Water Vapor and the Hydrologic Cycle
What’s Required for Rain?

- To get rain, you need **water vapor** and **rising motion**
  - **Condensation** (water vapor turning to liquid water) happens when **moist air cools**
    - And this cooling almost always happens with rising motion
- Let’s take a look at precipitation on a global scale...
Why does it rain where it does?

- For reference, the precip climatology from GPCP
What Causes Primary Precipitation Features?

- **Tropics:**
  - Rising motion & rain over **warmest temperatures**
  - **Diurnal** & **seasonal** precipitation

- **Midlatitudes**
  - Rising associated with high/low pressure systems
  - Storm track location/intensity is key
Average Precipitation

- Precipitation (mm/day):

Rainiest spots on global scale are **narrow bands** near the **equator**

Many of the driest places on Earth are over the ocean!
Most deserts are around 30 degrees latitude
Air rises above the warmest ocean surface

The circulation takes water vapor away from the deserts at 30 degrees and brings it into the tropical rainy regions.
Zonally averaged precip and evap

- Hadley cell is key to converging moisture towards the equator
  - From the dry subtropics into the deep tropics

Evap and precip annual means (NCEP Reanalysis 2)
Seasonal March of Tropical Rains

- Rain shifts northward in Northern summer (JJA), southward in Southern summer (DJF)

“Convergence zone”: where winds come together
“Inter-tropical convergence zone” (ITCZ): the tropical band.
The ITCZ follows the warmest ocean temperatures as they shift with the seasons
Vegetation follows the seasonal march of rainfall
Monsoon Circulations

- Land heats up in the summer, leads to rising/rain

India, Africa, Australia, etc all experience strong monsoons

El Nino cycles greatly modify the location/intensity of monsoons in India & Australia
Precipitation Changes with El Niño

- Warmer water & rainier over **central Pacific** during El Niño

El Niño sea surface temps

**ENSO precipitation anomalies (GPCP, cm/month)**

- East-west sloshing of warm water/precipitation
Midlatitude Precipitation

- Midlatitude precipitation is associated with "baroclinic eddies"
  - Rising motion is generated in particular regions of the weather systems
“Storm Tracks”

- Precipitation (mm/day):

Midlatitude precipitation is in **storm tracks**: preferred locations for storms.
Northward Moisture Flux

- Annual and zonal mean northward moisture flux in the atmosphere:

Equatorward moisture flux in the tropics
Poleward moisture flux in the extratropics
Zonally averaged precip and evap

- Midlatitude storms take moisture out of subtropics and transport it poleward

![Graph showing evaporative and precipitation annual means (NCEP Reanalysis 2)]
Moisture and Horizontal Temperature Gradients

- Next: moisture also strongly influences pole-to-equator temperature gradients
  - If moisture **evaporates** at low latitudes, but **condenses** at higher latitudes, this is exactly like a poleward transport of heat

- Let’s examine **atmosphere and oceanic energy transports**
Energy Transports

- Climate system transports energy polewards (from hot to cold)

Northward energy transport [PW], Feb. 1985 - Apr. 1989 mean (top offset m)

Total (atmosphere plus ocean) flux

Northward flux in NH, Southward flux in SH
Atmospheric and Oceanic Energy Transports
• Separated into atmospheric and oceanic components:

Atmospheric flux is larger in midlatitudes, oceanic flux is larger in deep tropics
Atmospheric Energy Fluxes

- Let’s take a closer look at the **atmospheric** energy fluxes
  - **Dry static energy** flux = internal + potential energy flux
  - Latent heat transport = moisture flux

![Diagram of atmospheric energy transport](image-url)
• Annual and zonal mean moisture flux in the atmosphere:

Equatorward moisture flux in the tropics
Poleward moisture flux in the extratropics
Hadley Cell Energy Fluxes

- Equatorward moisture flux & poleward dry static energy flux in the tropics are due to the Hadley cells

Moisture near the surface is converged equatorward by Hadley cells

High dry static energy air aloft causes total transport to be away from the equator
Hadley Cell Energy Transports

- Large dry static energy fluxes within Hadley cell ensure that total transport is poleward
  - High potential energy air being moved poleward

![Graph showing energy transport](image)

- Total atmospheric transport
- Dry static energy transport
- Latent heat transport
Midlatitude Moisture Flux

- Poleward moisture flux occurs in midlatitudes
  - Primarily accomplished by eddies
Moisture Flux in Midlatitudes

- Poleward moisture flux occurs in midlatitudes
  - Primarily accomplished by eddies
Moisture Flux as an Energy Flux

- Poleward moisture flux acts to flatten temperature gradients just like heat fluxes:
  - When the moisture condenses at higher latitudes, it warms those latitudes
Extratropical Energy Fluxes

- Comparison with dry and total flux:
  - Dry static energy flux = $\nu(c_pT + gz)$
    = flux of internal energy + potential energy
Extratropical Energy Fluxes

- Comparison with dry and total flux:
  - Moisture flux is roughly 50% of the total transport in midlatitudes
Water Vapor and Global Warming

- With global warming, atmospheric moisture content will increase
  - 20% increase with 3 K global temperature increase
- What effects will the increased moisture content have on the Earth’s climate?
  - More moisture flux => flatter temperature gradients in midlatitudes
  - This should weaken dry static energy transports
Energy Fluxes in IPCC Simulations

- Change in moisture flux in slab ocean global warming simulations:
  - Increase in poleward flux in extratropics
  - Increase in equatorward flux in tropics

From Held and Soden (2006)
Energy Fluxes in IPCC Simulations

- Energy fluxes in slab ocean global warming simulations:
  - Change in moisture flux
  - Change in total flux
  - Change in dry static energy flux

~70% compensation

From Held and Soden (2006)
Moisture and Horizontal Temperature Gradients

- Moisture plays major role in determining midlatitude temperature gradients
  - Roughly 50% of flattening of temperatures is by moisture
- Moisture fluxes are expected to increase with global warming
  - Due to increased moisture content
  - Will lead to decreased temperature gradients