1. Climatological position of the ITCZ is north of the equator because of cross-equatorial ocean heat transport.

2. ITCZ migrations are strongly damped by coupling of trade winds to ocean’s subtropical cells. (Brian Green)

3. Explore Strong coupling of the Indian monsoon with ocean circulation. (Nick Lutzko)
ITCZ resides in the warm hemisphere

Kang et al, 2008

Obvious explanation for relative warmth of the Northern Hemisphere might be albedo differences. However.....
Symmetry of Hemispheric planetary albedos

\[ \alpha_p = 0.298 \]

\[ \alpha_p = 0.299 \]

Donohoe and Battisti, 2011, J. Climate
Voigt et al, 2013: J. Climate
Stevens et al, 2015, GRL

Note, a 0.01 difference in \( \alpha_p \) implies a cross-equatorial heat transport of 0.2PW.
NH is warmer than the SH because of ocean circulation

To compensate, ITCZ shifts north to ensure that atmosphere transports heat south across Equator

Atlantic

All oceans

Trenberth and Caron, 2001

Lumpkin and Speer, 2007
Heat transport can be up-gradient in the ocean because the ocean is mechanically forced

ITCZ is in the NH because of ocean circulation

Kang et al, 2008

Coupling of ITCZ/Monsoons to ocean circulation
(John Marshall, MIT)

1. Climatological position of the ITCZ is north of the equator because of cross-equatorial ocean heat transport.
2. ITCZ migrations are strongly damped by coupling of trade winds to ocean’s subtropical cells. (Brian Green)
3. Explore Strong coupling of the Indian monsoon with ocean circulation. (Nick Lutzko)
Overturning Circulation

Surface Winds

ITCZ on the Equator
Overturning Circulation

Anomalous Surface Winds

Northward ITCZ shift
Overturning Circulation

Anomalous Surface Winds

Anomalous Ocean Ekman Transport

Northward ITCZ shift
Overturning Circulation

Anomalous Surface Winds

Asymmetric component of overturning circulation

Anomalous Ocean Ekman Transport

Northward ITCZ shift
Overturning Circulation

Northward ITCZ shift

Anomalous Surface Winds

Anomalous Ocean Ekman Transport

Asymmetric component of overturning circulation

Anomalous heat transport
The ITCZ is ‘sticky’

\[ \Delta \phi_{ITCZ} = b \cdot SW \cdot C \]

where ‘C’ is the compensation

\[ C = \frac{1}{1 + \frac{F_0}{F_A} + \frac{LW}{F_A}} \]

\( \Delta \phi_{ITCZ} \) = 0.4

MITgcm with Frierson moist physics

Green and Marshall, J. Climate, 2017
Dynamics of the Ocean’s Cross-Equatorial Cell

Fig. 9. Pathways of anomalous CEC currents in the large basin. (a) Surface branch. (b) Return branch. Current speed is shown by shading, and direction is shown by arrows.
Dynamics of the Ocean’s Cross-Equatorial Cell

Fig. 9. Pathways of anomalous CEC currents in the large basin. (a) Surface branch. (b) Return branch. Current speed is shown by shading, and direction is shown by arrows.

Literature on the Cross-equatorial Cell of the Indian Ocean
Fritz Schott (observationally)
Jay McCreary (theoretically)
and collaborators
Coupling of Monsoon with Ocean Circulation

1. Coupling of Hadley Cell with ocean’s subtropical cells
2. Damping of ITCZ migrations (Brian Green)
3. Coupling of monsoons with ocean circulation (Nick Lutsko)

Schematic from Peter Webster

Loschnigg and Webster, J. Climate, 2000

Asymmetric component of overturning circulation in Indian Sector
Minimalist model of coupling of Monsoon to the ocean

Ocean heat transport:

\[ F(\phi) = 2\pi a \cos \phi c_p \frac{\tau_x}{f} \Delta T \]

GFDL dynamical core, Frierson physics

Seasonal Cycle

24m mixed layer with interactive q-flux

Surface stress from atmospheric model

Temperature difference across the thermocline. Prescribed and held constant

GFDL dynamical core, Frierson physics
Surface winds, precipitation and Moist Static Energy

Summer

Interactive ocean

$\Delta T = 10K$
ΔT = 10K
Observed Surface wind and precipitation

Animation courtesy of Simona Bordoni
Enhancing role of ocean circulation

Increasing $\Delta T$

Summer

![Graph showing SST (Sea Surface Temperature) with different lines representing OCEAN and LAND regions, with a clear indication of increasing temperature $\Delta T$.](image-url)
Enhancing role of ocean circulation

Increasing $\Delta T$

Summer

![Graphs showing SST and MSE with increasing temperature differentials (ΔT) for ocean and land. The graphs illustrate the changes in SST and MSE with latitude, highlighting the enhanced role of ocean circulation in temperature distribution.]
Enhancing role of ocean circulation

Increasing $\Delta T$

Summer

- SST
- MSE
- Precip
Enhancing role of ocean circulation

Increasing $\Delta T$

Summer

**SST**

**MSE**

**Precip**

**Surface wind**
Overturning circulation
Overturning circulation and zonal wind

$ci=2\text{ m/s}$

westerlies
Monsoon Indices

**Maximum Zonal Wind Shear [ms⁻¹]**

- Increasing $\Delta T$

**Meridional Wind Shear at the Equator [ms⁻¹]**

- Increasing $\Delta T$

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**Pressure [hPa]**

- $\sim$30
- $\sim$20
- $\sim$10
- $\sim$0
- $\sim$10
- $\sim$20
- $\sim$30

---

**Pressure [hPa]**

- $\sim$1000
- $\sim$900
- $\sim$800
- $\sim$700
- $\sim$600
- $\sim$500
- $\sim$400
- $\sim$300
- $\sim$200

---

**Pressure [hPa]**

- $\sim$1000
- $\sim$900
- $\sim$800
- $\sim$700
- $\sim$600
- $\sim$500
- $\sim$400
- $\sim$300
- $\sim$200
Ocean Heat Transport

Summer

OHT (PW)

LAND

OHT at EQ (PW)

(time)
Summary

Western boundary currents in the Atmosphere and Ocean

Ekman Transport

Net downward surface heat flux

W/m²

Peter Webster and collaborators
Conclusions

Coupling of the trade winds with ocean’s subtropical cells in the deep tropics has a profound effect on rainfall patterns:

Strongly damps ITCZ migrations
Fundamental to the dynamics of the Indian Monsoon

Many discussions with

Brian Green, David McGee, Alan Plumb, Nick Lutsko, MIT
Aaron Donohoe, Dargan Frierson, UW
Simona Bordoni, Tapio Schneider, Caltech
Peter Webster, Georgia Tech
In present climate there is a small 0.2 PW net (A+O) northward transport of heat across the equator

If this transport was achieved by atmosphere, ITCZ would be south of equator!

Donohoe et al, 2013, J. Climate
Marshall et al, 2014; Climate Dynamics
In present climate there is a small 0.2 PW net (A+O) northward transport of heat across the equator

\[ AHT + OHT \geq 0 \]

\[ OHT > 0 \]

and so, atmospheric heat transport must be southward

\[ AHT < 0 \]

If this transport was achieved by atmosphere, ITCZ would be south of equator!

ITCZ is ‘pushed northward’ by OHT

Donohoe et al, 2013, J. Climate
Marshall et al, 2014; Climate Dynamics
ITCZ is in the NH because of ocean circulation

Kang et al, 2008