Climate Dynamics

Simple Climate Models

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Overview : 4 Lectures

- 1) Basic facts and findings
  - The global energy balance
  - Zero-dimensional EBM's
- 2) Introducing latitudinal effects
  - 1D (meridional) EBM's
  - ice/albedo feedback
- 3) Introducing vertical effects (in the atmosphere)
  - 1D radiative-convective models
- 4) 2D (meridional & vertical) models
  - statistical-dynamical models
  - the atmosphere
  - the ocean
  - and land ???

Acknowledgements & materials

- ♦ Developed from MIT course of Peter Stone
  - see Stone (1997)
  - similar content, different presentation
- ♦ Material (and many illustrations) from
  - McGuffie & Henderson-Sellers "A Climate Modelling Primer" (2nd edition, 1996) : £29-95 paperback
  - Trenberth (1992) "Climate System Modelling"
  - Kump, Kasting & Crane (1999) "The Earth System"

Simple Climate Models

Lecture 1

Basic facts and findings

The global energy balance

Zero-dimensional EBM's

The Climate System

- Ocean
- Atmosphere
- Cryosphere (both land and sea-ice)
- Hydrosphere (Evaporation, precipitation, groundwater, rivers...)
- Biosphere (both terrestrial & marine)
- Geosphere : tectonics (continental configuration), volcanic dust & CO_2
- ... and the *interactions* between them

Simple Models

- "Simple" means one or more of ...
- low dimensional
    - zero, one, two, three (?) ....
  - low order, i.e. coarse resolution
    - up to (say) ~ 30 x 30 x 30....
  - low complexity
    - use parameterisation rather than detailed simulation of complex processes....

      (a higher-order intellectual activity !)

Simple Models : Types

- Energy Balance Models
  - may be zero, one or two dimensional
  - model the land/sea surface and its interactions with the rest of the Universe
  - do not really model the atmosphere...
- Radiative-Convective Models (atmosphere)
  - usually 1D (vertical) :
  - point-wise or global average ?
- Box models (many variants thereof)
- Meridional/vertical models (2D)
  - "statistical-dynamical"
  - atmosphere and/or ocean

The Global Energy Balance

- At the top of the atmosphere (TOA)...
  - Earth receives incoming Short-wave (UV/Visible) radiation
    - some is reflected (albedo)
  - Earth emits Outgoing Long-wave (thermal infra-red) Radiation (OLWR)
    - Black-body radiation
    - at the effective TOA temperature (T_{eff})
    - NB : atmospheric lapse rates... $T_{eff} < T_s$
- OLWR from surface
  - is perturbed by atmospheric IR absorption & re-emission (the greenhouse effect)

Incoming Short-wave Radiation

- Solar Constant : S_0= ~ 1360 W m^{-2}
- Projected Area of Earth = πR^2
- Surface Area of Earth = $4 \pi R^2$
- ∴ Global average insolation
  $S_{bar} = S_0 / 4 = 340$ W m^{-2}
- at the equator, $S_{equ} = S_0 / \pi = 433$ W m^{-2}
- varies roughly as $\cos(\theta)$
  - but NB effect of obliquity
  - at the poles, if obliquity were zero, S would be zero, and it would be very cold indeed ....

Climate Forcing

- "climate forcings" are usually expressed as (vertical) heat fluxes (in W m^{-2})
- for $2xCO_2$, $G_{CO2} \approx 4$ W m^{-2}
- for clouds, $C_{net} \approx 0 \pm 20$ W m^{-2}
- NB vertical divergences (gradients) of forcing fluxes yield heating rates (e.g. in K per day)
  - if these are non-zero, we have imbalance, and thus non steady-states (or there must be other transports not yet accounted for)

Albedo

- Albedo (α) = SW reflectivity

Water	<0.1
Vegetation	0.1 to 0.2
Bare Land	0.2 to 0.3
Clouds	~0.5
Ice & snow	0.5 to 0.9

- Planetary average ~0.3
  - mostly due to clouds (2/3)
  - and snow/ice (1/3)

Outgoing Long-wave Radiation (OLWR)

- Stefan-Boltzmann law : $F = \sigma T^4$
  - $\sigma = 5.67$ E(-8) W m^{-2} K^{-4}
  - $\Rightarrow$ dominant (negative) **feedback**
- but : IR absorption/emission by the atmosphere
  - transmissivity(= emissivity) $\varepsilon \approx 0.6$
- causes GH effect : mainly due to water vapour
  - T_s-$T_{eff} \approx 33$ ºC (or “g” =40%)
- but vapour pressure increases with temperature & thus transmissivity **decreases** ($\Rightarrow$ positive feedback)
  - NB : Clausius-Clapeyron relationship
  - $q_s=q_0 \exp(-5420/T)$

Estimation of OLWR

- Empirical
  - Budyko (1969) : linear relationship
  - Sellers (1969) : non-linear relationship
  - from satellites (ERBE etc)
- Theoretical
  - 1D radiative convective models
  - Pierrehumbert (1995)
  - Hartmann & Michelson (1993)
- Should be somewhat non-linear...
- Still not very well established ($\pm$ 20 W m^{-2})

Budyko's Linear Approximation

- $F \approx 204 + 2.17\ T_s$ (W m^{-2})
  - (NB : $\exists$ various values for the constants)
- this implies a Climate Sensitivity (with no ice-albedo feedback) of $\lambda = 1/2.17 = 0.46$ K per W m^{-2}
- whereas, for a pure Stefan-Boltzmann black body, $\lambda \approx 0.3$ K per W m^{-2}
- the difference is due to the water vapour greenhouse effect (positive feedback)

Energy Balance Models

- ♦ Budyko (1969), Sellers (1969)
- ♦ see also North (1975), North et al (1981)
- ♦ Simplest case : zero-dimensional models
  - apply to globally averaged conditions
  - surprisingly successful & useful
    - (if carefully parameterised...)
  - because OLWR is well approximated by a linear function of T_s
  - so OLWR is not dependent on spatial distribution of heat (temperature)

Globally Averaged EBM

- ♦ For global energy balance :
- ♦ $(1-\alpha)\, S_{bar} = \varepsilon\, \sigma\, T_s^{\,4}$ (Stefan-Boltzmann)
    - where transmissivity $\varepsilon \approx 0.6$
    - albedo $\alpha \approx 0.3$
    - $S_{bar} = 340\ \mathrm{W\ m^{-2}}$
- ♦ $\therefore T_s = \{(1-\alpha)\, S_{bar} / (\varepsilon\, \sigma)\}^{0.25} - 273.2$
- ♦ alternatively....
- ♦ $(1-\alpha)\, S_{bar} = F \approx 204 + 2.17\, T_s$ (Budyko)
- ♦ $\therefore T_s = \{(1-\alpha)\, S_{bar} - 204\} / 2.17$

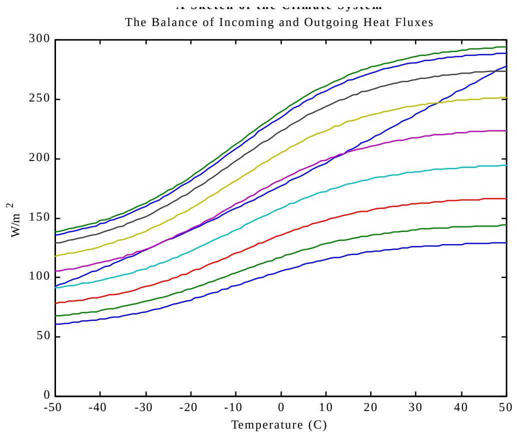
Global mean temperatures

- ♦ For Budyko' parameterisation, with
  - albedo $\alpha \approx 0.3$
  - $S_{bar} = 340$ W m^{-2}
- ♦ (and also for S-B with transmissivity $\varepsilon \approx 0.6$)
- ♦ $T_s \approx 16$ ºC
- ♦ For albedo > ≈ 0.4, T_s (Budyko) < 0 ºC
  - (∴ ice everywhere ...)
- ♦ T_s (Budyko) varies more than T_s (S-B)
  - due to water-vapour GH effect (+ve feedback)

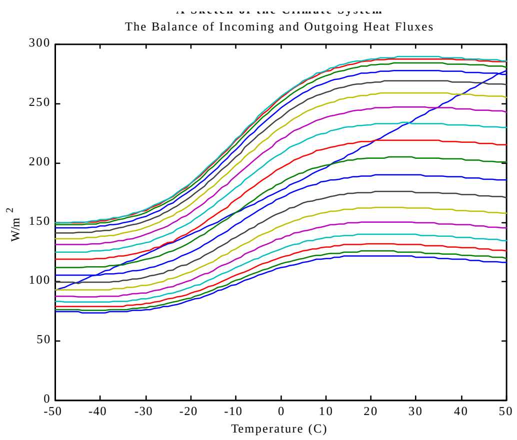
Ice/albedo feedback

- ♦ for T_s >~ -10 ºC, $\alpha \approx 0.3$
- ♦ for T_s <~ -10 ºC, $\alpha \approx 0.7$
- ♦ approximate by step or logistic function
- ♦ may have multiple stable states
- ♦ possibility of "Snowball Earth"
  - occurred twice ???
    - Huronian and late pre-Cambrian glaciations
    - at circa 2000 and 700 Ma BP

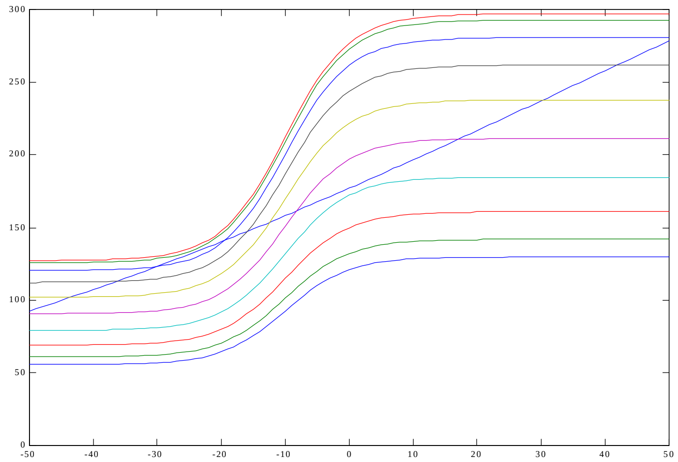
Effect of Ice-albedo feedback (no mixing)



Effect of Ice-albedo feedback (with mixing)



Balance between Incoming SW and Outgoing LW Radiation (for various latitudes)
With Ice/Albedo and Water Vapour Feedbacks (Budyko approximation for OLWR)



Runaway humid greenhouse ?

- OLWR has max (capped) at ≈ 320 W m^{-2}
- and at the equator...
- $(1-\alpha)\ S_{bar} \approx 0.7 \times 433 = 303$ W m^{-2}
- if S increases, or α decreases, could get runaway humid greenhouse effect
- the tropics are close to this state, now
- would continue until all ocean water has boiled (vapour pressure ≈ 400 bar, $T_s \approx 635$ K, 362 ºC...)
- has probably occurred on Venus
- likely for Earth in 1000 Ma (see Kasting 1988)

Sketch for logistic model

IR Saturation and the GH Effect

- If atmosphere is virtually opaque (absorption due to water vapour) why does a bit more absorption due to CO_2 matter ?
- $T_s = \{(1- \alpha) S_{bar} /(\varepsilon\, \sigma)\}^{0.25} - 273.2$
- but $\varepsilon = \exp(- \tau)$, where τ = optical thickness
  - (proportional to concentration of absorbing substances)

  $\therefore\ \Delta T_s \propto \exp(\tau/4)$: increases without limit...
- NB : continuous (layered) radiative equilibrium calculation $\Rightarrow \varepsilon = 2/(\tau+1)$ (?2?)
  - Salby, ML, pp88-94 in Trenberth (1992)

Effects of high & low clouds

Forcing the system

(Climate sensitivities)

- ♦ Values of λ (K per W m^{-2})
  - black body 0.30
  - + water vapour (g-h effect) 0.46
  - + ice-albedo feedback ???
- ♦ Doubling CO2 ⇒ forcing ≈ +4 W m^{-2}
  - ⇒ **ΔT** ≈ 2.5 ºC
- ♦ Ice introduces non-linearity
  - occurs only near the poles
  - must consider spatial variation
  - ⇒ need at least a 1D (meridional) model...