal effects matter

\[
\bar{N} = \bar{F} + \bar{R} \left( T(x) \right)
\]

Global temperature expansion

Regional temperatures expansion
(Correct)

\[
\bar{R} \approx \frac{\partial \bar{R}}{\partial T} \bar{T}
\]

\[
\bar{R} \approx \sum_{x} \frac{\partial \bar{R}}{\partial T(x)} \frac{T(x)}{\bar{T}} \bar{T}
\]

Radiative response pattern
Nonlocal effects matter

\[ \overline{N} = \overline{F} + \overline{R} \left( T(x) \right) \]

Global temperature expansion

\[ \overline{R} \approx \frac{\lambda}{\frac{\partial \overline{R}}{\partial T}} \]

Regional temperatures expansion (Correct)

\[ \overline{R} \approx \sum_x \frac{\lambda}{\frac{\partial R}{\partial T(x)}} \frac{T(x)}{\overline{T}} \]

Radiative response pattern
Green’s Function

\[ \frac{\partial \bar{R}}{\partial T(x)} \]

Regional temperatures expansion
(Correct)

\[ \bar{R} \approx \sum_x \frac{\partial \bar{R}}{\partial T(x)} \frac{T(x)}{\bar{T}} \]

Zhou et al 2017, Dong et al 2019

Radiative response. pattern
Pattern effect summary

\[ \lambda = \sum \frac{\partial R}{\partial T(x)} \times \frac{\Delta T(x)}{\Delta T} \]

historical

Pattern effect:
Long-term warming pattern
Will actuate more
Positive feedbacks

\[ \lambda_{hist} < \lambda_{eq} < 0 \]
Earth’s Energy Budget

\[ \overline{N} = \overline{F} + \overline{R}(T(x)) \]

\[ \overline{R} \approx \sum_x \lambda \frac{\partial \overline{R}}{\partial T(x)} \frac{T(x)}{\overline{T}} \]
Frameworks:

Earth’s Energy Budget
\[ \bar{N} = \bar{F} + \bar{R} \left( T(x) \right) \]

Time dependent feedbacks
\[ N = F + \lambda(t)T(t) \]
Murphy 1995, Senior and Mitchell 2000

Heat uptake efficacy
\[ \varepsilon N = F + \lambda T \]
Winton et al 2010

Stability
\[ N = F + \lambda T + \beta S \]
Ceppi and Gregory 2020

Warm Pool
\[ N = F + \alpha T + \gamma T^# \]
Fueglistaler 2019, Dong et al 2019
Earth’s Energy Budget
\[ \bar{N} = \bar{F} + \bar{R}(T(x)) \]

Time dependent feedbacks
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Ceppi and Gregory 2020

Warm Pool
\[ N = F + \alpha T + \gamma T^\# \]
Fueglistaler 2019, Dong et al 2019

\[ \bar{R} \approx \sum_{x} \frac{\partial \bar{R}}{\partial T(x)} \frac{T(x)}{T} \]
Time dependent feedback

\[ \lambda = \sum \frac{\partial \bar{R}}{\partial T(x)} \times \frac{T(x)}{\bar{T}} \]
Time dependent feedback

\[ \lambda(t) = \sum \frac{\partial R}{\partial T(x)} \times \frac{T(x, t)}{\bar{T}} \]

\[ \lambda(t) = \sum \frac{\partial R}{\partial T(x)} \times \frac{T(x, t)}{\bar{T}} \]

[Images of world maps showing temperature patterns for abrupt-4xCO2]
Time dependent feedback

\[ \lambda(t) = \sum \frac{\partial R}{\partial T(x)} \times \frac{T(x, t)}{\overline{T}} \]

- **λ(t)**: Time dependent feedback
  - \( \sum \frac{\partial R}{\partial T(x)} \): Summation of the partial derivative of the radiation \( R \) with respect to temperature \( T(x) \)
  - \( \frac{T(x, t)}{\overline{T}} \): Ratio of temperature at time \( t \) to the mean temperature \( \overline{T} \)
- **amip**: Historical simulations with AMIP forcing
- **abrupt-4xCO2**: Abrupt increase in CO2 concentration by a factor of 4

**Figure 1**: Evolution of selected nine-year moving averaged quantities from CAM5.3 simulations.

- **Figure 2**: Evolution of decadal net and cloud feedbacks from CAM5.3 simulations.

**Graphical Representation**:

- **Heatmaps**:
  - **amip**: Historical simulations with AMIP forcing
  - **abrupt-4xCO2**: Abrupt increase in CO2 concentration by a factor of 4

**Legend**:

- **(W/m²)/K** represent the units for the feedbacks

**Table**:

<table>
<thead>
<tr>
<th>Year</th>
<th>30-year net feedback (W m⁻² K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1900</td>
<td></td>
</tr>
<tr>
<td>1950</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
</tr>
</tbody>
</table>

**References**:

- DOI: 10.1038/NGEO2828
Time dependent feedback

\[ \lambda(t) = \sum \frac{\partial R}{\partial T(x)} \times \frac{T(x, t)}{\overline{T}} \]

(a) Years 1–20 warming pattern

(b) Years 21–150 warming pattern

(c) CMIP5 AOGCM-mean

\[ \overline{N} = \overline{F} - \sum_{x} \frac{\partial R}{\partial T(x)} \frac{T(x, t)}{\overline{T}} \]
\[ \lambda(t) = \sum \frac{\partial R}{\partial T(x)} \times \frac{T(x, t)}{\overline{T}} \]

Figure 4 shows the geographical distribution of the radiative feedback terms (top to bottom) net TOA, net CRE, LW clear-sky feedback, SW clear-sky feedback, LW cloud radiative effect, and SW cloud radiative effect, on (left) short (years 1–20) and (middle) long (years 21–150) time scales, and (right) their difference (long minus short), for the CMIP5 AOGCM mean. Plots are calculated from linear regression of local radiative fluxes against global.

A large Northern Hemisphere (NH) polar amplification is well established early on in the simulation in all models. Figs. 5d–f. Note that, as with Fig. 4, the BCC and BNU warming patterns for the individual models are shown in Fig. 5a, which must be zero in the global mean by construction. The zonal-mean surface warming pattern (i.e., Fig. 5b) remains years (Fig. 5b). Figure 5c shows the change in pattern (i.e., Fig. 5b) determined from OLS regression of local.

Figure 5 shows the instantaneous SW absorption component of the 4xCO2 strengths identified in section 2. Surface warming may drive the change in feedback effective radiative forcing.
Warning: do not confuse these two:

\[
\frac{\partial R}{\partial T(x)} = \sum_y \frac{\partial R(y)}{\partial T(x)}
\]

\[
\frac{\partial R(y, t)}{\partial \bar{T}} = \sum \frac{\partial R(y)}{\partial T(x)} \frac{T(x, t)}{\bar{T}}
\]

Fig. 4 shows the geographical distribution of the radiative feedback terms (top to bottom) net TOA, net CRE, LW clear-sky feedback, SW clear-sky feedback, LW cloud radiative effect, and SW cloud radiative effect, on (left) short (years 1–20) and (middle) long (years 21–150) time scales, and (right) their difference (long minus short), for the CMIP5 AOGCM mean. Plots are calculated from linear regression of local radiative fluxes against global fluxes.

Fig. 5 shows the surface warming pattern (i.e., Fig. 5b) remaining years (Fig. 5b). Figure 5c shows the change in global mean surface warming pattern [determined from OLS regression of local fluxes over the relevant time periods]. The zonal-mean surface warming patterns for the individual models are shown in Figs. 5d–f. Note that, as with Fig. 4, the BCC and BNU warming patterns for the individual models are shown in the global mean by construction. The zonal-mean surface warming pattern (i.e., Fig. 5b) for the first 20 yr (Fig. 5a) and the remaining years (Fig. 5b).
Earth’s Energy Budget

\[ \overline{N} = \overline{F} + \overline{R}(T(x)) \]

Time dependent feedbacks

\[ N = F + \lambda(t)T(t) \]

Murphy 1995, Senior and Mitchell 2000

Heat uptake efficacy

\[ \varepsilon N = F + \lambda T \]

Winton 2010

Stability

\[ N = F + \lambda T + \beta S \]

Ceppi and Gregory 2020

Warm Pool

\[ N = F + \lambda T + \gamma T^* \]

Fueglistaler 2019

\[ \overline{R} \approx \sum_x \frac{\partial \overline{R}}{\partial T(x)} \frac{T(x)}{\overline{T}} \]
Forcing efficacy

Equilibrium
$$0 = \bar{F} + \lambda T$$

CO$_2$
$$0 = \bar{F}_{CO_2} + \lambda_{CO_2} T$$

Ocean Heat Uptake
$$0 = -N + \lambda_{OHU} T$$

Hansen 1995, Winton et al 2010
Forcing efficacy

Equilibrium

\[ 0 = \overline{F} + \lambda T \]

[CO₂]

\[ 0 = \overline{F}_{CO₂} + \lambda_{CO₂} T \]

Ocean Heat Uptake

\[ 0 = -\epsilon_N N + \lambda_{CO₂} T \]

Hansen 1995, Winton et al 2010
Forcing efficacy

**Energy Budget**

\[ \varepsilon_N N = \overline{F} + \lambda T \]

**CO₂**

\[ 0 = \overline{F}_{CO₂} + \lambda_{CO₂} T \]

**Ocean Heat Uptake**

\[ 0 = -\varepsilon_N N + \lambda_{CO₂} T \]

Winton et al 2010, Held et al 2010
Forcing efficacy

\[ \varepsilon_N = \frac{\lambda_{CO_2}}{\lambda_N} \]
Forcing efficacy

\[ \varepsilon_N = \frac{\lambda_{CO_2}}{\lambda_N} = \frac{\sum_x \left( \frac{\partial R}{\partial T(x)} \right) T_{CO_2}(x)}{\sum_x \left( \frac{\partial R}{\partial T(x)} \right) T_N(x)} \]

---

Figure 5: Geographical distribution of the pattern of surface air temperature change for (a) years 1–20, (b) years 21–150, and (c) their difference for the CMIP5 AOGCM mean. Plots show the slope of the linear regression of local \( D_T \) against global \( D_T \) for the relevant time periods and are dimensionless. By construction, the global mean of (a), (b) is unity, while (c) is zero. (d)–(f) The zonal-mean patterns, where thin lines are individual CMIP5 models.
Earth’s Energy Budget

\[ \bar{N} = \bar{F} + \bar{R} \left( T(x) \right) \]

Time dependent feedbacks

\[ N = F + \lambda(t)T(t) \]
Murlpy 1995, Senior and Mitchell 2000

Heat uptake efficacy

\[ \epsilon N = F + \lambda T \]
Winton 2010

Warm Pool

\[ N = F + \alpha T + \gamma T^{#} \]
Fueglistaler 2019

Stability

\[ N = F + \lambda T + \beta S \]
Ceppi and Gregory 2020
Radiative response dominated by warm pool

\[
\frac{\partial \bar{R}}{\partial T(x)}
\]

\[
N = F + \alpha T + \gamma T^#
\]

Fueglistaler 2019, Dong et al 2019
Warm pool location varies between models and in time

\[
\frac{\partial \bar{R}}{\partial T(x)}
\]

\(\text{NOAA ERSST}\)

\(\text{CESM2}\)
Roadmap

- Global feedback framework and it’s failure
- A refined view of the radiative response

**Open Questions**
- Radiative response
- Forcing and heat uptake
- Patterns
Open questions: Green’s Function is not quantitative

Nonlinearity? $T(x)^2, T(x) \cdot T(y)$?

Non-geographical framework?

Observational constrained? (~150 DOFs)
Open questions: Warming Patterns

\[ N(t) = \bar{F} + \bar{R}(T(x, t)) \]
Open questions: Warming Patterns

\[ N(t) = F + R(T(x, t)) \]

\[ T(x, t) = \sum \psi(x)\phi(t) \]

Internal Variability:
- ENSO?
- PDO?
- IPO?
- AMO?

Forced Response?
- CO2 - fast/slow mode?
- Aerosols
- Volcanoes
- Meltwater
Open questions: Coupled problem

\[ R(y) \]

\[ T(x) \]

\[ N(z) \]
The AMIP/CFMIP problem

Open questions: Coupled problem

The AMIP/CFMIP problem

\[
\frac{\partial R(y)}{\partial T(x)}
\]
Open questions: Climate Dynamics

$$T(x) = \frac{\partial T(x)}{\partial F(y)} F(y)$$

$$\frac{\partial R(y)}{\partial T(x)}$$

$$R(y)$$

$$T(x)$$

$$N(z)$$

Please reach out if you are interested in participating:

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Co-authors listed in reference section below
Open questions: Climate Dynamics

![Diagram](Image)

**2.3. Passive Ocean Heat Uptake Using GFs**

The global integral of heat passively absorbed (or, OHC) is particularly useful for emulating passive ocean heat uptake. Specifically, the ocean depending on local ventilation characteristics (i.e., the heat capacity of seawater, respectively. Note that the heat sourced in each patch is dispersed throughout the ocean, quantifies the total fraction of waters last in contact with (ventilated from) patch at time 0 for points over patch.

Here, the ocean is assumed to be in a steady state, and a later time

\[ \frac{\partial R(y)}{\partial T(x)} = \frac{\partial T(x)}{\partial R(y)} \]

\[ \frac{\partial N(z)}{\partial T(x)} = \frac{\partial T(x)}{\partial N(z)} \]

**Summary of the pattern effect on passive ocean heat uptake.** (a) Distribution of CMIP5 ensemble-mean SST anomalies within patch, OHU at time \( t \), \( j \). When integrated over all interior points, (forced everywhere at the same global mean rate, \( \text{OHU} \), can thus be expressed as

\[ \frac{\partial}{\partial T(x)} (R \text{ SST}) = \frac{\partial}{\partial N(z)} (\text{OHU SST}) \]

(b). The rate of passive ocean heat uptake per patch, which is defined as

\[ \text{OHU} \]

\[ \text{Total heat uptake per patch (see Equation 4) averaged for years 100–140. This total uptake results from the} \]

(d) Fraction of total patch heat uptake for the spatially varying experiment
Open questions: Climate Dynamics

\[
\begin{align*}
\frac{\partial R(y)}{\partial T(x)} & \quad \frac{\partial T(x)}{\partial R(y)} \\
\frac{\partial T(x)}{\partial N(z)} & \quad \frac{\partial N(z)}{\partial T(x)}
\end{align*}
\]

Q-flux green’s functions

Liu et al 2018
Open questions: Near-term warming

ECS: \[ T = \frac{\overline{F}}{\lambda} \]

\[ \lambda = \frac{\partial R}{\partial T} \]

Gregory and Mitchell 1997, Held et al 2010
Open questions: Near-term warming

\[ T = \frac{\bar{F}}{\lambda + \kappa} \]

\[ \kappa = \frac{\partial N}{\partial T} \]

\[ T = \frac{\bar{F}}{\lambda} \]

\[ \lambda = \frac{\partial R}{\partial T} \]

ECS:

\[ T = \frac{\bar{F}}{\lambda} \]

\[ \kappa = \frac{\partial N}{\partial T} \]

TCR:

\[ T = \frac{\bar{F}}{\lambda + \kappa} \]

\[ \lambda = \frac{\partial R}{\partial T} \]

Gregory and Mitchell 1997, Held et al 2010
\[ \lambda(t) = \sum \frac{\partial \bar{R}}{\partial T(x)} \times \frac{T(x, t)}{\bar{T}} \]

\[ \bar{N} = \bar{F} - \sum_{x} \frac{\partial \bar{R}}{\partial T(x)} \frac{T(x, t)}{\bar{T}} \]

(a) Years 1-20 warming pattern

(b) Years 21-150 warming pattern

(c) CMIP5 AOGCM-mean

Andrews et al 2015
\[ \lambda(t) = \sum \frac{\partial R}{\partial T(x)} \times \frac{T(x, t)}{\bar{T}} \]

**Summary slide Option 2**

- **historical**
- **abrupt-4xCO2**

Zhou et al. 2016
Supplementary Slides
Feedbacks are just Taylor Series in disguise

Global-temperature

\[ \Delta \bar{R} \approx \lambda \frac{\partial \bar{R}}{\partial \bar{T}} \Delta \bar{T} \]

Regional Temperatures

\[ \Delta \bar{R} \approx \lambda \sum_x \frac{\partial \bar{R}}{\partial T(x)} \frac{\Delta T(x)}{\Delta \bar{T}} \Delta \bar{T} \]

Radiative Response

Warming pattern

Roe et al 2008

Proistosescu & Huybers 2017

Armour et al 2013
Anatomy of a low cloud feedback

\[
\Delta \bar{R} \approx \sum_{x,y} \frac{\partial R(y)}{\partial M(y)} \frac{\partial M(y)}{\partial T(x)} \frac{\Delta T(x)}{\Delta \bar{T}} \Delta \bar{T}
\]

Cloud Radiative Effect  
Meteorology  
Warming pattern

Klein et al 2017  
Scott et al 2020  
Myers et al 2022
Anatomy of a low cloud feedback

\[ \Delta \bar{R} \approx \sum_{x,y} \frac{\partial R(y)}{\partial C(\tau, p, y)} \frac{\partial C(\tau, p, y)}{\partial M(y)} \frac{\partial M(y)}{\partial T(x)} \frac{\Delta T(x)}{\Delta \bar{T}} \]

Cloud Radiative Effect  Cloud fraction  Meteorology  Warming pattern

Klein et al 2017  Scott et al 2020  Myers et al 2022
\[ \Delta R \approx \sum_{x,y} \frac{\partial R(y)}{\partial C(\tau, p, y)} \frac{\partial C(\tau, p, y)}{\partial M(y)} \frac{\partial M(y)}{\partial T(x)} \frac{\Delta T(x)}{\Delta \bar{T}} \]
Tropical Climate Dynamics

Wood & Bretherton 2006
Klein & Hartmann 1993
Arakawa 1975
Stevens 2005
Response to East Pacific warming

- \( T_{f,W} \), moist adiabat
- \( T_{f,E} \)
- Weak Temp. Gradient
- Hadley/Walker
- EIS
- Trade inversion
- \( \text{ΔSST} \)
- \( \text{SST}_{WP} \) (Warm Pool)
- \( \text{SST}_{EP} \) (Subtropics)

**Legend:**
- 30°C
- 25°C
- 20°C
Response to East Pacific warming

$T_{f,W}$ moist adiabat

$SST_{WP}$

Weak Temp. Gradient

$T_{f,E}$

$SST_{EP} + \Delta SST$

Warm Pool

Subtropics

LW

Trade inversion

SW

Hadley/Walker

EIS

$\Delta SST$
Response to East Pacific warming

Warming the cool tropical SSTs

⇒

Positive (downward) radiative response

\( \Delta SST \)
Response to Warm Pool warming

$$T_{f,W}$$ moist adiabat

$$T_{f,E}$$

Weak Temp. Gradient

Hadley/Walker

EIS

Trade inversion

$$\Delta SST$$

Zhou et al 2017
Dong et al 2019

SST_{WP} SST_{EP}

Warm Pool Subtropics

ΔSST

SST (K)
Response to Warm Pool warming

\[ \text{SST}_{WP} + \Delta \text{SST} \]

Warm Pool

Subtropics

\[ \text{SST}_{EP} \]

Weak Temp. Gradient

\[ T_{f,W} \quad \text{moist adiabat} \]

\[ T_{f,E} \]

Trade inversion

\[ \text{EIS} \]

Hadley/Walker

\[ \Delta \text{SST} \]
Response to Warm Pool warming

$SST_{WP} + \Delta SST$ $SST_{EP}$

Warm Pool Subtropics

Weak Temp. Gradient

$T_{f,W}$ $T_{f,E}$

moist adiabat

Hadley/Walker

EIS

Trade inversion

$\Delta SST$
Response to Warm Pool warming

- **Warm Pool**: $SST_{WP} + \Delta SST$
- **Subtropics**: $SST_{EP}$

**Weakened Temperature Gradient**

**Hadley/Walker Circulation**

**Trade Inversion**

**LW** and **SW** represent longwave and shortwave radiation, respectively.

\(\Delta SST\) indicates the change in sea surface temperature.
Response to Warm Pool warming

Warming the warmest SSTs
⇒
Negative (outgoing) radiative response

\[ \Delta SST \]

\[ SST_{WP} + \Delta SST \]

\[ SST_{EP} \]

Warm Pool

Subtropics

Weak Temp. Gradient

Hadley/Walker

Trade inversion

EIS

\[ T_{f,W} \]

\[ T_{f,E} \]
Response to Warm Pool warming

\[ \Delta R \approx \sum_{x,y} \frac{\partial R(y)}{\partial C(\tau, p, y)} \frac{\partial C(\tau, p, y)}{\partial M(y)} \frac{\partial M(y)}{\partial T(x)} \frac{\Delta T(x)}{\Delta T} \]

\( SST_{WP} + \Delta SST \)  
\( SST_{EP} \)

Warm Pool  
Subtropics

Weak Temp. Gradient

Hadley/Walker

EIS

Trade inversion

LW

SW

Radiative Transfer  
Cloud physics  
Atmospheric Circulation  
Coupled Dynamics