Introduction to Atmospheric Thermodynamics

How the Atmosphere Responds to Heating
Bibliography

• Bohren and Albrecht, 1998, *Atmospheric Thermodynamics*
  – *Good book on thermodynamics (it’s funny, really)*

• Fred Adams, *Origins of Existence*
  – *Interesting treatise on astronomy, cosmology, entropy and evolution (just for fun).*

• J.D. Neelin, *Climate Change and Climate Modeling*
  – *Good overview book for the course*

• JP Peixoto and AH Oort, *Physics of Climate*
  – *An oldie but goodie. A classic overview of the climate.*

• Papers:
Overview

• Short introduction to atmospheric thermodynamics
  – Atmospheric Energy Balance
  – Surface Energy Balance

• Short overview of global climate
  – Chapter 2 from *Climate Change and Climate Modeling* by JD Neelin
First and Second Laws of Thermodynamics

• In a closed system, energy is conserved
  – Heat ↔ Work

• In a closed system, entropy increases
  – Entropy (S) is the *amount of energy not available to do work*
  – In a probabilistic framework, S is a measure of the disorder of the system
    • $k_B = \text{boltzmann’s constant}$
    • $p_i = \text{probability of state } i$

  – Change in Entropy, $\Delta S = Q/T$
    $Q = \text{heat}$  $T = \text{absolute temperature}$

See Bohren and Albrecht, 1998, *Atmospheric Thermodynamics*
Will entropy prevail?

Gravity produces intense temperature gradients

\[ T_{\text{sun}} = 5,778K \quad \text{Cosmic Background}=2.8K \]

Time it takes for 1 gram of matter with a density of \(10^{24}\) particles per cubic centimeter to form by chance: \(10^{1054} \text{ seconds} \ldots \infty\)

See Fred Adams, *Origins of Existence*
The importance of energy gradients

Available Potential Energy = Energy available to do work
ATM APE is a function of temperature gradients

Generation of Available Potential Energy occurs when you increase a temperature gradient:
- heating a hot region
- cooling a cool region

Vertical Available Potential Energy = CAPE
- energy available to drive convection
- produced by cooling the top of the ATM
- or warming the bottom of the ATM

Meridional Production of APE = \text{Int}(\Gamma[T_{\text{lat}} - T_{\text{avg}}] [Q_{\text{lat}} - Q_{\text{avg}}])

Zonal Production of APE = \text{Int}(\Gamma[T_{\text{lon}} - T_{\text{avg}}] [Q_{\text{lon}} - Q_{\text{avg}}])
Entropy and Heat Engines

Time 1

Cold high $p$  $\rightarrow$  Warm low $p$

\[ \frac{\partial T}{\partial x} \propto \text{Available Energy} \] , \[ \frac{\partial T}{\partial x} \rightarrow \frac{\partial p}{\partial x} \propto u \]

Time 2

Isothermal Uniform pressure
Generation of Available Potential Energy

Time 1
- Cold: high p
- Warm: low p

\[
\frac{\partial T}{\partial x} \propto \text{Available Energy}, \quad \frac{\partial T}{\partial x} \rightarrow \frac{\partial p}{\partial x} \propto u
\]

Time 2
- Cooling the cool
- Warming the warm
Fig. 2.1, J.D. Neelin, *Climate Change and Climate Modeling*
Meridional Temperature Gradients

Fig. 2.6, J.D. Neelin, *Climate Change and Climate Modeling*
Incoming Solar and Outgoing Longwave ERBE Radiation Gradients

Fig. 2.9 & 2.10, J.D. Neelin, *Climate Change and Climate Modeling*
Major Features of the general circulation

Fig. 2.12, J.D. Neelin, *Climate Change and Climate Modeling*
Energy Pathways

Fig. 2.8, J.D. Neelin, *Climate Change and Climate Modeling*
Net Shortwave Radiation

Net Short-Wave Radiation

Data: NCEP/NCAR Reanalysis Project, 1959-1997 Climatologies
Animation: Department of Geography, University of Oregon, March 2000
Net Radiation

Data: NCEP/NCAR Reanalysis Project, 1959-1997 Climatologies
Animation: Department of Geography, University of Oregon, March 2000
Sensible Heat Flux

Data: NCEP/NCAR Reanalysis Project, 1959-1997 Climatologies
Animation: Department of Geography, University of Oregon, March 2000
Latent Heat Flux

Data: NCEP/NCAR Reanalysis Project, 1959-1997 Climatologies
Animation: Department of Geography, University of Oregon, March 2000
Changes in Heat Storage

Data: NCEP/NCAR Reanalysis Project, 1969-1997 Climatologies
Animation: Department of Geography, University of Oregon, March 2000
Types of Atmospheric Energy

\[ I = g^{-1} \int_{0}^{p_s} c v T_p dp \]

Potential, \( P = \int_{0}^{p_s} z_p dp \)

Kinetic, \( K = 0.5 \int_{0}^{p_s} (u^2 + v^2) dp \)

Latent, \( Q = Lg^{-1} \int_{0}^{p_s} q dp \)

See Peixoto and Oort, 1992, Physics of Climate
Trenberth and Stepaniak, 2003, Covariability of Components of Poleward Atmospheric Energy Transports, J. of Climate
Atmospheric Energy Balance

SWLW ↑↓ TOA

Latent Heat Flux↑
Sensible Heat Flux↑

←Convergence(Uφ)
←Convergence(UT)
Atmospheric Energy Balance

\[
\frac{\partial (K + P + I)}{\partial t} = - \nabla \cdot (F_K + F_P + F_I) + Q_1 + Q_f
\]

- \( F_K = \text{kinetic energy flux} \)
- \( F_P = \text{geopotential height flux} \)
- \( F_I = \text{internal energy flux} \)
- \( \nabla = \text{divergence operator} \)

\[
Q_1 + Q_f = R_{TOA} + R_{surf} + SH + LP = \text{diabatic atmospheric c heating}
\]

- \( R_{TOA} = \text{radiation balance at top of atmosphere} \)
- \( R_{surf} = \text{radiation balance at the surface} \)
- \( SH = \text{sensible heat flux from the surface} \)
- \( LP = \text{diabatic heating due precipitated ion} \)
Radiation Components

Net Shortwave TOA

Surface Absorbed Longwave
Surface Energy Fluxes Components

Longwave Emitted by Surface

Evaporation
Div(UP) and Div(UI) Climatologies

Div(UI)

Div(UP)

+500 W m$^{-2}$

+500 W m$^{-2}$

-500 W m$^{-2}$

-500 W m$^{-2}$

12 km

0 km

Cooling

Sub-tropical High

Warm Pool Warming
Div(UP) and Div(UI) Correlations

Warm Pool
Sub-tropical High
Warming

-0.9
-1

12 km
0 km
12 km
0 km

Cooling
Moist and Dry Static Energy

- Analogous to dry static energy but includes energy impacts of latent heating
  \[ \delta q = d(c_p dT + gz + Lr) \]
  - \( L \) is latent heat of vaporization, \( r \) is specific humidity (mass of vapor/mass of air)
  - Total static energy in air parcel includes latent energy tied up in water vapor content

\[
\text{DSE} = I + P \\
\text{MSE} = I + P + LQ, \quad Q=\text{total water vapor}
\]
Vertical Structure of Atmosphere

Fig. 2.11, J.D. Neelin, *Climate Change and Climate Modeling*
Parameterizations of Sensible and Latent Heat Fluxes

\[ R_{\text{net}} = \varepsilon T_s^4 \]

\[ R_{\text{up}} = e T_s^4 \]

\[ \text{Sensible Heating} = C_1 U (T_s - T_a) \]

\[ \text{Latent Heating} = C_2 U (q_s - q_a) \]

Convection between the surface and PBL is assumed to be random small scale convection, with an intensity typically assumed to be proportional to the mean wind, U. This motion is assumed to be random up and down motions, which mix the lower atmosphere.

The upward transport under these conditions will depend on the vertical gradient of temperature (T) or water vapor (q).
Adiabatic Processes

• No external heating
  – Conversions between internal and potential energy
  – Temperature changes produced by expansion and contraction
  – Important in parcels undergoing vertical motion
  – $c_p \, dT = -g \, dz$
Dry Adiabatic Lapse Rate

- Rate at which rising air parcel cools due to expansion
  - Constant for dry adiabatic process (no heat exchange with environment)
  - \(-\frac{dT}{dz} = \frac{g}{c_p} = \Gamma_d = \frac{9.8K}{km}\)

- Atmosphere heated from below - unstable
  - Other side of greenhouse effect
  - Warmest at bottom
  - Dry adiabatic lapse rate is upper bound for ambient atmospheric lapse rate
    - Steeper ambient rate triggers vertical motion, lifting warmer air

- Adiabatic lapse rate in terms of pressure
  - \(T(p) = T(p_s) \left(\frac{p}{p_s}\right)^{R/c_p}\)
  - Where \(p_s\) is the surface pressure and \(T(p_s)\) the surface temperature
Relationship between adiabatic and ambient lapse rates determines stability

Ambient rate larger, rising parcel warmer and less dense

Ambient rate cooler, rising parcel cooler and denser
Water in the Atmosphere

Role in energy budgets
Latent Heating

• Energy tied up in changes of state of water
  – No direct temperature change
  – Evaporation and melting take extra energy and cool the surface
  – Latent heats of vaporization and fusion
    • Latent heat of vaporization = $2.5 \times 10^6$ J/kg at 0°C
  – Condensation or freezing release latent heat and increase temperature
    • Important mechanism for transferring energy from surface into atmosphere
Saturation

Evaporation depends on temperature
Condensation depends on vapor content

Saturation (equilibrium) reached when two rates are the equal
Vapor content at saturation increases rapidly with increasing temperature

- Warmer atmosphere will hold more water vapor
- Water vapor is a strong greenhouse gas
- Works to magnify temperature changes (positive feedback)
Saturated Adiabatic Processes

• No external (diabatic) heating
  – Condensation or evaporation in saturated parcel impact rate of temperature change
  – Rising saturated parcel cools more slowly than unsaturated parcel due to release of latent heat through condensation
  – Sinking saturated parcel warms more slowly due to uptake of latent heat through evaporation
  – No longer an adiabatic process if water rains out
    • Latent heat is removed from parcel
Saturated Adiabatic Lapse Rate

- Depends on temperature and pressure
  - Generally about 5K-6K/km
- Ambient atmospheric lapse rate usually close to saturated adiabatic lapse rate
Mean Circulation

Precipitation

SSTs

Fig. 2.13-14,16, J.D. Neelin
Climatological Wind Fields

Fig. 2.15, J.D. Neelin, *Climate Change and Climate Modeling*

(a) 200 mb wind field

(b) 925 mb wind field
The Carbon Cycle

Fig. 2.20-21, J.D. Neelin
Conclusions/Questions

• Anthropogenic climate change will add heat to the earth climate system

• ‘Easy’ projections:
  – Warmer air temperatures
  – More water vapor
  – Melting Ice Caps
  – Rising sea levels

• ‘Hard’ projections
  – How will CC affect temperature gradients, and the associated circulation features?
Potential CC Impact Question(s)-1

Will CC warm the upper troposphere more than the lower Troposphere? Implication → More stability

Will CC warm the lower troposphere more than the upper Troposphere? Implication → Less stability
Potential CC Impact Question(s)-2

Will CC warm the upper latitudes more than the tropical atmosphere? Implication → Weaker SST gradients, slower winds?

Will CC warm the equatorial latitudes more than the polar atmosphere? Implication → Stronger SST gradients, faster winds?
One very robust CC response involves the increase in Water vapor with increasing T (~7% per Kelvin).

What implication will this have on climate, rainfall intensity water vapor related greenhouse warming, monsoons?