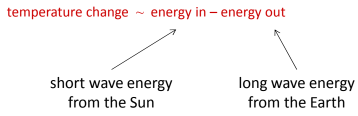
The Earth's Energy Imbalance

Richard McGehee
School of Mathematics
University of Minnesota

Mathematics of Climate Seminar
October 6, 2015

Energy Imbalance

Conservation of Energy



temperature change ~ energy in – energy out

short wave energy from the Sun

long wave energy from the Earth

Everything else is detail.

Energy Imbalance

Stefan-Boltzmann Law

$$F = \sigma T^4$$

power flux (W/m^2)

temperature (K)

Stefan-Boltzmann constant

$\sigma \approx 5.67 \times 10^{-8}$ W/m$^2 K^4$

Energy Imbalance

Stefan-Boltzmann Law

$$F = \sigma T^4$$

power flux (W/m^2)

temperature (K)

Stefan-Boltzmann constant

$\sigma \approx 5.67 \times 10^{-8}$ W/m$^2 K^4$

Example

http://astronomybythecosmos.com/tag/sun/

surface temperature of the Sun: 5780K

power flux: $5.67\text{x}10^{-8}$ x $(5780)^4 = 6.33\text{x}10^7$ W/m^2

total solar power output: $6.33\text{x}10^7$ x $4\pi(r_S)^2$,
where r_S = radius of the sun = $6.96\text{x}10^8$ m

total solar output: $3.85\text{x}10^{26}$ W

200 nanoseconds = time it takes for the sun to produce the equivalent of the annual global electricity production ($7.3\text{x}10^{19}$ Joules)

Energy Imbalance

Insolation

Solar flux at a distance r from the sun:

$$F = \frac{6.33\times10^7\,4\pi r_S^2}{4\pi r^2} = 6.33\times10^7\left(\frac{r_S}{r}\right)^2 \text{ W/m}^2$$

$r_S = 6.96\text{x}10^8$ m
$r = 1.5\text{x}10^{11}$ m

$F = 1368$ W/m^2

Power intercepted by the Earth:

$F \times \pi r_E^2$ Watts, r_E = radius of Earth $= 6.37\times10^6$ m

$F = 1.74\times10^{17}$ W

Energy Imbalance

Insolation

Solar flux at a distance r from the sun:

$$F = \frac{6.33\times10^7\,4\pi r_S^2}{4\pi r^2} = 6.33\times10^7\left(\frac{r_S}{r}\right)^2 \text{ W/m}^2$$

$r_S = 6.96\text{x}10^8$ m
$r = 1.5\text{x}10^{11}$ m

$F = 1368$ W/m^2

Power intercepted by the Earth:

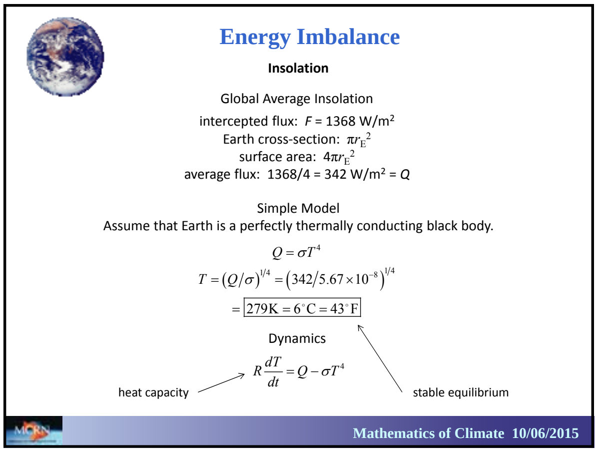
$F \times \pi r_E^2$ W, r_E = radius of Earth $= 6.37\times10^6$ m

$F = 1.74\times10^{17}$ W

Biologically Stored Energy

total coal reserves: 10^{15} kg
energy content: $3\text{x}10^7$ J/kg
total energy in coal reserves: $3\text{x}10^{22}$ J

= 2 days of insolation



Energy Imbalance

Insolation

Global Average Insolation

intercepted flux: F = 1368 W/m^2

Earth cross-section: πr_E^2

surface area: $4\pi r_E^2$

average flux: 1368/4 = 342 W/m^2 = Q

Simple Model

Assume that Earth is a perfectly thermally conducting black body.

$$Q = \sigma T^4$$

$$T = (Q/\sigma)^{1/4} = \left(342/5.67\times10^{-8}\right)^{1/4}$$

$$= \boxed{279\text{K} = 6^\circ\text{C} = 43^\circ\text{F}}$$

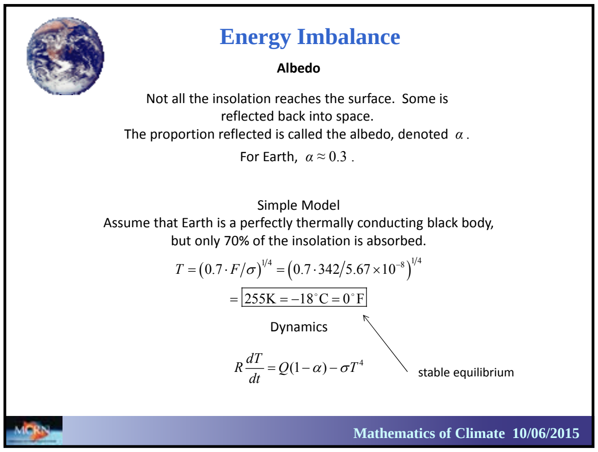
Dynamics

$$R\frac{dT}{dt} = Q - \sigma T^4$$

heat capacity

stable equilibrium

Mathematics of Climate 10/06/2015



Energy Imbalance

Albedo

Not all the insolation reaches the surface. Some is reflected back into space.

The proportion reflected is called the albedo, denoted α.

For Earth, $\alpha \approx 0.3$.

Simple Model

Assume that Earth is a perfectly thermally conducting black body, but only 70% of the insolation is absorbed.

$$T = (0.7\cdot F/\sigma)^{1/4} = \left(0.7\cdot 342/5.67\times10^{-8}\right)^{1/4}$$

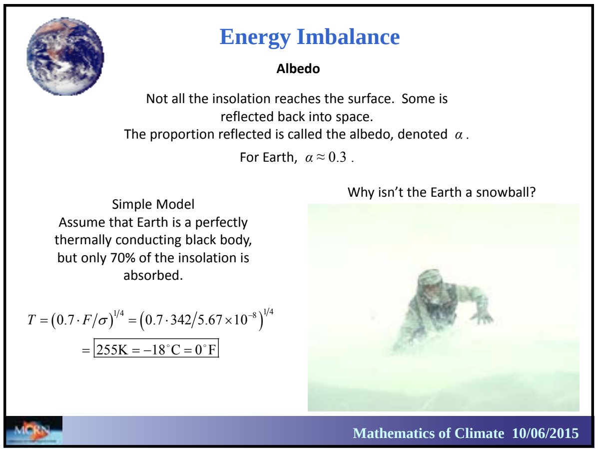
$$= \boxed{255\text{K} = -18^\circ\text{C} = 0^\circ\text{F}}$$

Dynamics

$$R\frac{dT}{dt} = Q(1-\alpha) - \sigma T^4$$

stable equilibrium

Mathematics of Climate 10/06/2015



Energy Imbalance

Albedo

Not all the insolation reaches the surface. Some is reflected back into space.

The proportion reflected is called the albedo, denoted α.

For Earth, $\alpha \approx 0.3$.

Simple Model

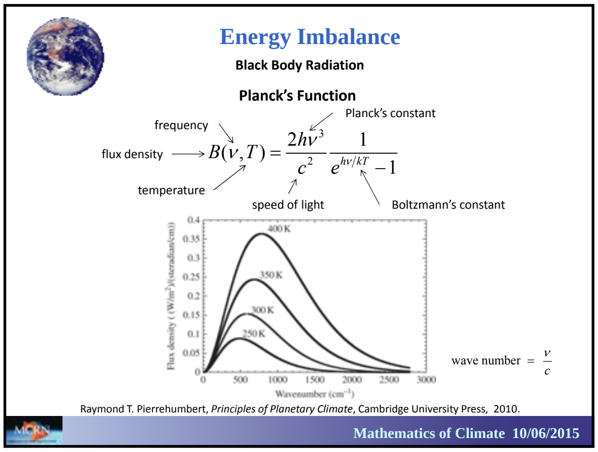
Assume that Earth is a perfectly thermally conducting black body, but only 70% of the insolation is absorbed.

$$T = (0.7\cdot F/\sigma)^{1/4} = \left(0.7\cdot 342/5.67\times10^{-8}\right)^{1/4}$$

$$= \boxed{255\text{K} = -18^\circ\text{C} = 0^\circ\text{F}}$$

Why isn't the Earth a snowball?

Mathematics of Climate 10/06/2015



Energy Imbalance

Black Body Radiation

Planck's Function

$$B(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$$

frequency

flux density

temperature

Planck's constant

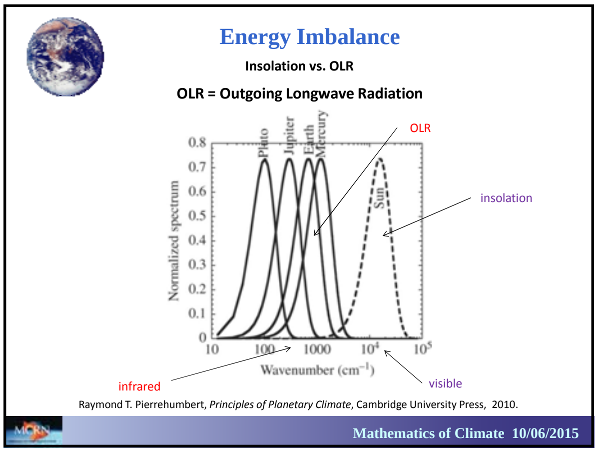
speed of light

Boltzmann's constant

wave number $= \dfrac{\nu}{c}$

Raymond T. Pierrehumbert, *Principles of Planetary Climate*, Cambridge University Press, 2010.

Mathematics of Climate 10/06/2015



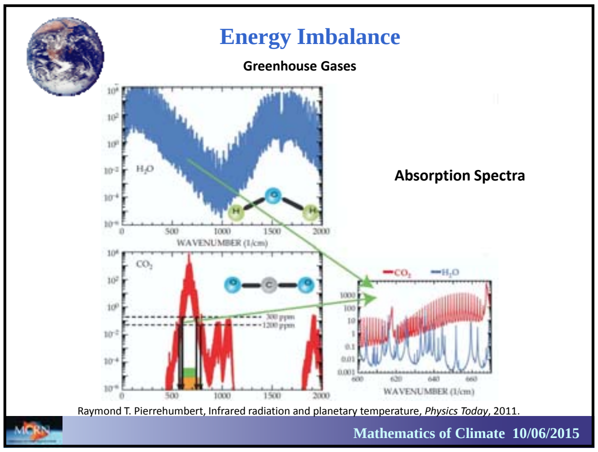
Energy Imbalance

Insolation vs. OLR

OLR = Outgoing Longwave Radiation

Raymond T. Pierrehumbert, *Principles of Planetary Climate*, Cambridge University Press, 2010.

Mathematics of Climate 10/06/2015



Energy Imbalance

Greenhouse Gases

Absorption Spectra

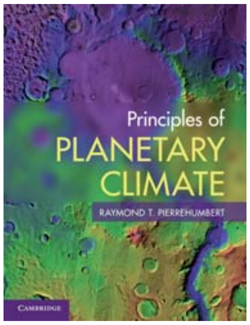
Raymond T. Pierrehumbert, Infrared radiation and planetary temperature, *Physics Today*, 2011.

Mathematics of Climate 10/06/2015

Energy Imbalance

Greenhouse Effect

How to learn more.



Energy Imbalance

James Hansen, *et al*, *Earth's Energy Imbalance: Confirmation and Implications*, SCIENCE **308** (2005), p. 1431

Average Insolation: 342 Watts per square meter

Current Heat Imbalance:

0.85 ± 0.15 Wm^{-2}

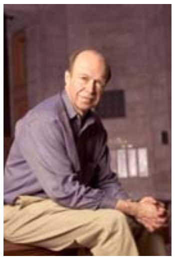
Unit of energy: Watt-year (W yr)

1 W yr = 3.15x10^{7} J

= 8761 W hr = 8.761 kWh

Yearly Insolation:

342 W yr m^{-2} = 1.08 x 10^{10} J



`https://en.wikipedia.org/wiki/James_Hansen`

Energy Imbalance

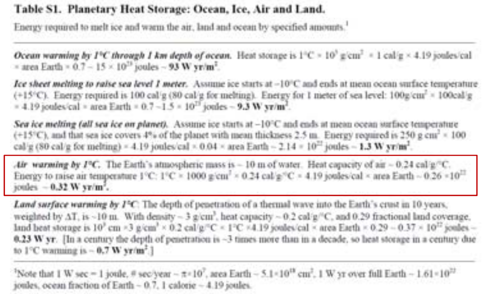


Table S1. Planetary Heat Storage: Ocean, Ice, Air and Land.

Energy required to melt ice and warm the air, land and ocean by specified amounts.[1]

Ocean warming by 1°C through 1 km depth of ocean. Heat storage is 1°C × 10^3 g/cm^2 × 1 cal/g × 4.19 joules/cal × area Earth × 0.7 ~ 15 × 10^{23} joules ~ **93 W yr/m^2**.

Ice sheet melting to raise sea level 1 meter. Assume ice starts at −10°C and ends at mean ocean surface temperature (+15°C). Energy required is 100 cal/g (80 cal/g for melting). Energy for 1 meter of sea level: 100g/cm^2 × 100cal/g × 4.19 joules/cal × area Earth × 0.7 ~1.5 × 10^{23} joules ~ **9.3 W yr/m^2**.

Sea ice melting (all sea ice on planet). Assume ice starts at −10°C and ends at mean ocean surface temperature (+15°C), and that sea ice covers 4% of the planet with mean thickness 2.5 m. Energy required is 250 g cm^2 × 100 cal/g (80 cal/g for melting) × 4.19 joules/cal × 0.04 × area Earth ~ 2.14 × 10^{22} joules ~ **1.3 W yr/m^2**.

Air warming by 1°C. The Earth's atmospheric mass is ~ 10 m of water. Heat capacity of air ~ 0.24 cal/g/°C. Energy to raise air temperature 1°C: 1°C × 1000 g/cm^2 × 0.24 cal/g/°C × 4.19 joules/cal × area Earth ~ 0.26 ×10^{22} joules ~ **0.32 W yr/m^2**.

Land surface warming by 1°C. The depth of penetration of a thermal wave into the Earth's crust in 10 years, weighted by ΔT, is ~10 m. With density ~ 3 g/cm^3, heat capacity ~ 0.2 cal/g/°C, and 0.29 fractional land coverage, land heat storage is 10^3 cm ×3 g/cm^3 × 0.2 cal/g/°C × 1°C ×4.19 joules/cal × area Earth × 0.29 ~ 0.37 × 10^{22} joules ~ **0.23 W yr**. [In a century the depth of penetration is ~3 times more than in a decade, so heat storage in a century due to 1°C warming is ~ **0.7 W yr/m^2**.]

[1] Note that 1 W sec = 1 joule, # sec/year ~ π×10^7, area Earth ~ 5.1×10^{18} cm^2, 1 W yr over full Earth ~ 1.61×10^{22} joules, ocean fraction of Earth ~ 0.7, 1 calorie ~ 4.19 joules.

James Hansen, et al, *Earth's Energy Imbalance: Confirmation and Implications*, SCIENCE 308 (2005), p. 1431

Energy Imbalance

Assume *all* insolation goes toward warming.

Energy to warm air 1ºC: 0.32 W yr m^{-2}
Power from Sun: 342 Wm^{-2}
Time: 0.32/342 = 0.00094 yr = **8.2 hr**

Assume a global heat imbalance of 0.85 W m^{-2}.

Energy to warm air 1ºC: 0.32 W yr m^{-2}
Heat imbalance: 0.85 Wm^{-2}
Time: 0.32/0.85 = 0.376 yr = **4.5 months**

Energy Imbalance

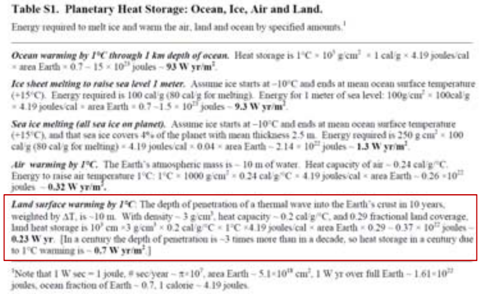


Table S1. Planetary Heat Storage: Ocean, Ice, Air and Land.

Energy required to melt ice and warm the air, land and ocean by specified amounts.[1]

Ocean warming by 1°C through 1 km depth of ocean. Heat storage is 1°C × 10^3 g/cm^2 × 1 cal/g × 4.19 joules/cal × area Earth × 0.7 ~ 15 × 10^{23} joules ~ **93 W yr/m^2**.

Ice sheet melting to raise sea level 1 meter. Assume ice starts at −10°C and ends at mean ocean surface temperature (+15°C). Energy required is 100 cal/g (80 cal/g for melting). Energy for 1 meter of sea level: 100g/cm^2 × 100cal/g × 4.19 joules/cal × area Earth × 0.7 ~1.5 × 10^{23} joules ~ **9.3 W yr/m^2**.

Sea ice melting (all sea ice on planet). Assume ice starts at −10°C and ends at mean ocean surface temperature (+15°C), and that sea ice covers 4% of the planet with mean thickness 2.5 m. Energy required is 250 g cm^2 × 100 cal/g (80 cal/g for melting) × 4.19 joules/cal × 0.04 × area Earth ~ 2.14 × 10^{22} joules ~ **1.3 W yr/m^2**.

Air warming by 1°C. The Earth's atmospheric mass is ~ 10 m of water. Heat capacity of air ~ 0.24 cal/g/°C. Energy to raise air temperature 1°C: 1°C × 1000 g/cm^2 × 0.24 cal/g/°C × 4.19 joules/cal × area Earth ~ 0.26 ×10^{22} joules ~ **0.32 W yr/m^2**.

Land surface warming by 1°C. The depth of penetration of a thermal wave into the Earth's crust in 10 years, weighted by ΔT, is ~10 m. With density ~ 3 g/cm^3, heat capacity ~ 0.2 cal/g/°C, and 0.29 fractional land coverage, land heat storage is 10^3 cm ×3 g/cm^3 × 0.2 cal/g/°C × 1°C ×4.19 joules/cal × area Earth × 0.29 ~ 0.37 × 10^{22} joules ~ **0.23 W yr**. [In a century the depth of penetration is ~3 times more than in a decade, so heat storage in a century due to 1°C warming is ~ **0.7 W yr/m^2**.]

[1] Note that 1 W sec = 1 joule, # sec/year ~ π×10^7, area Earth ~ 5.1×10^{18} cm^2, 1 W yr over full Earth ~ 1.61×10^{22} joules, ocean fraction of Earth ~ 0.7, 1 calorie ~ 4.19 joules.

James Hansen, et al, *Earth's Energy Imbalance: Confirmation and Implications*, SCIENCE 308 (2005), p. 1431

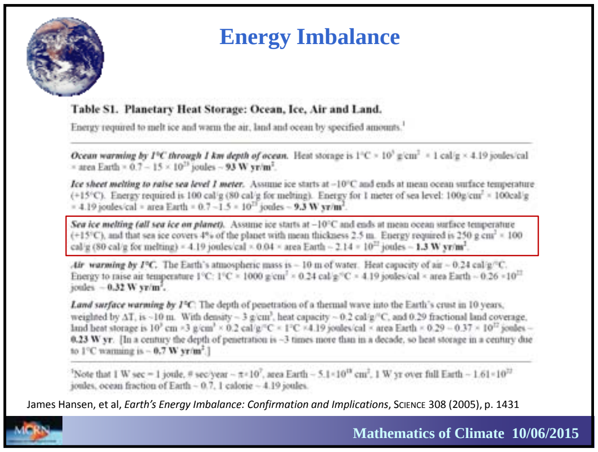
Energy Imbalance

Assume *all* insolation goes toward warming.

Energy to warm land surface 1ºC: 0.7 W yr m^{-2}
Power from Sun: 342 Wm^{-2}
Time: 0.7/342 = 0.0020 yr = **18 hr**

Assume a global heat imbalance of 0.85 W m^{-2}.

Energy to warm land surface 1ºC: 0.7 W yr m^{-2}
Heat imbalance: 0.85 Wm^{-2}
Time: 0.7/0.85 = 0.376 yr = **9.9 months**



Energy Imbalance

Table S1. Planetary Heat Storage: Ocean, Ice, Air and Land.

Energy required to melt ice and warm the air, land and ocean by specified amounts.[1]

Ocean warming by 1°C through 1 km depth of ocean. Heat storage is 1°C × 10^5 g/cm^2 × 1 cal/g × 4.19 joules/cal × area Earth × 0.7 ~ 15 × 10^{23} joules ~ **93 W yr/m^2**.

Ice sheet melting to raise sea level 1 meter. Assume ice starts at –10°C and ends at mean ocean surface temperature (+15°C). Energy required is 100 cal/g (80 cal/g for melting). Energy for 1 meter of sea level: 100g/cm^2 × 100cal/g × 4.19 joules/cal × area Earth × 0.7 ~1.5 × 10^{23} joules ~ **9.3 W yr/m^2**.

Sea ice melting (all sea ice on planet). Assume ice starts at –10°C and ends at mean ocean surface temperature (+15°C), and that sea ice covers 4% of the planet with mean thickness 2.5 m. Energy required is 250 g cm^2 × 100 cal/g (80 cal/g for melting) × 4.19 joules/cal × 0.04 × area Earth ~ 2.14 × 10^{22} joules ~ **1.3 W yr/m^2**.

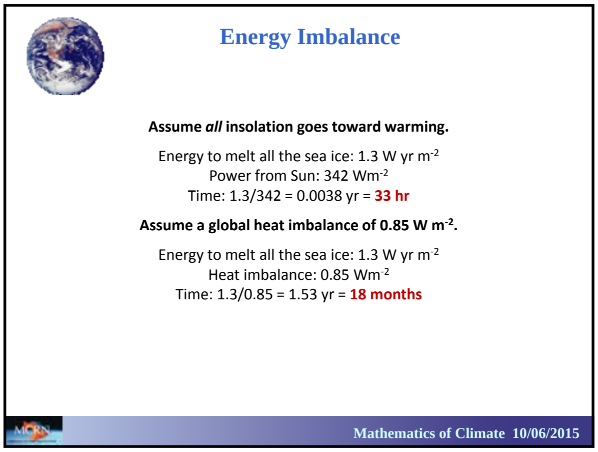
Air warming by 1°C. The Earth's atmospheric mass is ~ 10 m of water. Heat capacity of air ~ 0.24 cal/g/°C. Energy to raise air temperature 1°C: 1°C × 1000 g/cm^2 × 0.24 cal/g/°C × 4.19 joules/cal × area Earth ~ 0.26 ×10^{22} joules ~ **0.32 W yr/m^2**.

Land surface warming by 1°C. The depth of penetration of a thermal wave into the Earth's crust in 10 years, weighted by ΔT, is ~10 m. With density ~ 3 g/cm^3, heat capacity ~ 0.2 cal/g/°C, and 0.29 fractional land coverage, land heat storage is 10^3 cm ×3 g/cm^3 × 0.2 cal/g/°C × 1°C ×4.19 joules/cal × area Earth × 0.29 ~ 0.37 × 10^{22} joules ~ **0.23 W yr**. [In a century the depth of penetration is ~3 times more than in a decade, so heat storage in a century due to 1°C warming is ~ **0.7 W yr/m^2**.]

[1] Note that 1 W sec = 1 joule, # sec/year ~ π×10^7, area Earth ~ 5.1×10^{18} cm^2, 1 W yr over full Earth ~ 1.61×10^{22} joules, ocean fraction of Earth ~ 0.7, 1 calorie ~ 4.19 joules.

James Hansen, et al, *Earth's Energy Imbalance: Confirmation and Implications*, SCIENCE 308 (2005), p. 1431

Mathematics of Climate 10/06/2015



Energy Imbalance

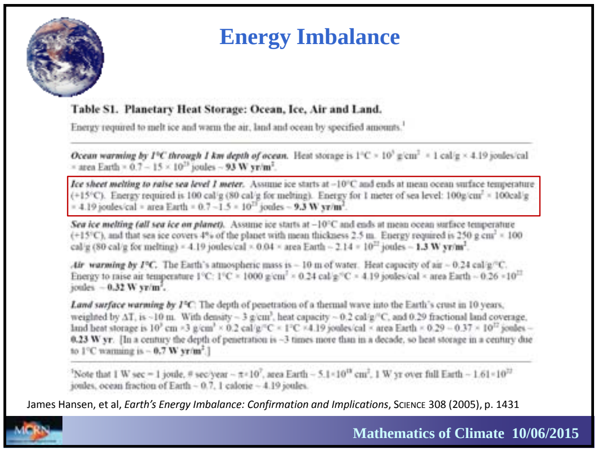
Assume *all* insolation goes toward warming.

Energy to melt all the sea ice: 1.3 W yr m^{-2}
Power from Sun: 342 Wm^{-2}
Time: 1.3/342 = 0.0038 yr = **33 hr**

Assume a global heat imbalance of 0.85 W m^{-2}.

Energy to melt all the sea ice: 1.3 W yr m^{-2}
Heat imbalance: 0.85 Wm^{-2}
Time: 1.3/0.85 = 1.53 yr = **18 months**

Mathematics of Climate 10/06/2015



Energy Imbalance

Table S1. Planetary Heat Storage: Ocean, Ice, Air and Land.

Energy required to melt ice and warm the air, land and ocean by specified amounts.[1]

Ocean warming by 1°C through 1 km depth of ocean. Heat storage is 1°C × 10^5 g/cm^2 × 1 cal/g × 4.19 joules/cal × area Earth × 0.7 ~ 15 × 10^{23} joules ~ **93 W yr/m^2**.

Ice sheet melting to raise sea level 1 meter. Assume ice starts at –10°C and ends at mean ocean surface temperature (+15°C). Energy required is 100 cal/g (80 cal/g for melting). Energy for 1 meter of sea level: 100g/cm^2 × 100cal/g × 4.19 joules/cal × area Earth × 0.7 ~1.5 × 10^{23} joules ~ **9.3 W yr/m^2**.

Sea ice melting (all sea ice on planet). Assume ice starts at –10°C and ends at mean ocean surface temperature (+15°C), and that sea ice covers 4% of the planet with mean thickness 2.5 m. Energy required is 250 g cm^2 × 100 cal/g (80 cal/g for melting) × 4.19 joules/cal × 0.04 × area Earth ~ 2.14 × 10^{22} joules ~ **1.3 W yr/m^2**.

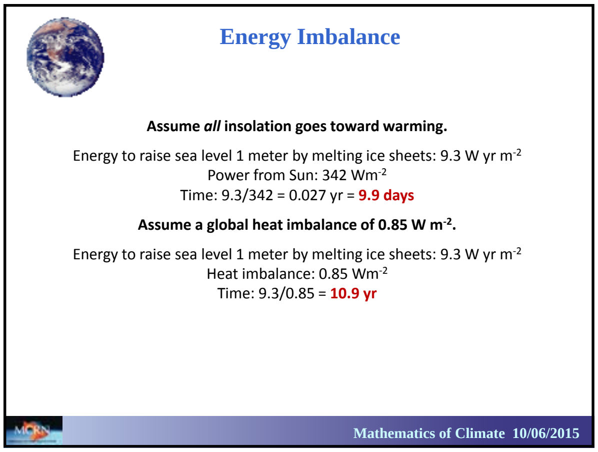
Air warming by 1°C. The Earth's atmospheric mass is ~ 10 m of water. Heat capacity of air ~ 0.24 cal/g/°C. Energy to raise air temperature 1°C: 1°C × 1000 g/cm^2 × 0.24 cal/g/°C × 4.19 joules/cal × area Earth ~ 0.26 ×10^{22} joules ~ **0.32 W yr/m^2**.

Land surface warming by 1°C. The depth of penetration of a thermal wave into the Earth's crust in 10 years, weighted by ΔT, is ~10 m. With density ~ 3 g/cm^3, heat capacity ~ 0.2 cal/g/°C, and 0.29 fractional land coverage, land heat storage is 10^3 cm ×3 g/cm^3 × 0.2 cal/g/°C × 1°C ×4.19 joules/cal × area Earth × 0.29 ~ 0.37 × 10^{22} joules ~ **0.23 W yr**. [In a century the depth of penetration is ~3 times more than in a decade, so heat storage in a century due to 1°C warming is ~ **0.7 W yr/m^2**.]

[1] Note that 1 W sec = 1 joule, # sec/year ~ π×10^7, area Earth ~ 5.1×10^{18} cm^2, 1 W yr over full Earth ~ 1.61×10^{22} joules, ocean fraction of Earth ~ 0.7, 1 calorie ~ 4.19 joules.

James Hansen, et al, *Earth's Energy Imbalance: Confirmation and Implications*, SCIENCE 308 (2005), p. 1431

Mathematics of Climate 10/06/2015



Energy Imbalance

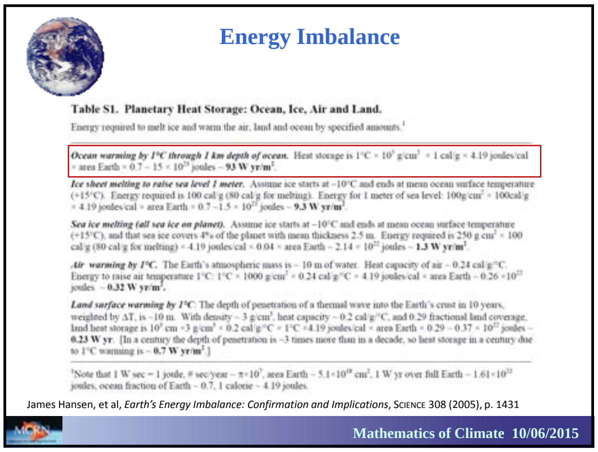
Assume *all* insolation goes toward warming.

Energy to raise sea level 1 meter by melting ice sheets: 9.3 W yr m^{-2}
Power from Sun: 342 Wm^{-2}
Time: 9.3/342 = 0.027 yr = **9.9 days**

Assume a global heat imbalance of 0.85 W m^{-2}.

Energy to raise sea level 1 meter by melting ice sheets: 9.3 W yr m^{-2}
Heat imbalance: 0.85 Wm^{-2}
Time: 9.3/0.85 = **10.9 yr**

Mathematics of Climate 10/06/2015



Energy Imbalance

Table S1. Planetary Heat Storage: Ocean, Ice, Air and Land.

Energy required to melt ice and warm the air, land and ocean by specified amounts.[1]

Ocean warming by 1°C through 1 km depth of ocean. Heat storage is 1°C × 10^5 g/cm^2 × 1 cal/g × 4.19 joules/cal × area Earth × 0.7 ~ 15 × 10^{23} joules ~ **93 W yr/m^2**.

Ice sheet melting to raise sea level 1 meter. Assume ice starts at –10°C and ends at mean ocean surface temperature (+15°C). Energy required is 100 cal/g (80 cal/g for melting). Energy for 1 meter of sea level: 100g/cm^2 × 100cal/g × 4.19 joules/cal × area Earth × 0.7 ~1.5 × 10^{23} joules ~ **9.3 W yr/m^2**.

Sea ice melting (all sea ice on planet). Assume ice starts at –10°C and ends at mean ocean surface temperature (+15°C), and that sea ice covers 4% of the planet with mean thickness 2.5 m. Energy required is 250 g cm^2 × 100 cal/g (80 cal/g for melting) × 4.19 joules/cal × 0.04 × area Earth ~ 2.14 × 10^{22} joules ~ **1.3 W yr/m^2**.

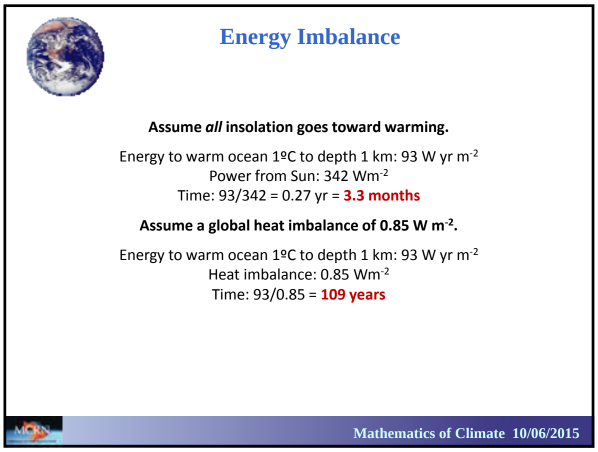
Air warming by 1°C. The Earth's atmospheric mass is ~ 10 m of water. Heat capacity of air ~ 0.24 cal/g/°C. Energy to raise air temperature 1°C: 1°C × 1000 g/cm^2 × 0.24 cal/g/°C × 4.19 joules/cal × area Earth ~ 0.26 ×10^{22} joules ~ **0.32 W yr/m^2**.

Land surface warming by 1°C. The depth of penetration of a thermal wave into the Earth's crust in 10 years, weighted by ΔT, is ~10 m. With density ~ 3 g/cm^3, heat capacity ~ 0.2 cal/g/°C, and 0.29 fractional land coverage, land heat storage is 10^3 cm ×3 g/cm^3 × 0.2 cal/g/°C × 1°C ×4.19 joules/cal × area Earth × 0.29 ~ 0.37 × 10^{22} joules ~ **0.23 W yr**. [In a century the depth of penetration is ~3 times more than in a decade, so heat storage in a century due to 1°C warming is ~ **0.7 W yr/m^2**.]

[1] Note that 1 W sec = 1 joule, # sec/year ~ π×10^7, area Earth ~ 5.1×10^{18} cm^2, 1 W yr over full Earth ~ 1.61×10^{22} joules, ocean fraction of Earth ~ 0.7, 1 calorie ~ 4.19 joules.

James Hansen, et al, *Earth's Energy Imbalance: Confirmation and Implications*, SCIENCE 308 (2005), p. 1431

Mathematics of Climate 10/06/2015



Energy Imbalance

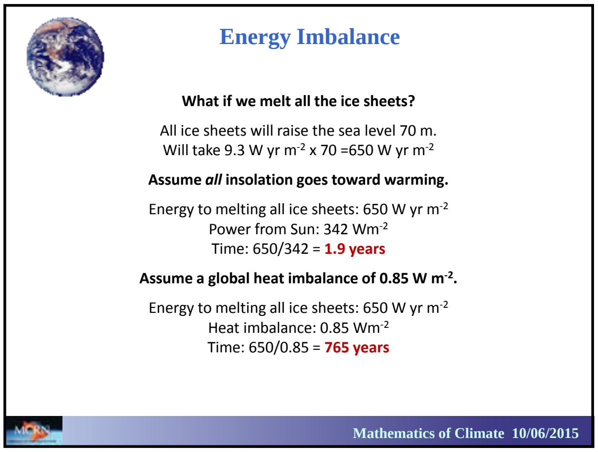
Assume *all* insolation goes toward warming.

Energy to warm ocean 1ºC to depth 1 km: 93 W yr m^{-2}
Power from Sun: 342 Wm^{-2}
Time: 93/342 = 0.27 yr = **3.3 months**

Assume a global heat imbalance of 0.85 W m^{-2}.

Energy to warm ocean 1ºC to depth 1 km: 93 W yr m^{-2}
Heat imbalance: 0.85 Wm^{-2}
Time: 93/0.85 = **109 years**

Mathematics of Climate 10/06/2015



Energy Imbalance

What if we melt all the ice sheets?

All ice sheets will raise the sea level 70 m.
Will take 9.3 W yr m^{-2} x 70 =650 W yr m^{-2}

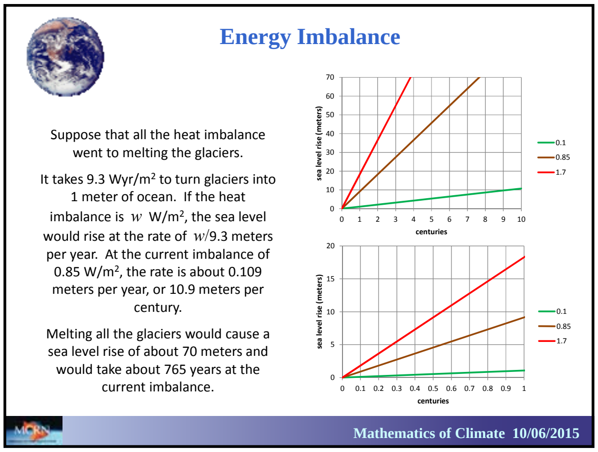
Assume *all* insolation goes toward warming.

Energy to melting all ice sheets: 650 W yr m^{-2}
Power from Sun: 342 Wm^{-2}
Time: 650/342 = **1.9 years**

Assume a global heat imbalance of 0.85 W m^{-2}.

Energy to melting all ice sheets: 650 W yr m^{-2}
Heat imbalance: 0.85 Wm^{-2}
Time: 650/0.85 = **765 years**

Mathematics of Climate 10/06/2015



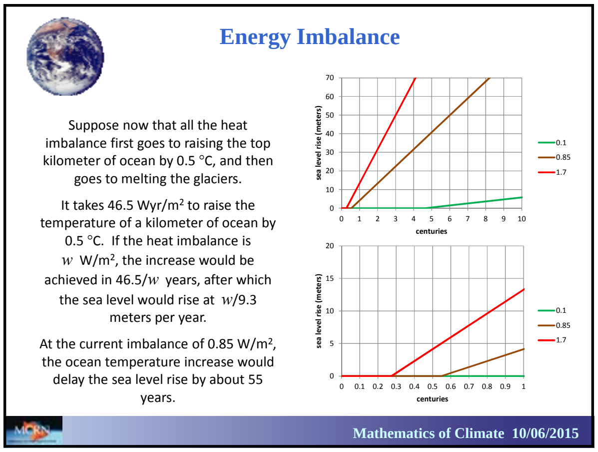
Energy Imbalance

Suppose that all the heat imbalance went to melting the glaciers.

It takes 9.3 Wyr/m^2 to turn glaciers into 1 meter of ocean. If the heat imbalance is w W/m^2, the sea level would rise at the rate of $w/9.3$ meters per year. At the current imbalance of 0.85 W/m^2, the rate is about 0.109 meters per year, or 10.9 meters per century.

Melting all the glaciers would cause a sea level rise of about 70 meters and would take about 765 years at the current imbalance.

Mathematics of Climate 10/06/2015



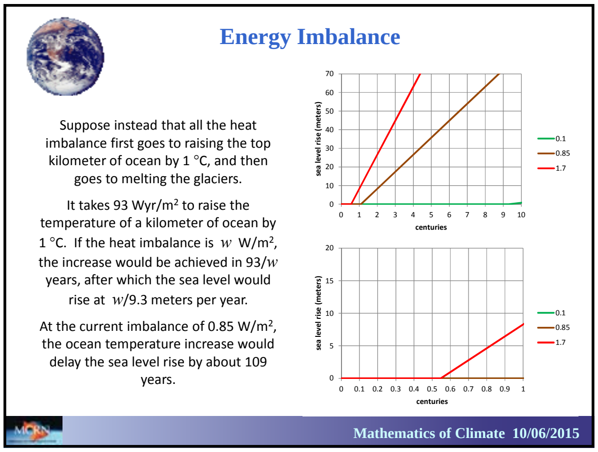
Energy Imbalance

Suppose now that all the heat imbalance first goes to raising the top kilometer of ocean by 0.5 °C, and then goes to melting the glaciers.

It takes 46.5 Wyr/m^2 to raise the temperature of a kilometer of ocean by 0.5 °C. If the heat imbalance is w W/m^2, the increase would be achieved in $46.5/w$ years, after which the sea level would rise at $w/9.3$ meters per year.

At the current imbalance of 0.85 W/m^2, the ocean temperature increase would delay the sea level rise by about 55 years.

Mathematics of Climate 10/06/2015



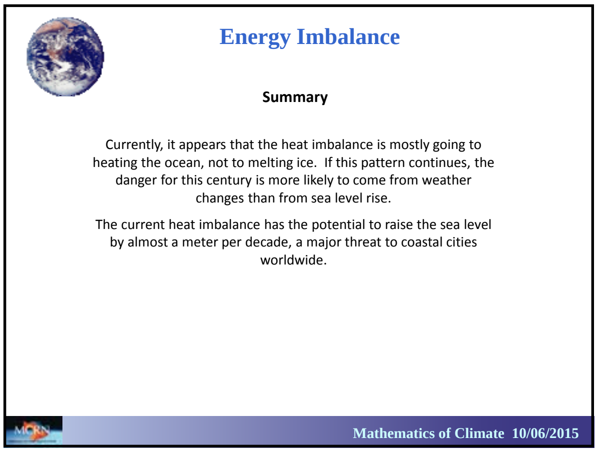
Energy Imbalance

Suppose instead that all the heat imbalance first goes to raising the top kilometer of ocean by 1 °C, and then goes to melting the glaciers.

It takes 93 Wyr/m^2 to raise the temperature of a kilometer of ocean by 1 °C. If the heat imbalance is w W/m^2, the increase would be achieved in $93/w$ years, after which the sea level would rise at $w/9.3$ meters per year.

At the current imbalance of 0.85 W/m^2, the ocean temperature increase would delay the sea level rise by about 109 years.

Mathematics of Climate 10/06/2015



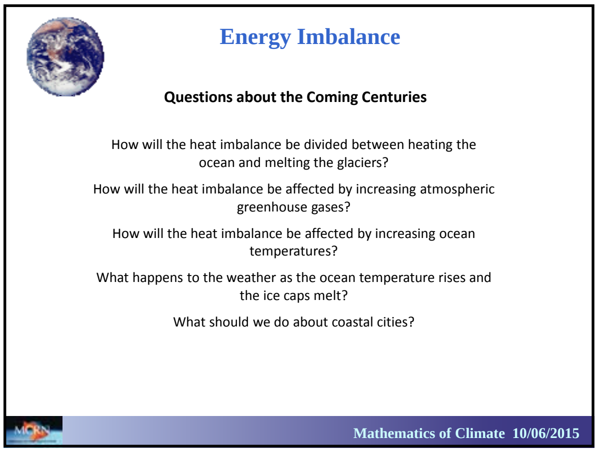
Energy Imbalance

Summary

Currently, it appears that the heat imbalance is mostly going to heating the ocean, not to melting ice. If this pattern continues, the danger for this century is more likely to come from weather changes than from sea level rise.

The current heat imbalance has the potential to raise the sea level by almost a meter per decade, a major threat to coastal cities worldwide.

Mathematics of Climate 10/06/2015



Energy Imbalance

Questions about the Coming Centuries

How will the heat imbalance be divided between heating the ocean and melting the glaciers?

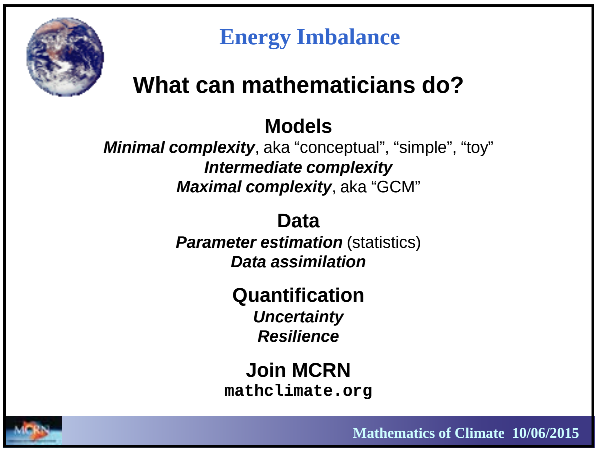
How will the heat imbalance be affected by increasing atmospheric greenhouse gases?

How will the heat imbalance be affected by increasing ocean temperatures?

What happens to the weather as the ocean temperature rises and the ice caps melt?

What should we do about coastal cities?

Mathematics of Climate 10/06/2015



Energy Imbalance

What can mathematicians do?

Models
Minimal complexity, aka “conceptual”, “simple”, “toy”
Intermediate complexity
Maximal complexity, aka “GCM”

Data
Parameter estimation (statistics)
Data assimilation

Quantification
Uncertainty
Resilience

Join MCRN
`mathclimate.org`

Mathematics of Climate 10/06/2015