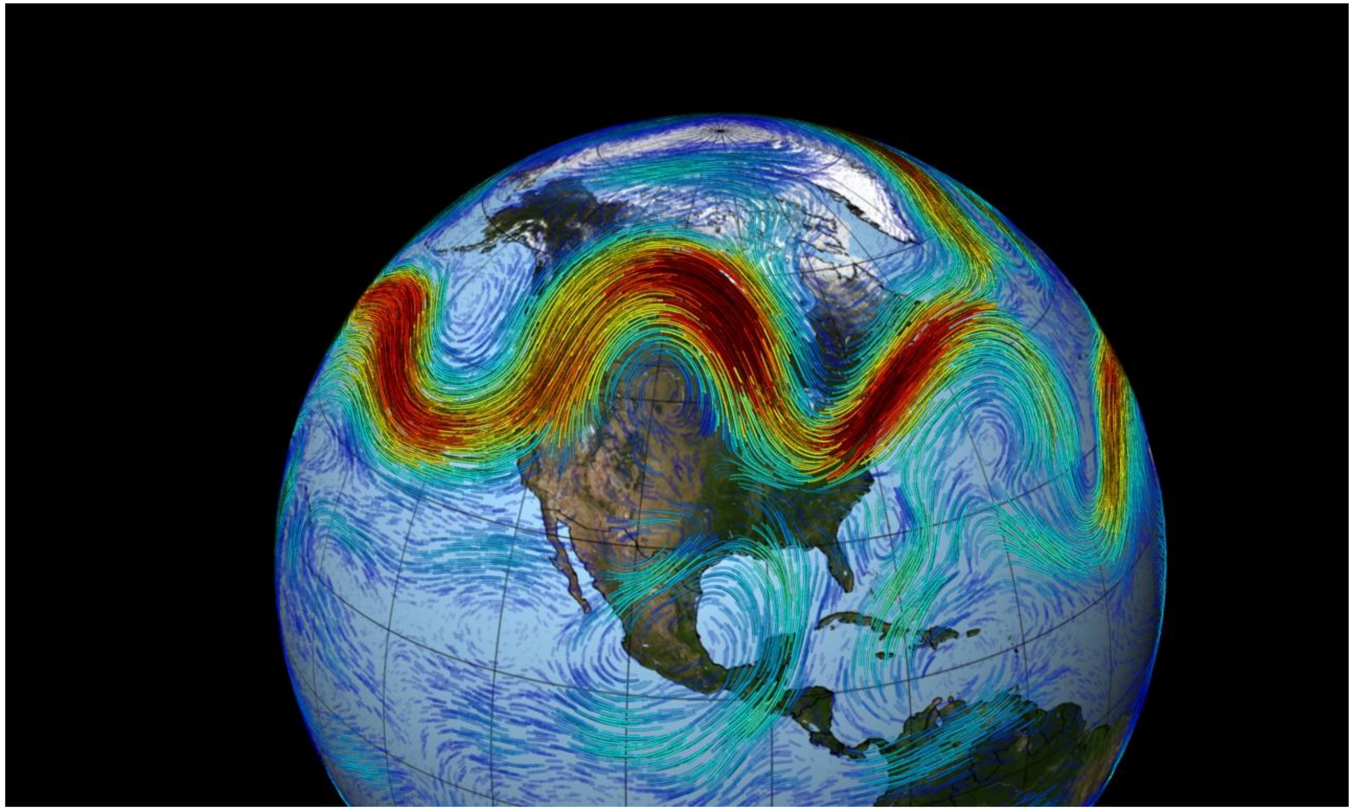
OSHER
LIFELONG
LEARNING
INSTITUTE

Demystifying Climate Change

SECOND ATTEMPT

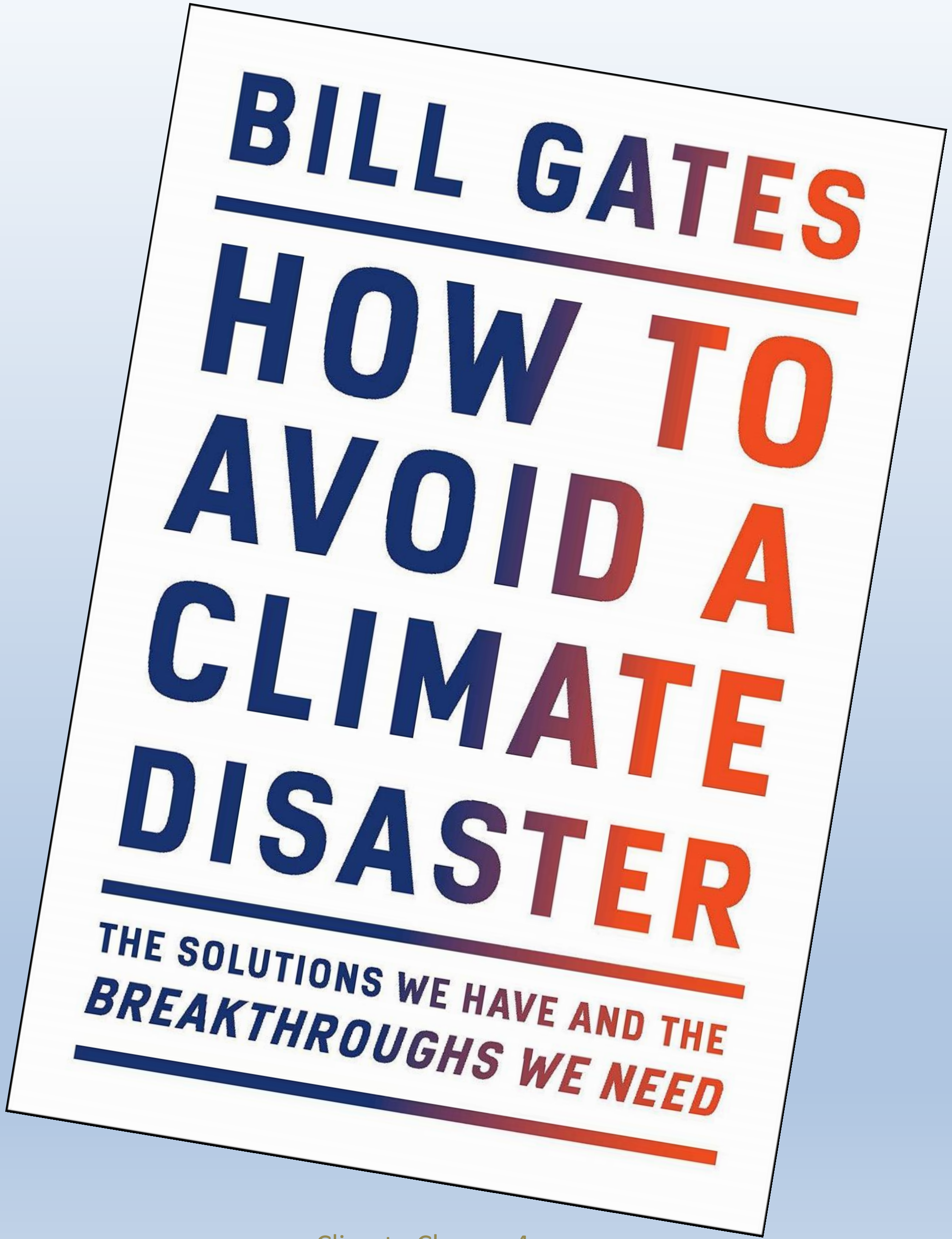
Session 4
Global Circulation and Dynamics of Earth Systems



OLLI at Illinois
Spring 2021

D. H. Tracy
DavidHTracy@gmail.com

Out last week…



Course Outline

1. Building Blocks: Some important concepts
2. Our Goldilocks Earth: a Radiative Balancing Act
3. The Role of the Atmosphere: Greenhouse Gases & Clouds
4. **Global Circulation and Dynamics of the Earth System:**
   Oceans, Atmosphere, Biosphere, Cryosphere, People, Lithosphere
5. Natural Variability of the Climate, short and long term. Ice Ages
6. Carbon Dioxide and other Greenhouse Gases: where do they come from, where do they go, how are they regulated?
7. Impacts and Future Projections for Global Warming -- Uncertainties
8. Amelioration Strategies. The Climate debate. Policy options.

Today’s Plan

- The Radiative Forcing Concept
- The Climate Feedback Concept

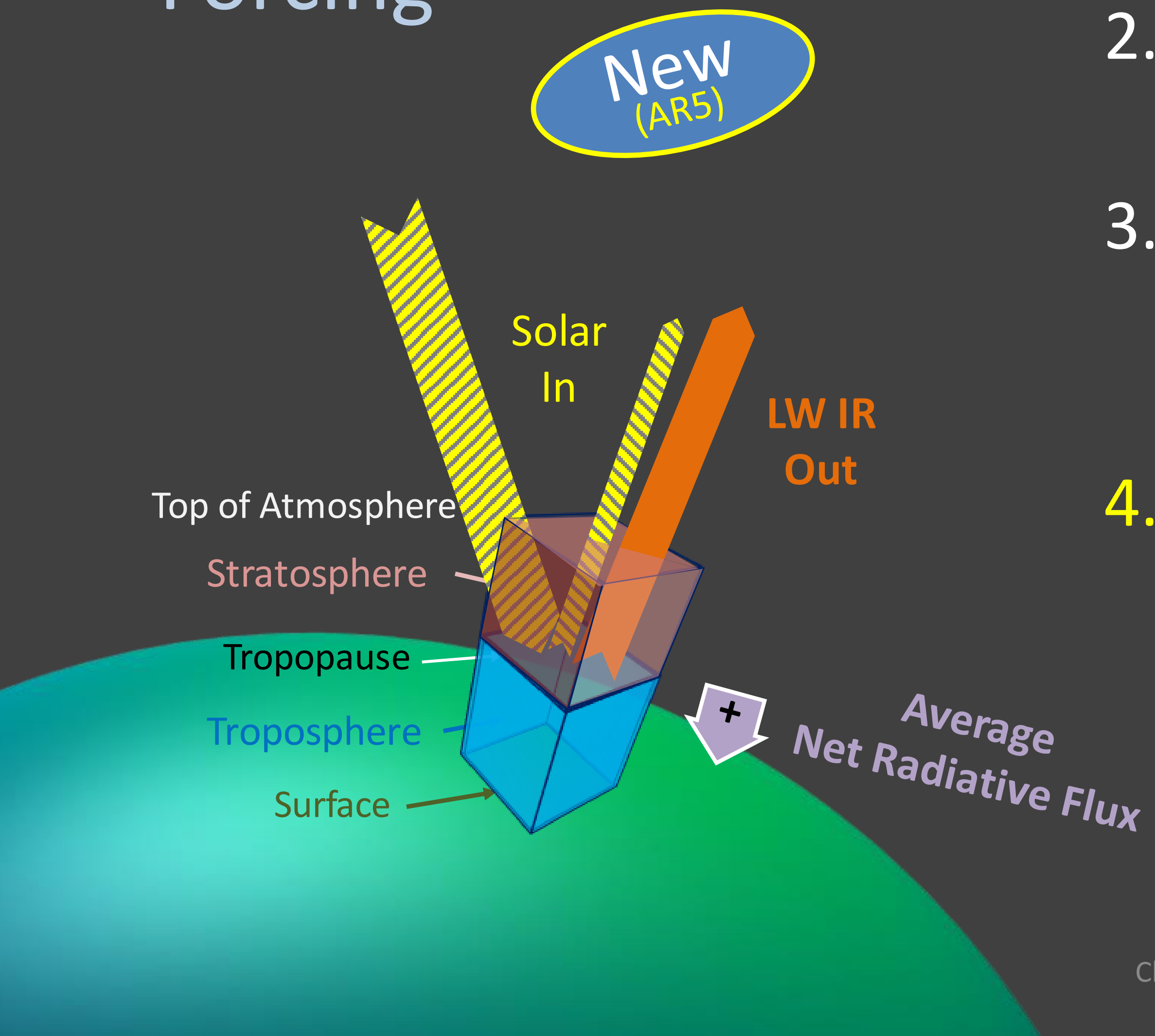
Briefly

- Global Systems
  - Atmosphere
  - Oceans
  - Cryosphere
  - Biosphere
  - Lithosphere
  - Human Inputs

Defining Radiative Forcing

Effective Radiative Forcing (ERF): the rules

1. Change is relative to **1750** CE (pre-industrial)
2. Change in Net Radiative Flux at the Tropopause
3. Stratosphere, Troposphere, Land Temperature, Vegetation and Snow Cover *are* allowed to adjust, *but*
4. Sea Temperature and Sea Ice, Ice Caps are held fixed.



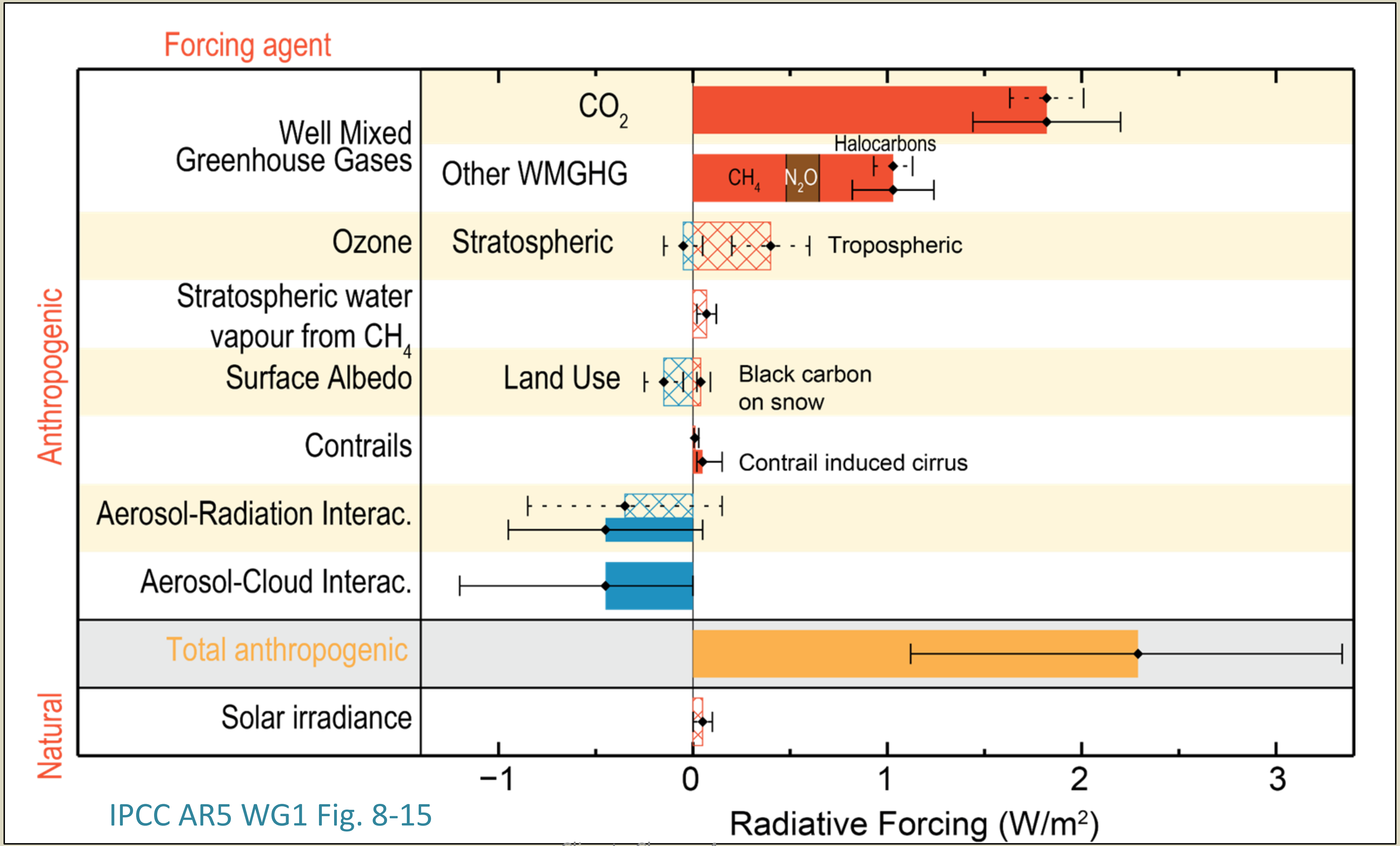
Radiative Forcing of Climate Between 1750 and 2011

Effective **R**adiative **F**orcing

Solid: ERF

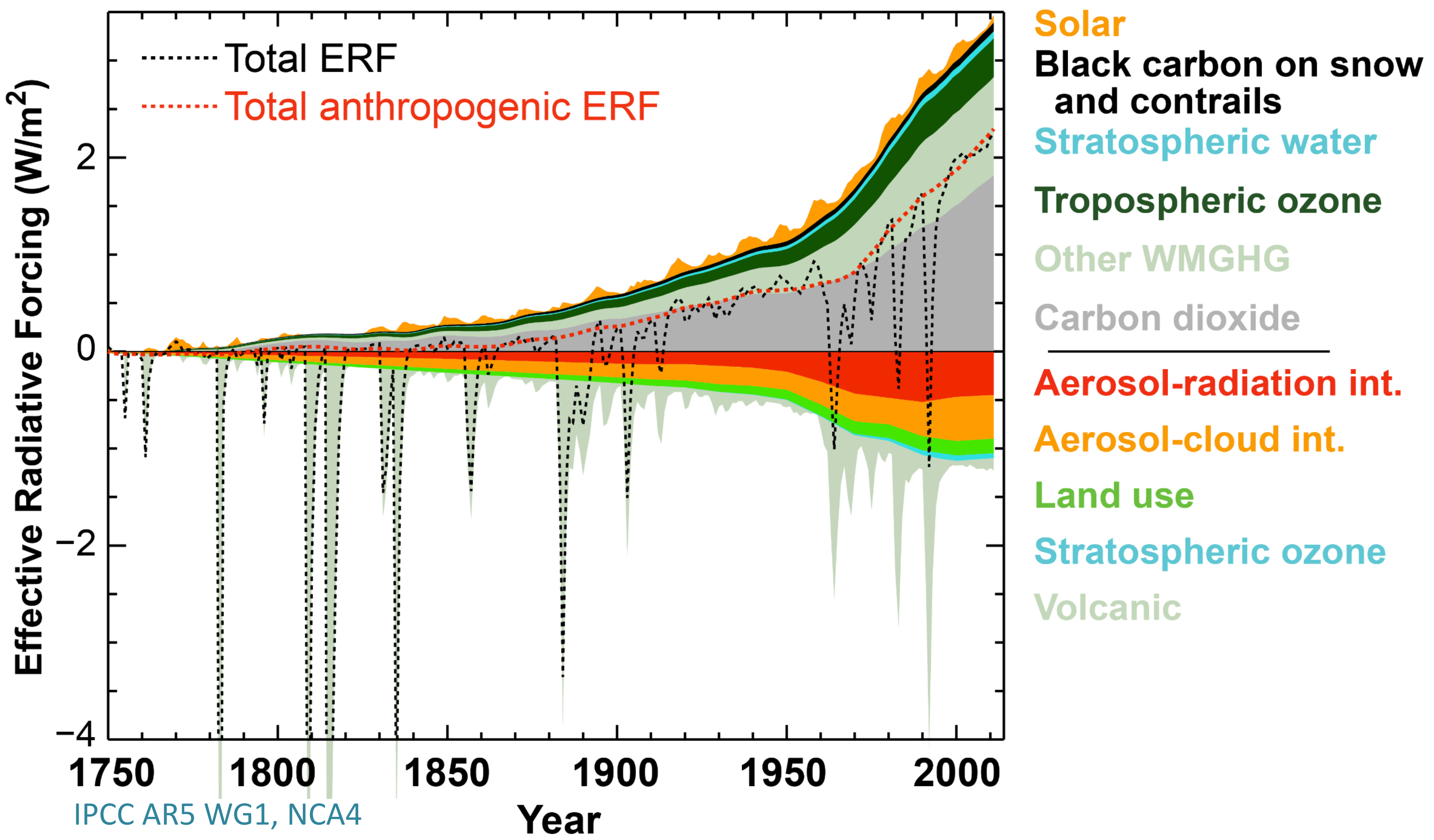
Ordinary **R**adiative **F**orcing

Hatched: RF



IPCC AR5 WG1 Fig. 8-15

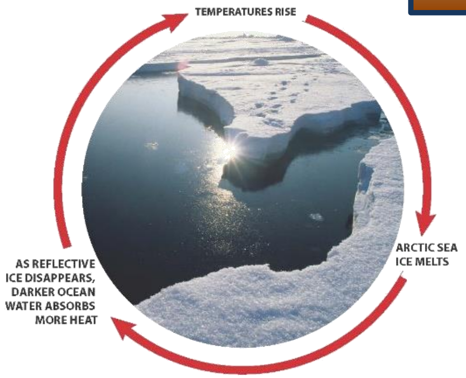
Time Evolution of Forcings



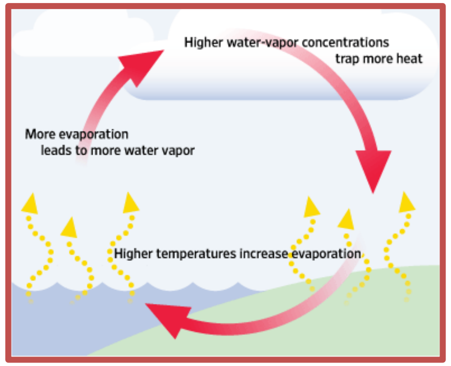
IPCC AR5 WG1, NCA4

Climate Feedbacks

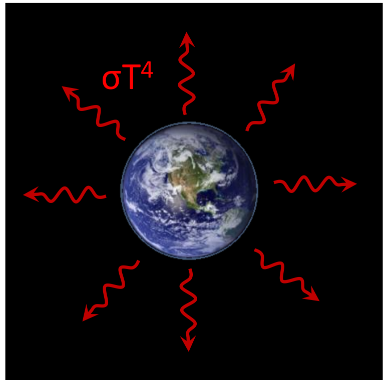
- *Internal* Response to an External Forcing
  - Can be Positive + or Negative –
- Example: Your home Thermostat
  - Negative feedback: <u>Opposes</u> the external driver



- Climate Positive Feedback Examples:
  - Ice Albedo Feedback Loop
  - **Water Vapor** Feedback **Big Effect >2x Impact**



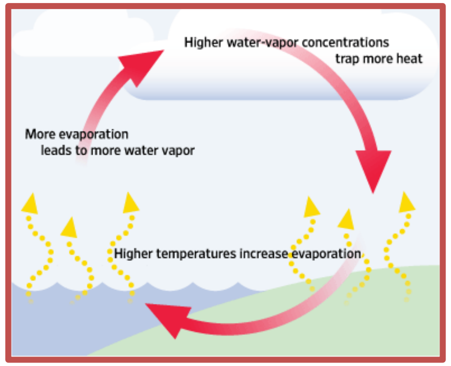
- Climate *Negative* Feedback Example:
  - **Blackbody Radiation**



Climate Feedbacks

- *Internal* Response to an External Forcing
  - Can be Positive + or Negative –
- Example: Your home Thermostat
  - Negative feedback: Opposes the external driver
- Climate Positive Feedb
  - Ice A
  - **Water vapor** Feedback **Big Effect >2x Impact**

…and there are many more Climate Feedbacks



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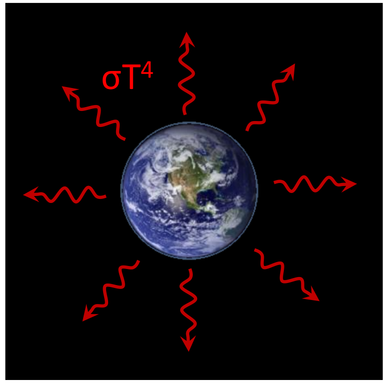
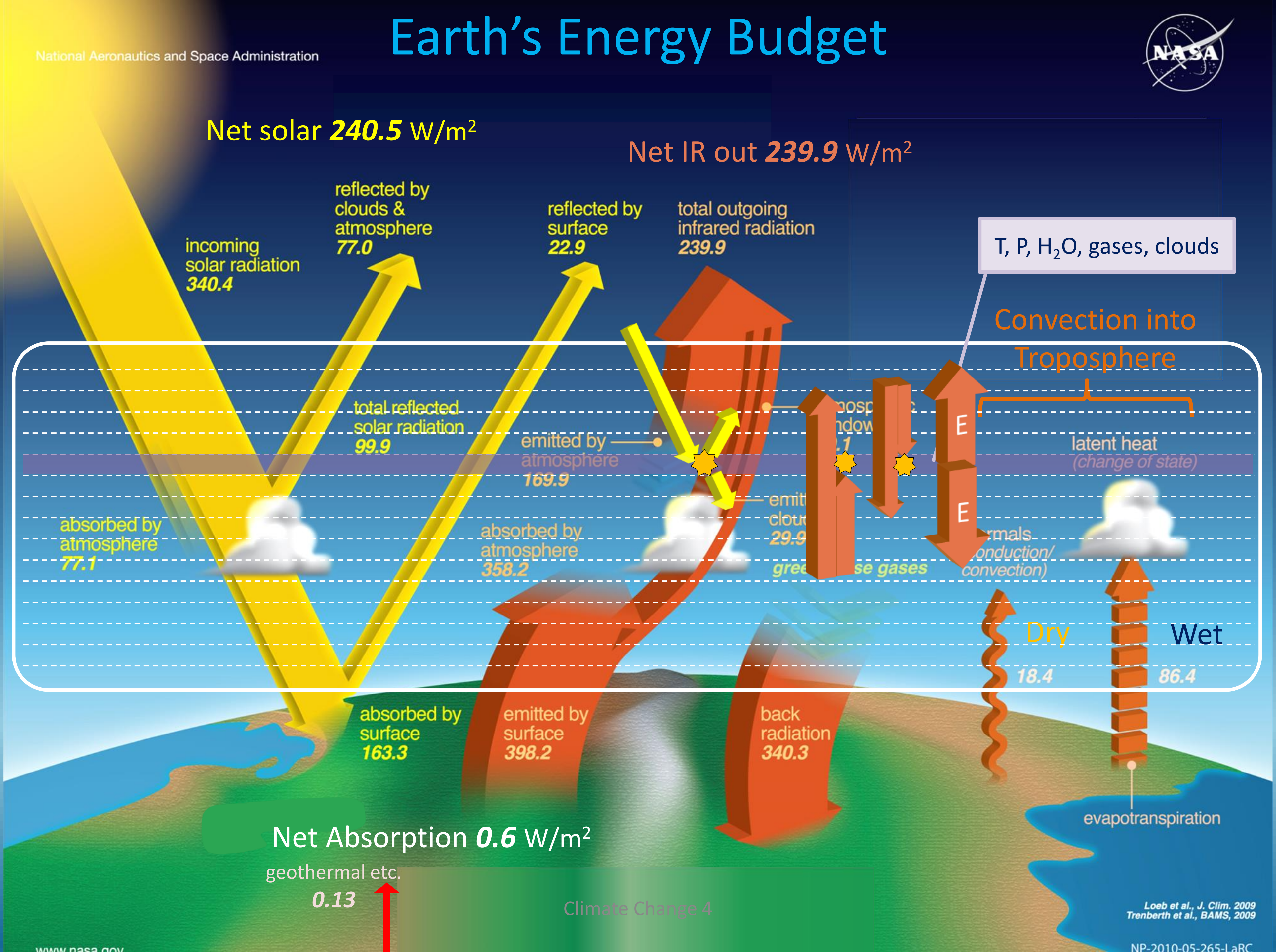
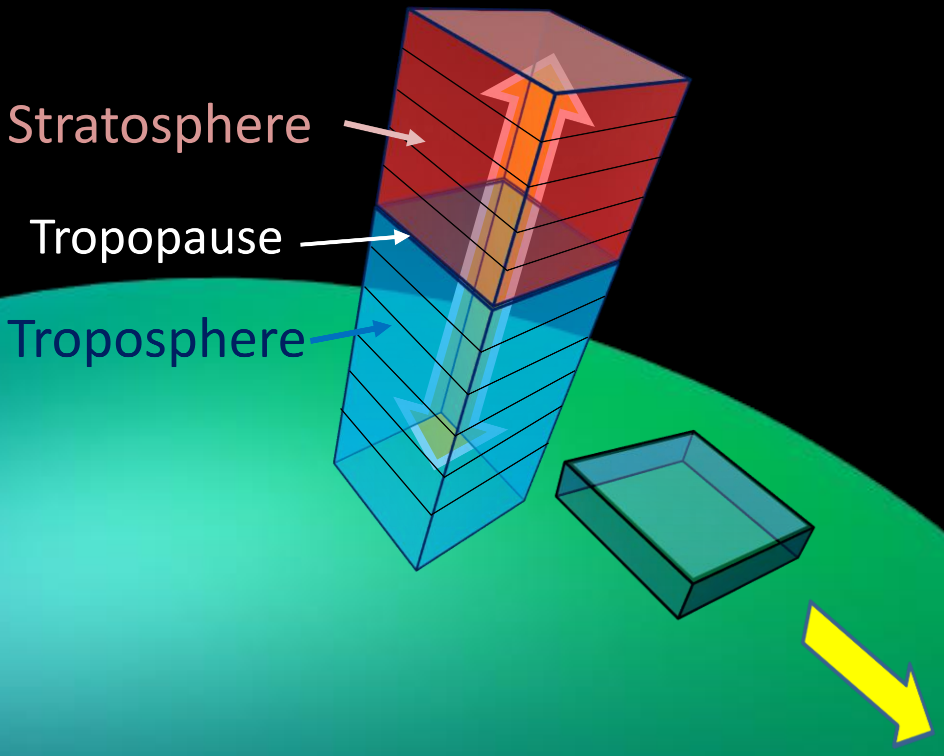


Earth's Energy Budget



Problem 1: Wind

Air layer parcels move laterally carrying heat, clouds, gases etc.



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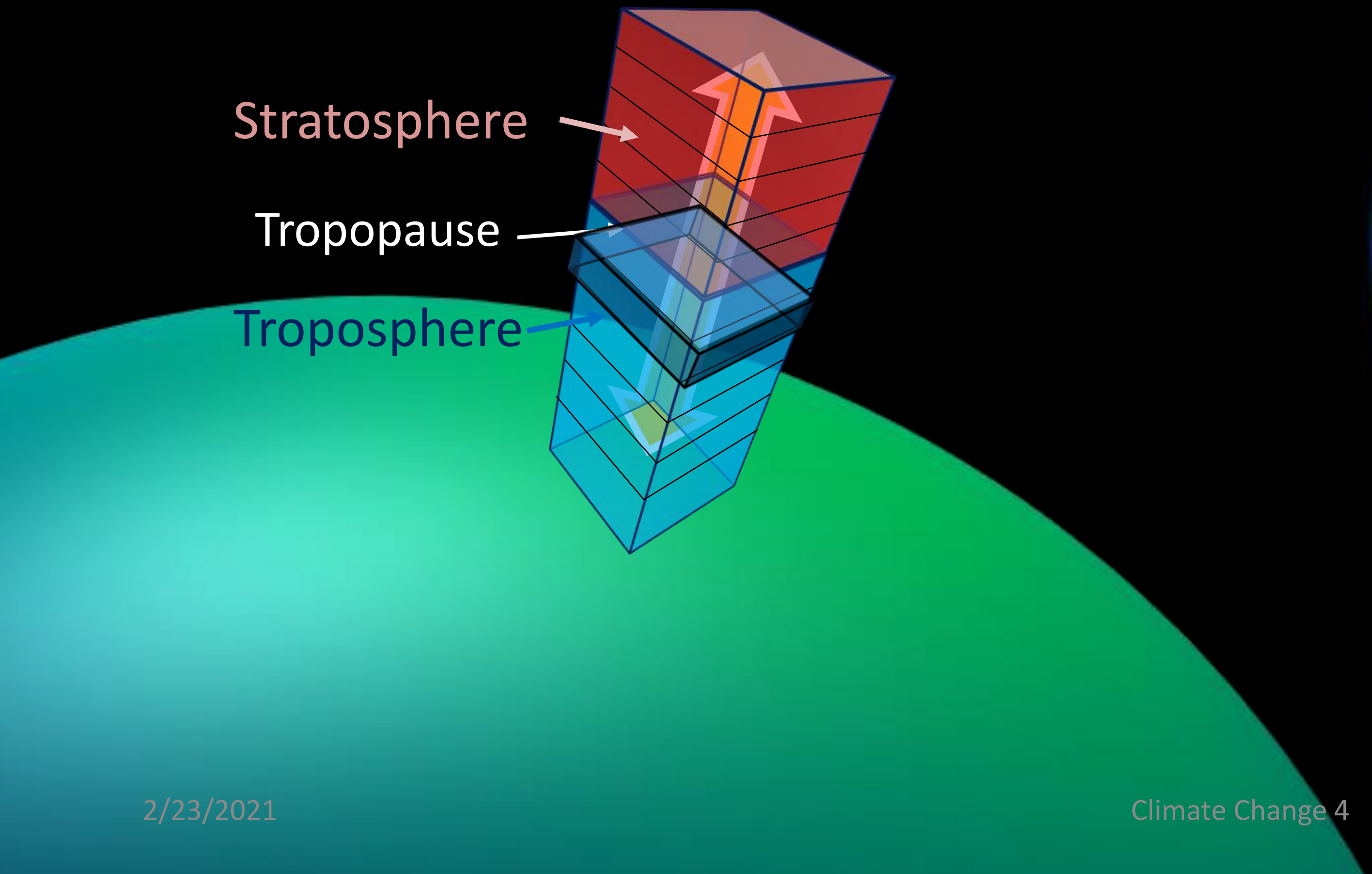
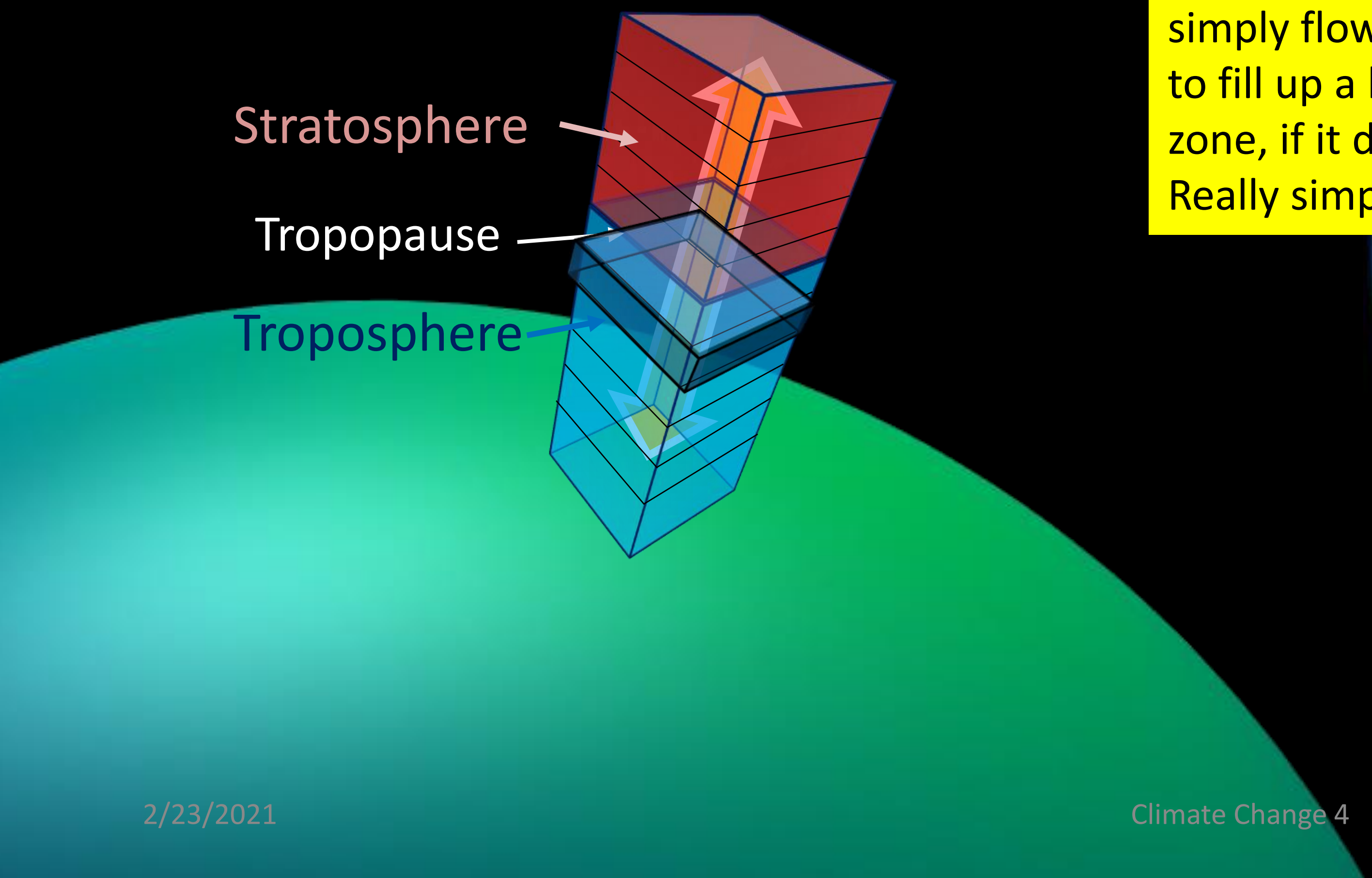


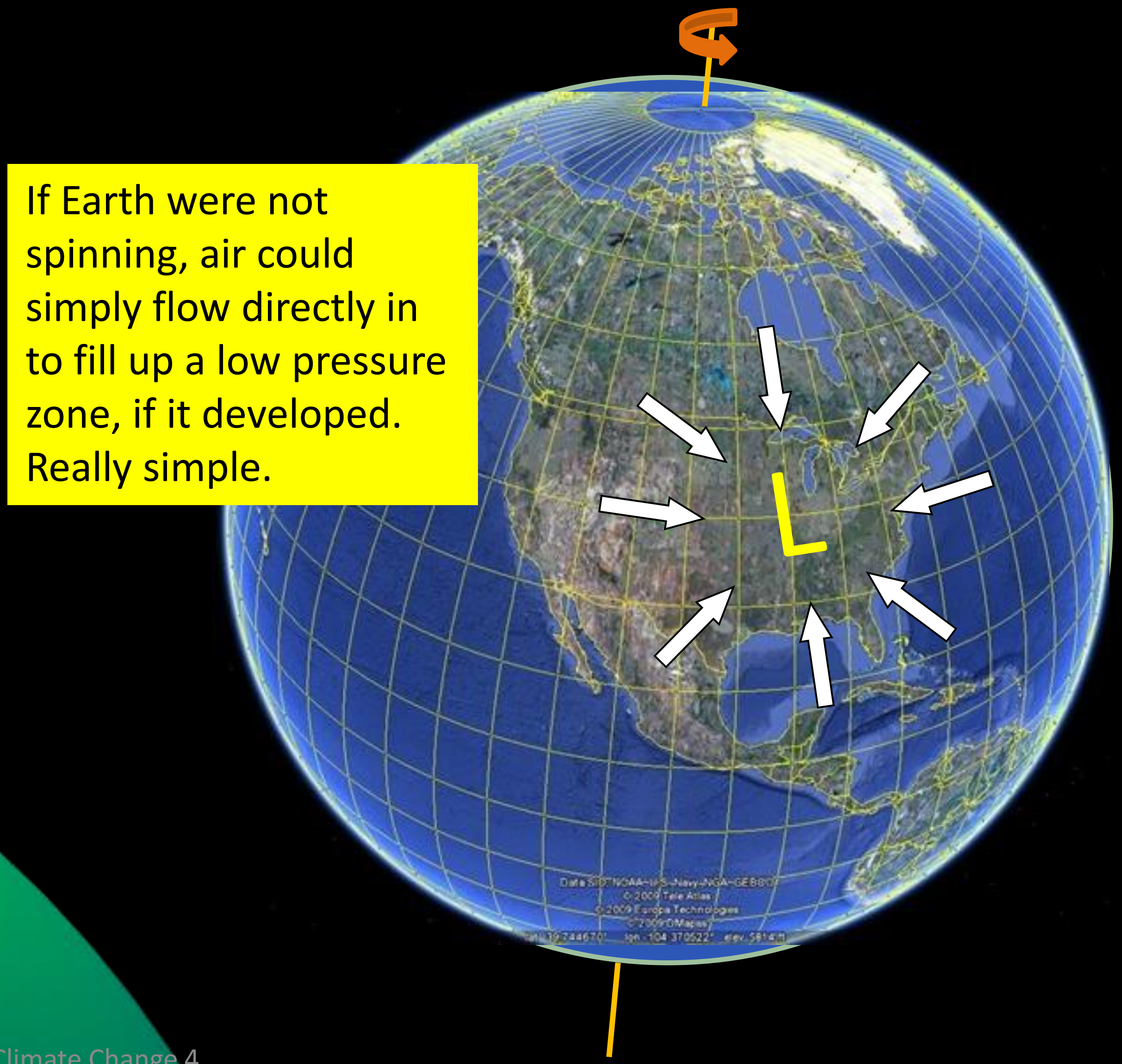
Problem 2: Spin

Problem 1: Wind

Air layer parcels move laterally carrying heat, clouds, etc.



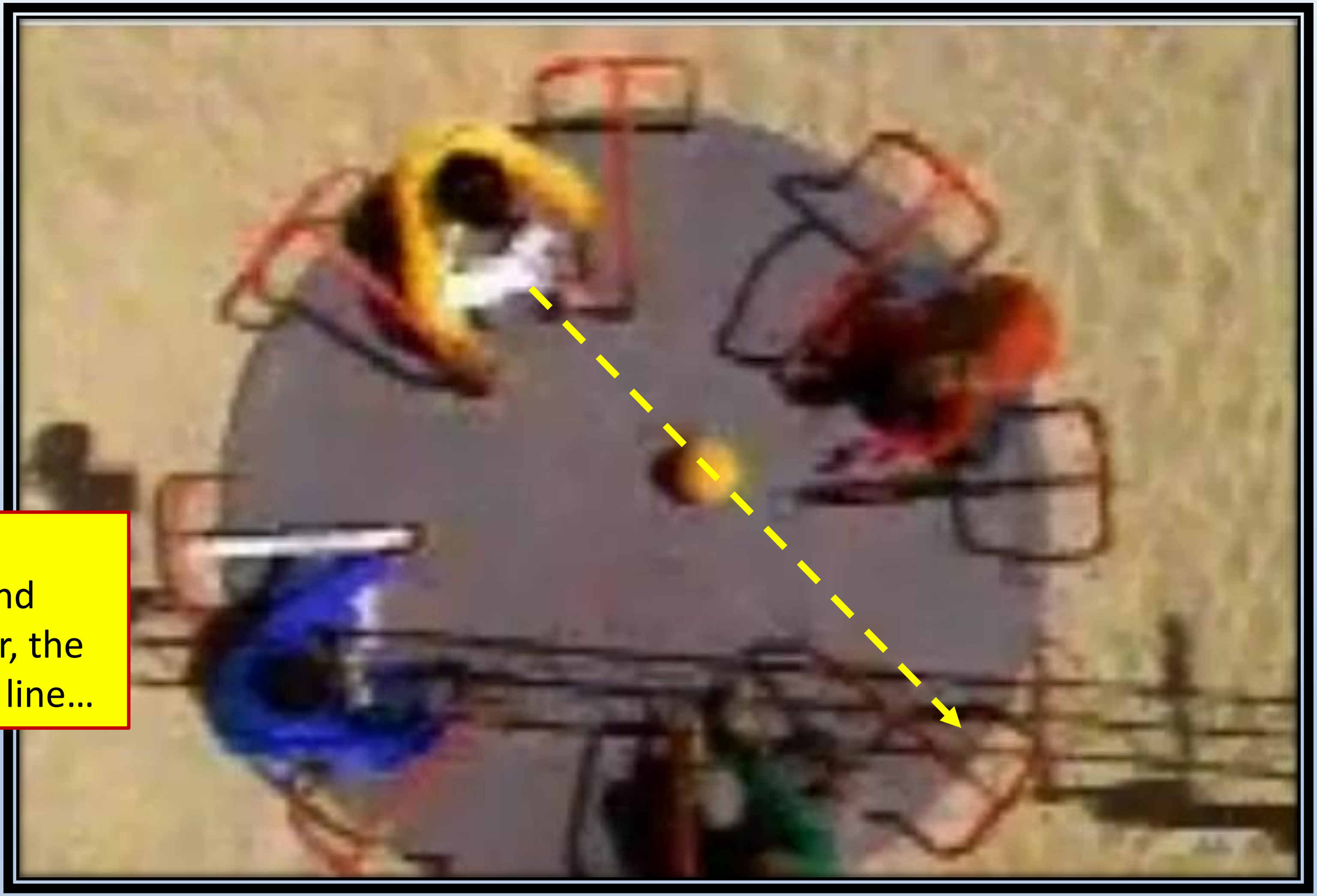
Problem 2: Spin



Apparent Motion in a Rotating Frame

Life on a
Merry-Go-Round:
The Coriolis
“Force”

When one person on a rotating Merry-Go-Round throws a ball to another, the ball travels in a straight line…



SchoolTube
mamoloscience August 27, 2019

Apparent Motion in a Rotating Frame

Life on a Merry-Go-Round: The Coriolis “Force”

But to people on the rotating frame it *appears* to follow a curved path…
This is an illusion, but a powerful one.
To make sense of the apparent turn, we can invoke a fictious force, the “Coriolis” force.

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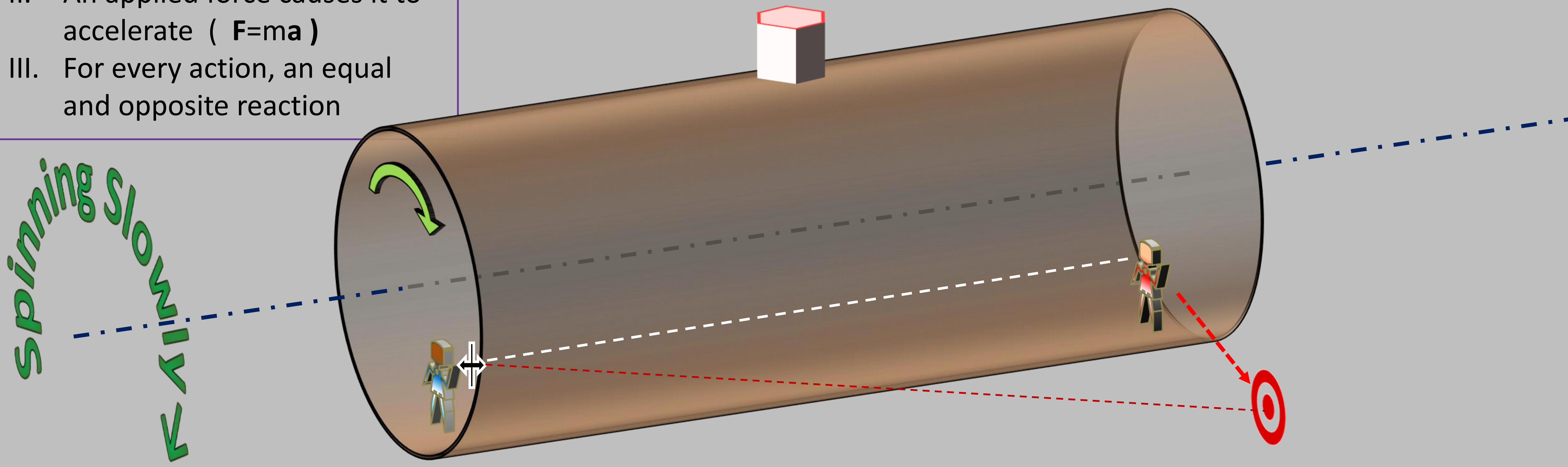
Newton's Laws of Motion:

I. A body in motion stays in motion in a straight line *unless*
II. An applied force causes it to accelerate (**F**=m**a**)
III. For every action, an equal and opposite reaction

Aboard Mars I



Aboard the rotating cylinder "Mars I" an astronaut throws a wrench to another astronaut, aiming to the right to compensate his motion at the moment.

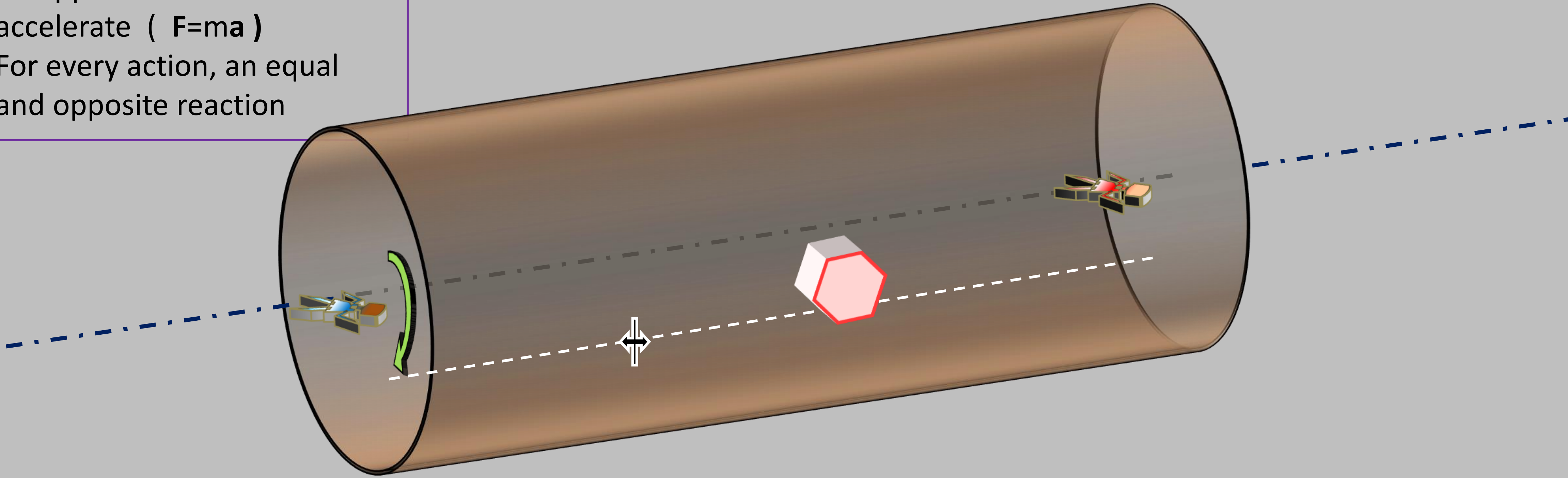
The wrench will follow a straight line path directly toward where is 2nd Astronaut will be when it arrives. No problem.

Newton's Laws of Motion:

I. A body in motion stays in motion in a straight line *unless*

II. An applied force causes it to accelerate (**F**=m**a**)

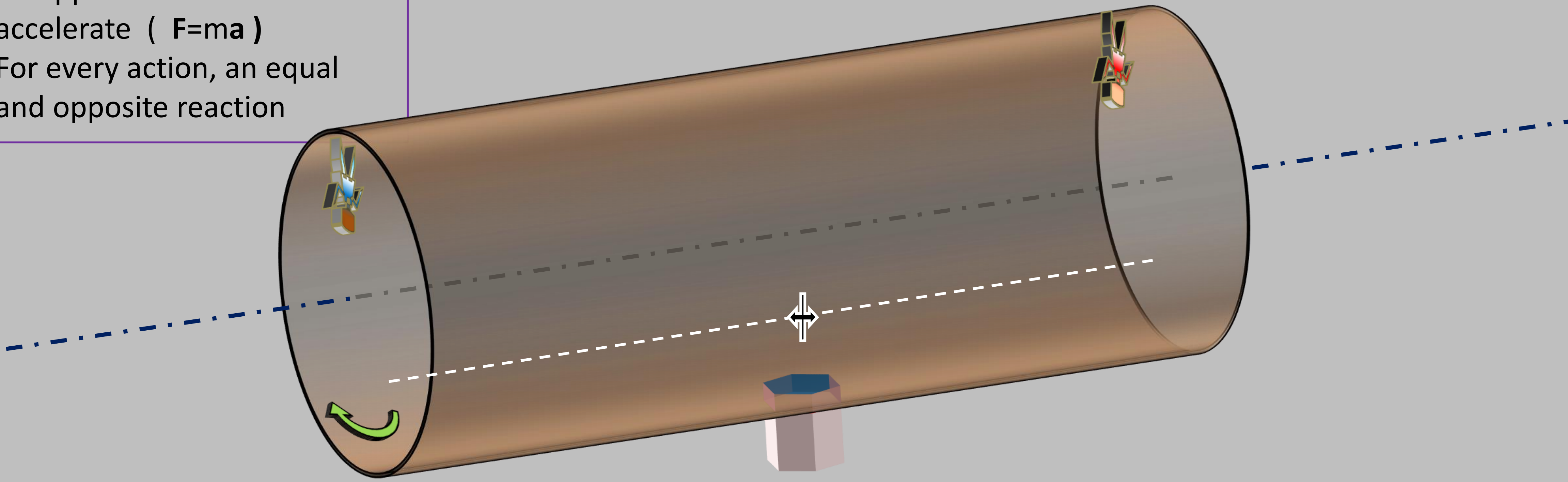
III. For every action, an equal and opposite reaction



When the ship has rotated 90º, the wrench is (let's say) 1/4 of the way to the end. No sweat.

Newton's Laws of Motion:

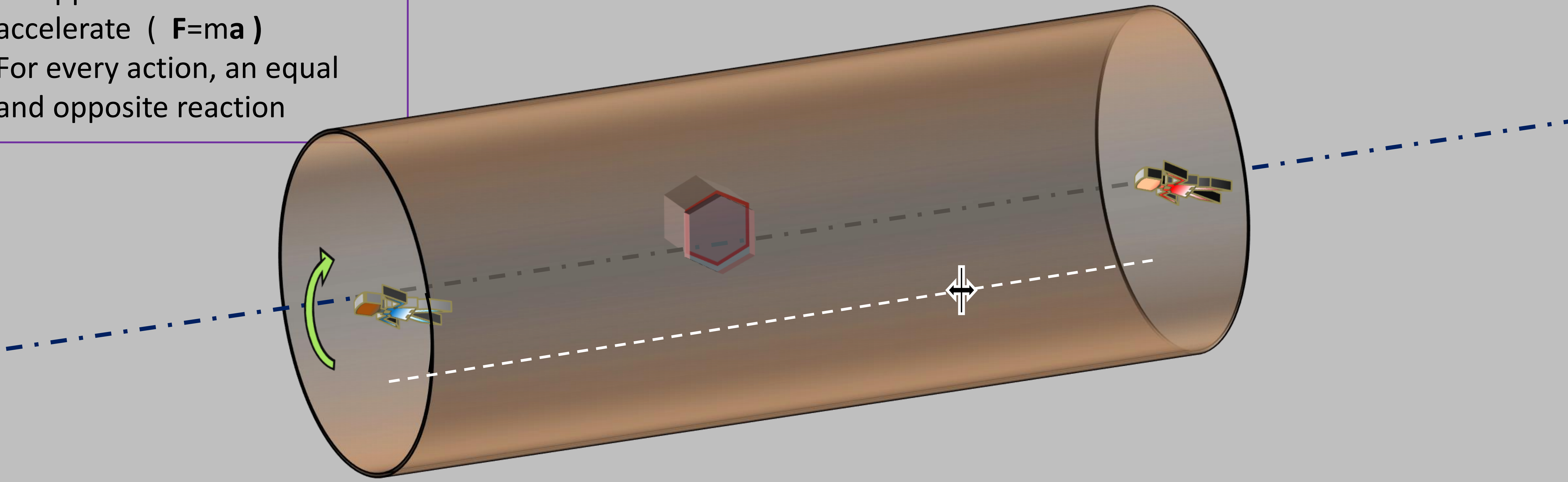
I. A body in motion stays in motion in a straight line *unless*
II. An applied force causes it to accelerate (**F**=m**a**)
III. For every action, an equal and opposite reaction



When the ship has rotated 180^{o}, the wrench is 1/2 of the way to the end. …

Newton's Laws of Motion:

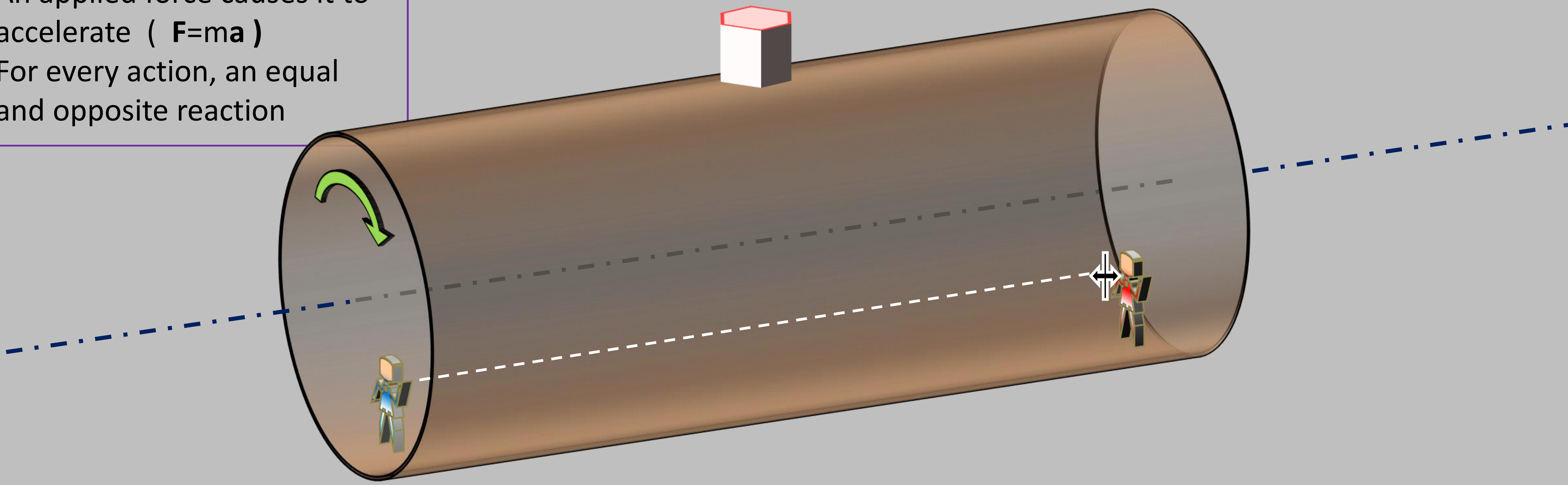
I. A body in motion stays in motion in a straight line *unless*
II. An applied force causes it to accelerate (**F**=m**a**)
III. For every action, an equal and opposite reaction



When the ship has rotated 270º, the wrench is 3/4 of the way to the end....

Newton's Laws of Motion:

I. A body in motion stays in motion in a straight line *unless*
II. An applied force causes it to accelerate (**F**=m**a**)
III. For every action, an equal and opposite reaction



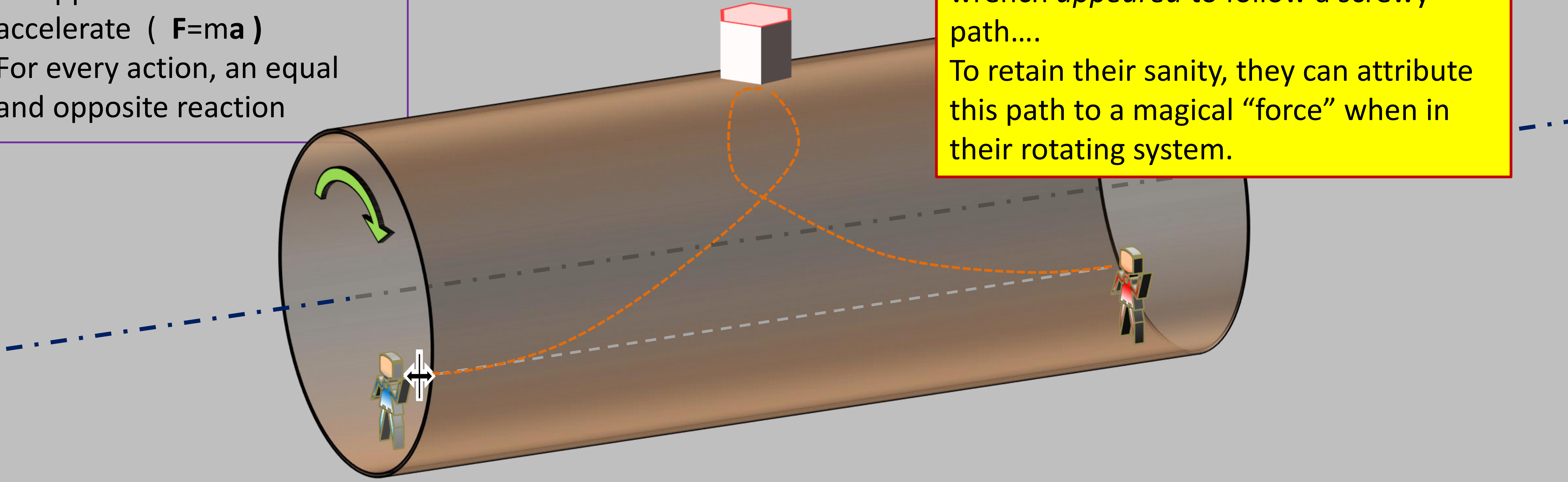
And finally, when the ship has rotated 360°, the wrench is all of the way to the end, and the 2nd astronaut is back to her original location. Perfectly simple….

Newton's Laws of Motion:

I. A body in motion stays in motion in a straight line *unless*
II. An applied force causes it to accelerate (**F**=m**a**)
III. For every action, an equal and opposite reaction

But as the Astronauts see it….

But to the Astronauts themselves, the wrench *appeared* to follow a screwy path….
To retain their sanity, they can attribute this path to a magical "force" when in their rotating system.

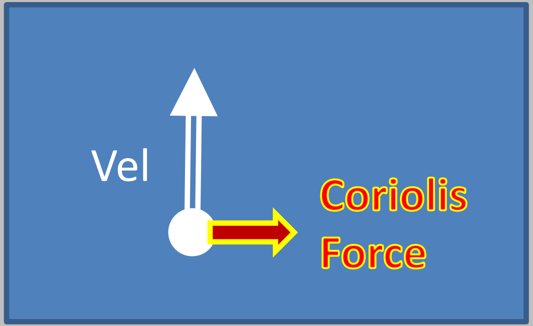


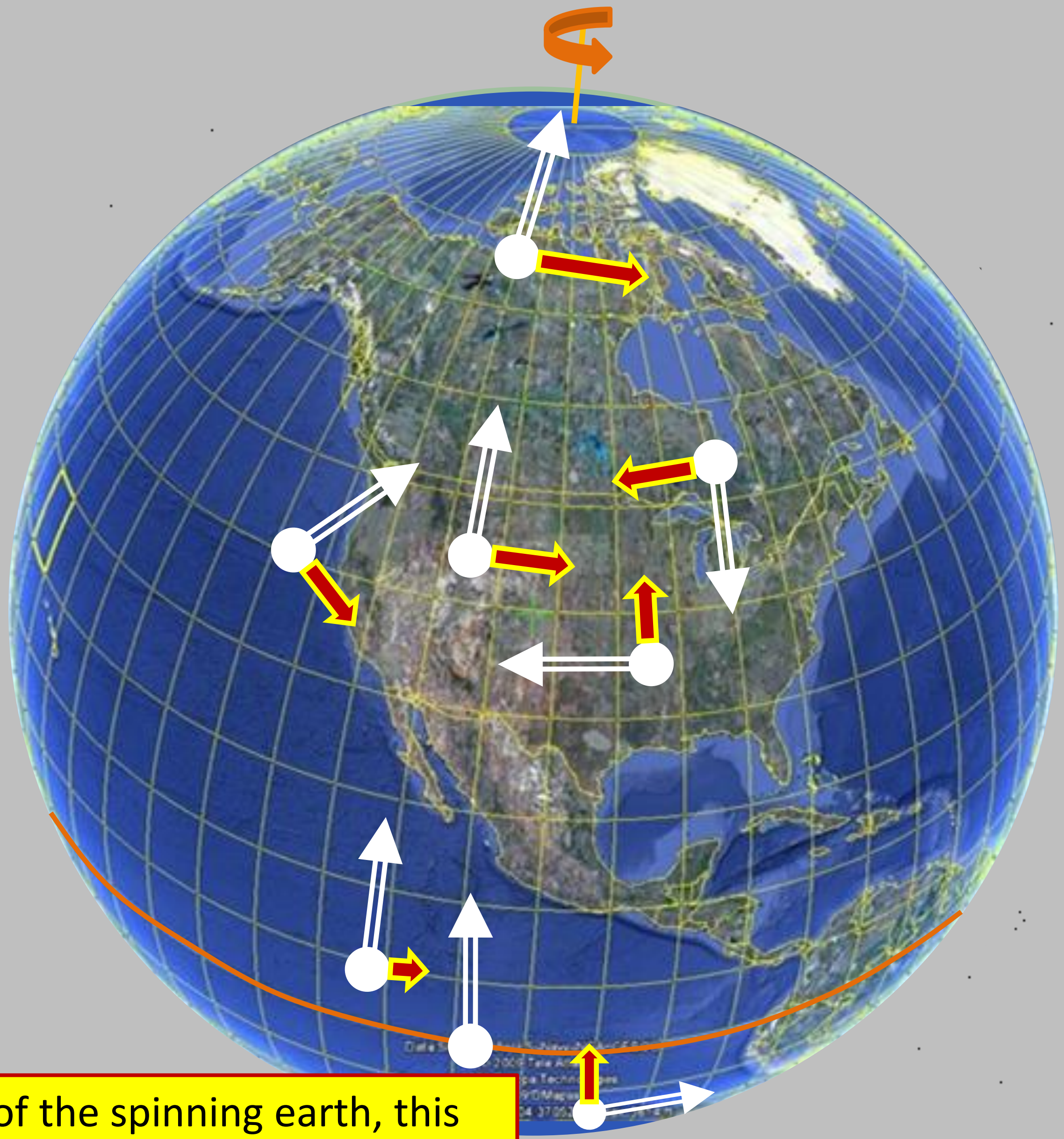
To use Newton's Laws in a spinning system, we need to invoke two fictional forces:

1. Centrifugal Force
2. **Coriolis Force**

Coriolis Force on Earth

- Proportional to Velocity
  - Only for *moving* objects
- Acts Perpendicular to Velocity
- Pushes to the <u>Right</u> in Northern Hemisphere
  - Left in Southern Hemisphere
- Vanishes on Equator



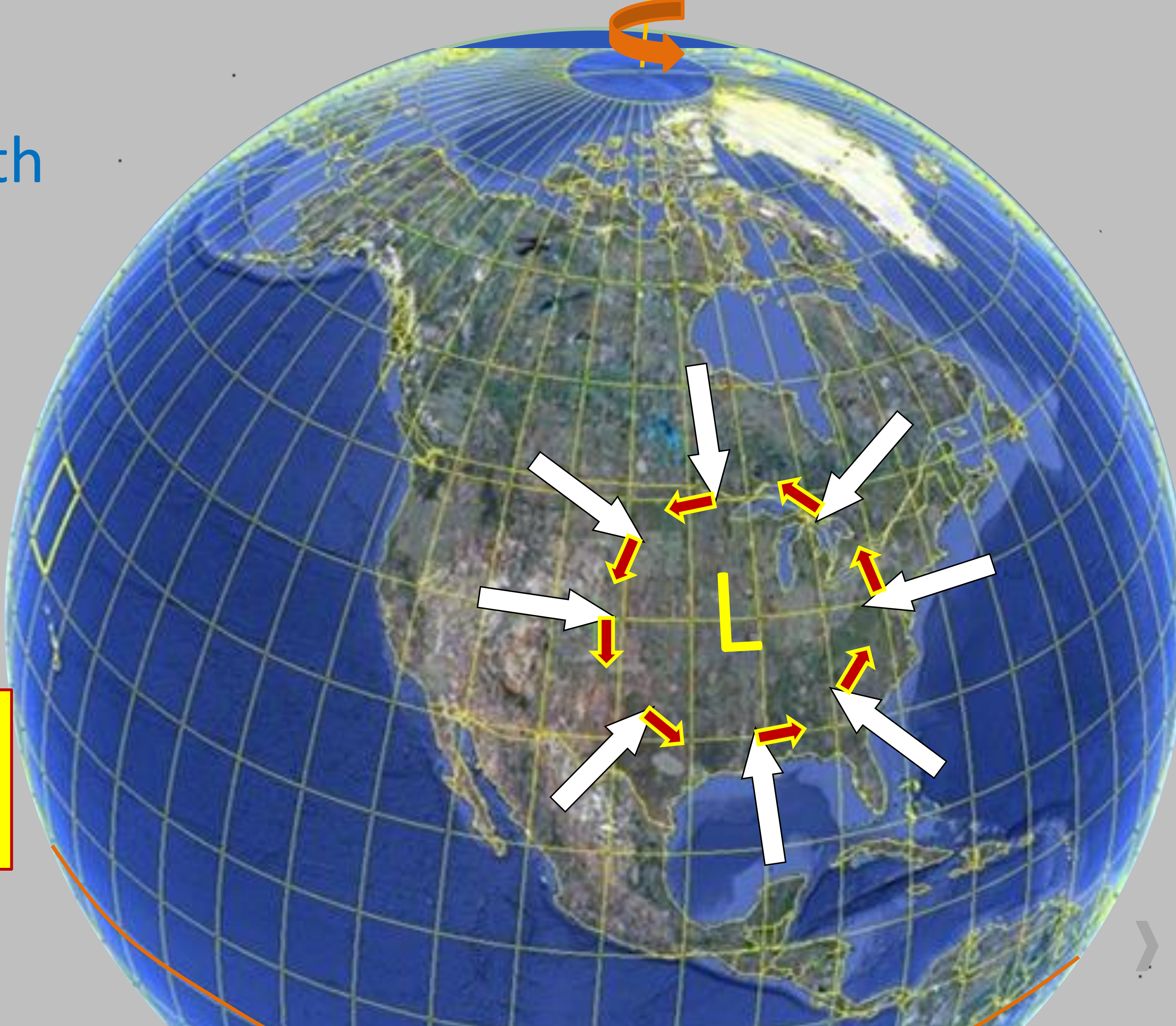


On the surface of the spinning earth, this Coriolis force plays out as a sideways force that appears, following certain rules…..

Consequences of Coriolis Force on Earth

- Low Pressure Develops
- Air masses start moving in, velocity increases
- Coriolis force pushes them to right

This applies to winds (moving air) rushing in to fill the void of a Low Pressure zone. In the Northern Hemisphere, they get pushed to the right…..



Consequences of Coriolis Force on Earth

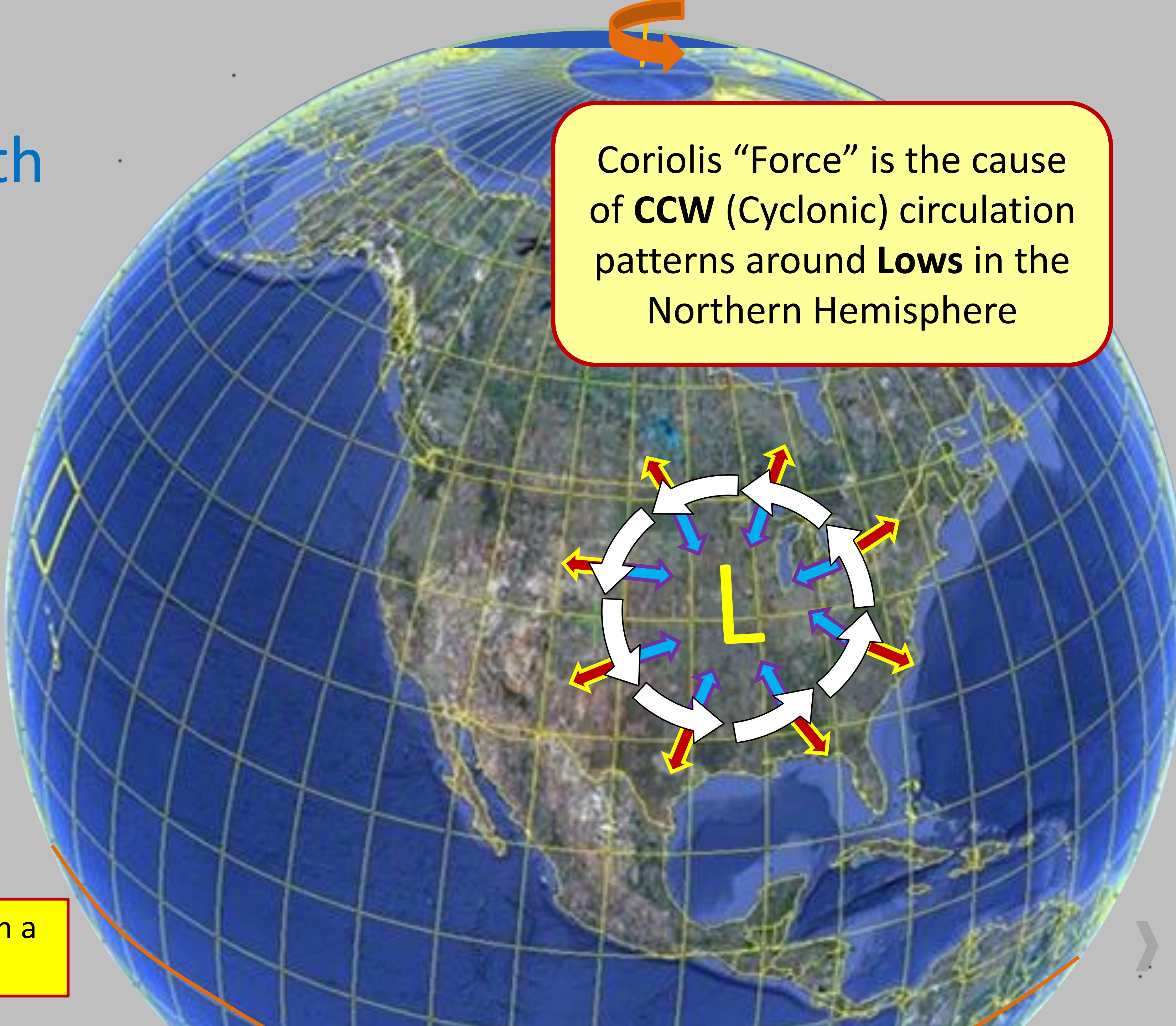
- Low Pressure Develops
- Air masses start moving in, velocity increases
- Coriolis force pushes them to right
- CCW Circulation develops around Low

.... deflecting them away from the Low....

Consequences of Coriolis Force on Earth

- Low Pressure Develops
- Air masses start moving in, velocity increases
- Coriolis force pushes them to right
- CCW Circulation develops around Low
- Eventually Coriolis force matches the pressure induced force

.... and finally forcing the wind to flow in a circle CCW around the Low.



Consequences of Coriolis Force on Earth

- Low Pressure Develops
- Air masses start moving in, velocity increases
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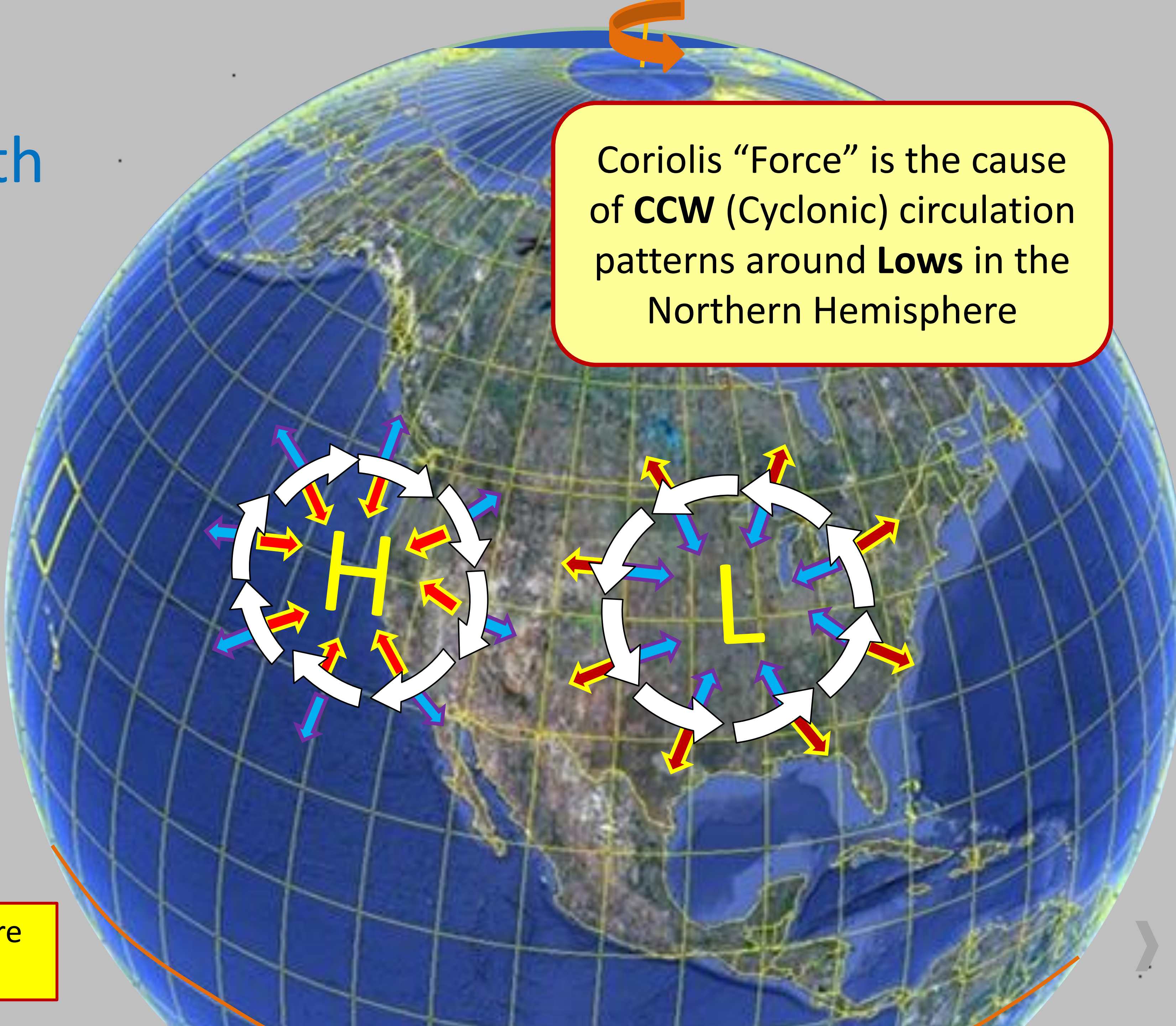
- CCW Circulation develops around Low
- Eventually Coriolis force matches the pressure induced force

The opposite happens for a High Pressure zone.



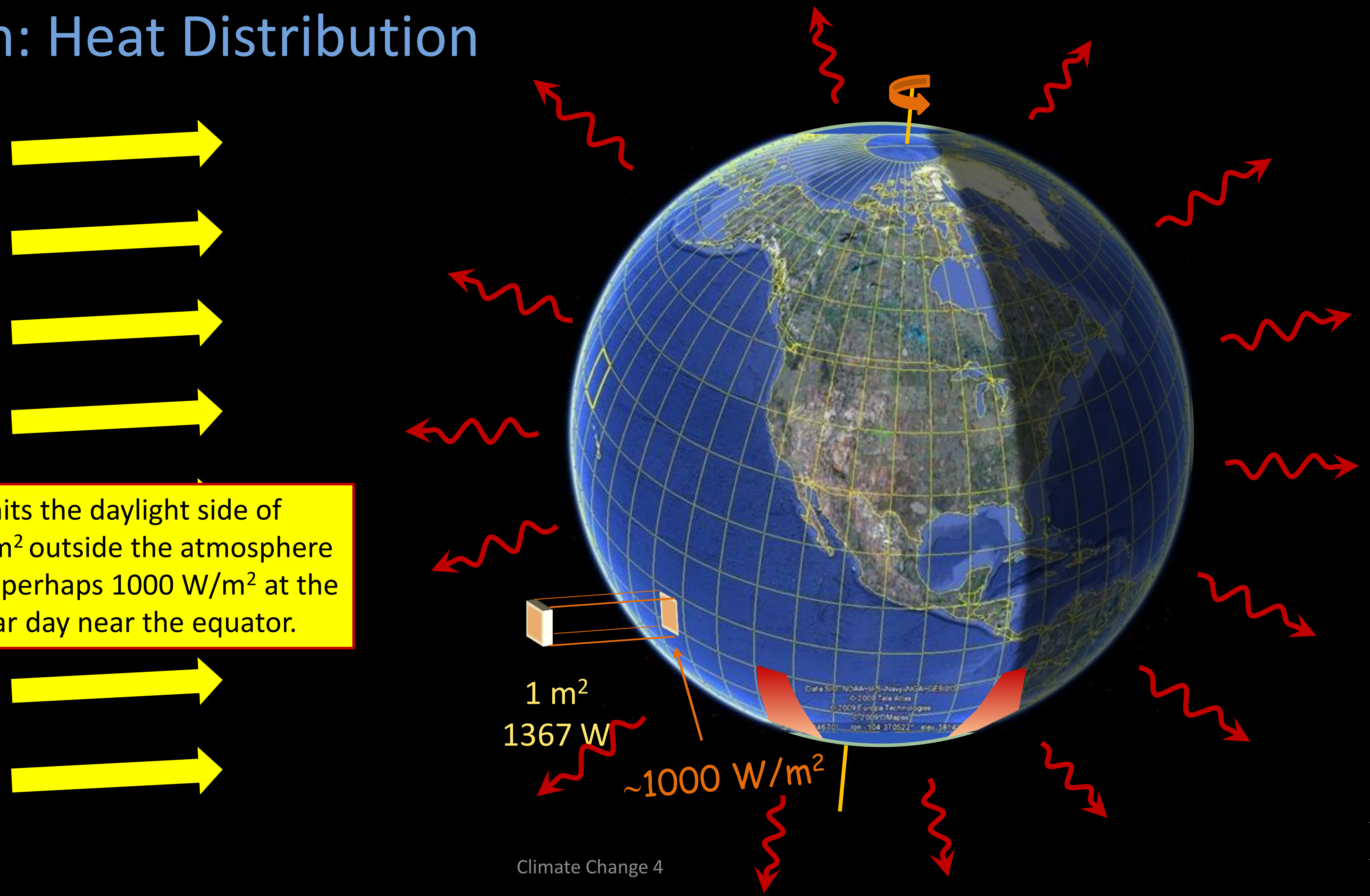
Coriolis “Force” is the cause of **CCW** (Cyclonic) circulation patterns around **Lows** in the Northern Hemisphere

Nothing happens at the Equator, and in the Southern Hemisphere rotations are reversed…..

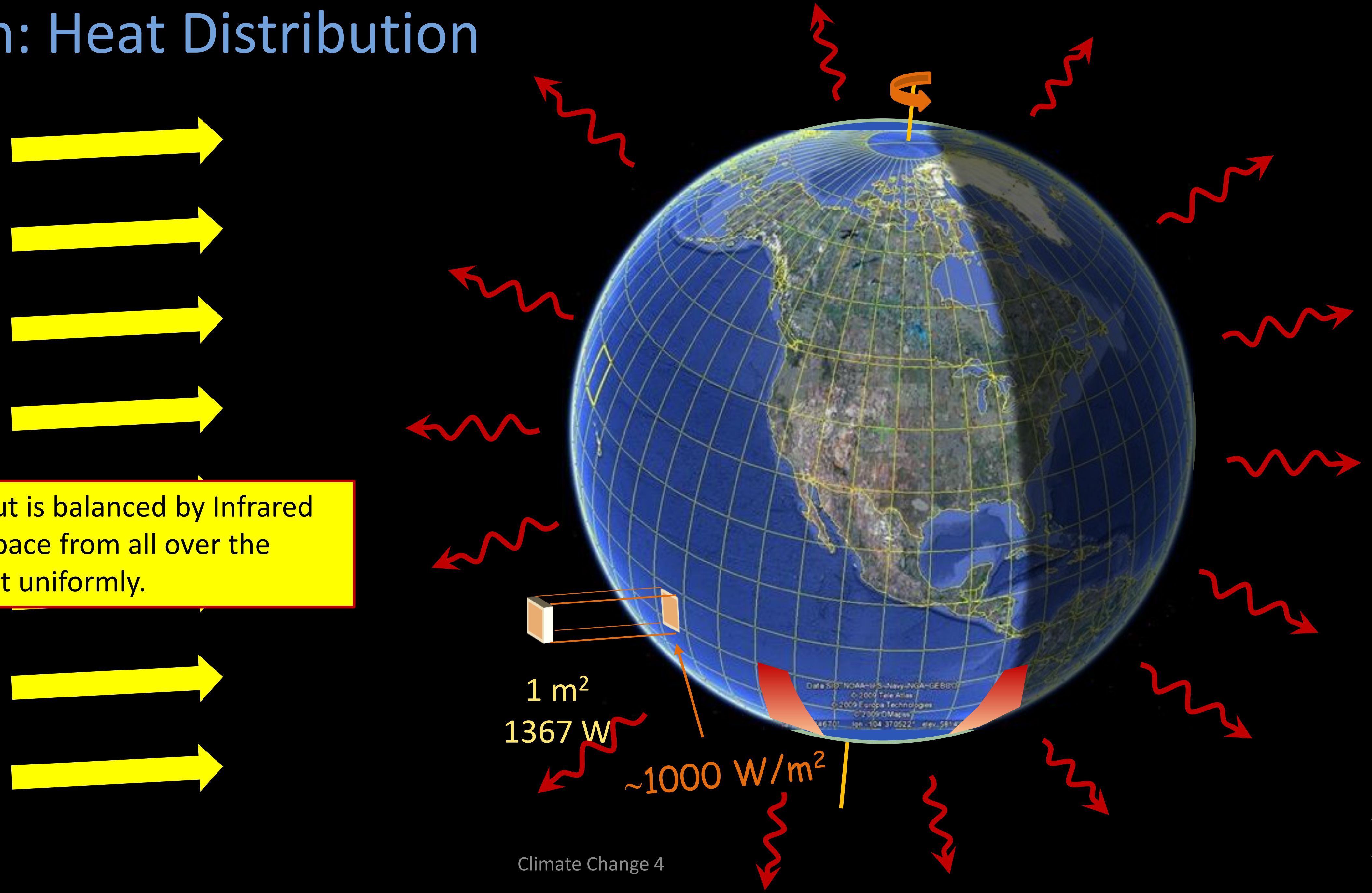
Add Atmosphere

Problem: Heat Distribution

Solar radiation hits the daylight side of earth, 1367 W/m^2 outside the atmosphere and reducing to perhaps 1000 W/m^2 at the surface on a clear day near the equator.



Problem: Heat Distribution



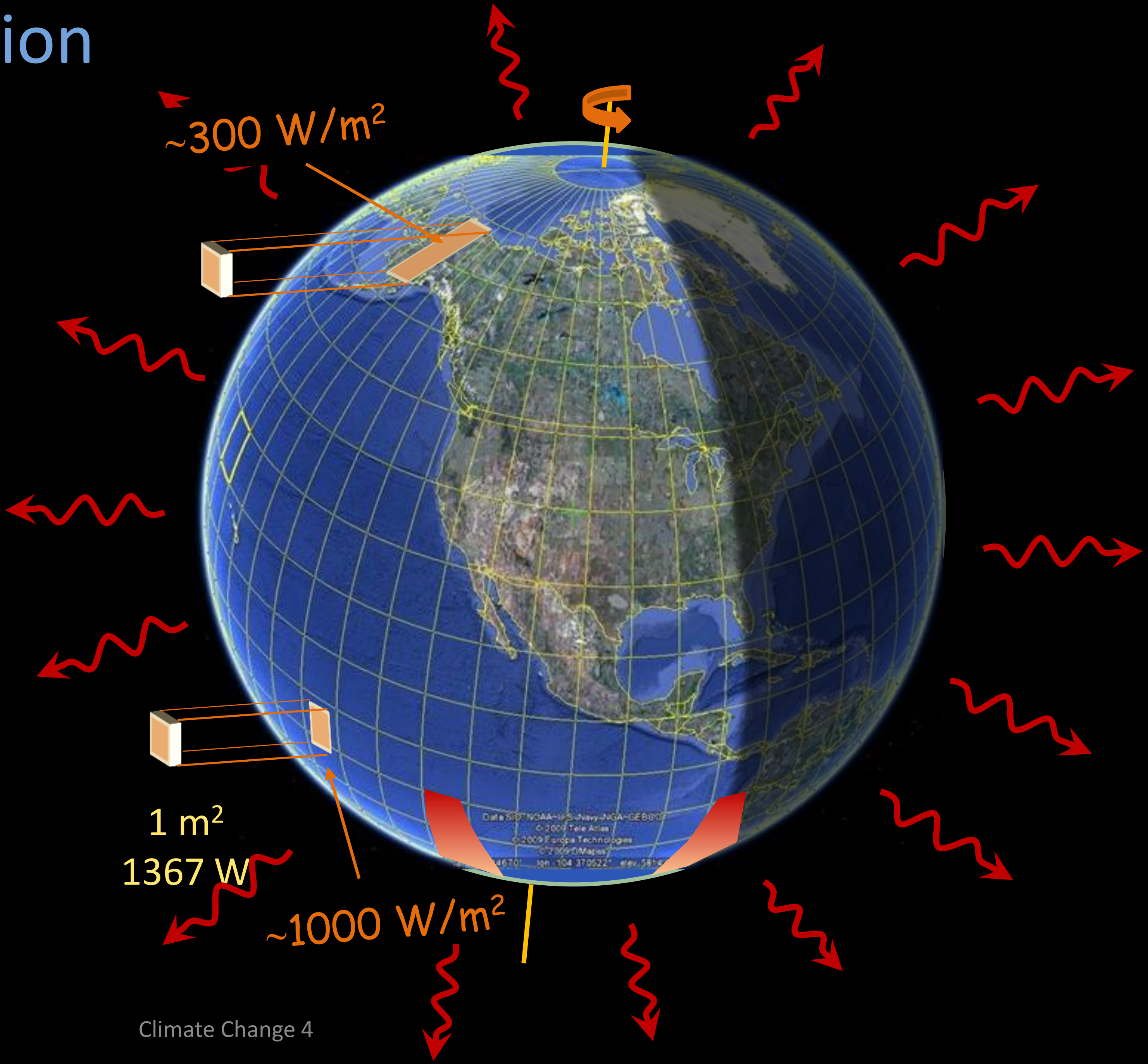
All this heat input is balanced by Infrared Radiation into space from all over the earth, somewhat uniformly.

Problem: Heat Distribution

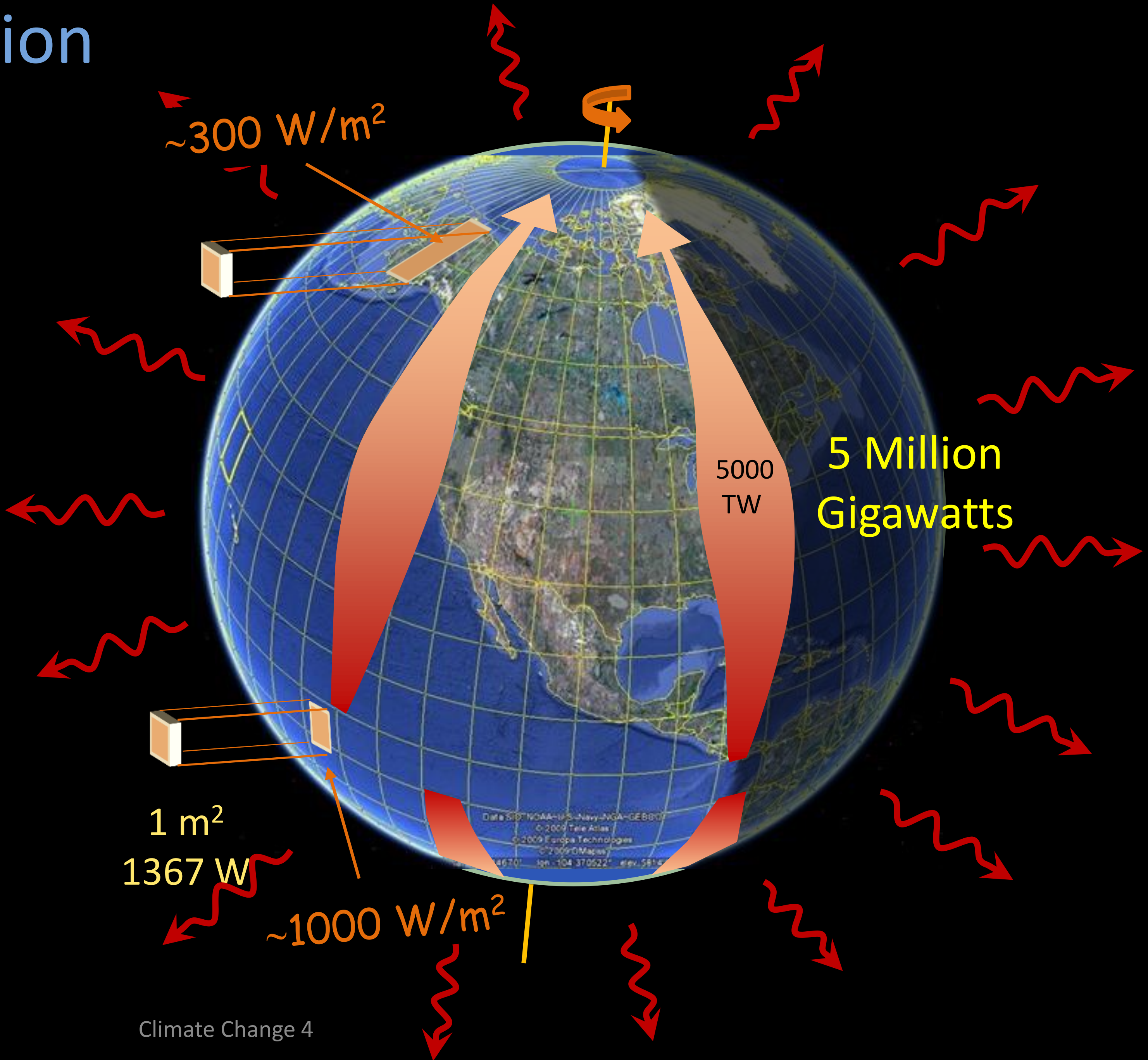
But at higher latitudes, the 1000W hitting the ground is spread out over many square meters, reducing the solar heat input per square meter to a much smaller value.

Thus, on average, the polar regions are getting a far, far smaller solar heat input, while still radiating quite a bit of IR.

How can this be?



Problem: Heat Distribution



This is only possible if huge amounts of heat are being regularly transported from low latitudes to polar regions.
It comes to 5 TerraWatts per hemisphere!

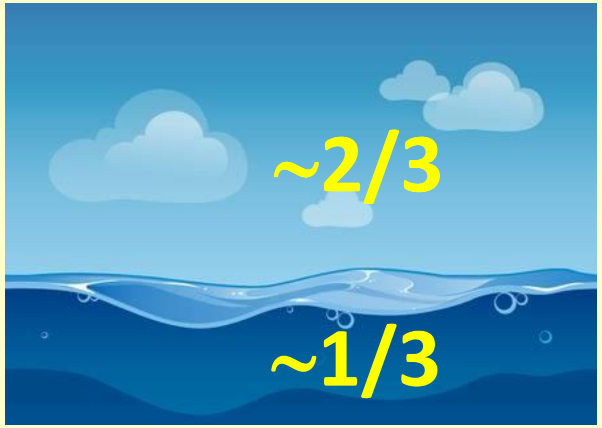
Problem: Heat Distribution

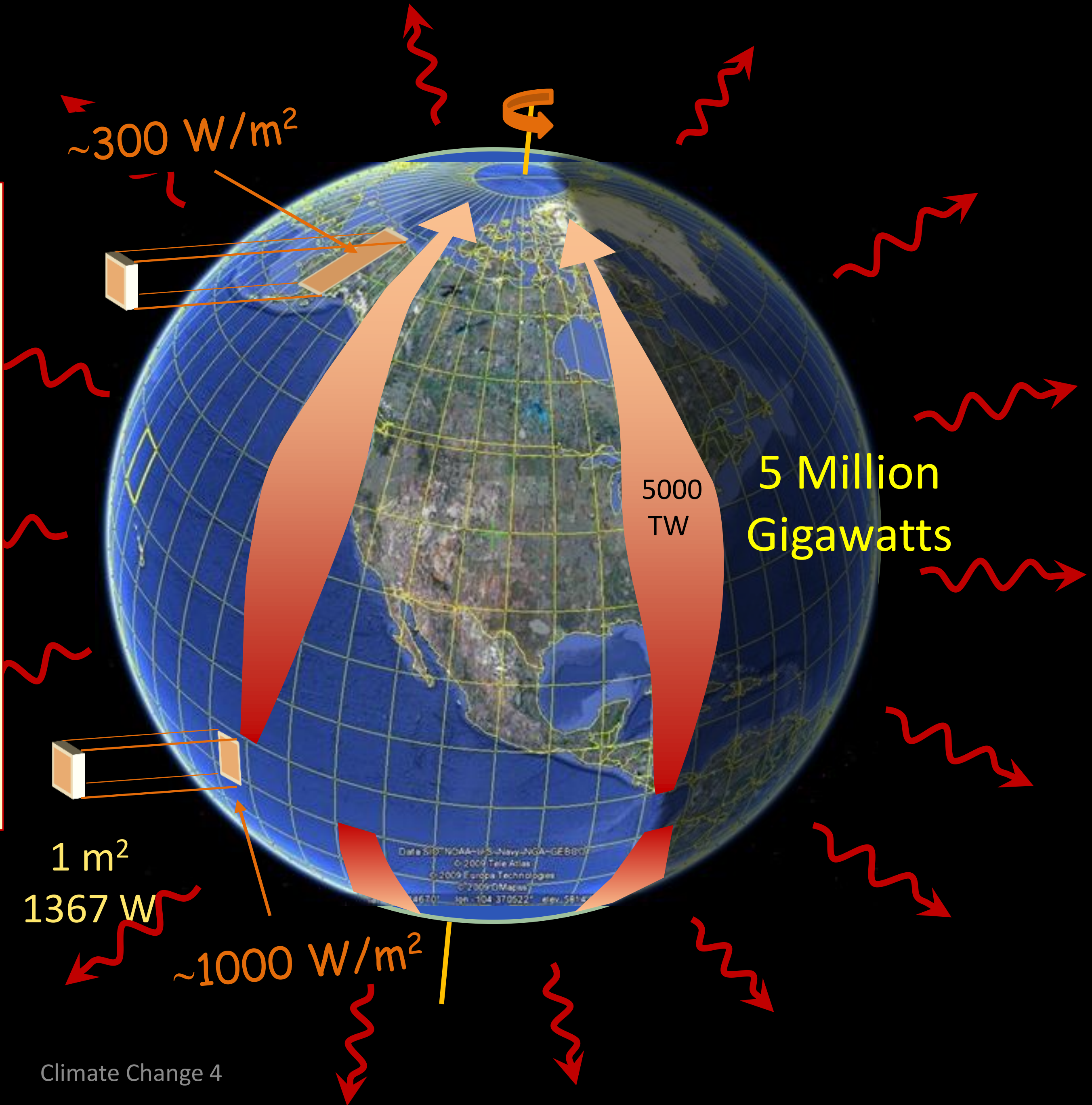
Logistical Problem:

How can the earth move this much heat poleward?

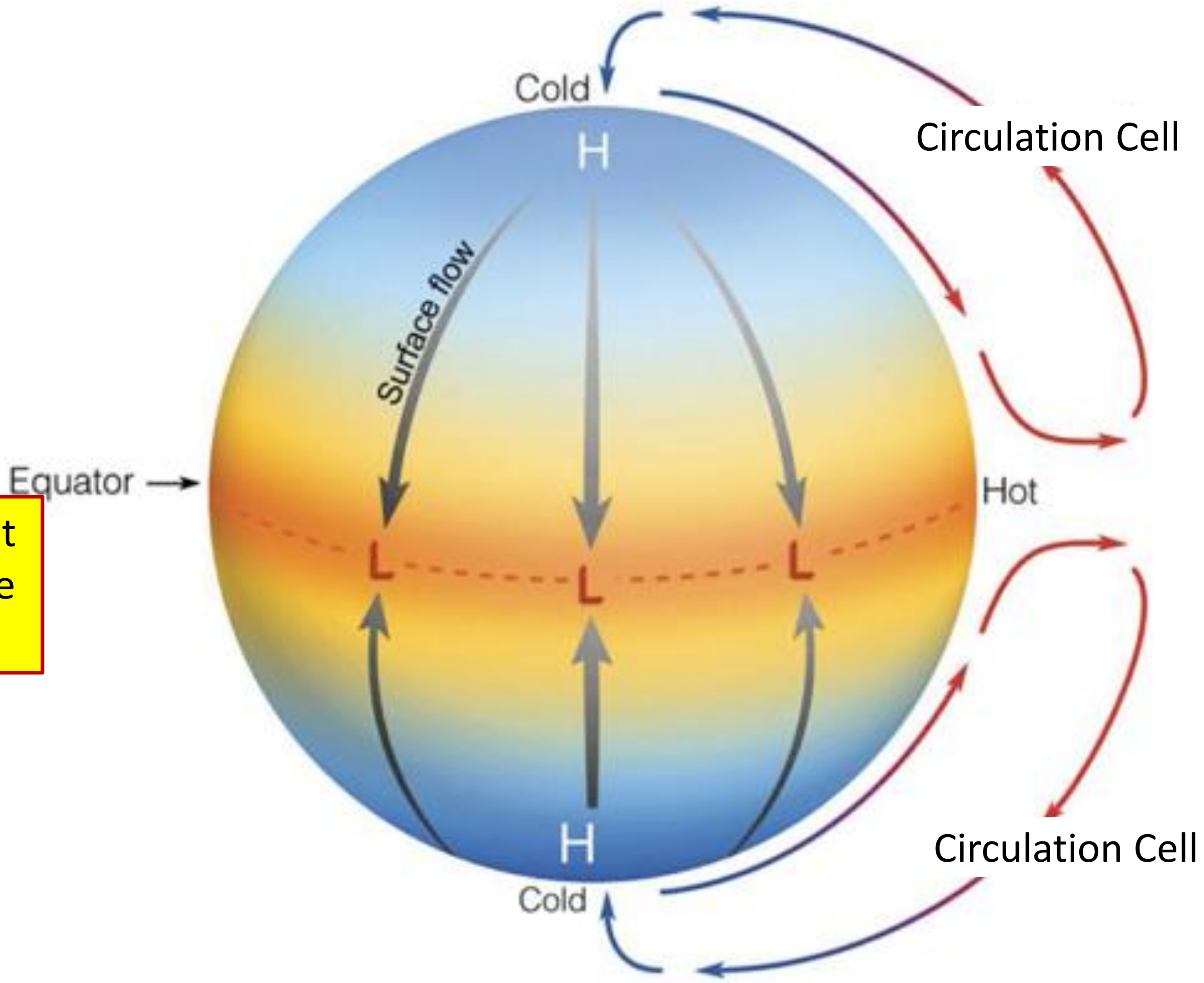
Answers:

1. By **Air**
2. By **Sea**





Naïve Expectation for Heat Redistribution via Air



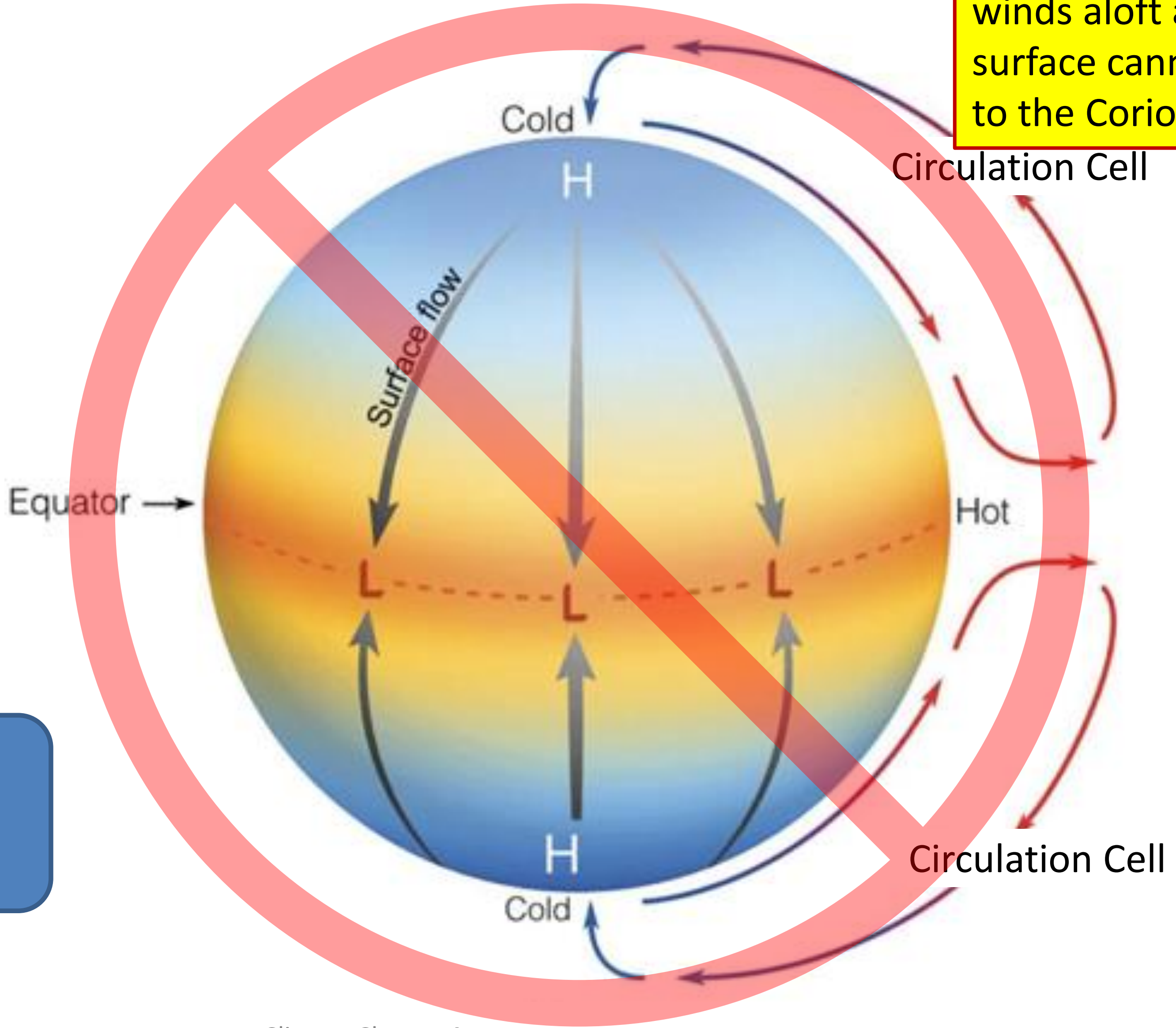
These simple air circulation patterns ought to work really well to transport heat to the poles, but…..

Naïve Expectation for Heat Redistribution via Air

The required straight line winds aloft and at the surface cannot happen due to the Coriolis effect…

This *would* work very well -- on a non-rotating planet

…but the Coriolis Force won't allow it

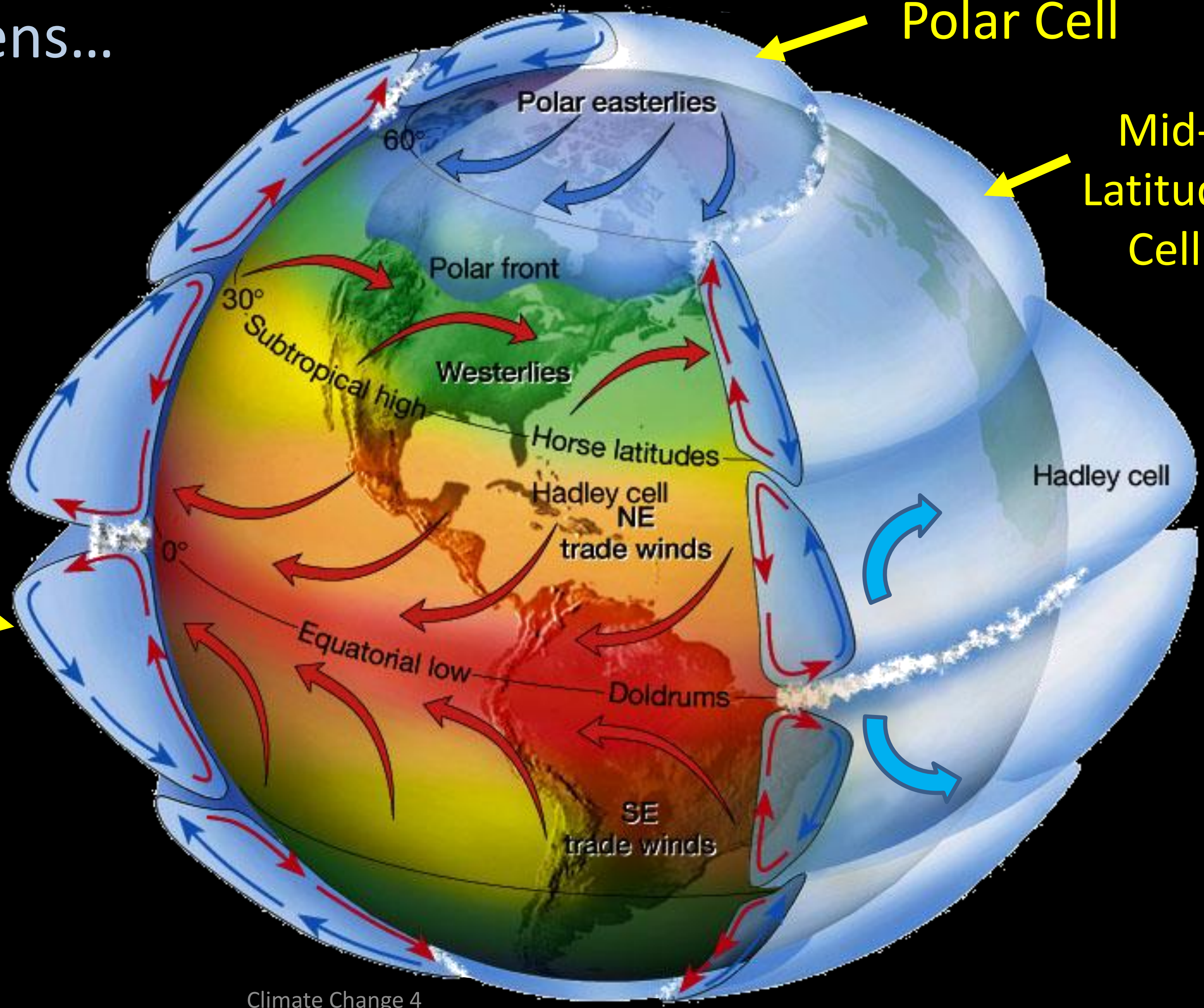


What Actually Happens…
…sort of

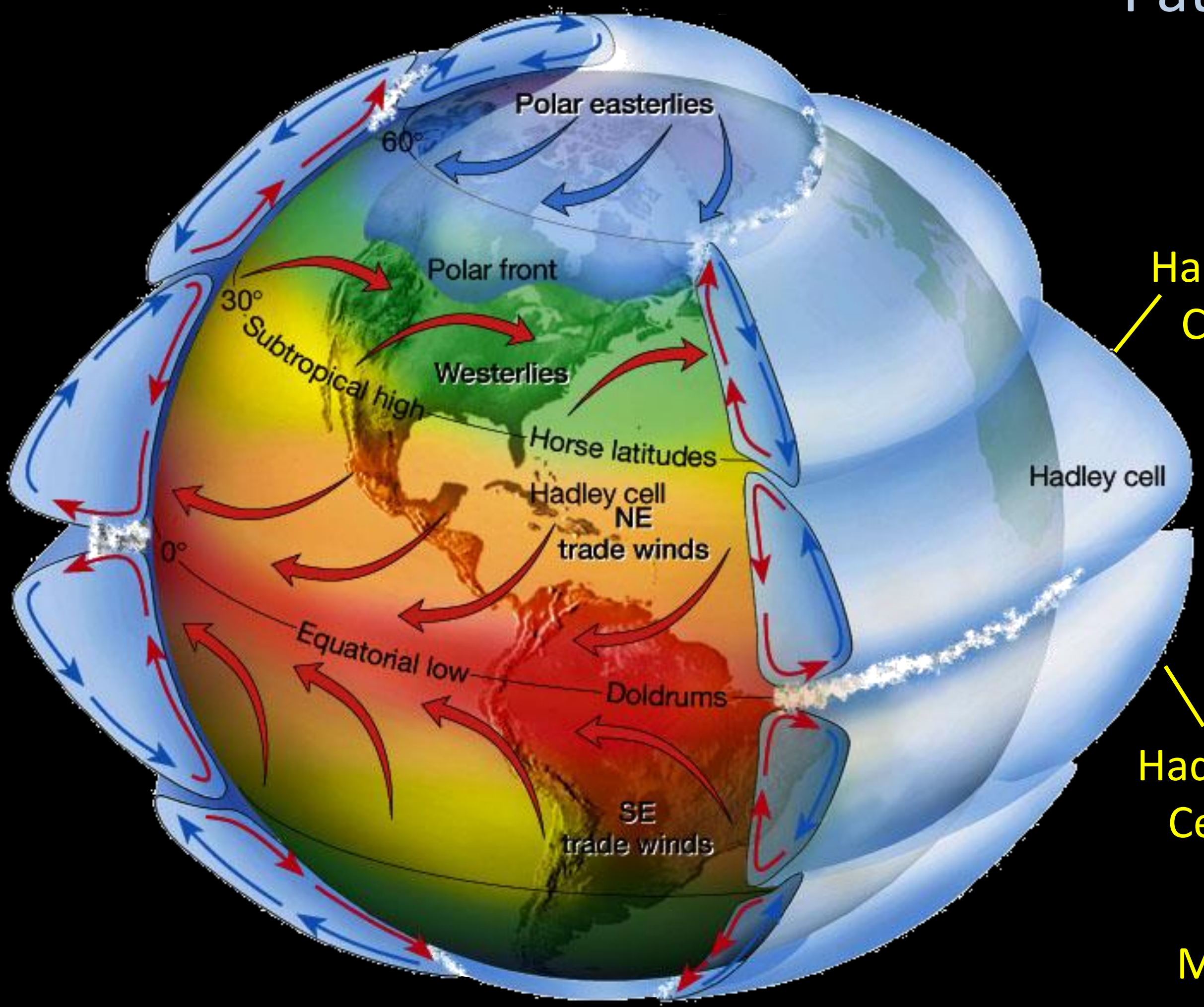
3 Cells in each hemisphere

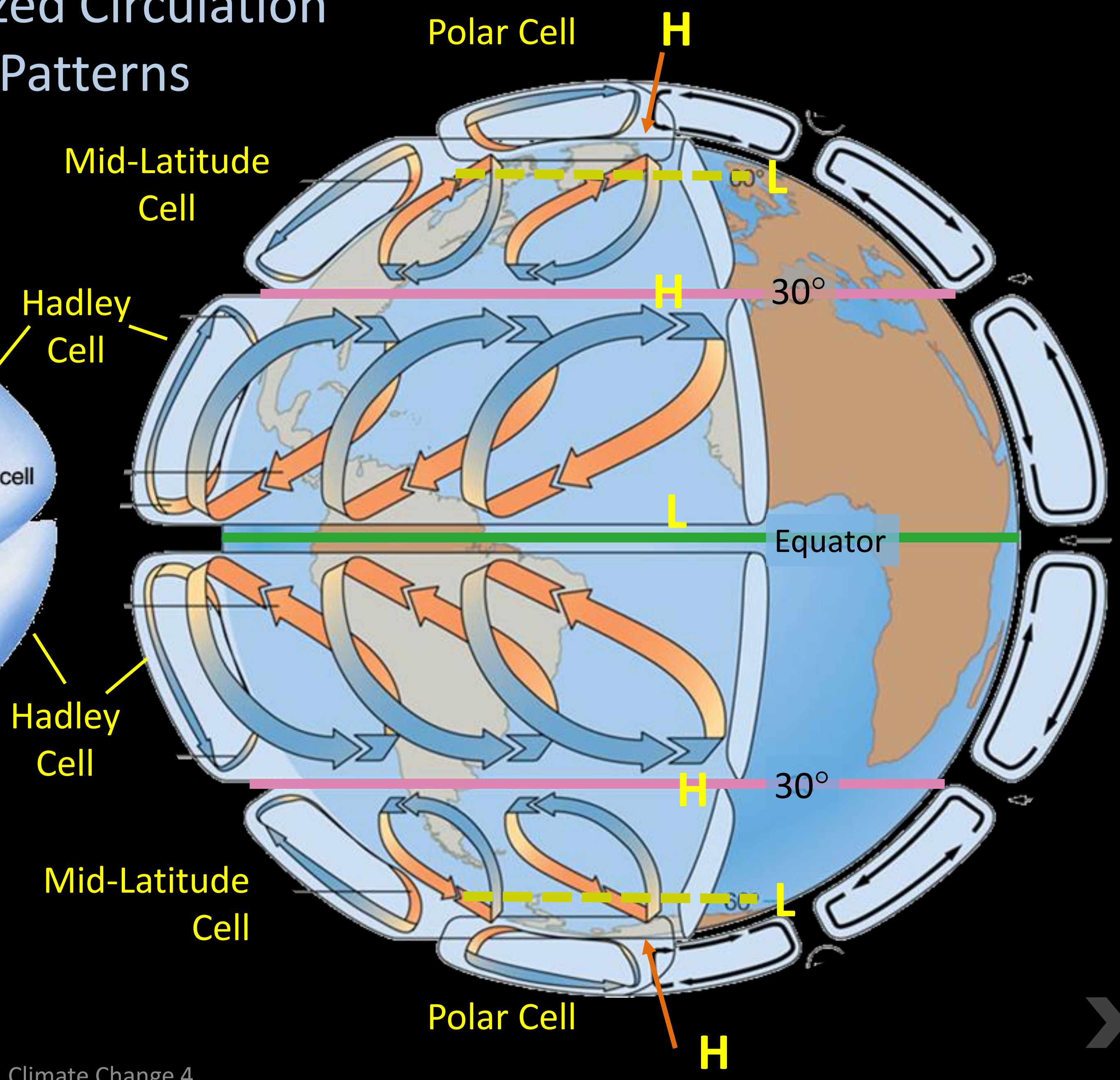
Hadley Cells

George Hadley
(1685-1768)
English Lawyer and
Amateur Meteorologist



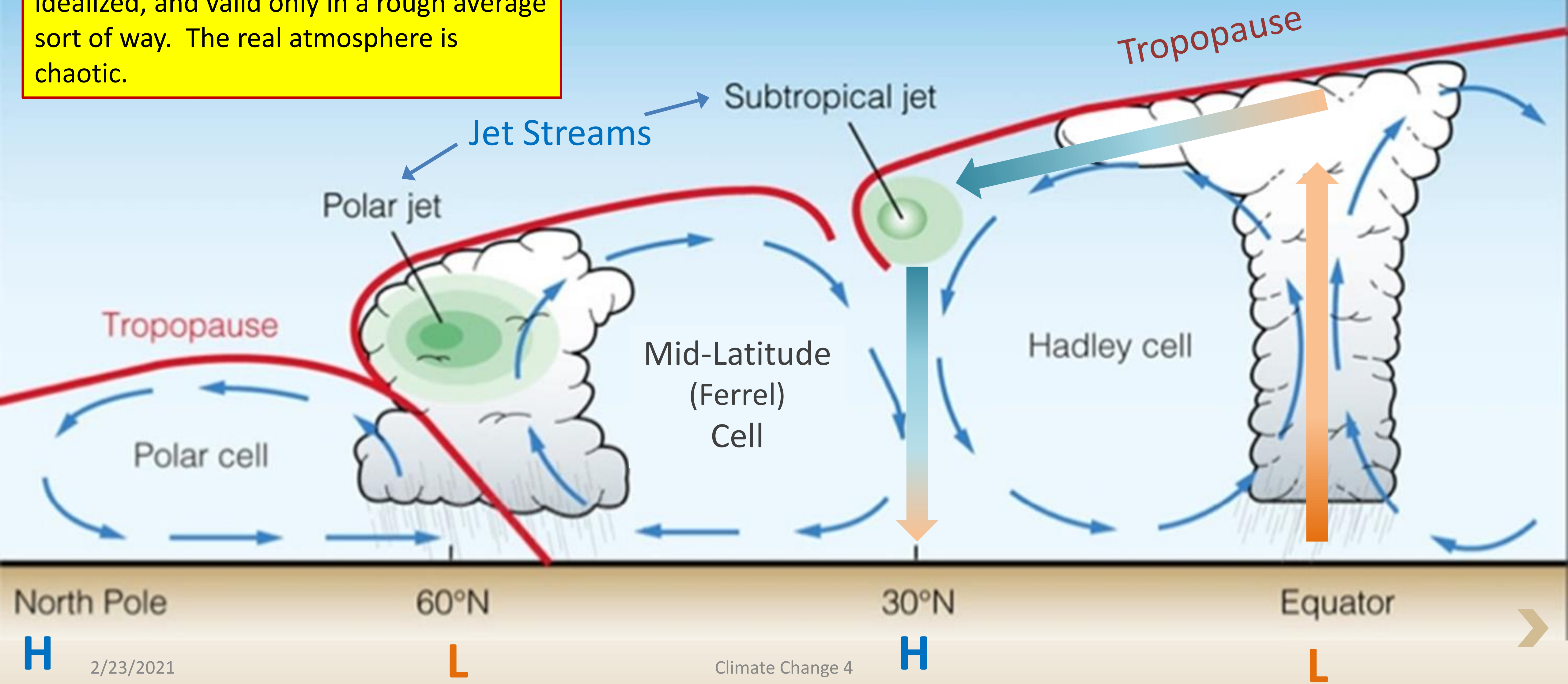
Idealized Circulation Patterns





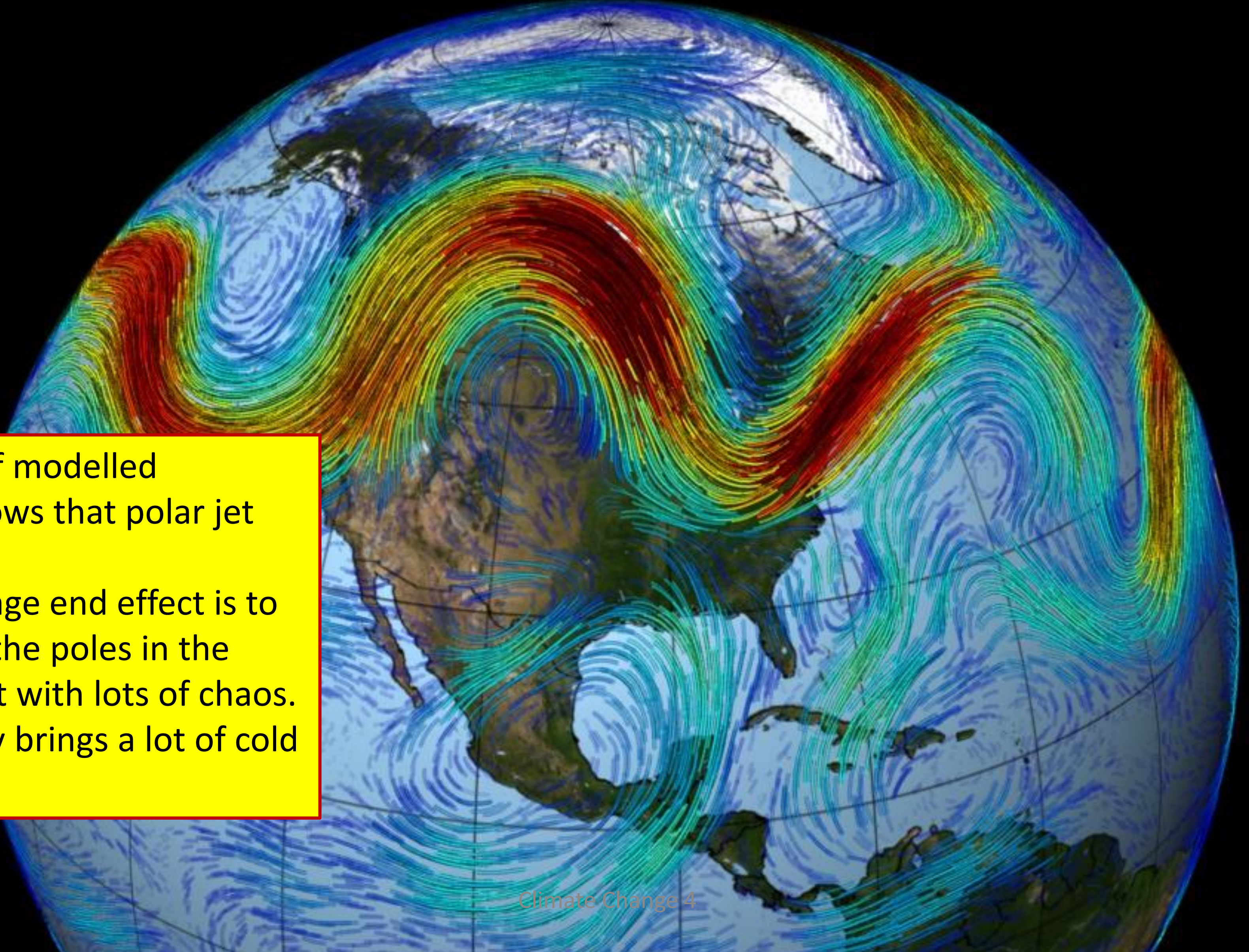
Side View of Cell Pattern

All these circulation patterns are highly idealized, and valid only in a rough average sort of way. The real atmosphere is chaotic.



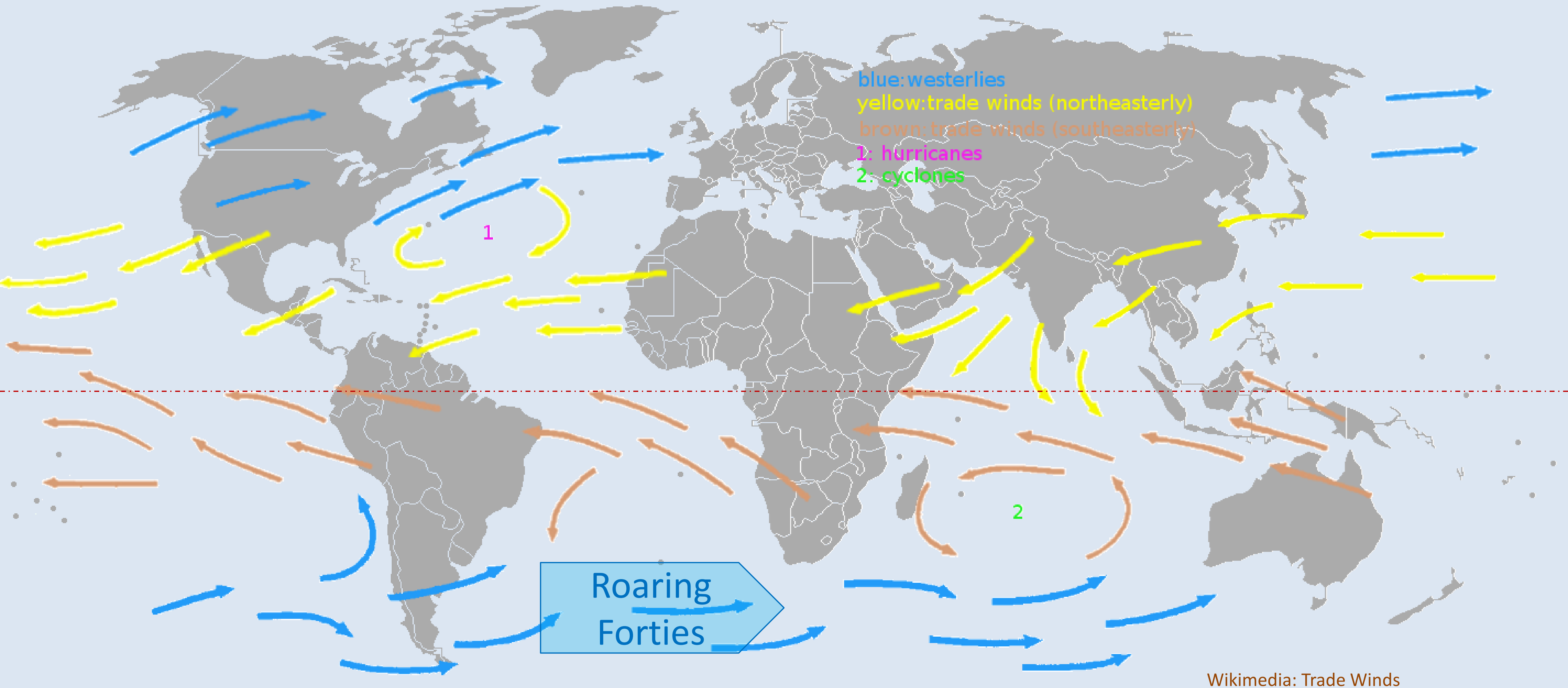
Modeled Circulation

NASA Goddard



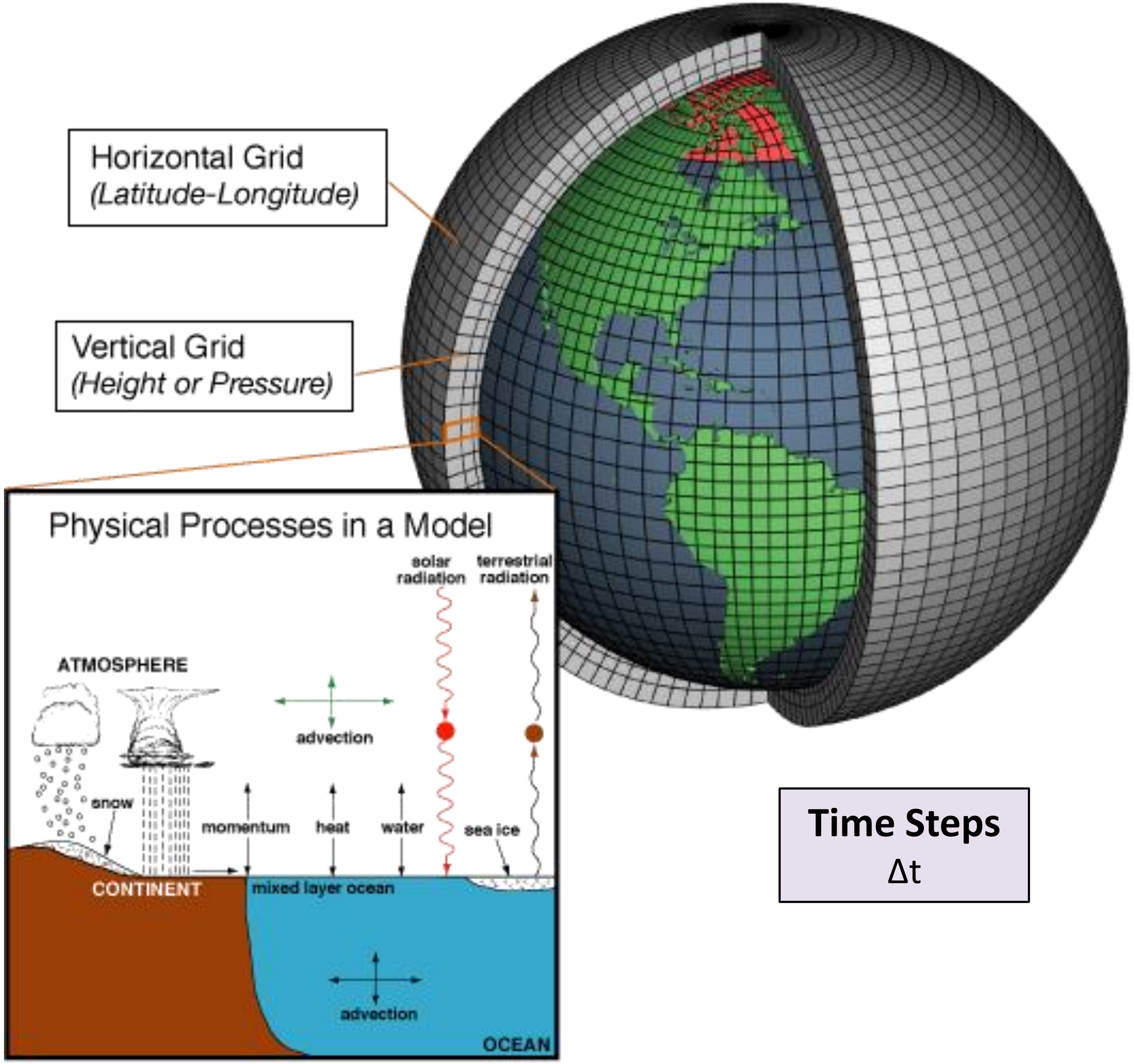
Movie of an example of modelled circulation patterns shows that polar jet meanders randomly.
Nevertheless, the average end effect is to transport heat toward the poles in the amount required, albeit with lots of chaos. Sometimes this actually brings a lot of cold polar air down to us.

Prevailing Global Wind Patterns



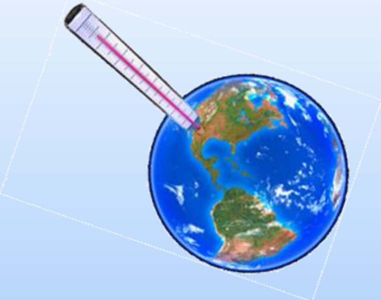
Wikimedia: Trade Winds

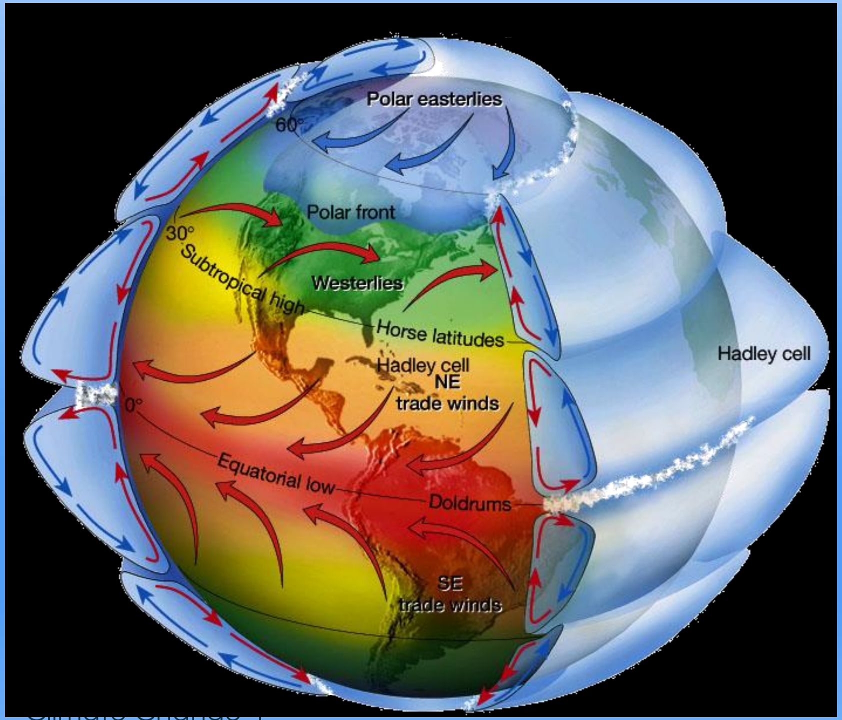
Building a General Circulation Model

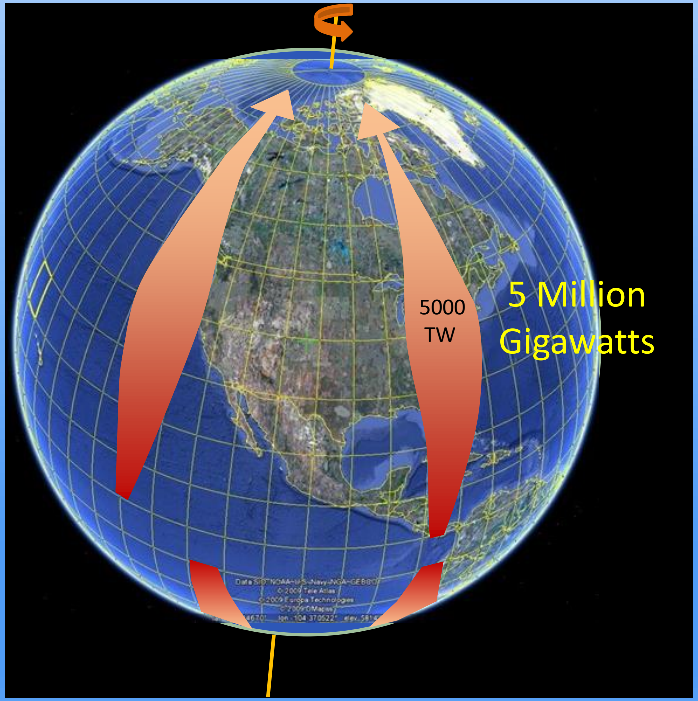


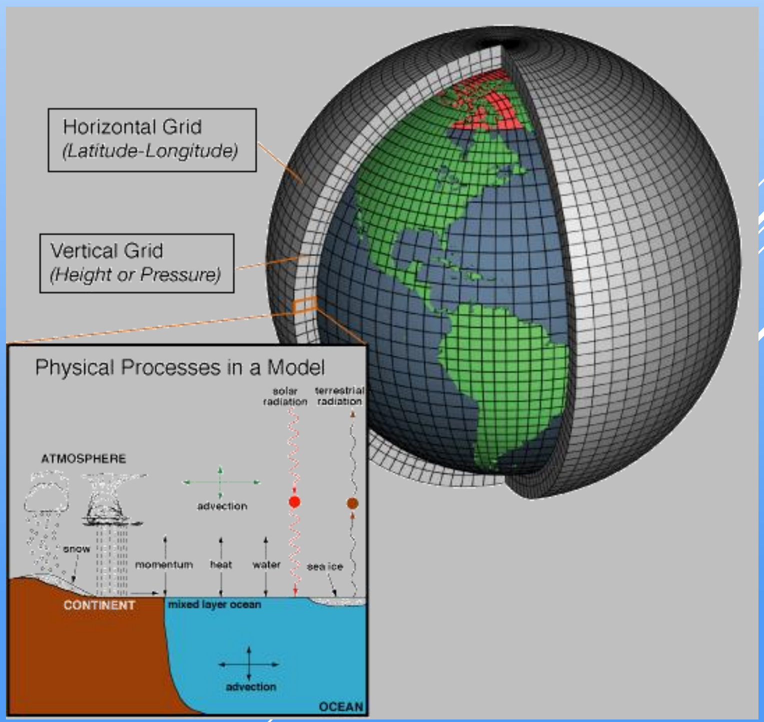
Time Steps
Δt

Questions about Atmospheric Circulation







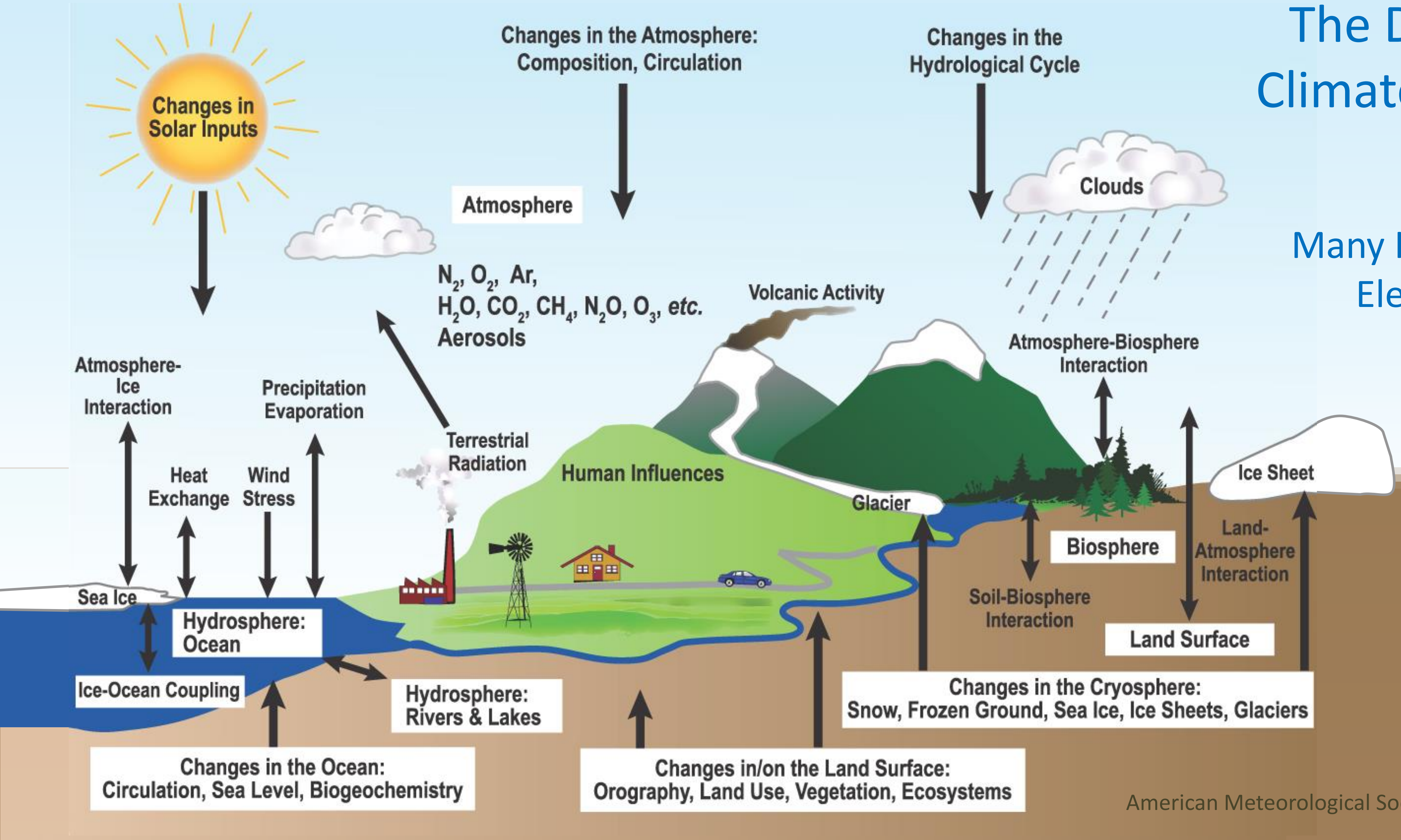


Dynamical Earth: The Subsystems

- Atmosphere ✓
- Oceans
- Cryosphere
- Biosphere
- Lithosphere
- People (*Anthrosphere?*)

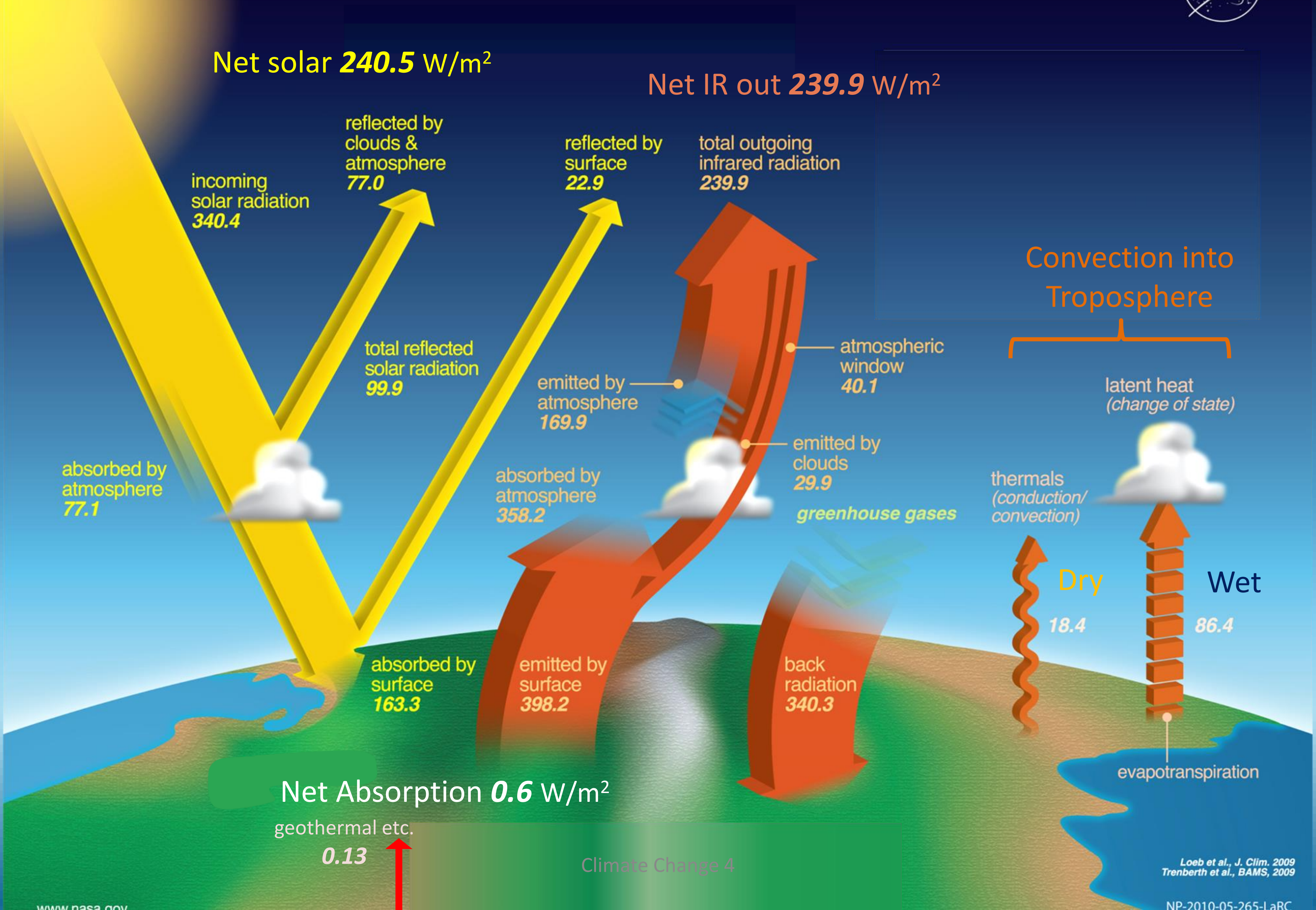
The Dynamic Climate System:

Many Interacting Elements



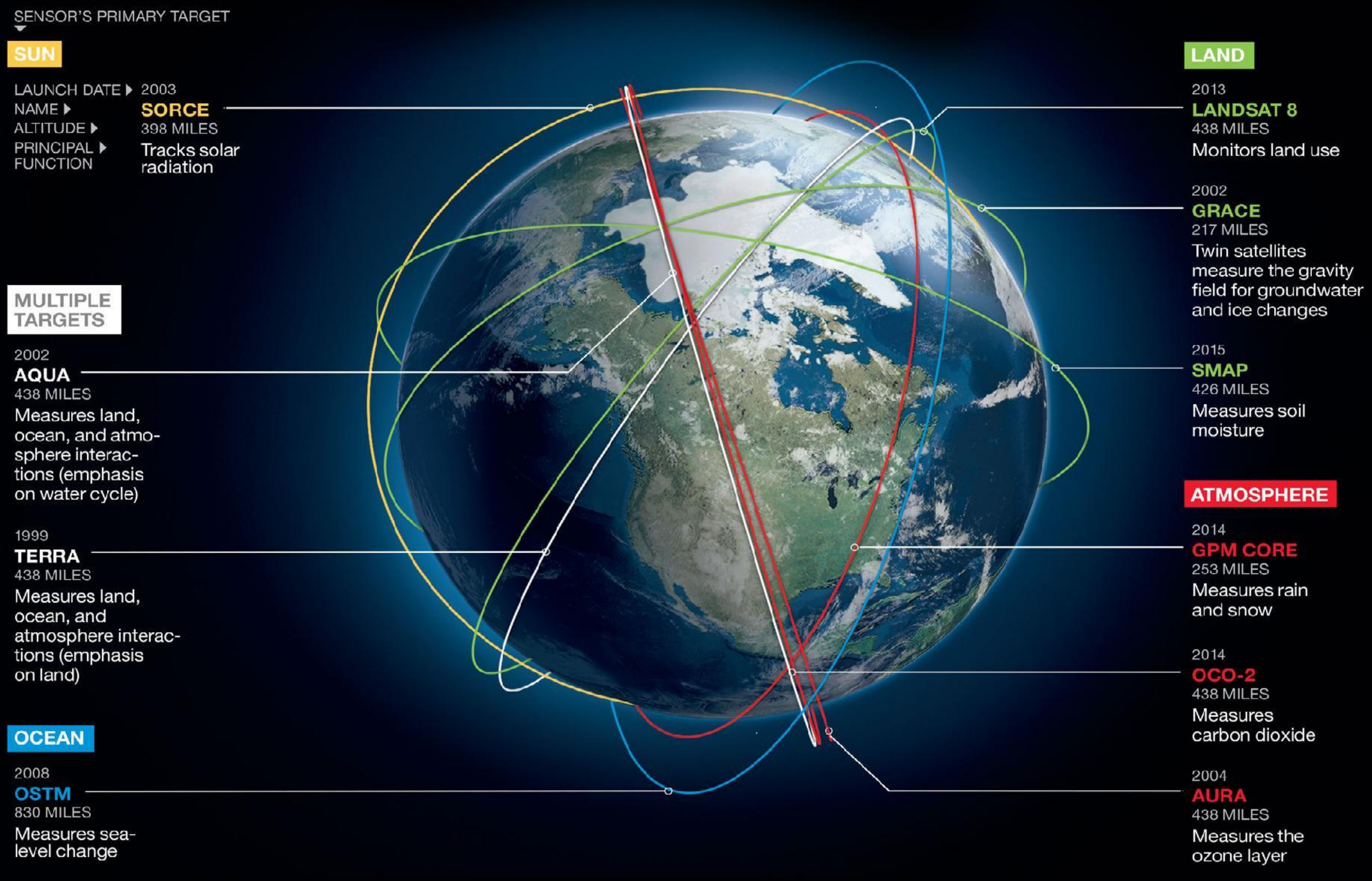
American Meteorological Society

Earth’s Energy Budget



600+ Earth Observing Satellites

NASA Earth Observation Fleet as of December 2018



Most Earth Observation Satellites are in Polar or High Inclination Orbits

These orbits allow all or most of the Earth's surface to be regularly observed.

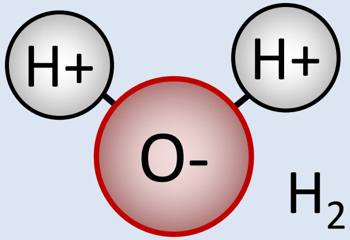
Oceans

- Compared to Atmosphere:
  - Mass is 260 x
  - Heat Capacity is 900 x
  - Response Time is typically 1000's of times slower

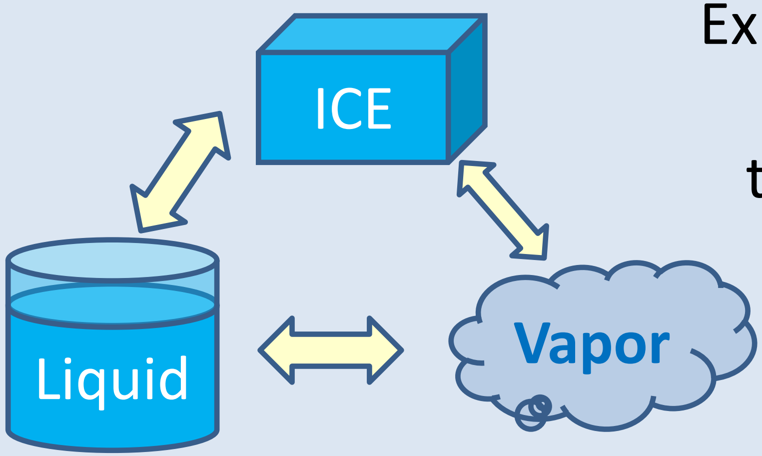
What if we turned up the heat input?

We won't reach equilibrium for a long time…

Water is Special Stuff



H_2O



Exists in 3 Phases
at ordinary
temperatures

Lots of Heat Needed to Warm up Water

To heat 1 kilogram liquid H_2O 1 Deg C
takes **1 Large Calorie**

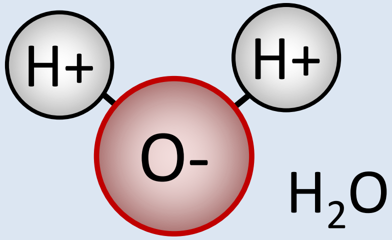
More than almost any
other substance

Lots of Heat Needed to Melt or Vaporize H_2O

To melt 1 kilogram of H_2O Ice
takes **80 Large Calories**

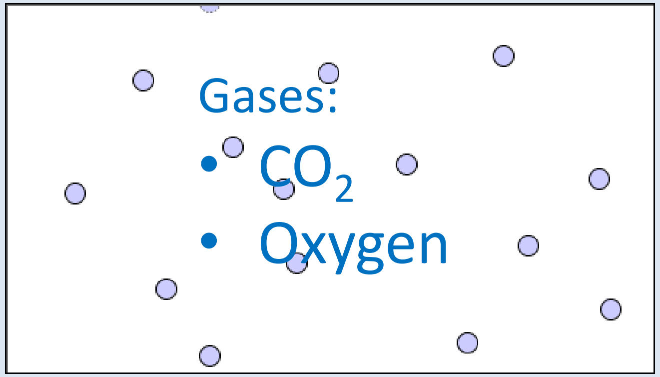
To vaporize 1 kilogram of H_2O
takes **540 Large Calories**

Water is Special Stuff

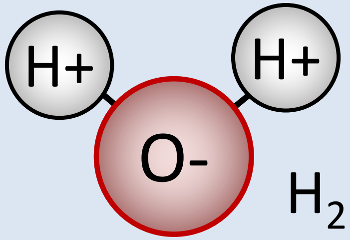


Ice Floats

Water is a Great Solvent



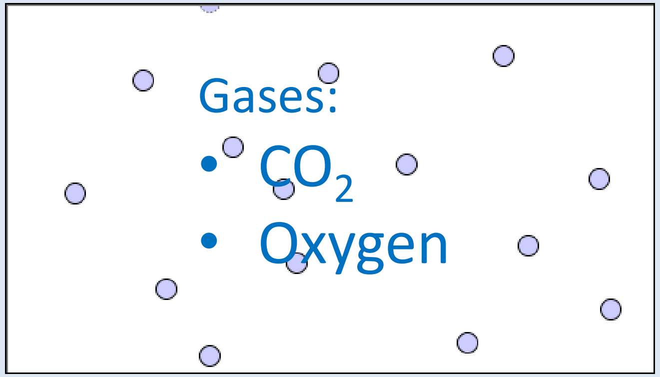
Water is Special Stuff



H_2O

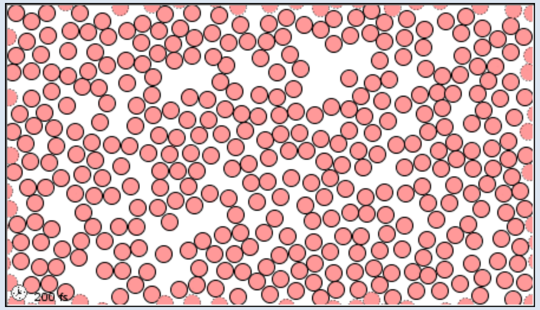
Ice Floats

Water is a Great Solvent

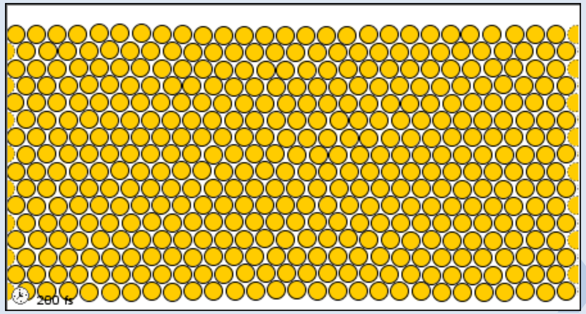


This is unusual. For most materials liquids are less dense, and solids sink

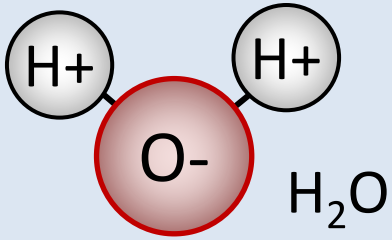
Normal Liquid



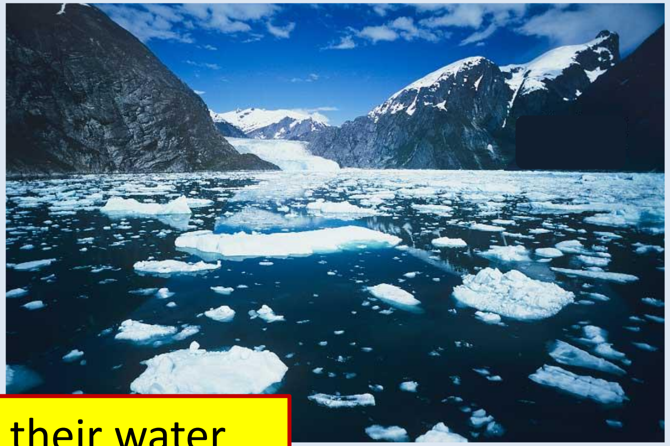
Normal Solid



Water is Special Stuff

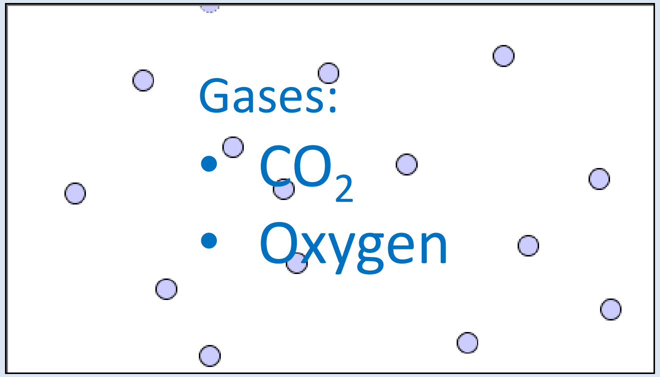


Ice Floats



Other rocky planets have lost their water to space, but we still have a lot of it….

Water is a Great Solvent



Water is a Survivor

- H_2O is Lightest Major Gas in Atmosphere
    - H_2 and Helium much lighter, but scarce
- Water freezes out, not much in Exosphere to escape
- Earth gravity relatively strong
- Magnetic field shields us from Solar Wind

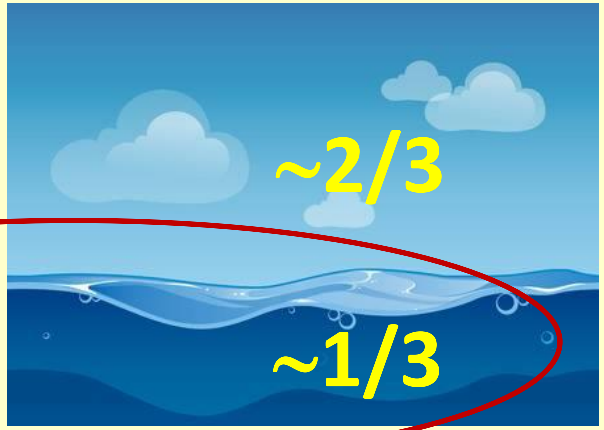
Problem: Heat Distribution

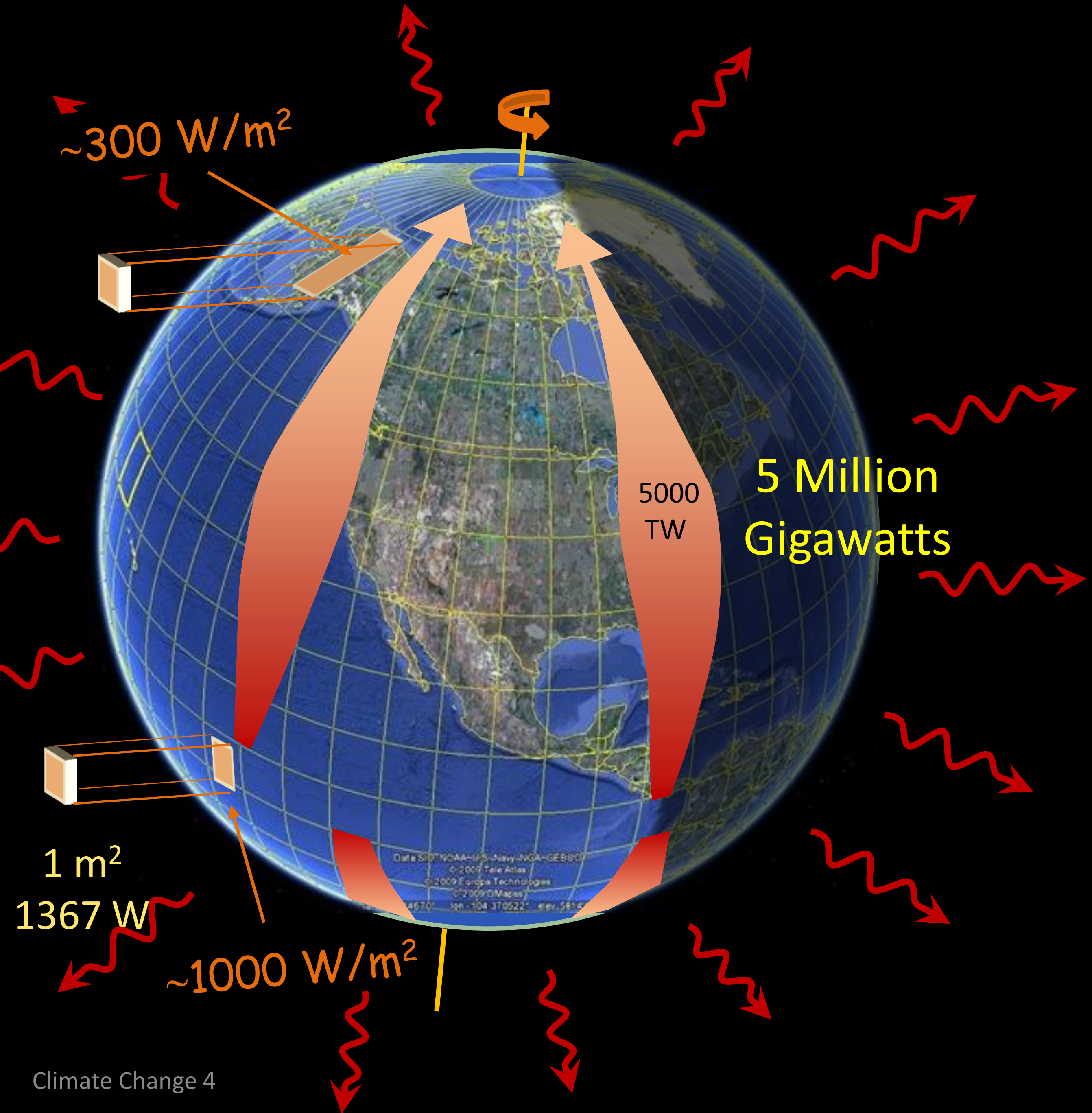
Logistical Problem:

How can the earth move this much heat poleward?

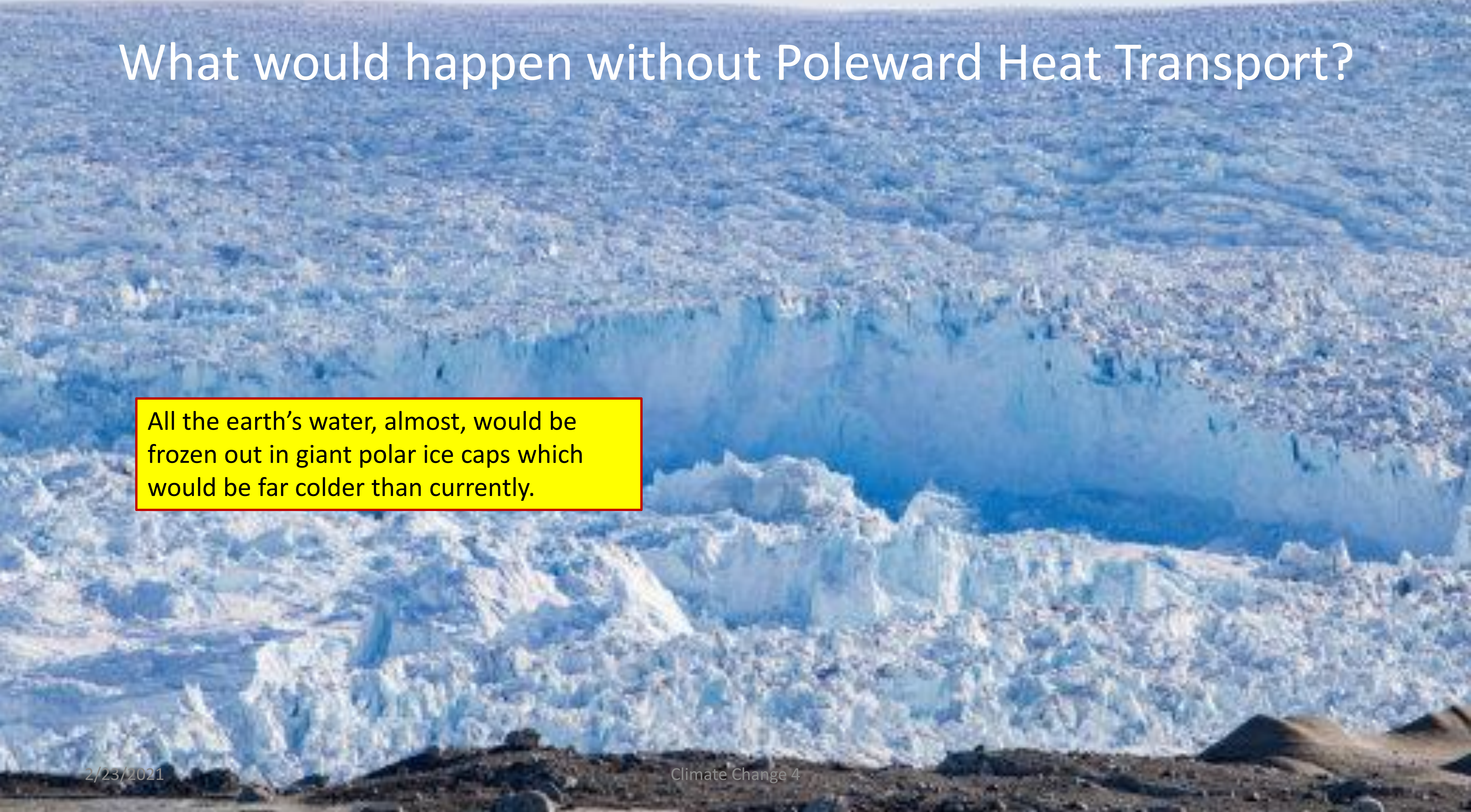
Answers:

1. By **Air**
2. By **Sea**

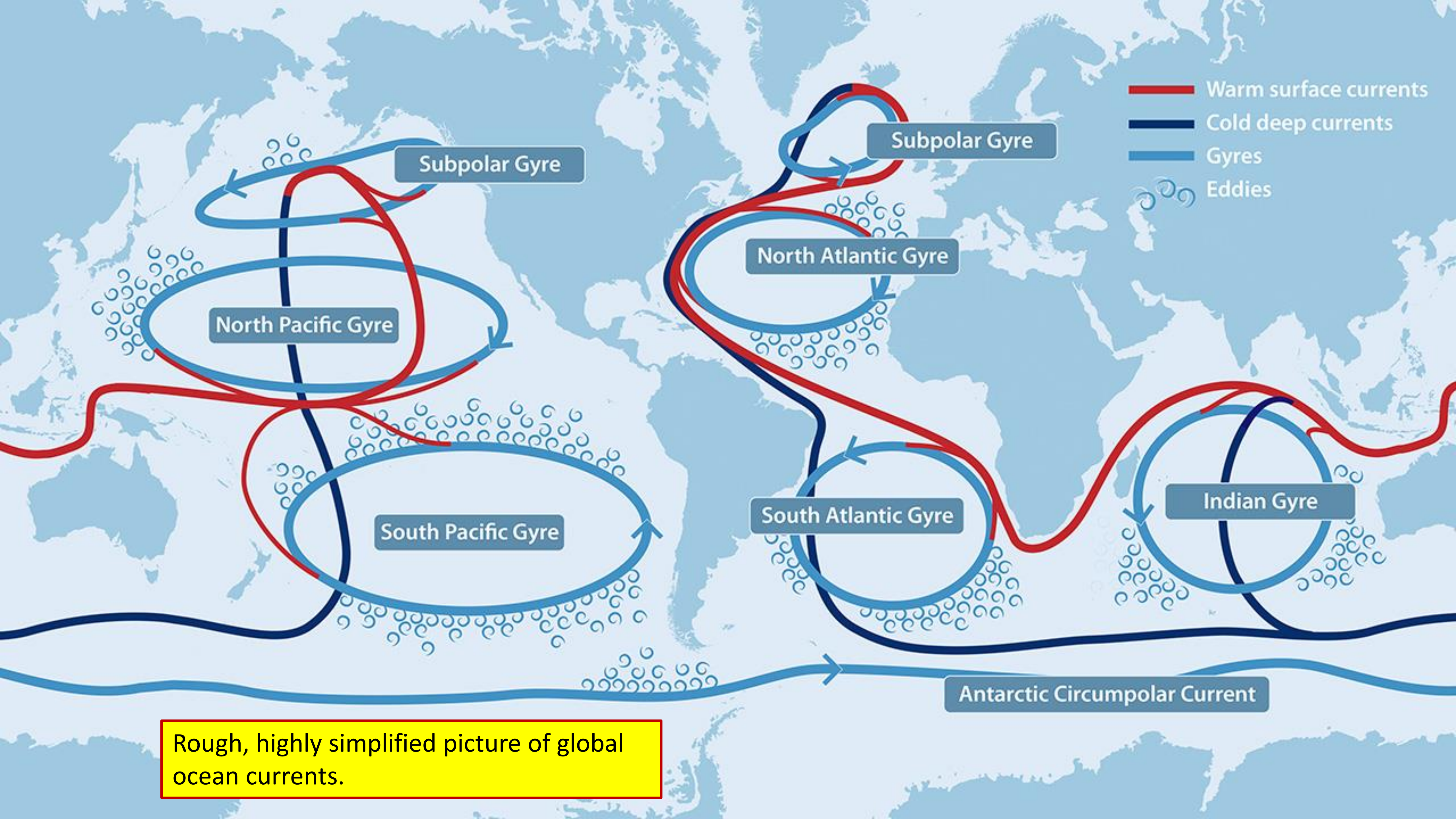




What would happen without Poleward Heat Transport?



All the earth’s water, almost, would be frozen out in giant polar ice caps which would be far colder than currently.



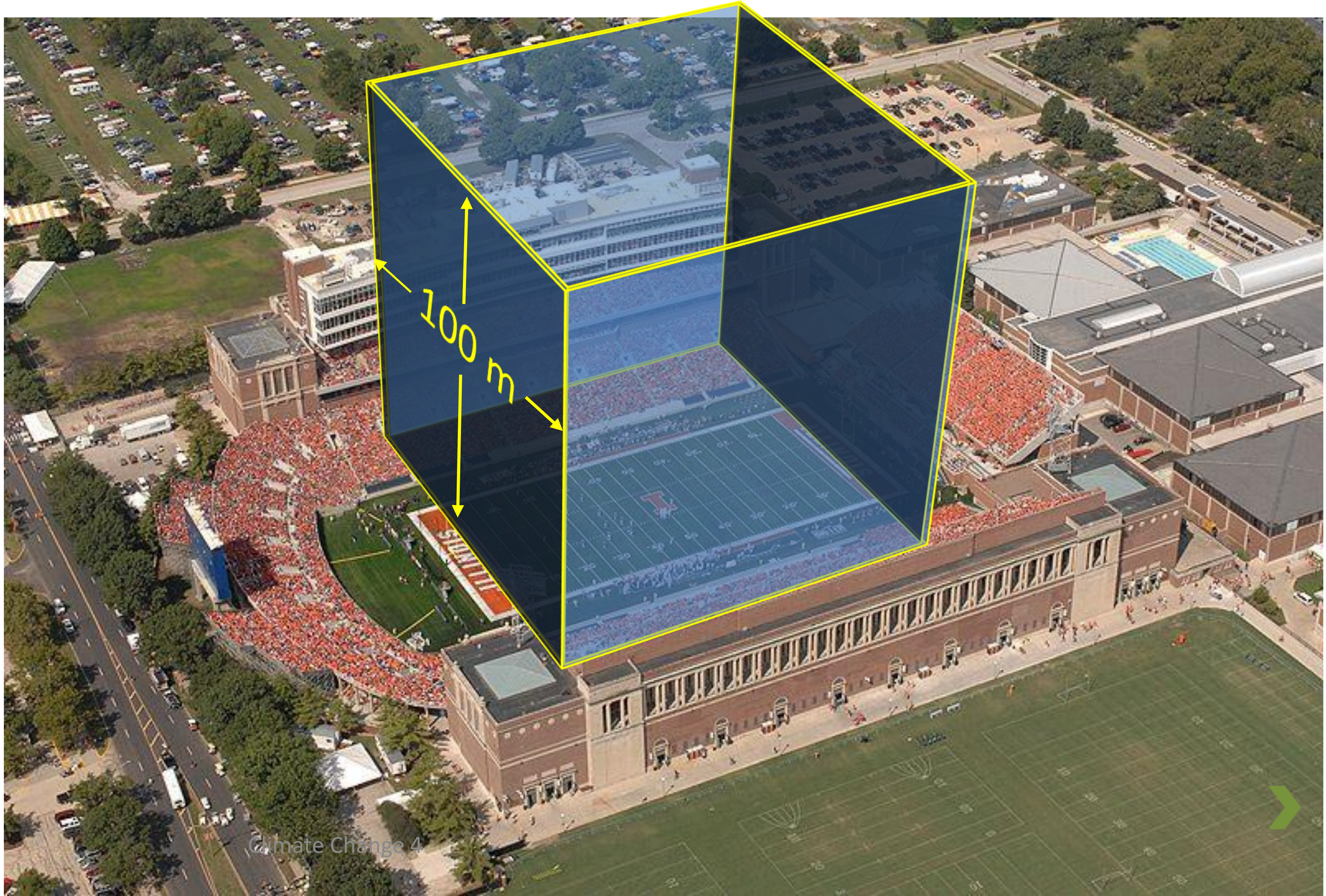
Rough, highly simplified picture of global ocean currents.

Sverdrup: Unit of water flow

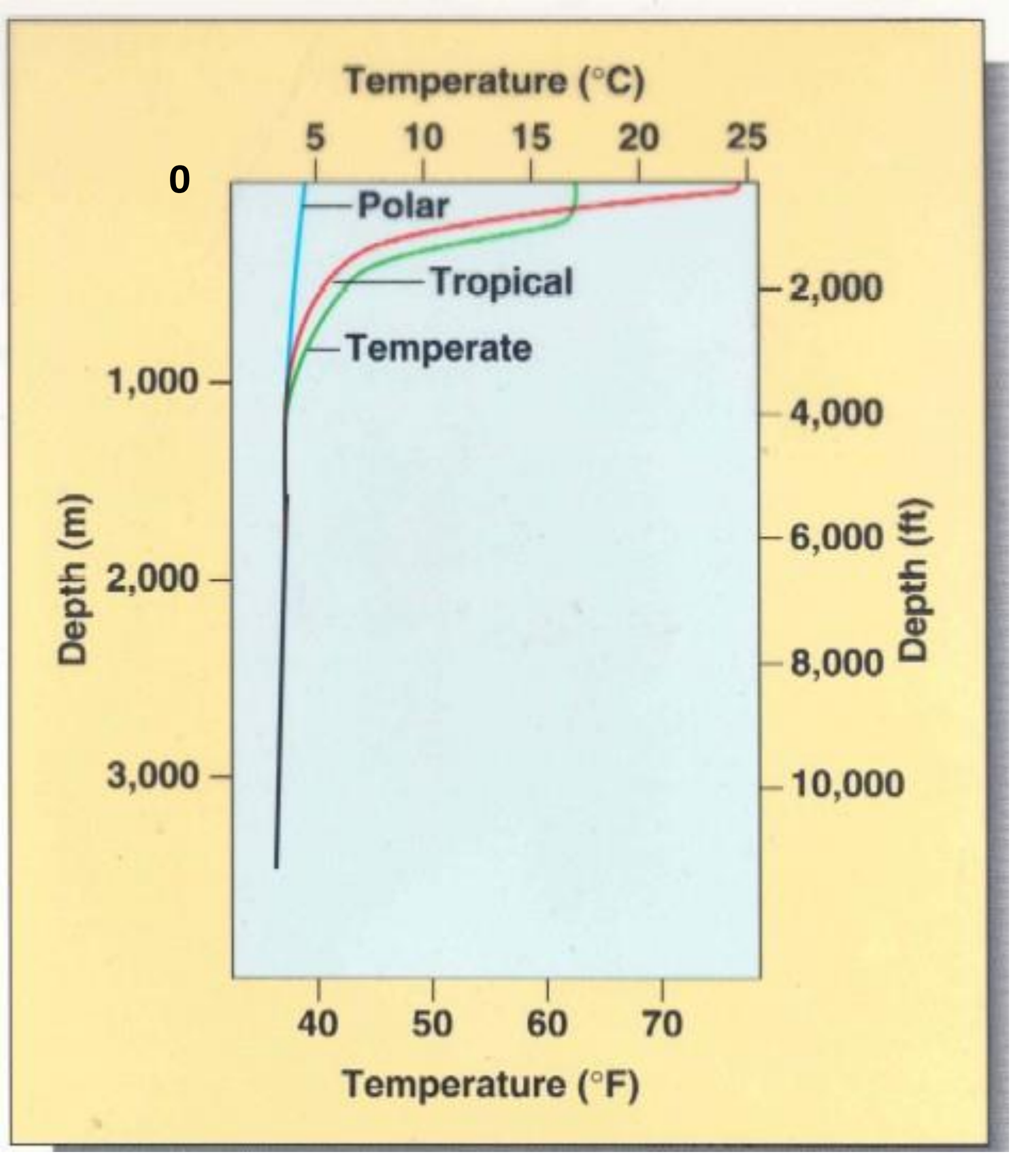
Harald Sverdrup (1888-1957)
Norwegian Oceanographer & Meteorologist
Put Scripps Institute of Oceanography on the map

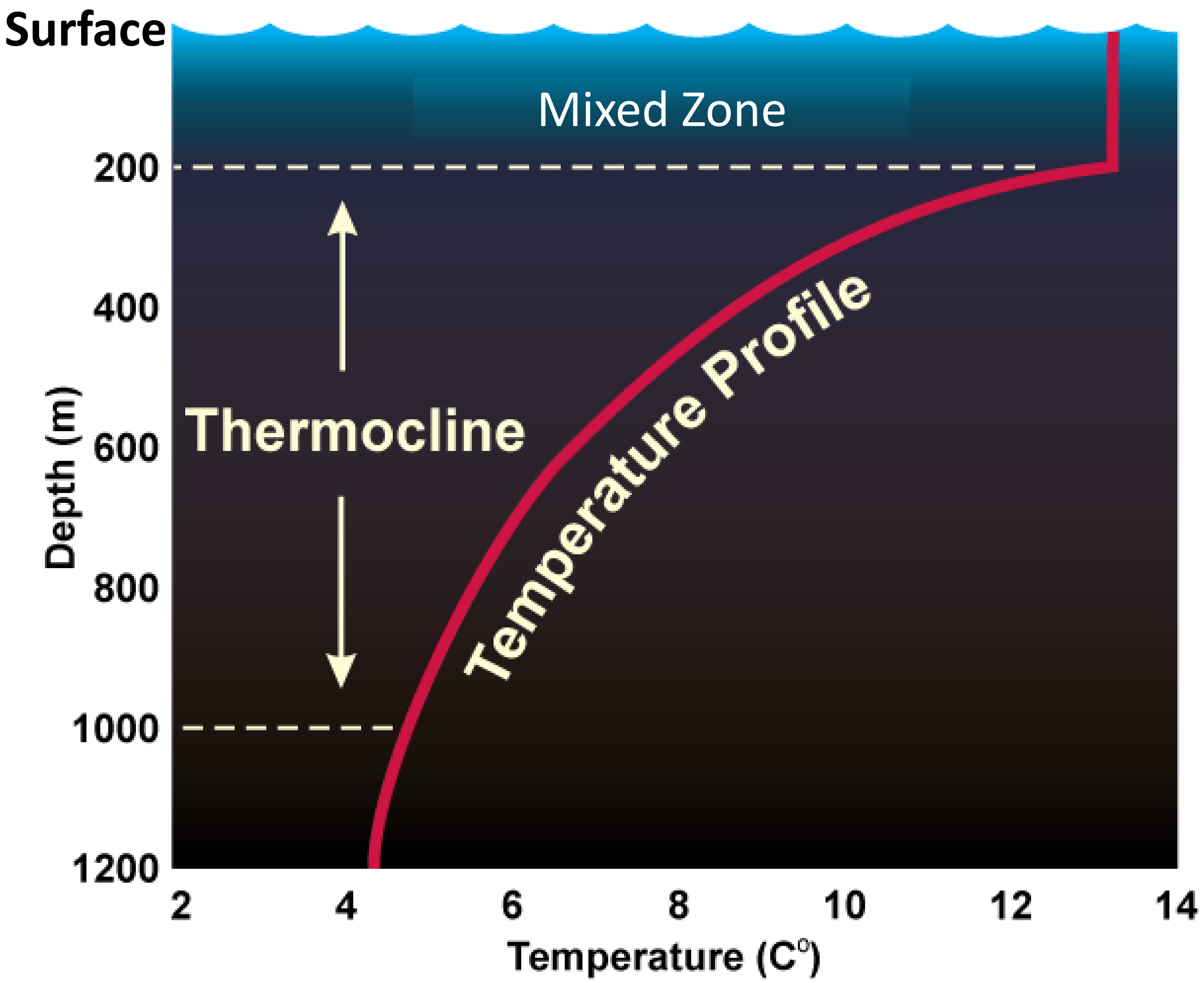
1 Sverdrup (Sv):

- A million cubic meters per *second*
- Roughly the combined flow of all world's rivers.
- 16 billion gallons/minute

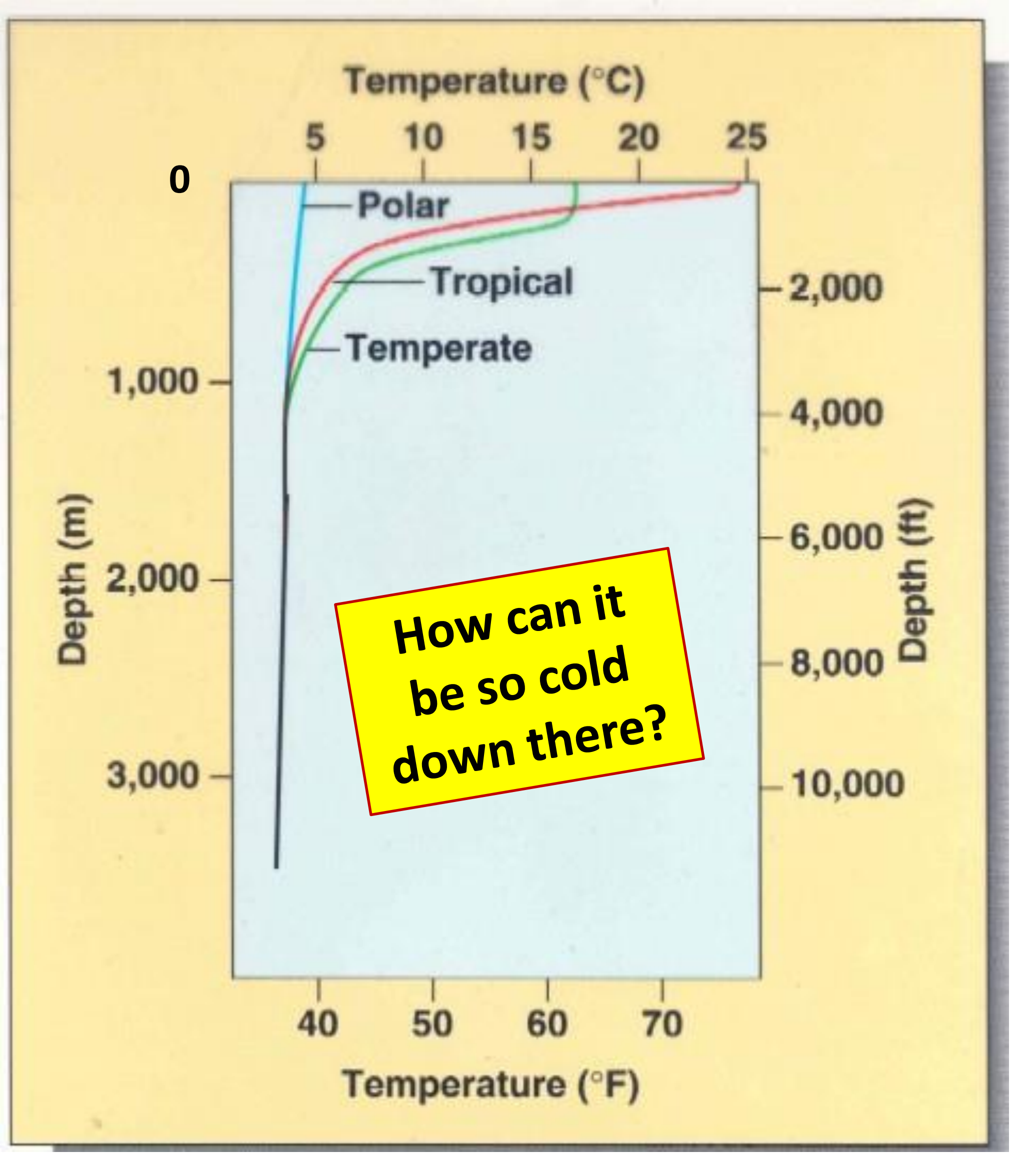


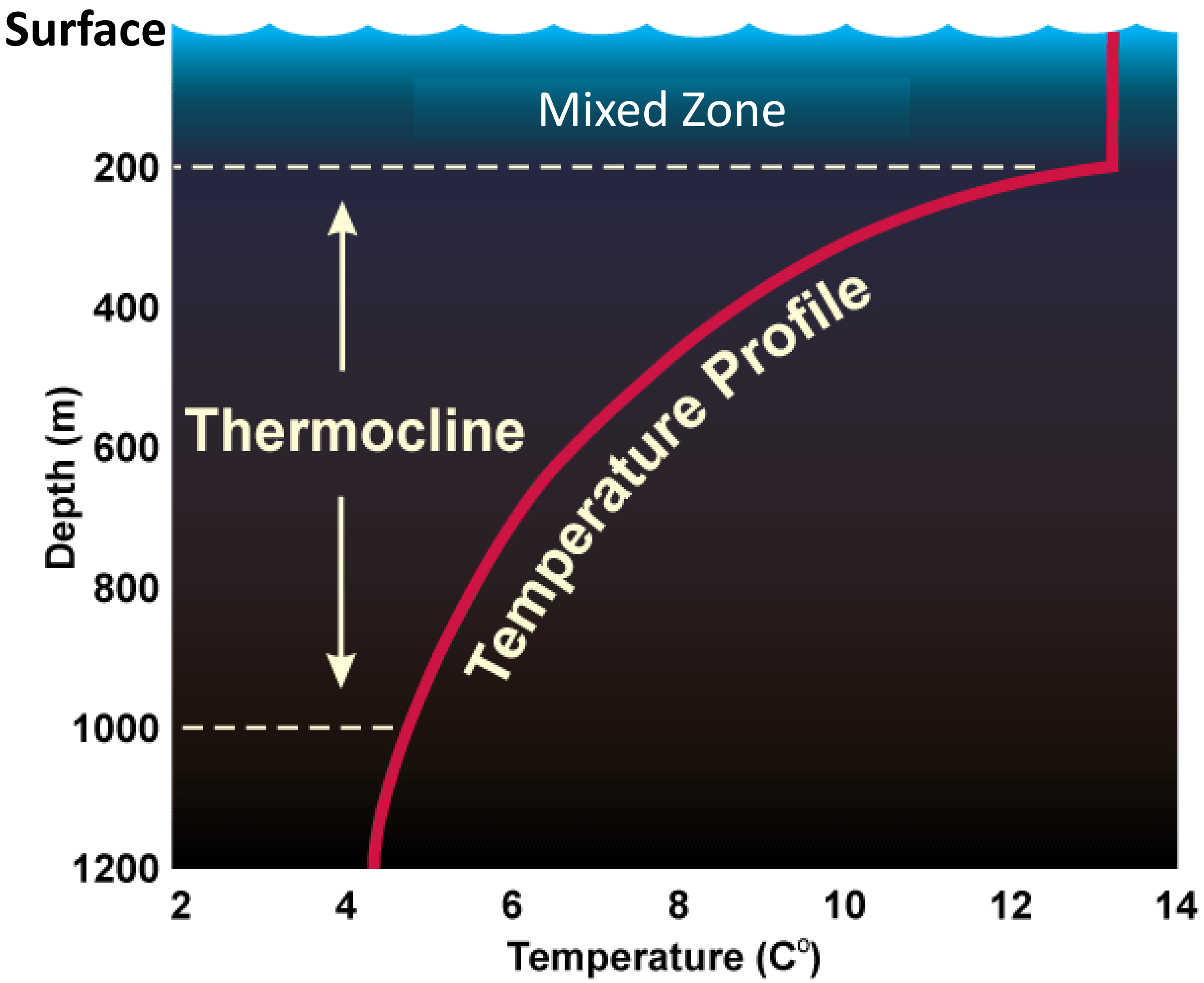
The Deep Ocean is Cold



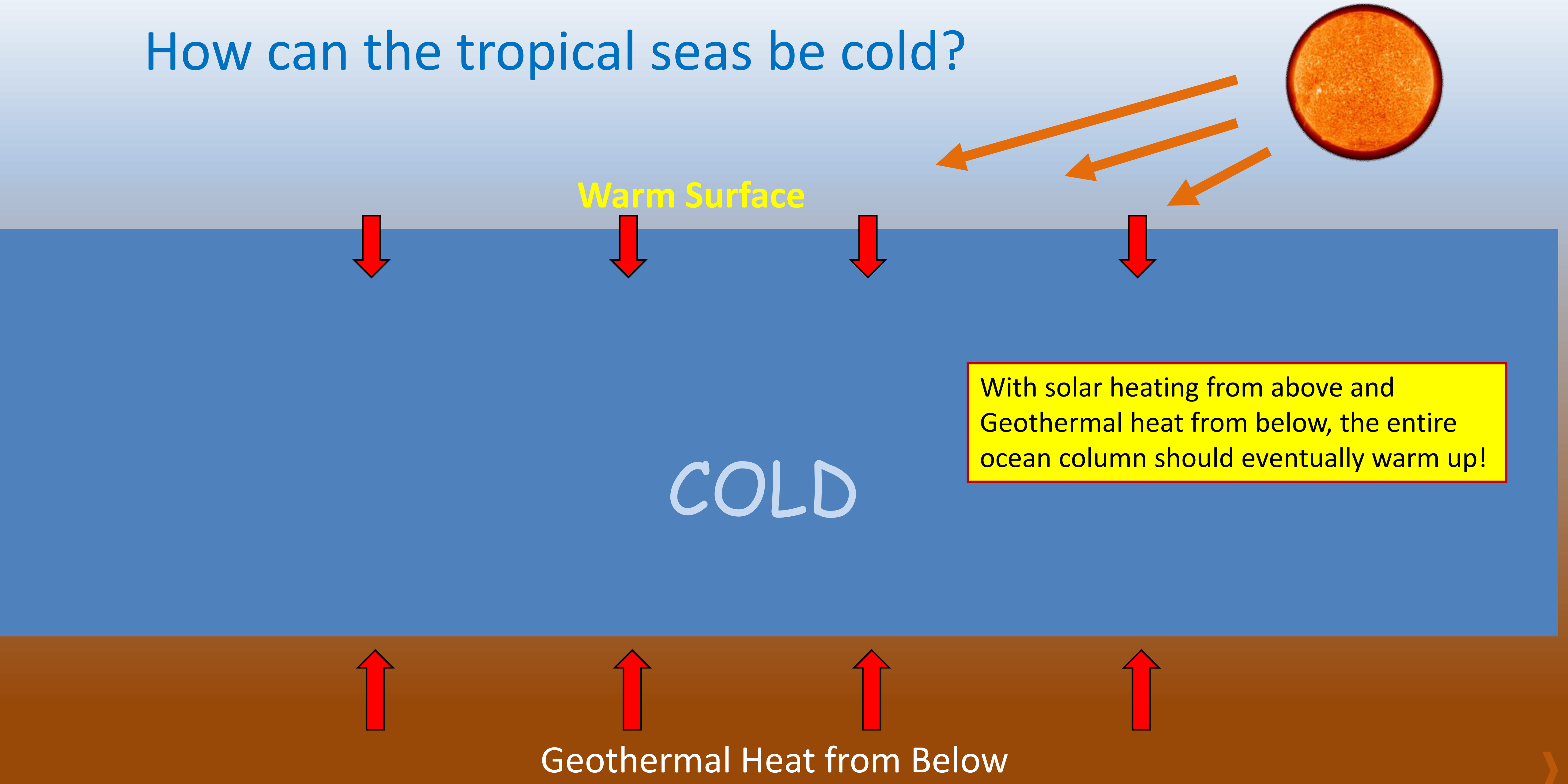


The Deep Ocean is Cold

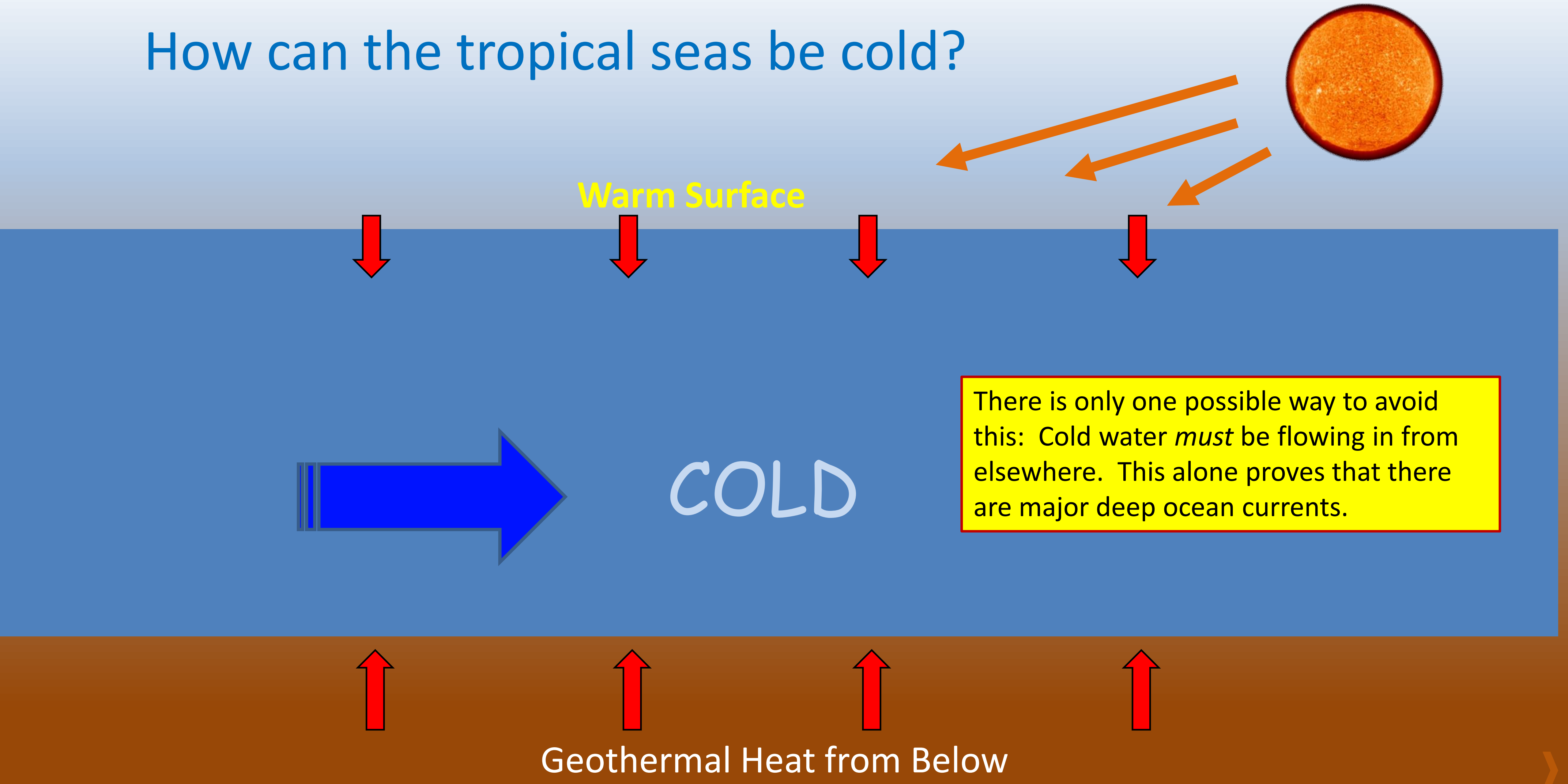




How can the tropical seas be cold?

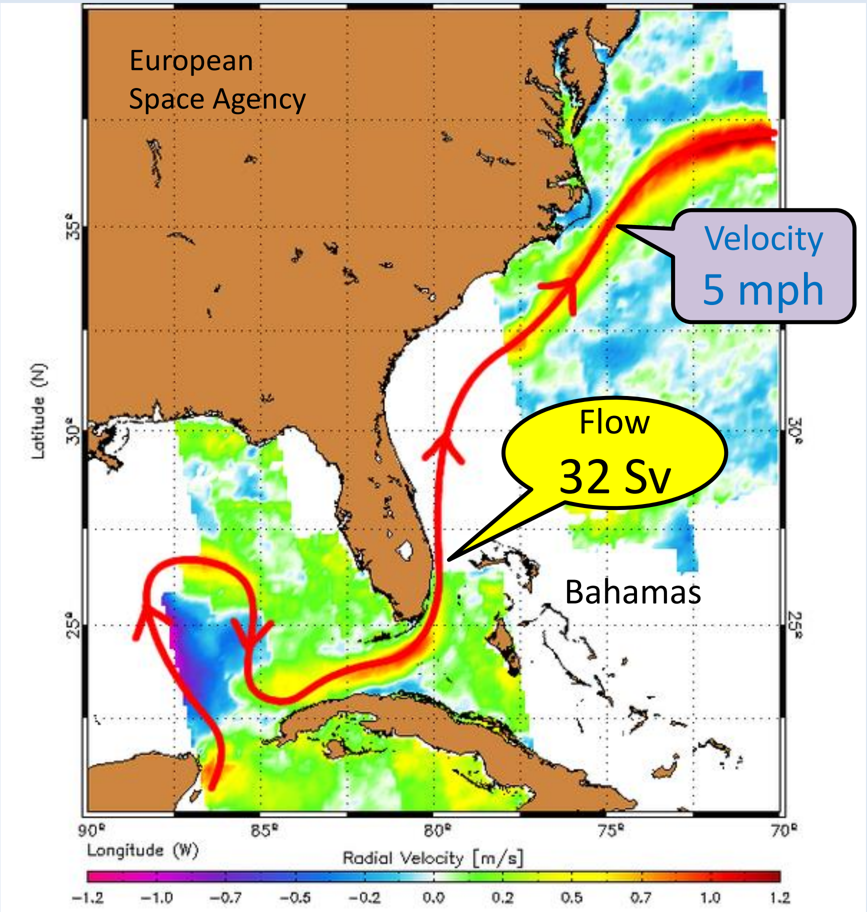


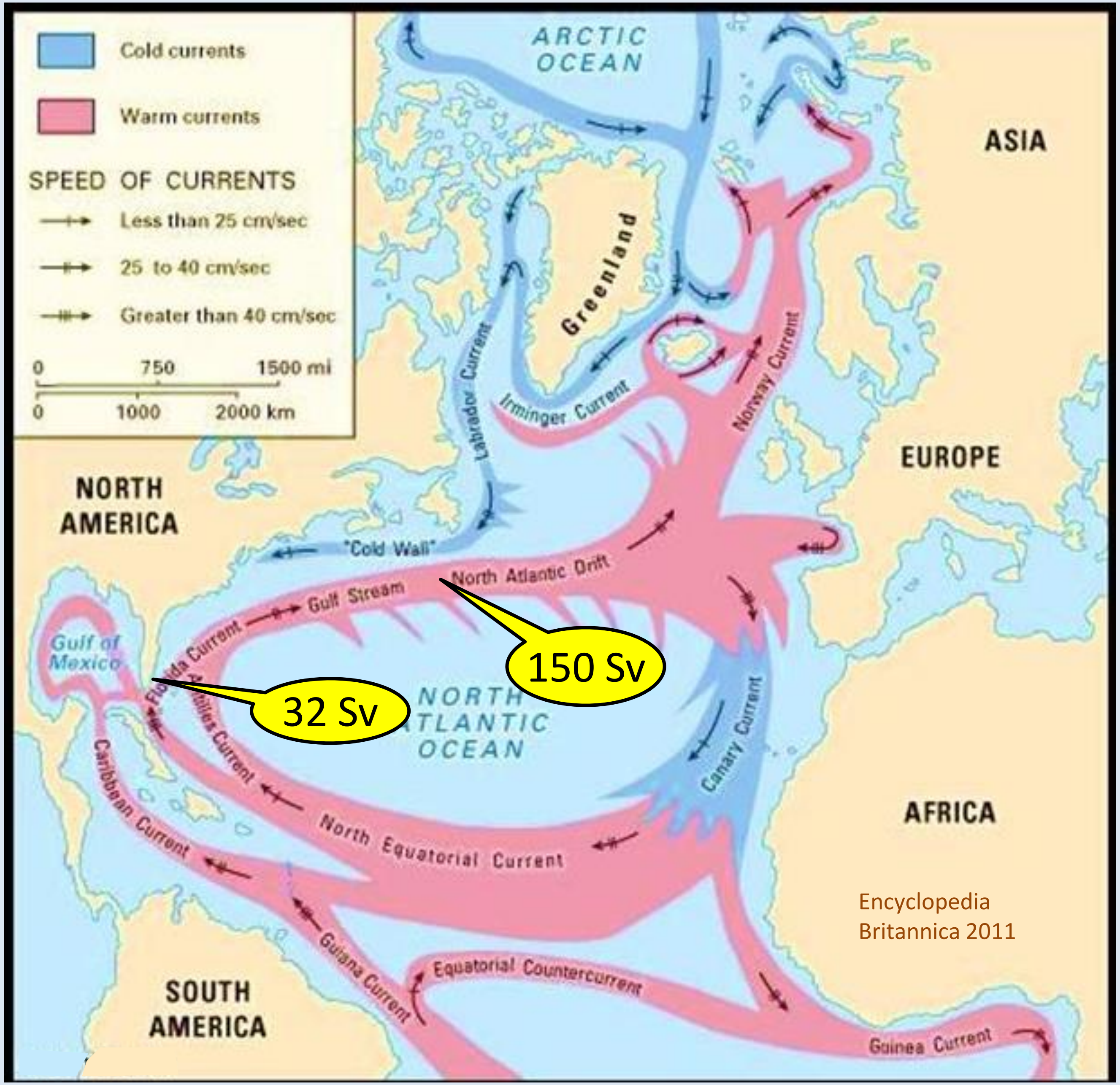
How can the tropical seas be cold?



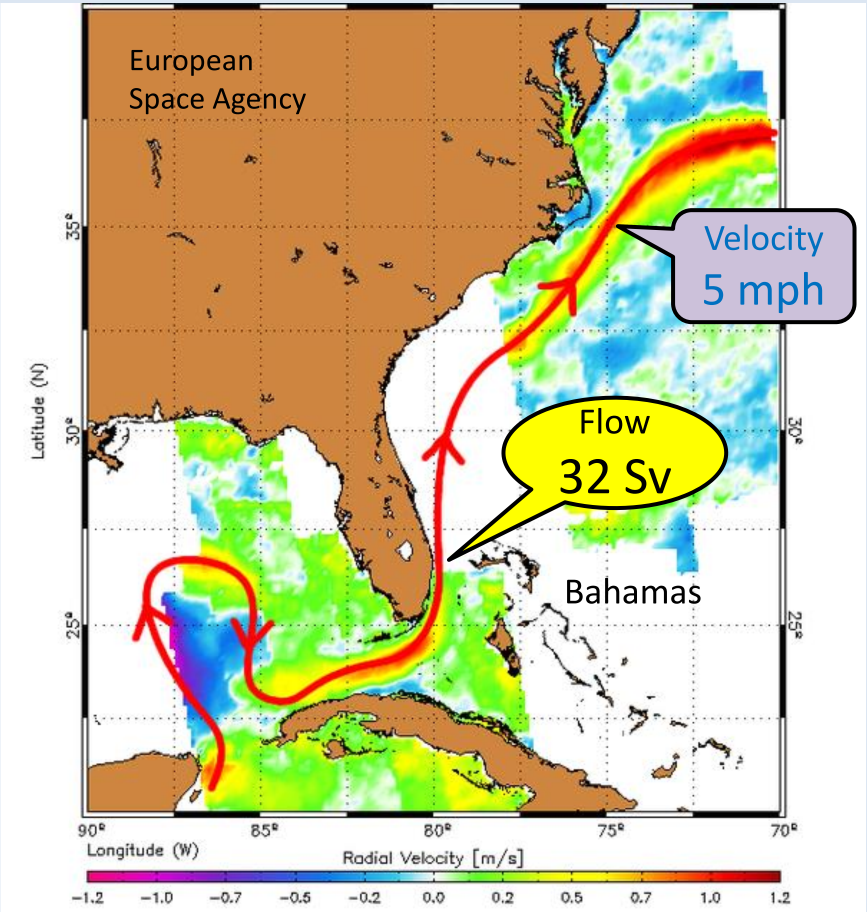
There is only one possible way to avoid this: Cold water *must* be flowing in from elsewhere. This alone proves that there are major deep ocean currents.

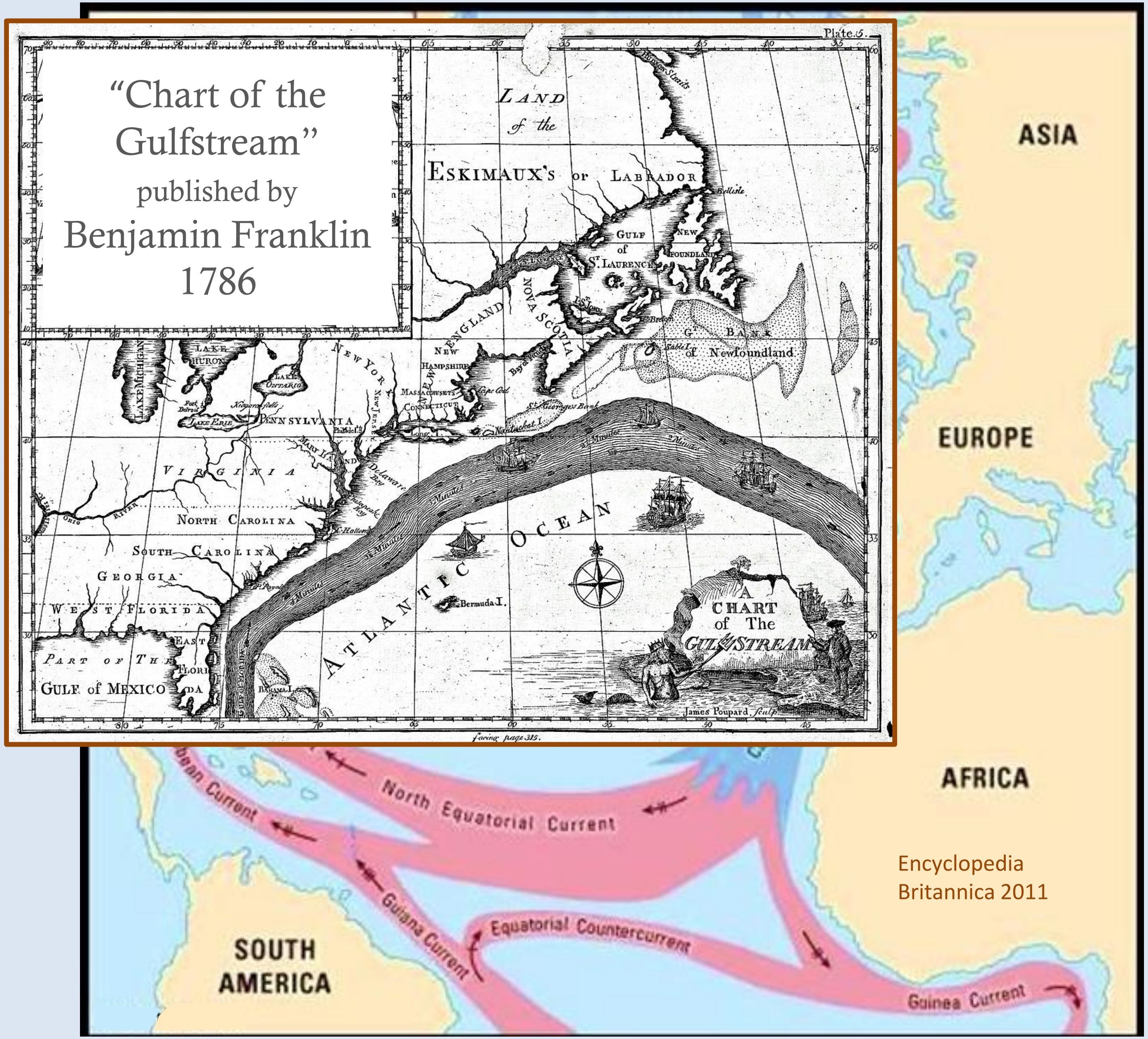
Surface Currents in North Atlantic





Surface Currents in North Atlantic



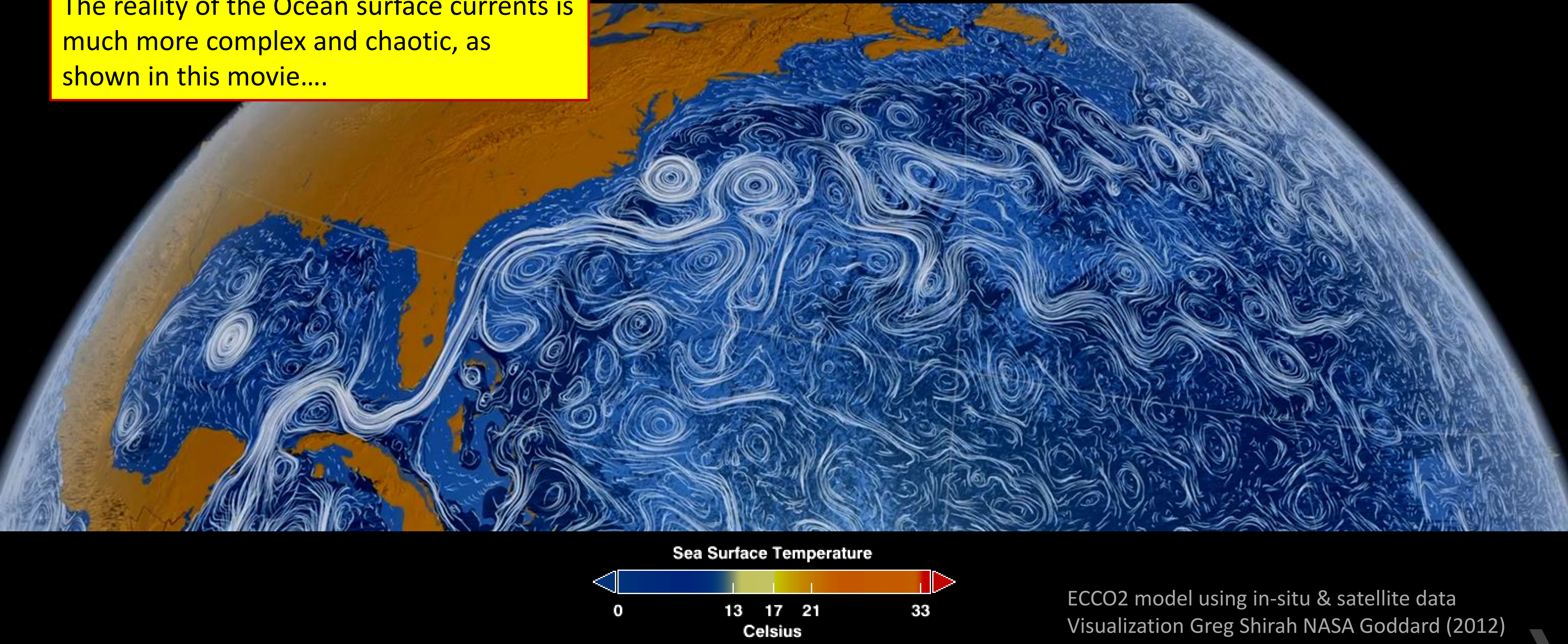


Encyclopedia
Britannica 2011

Visualization of Gulf Stream Eddies (NASA/MIT/JPL)

June 2005 → December 2007

The reality of the Ocean surface currents is much more complex and chaotic, as shown in this movie….

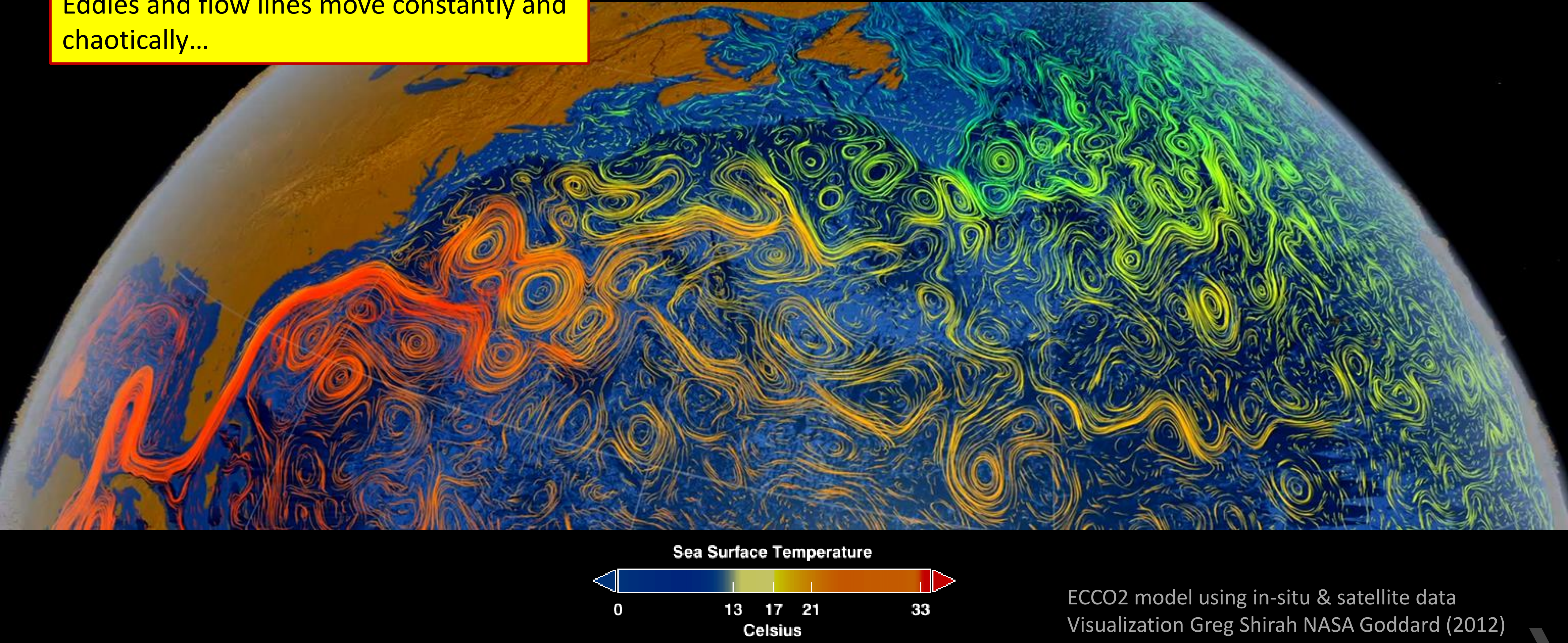


ECCO2 model using in-situ & satellite data
Visualization Greg Shirah NASA Goddard (2012)

Visualization of Gulf Stream Eddies (NASA/MIT/JPL)

June 2005 → December 2007

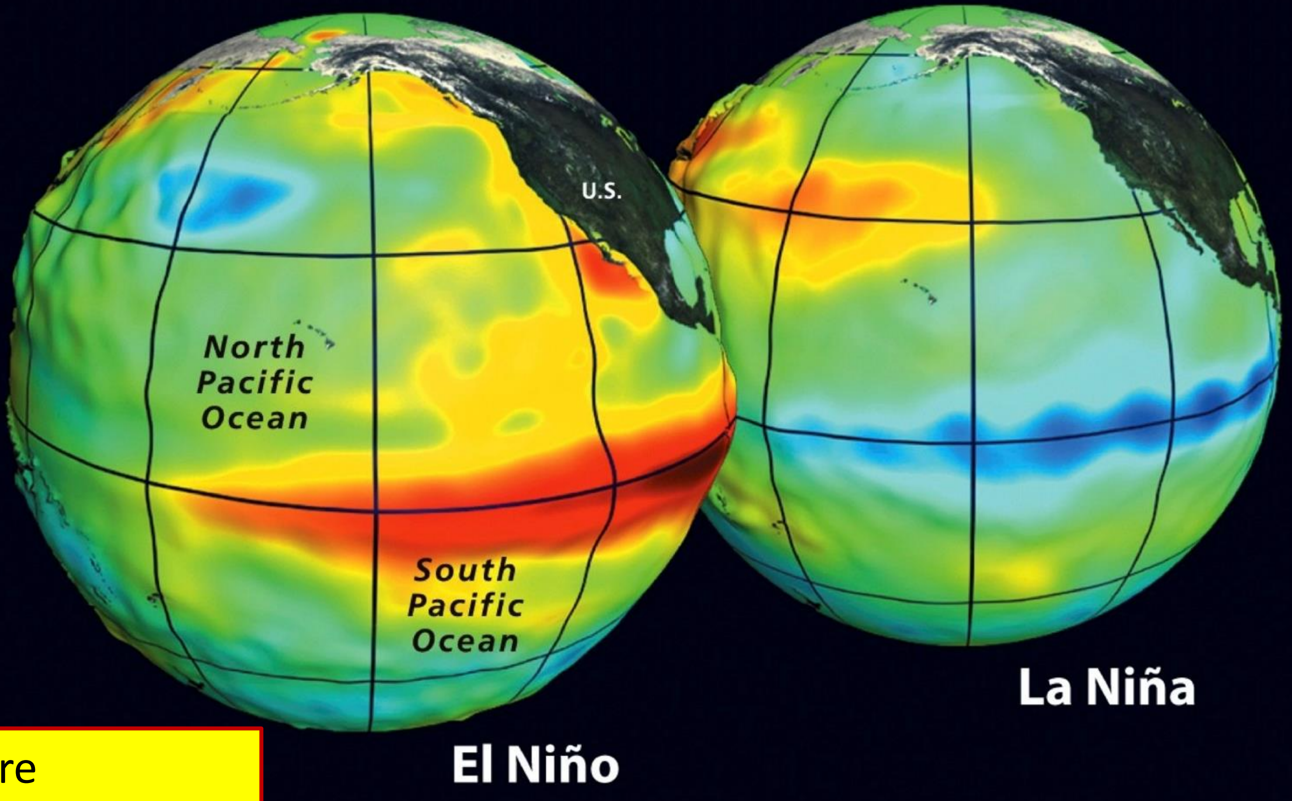
Eddies and flow lines move constantly and chaotically…



ECCO2 model using in-situ & satellite data
Visualization Greg Shirah NASA Goddard (2012)

Coupled Atmosphere-Ocean Modes: ENSO

El Niño Southern Oscillation

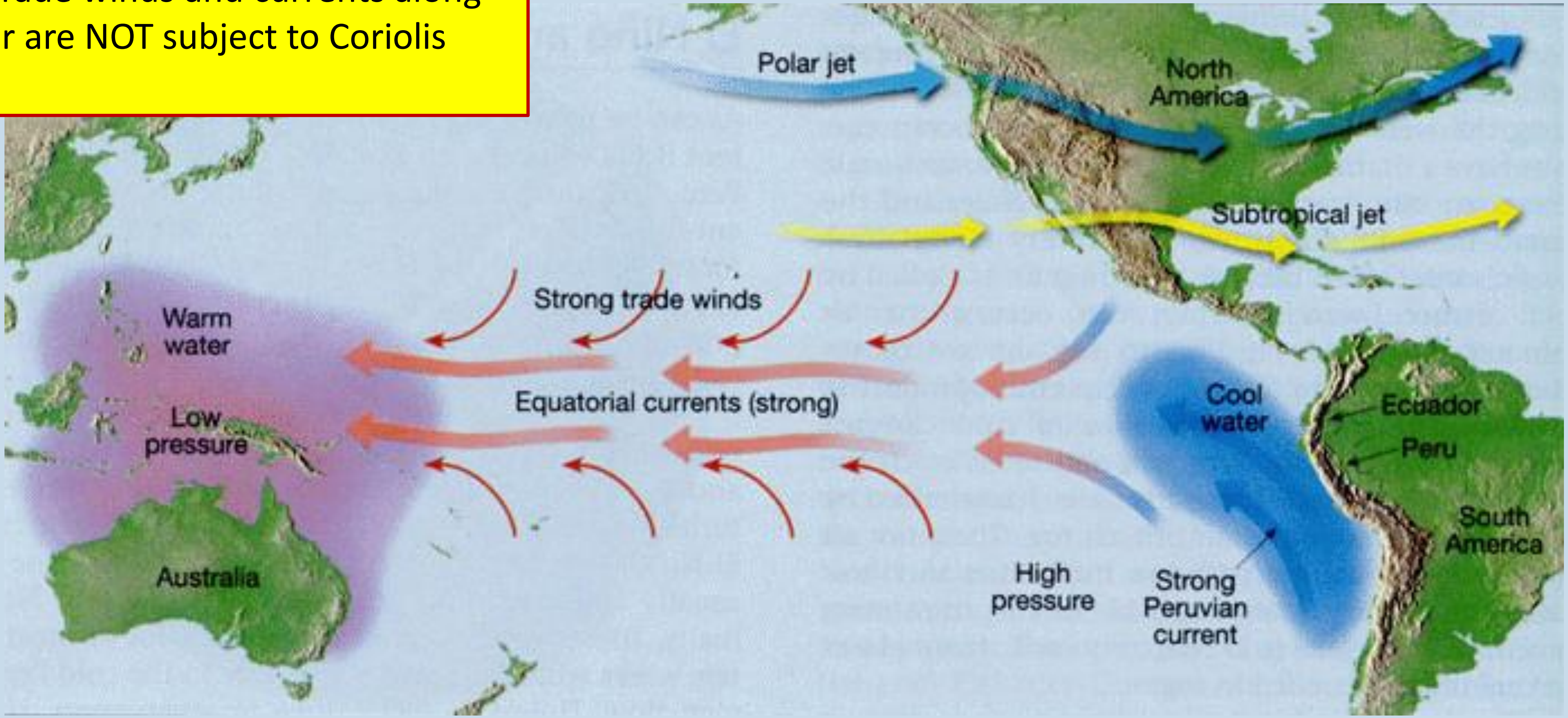


Red means positive temperature anomalies, blue negative anomalies… Bulges represent sea level variations.

G.Shirah, NASA Scientific Visualization

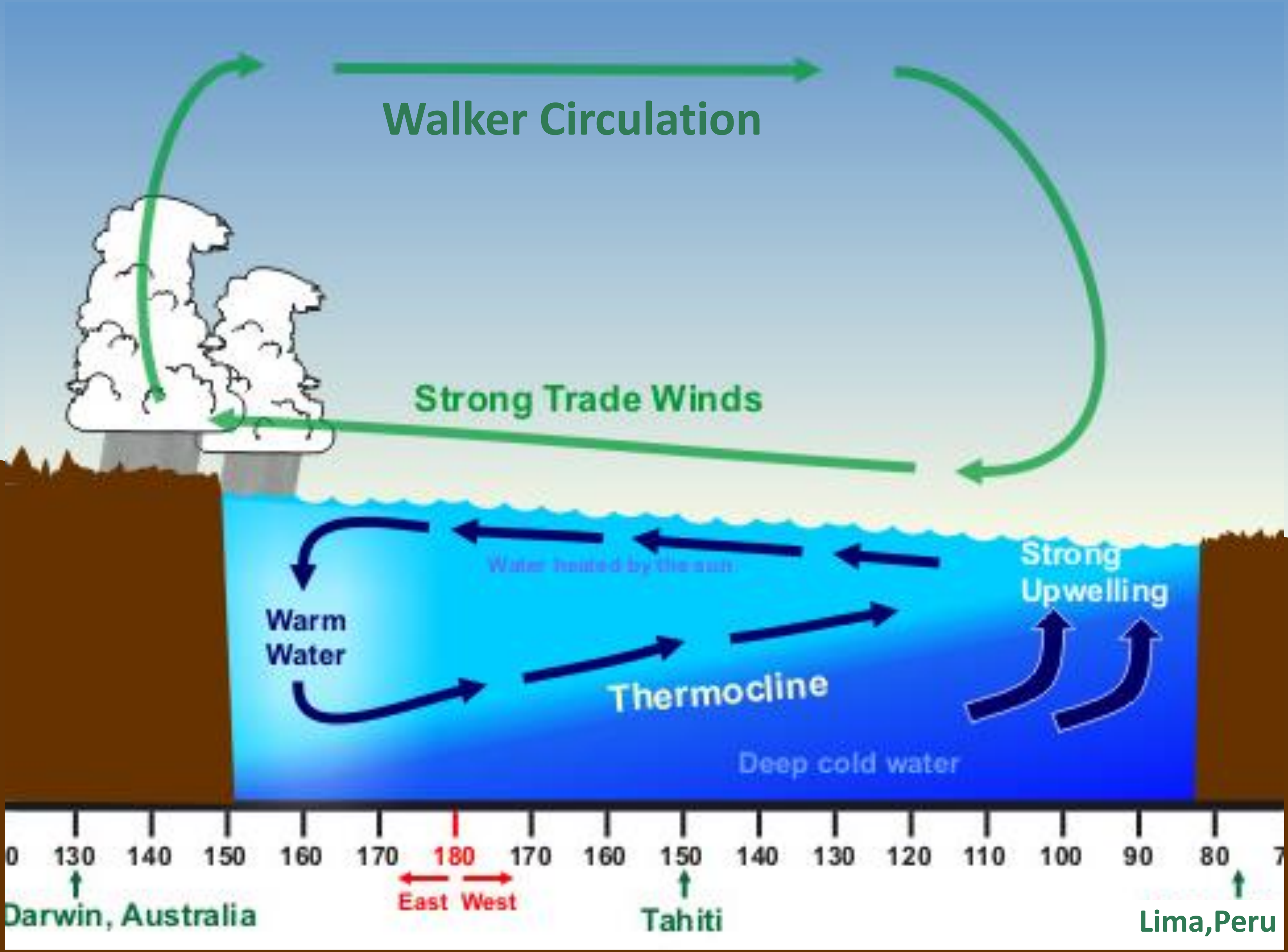
ENSO*: The Normal Situation in the Pacific

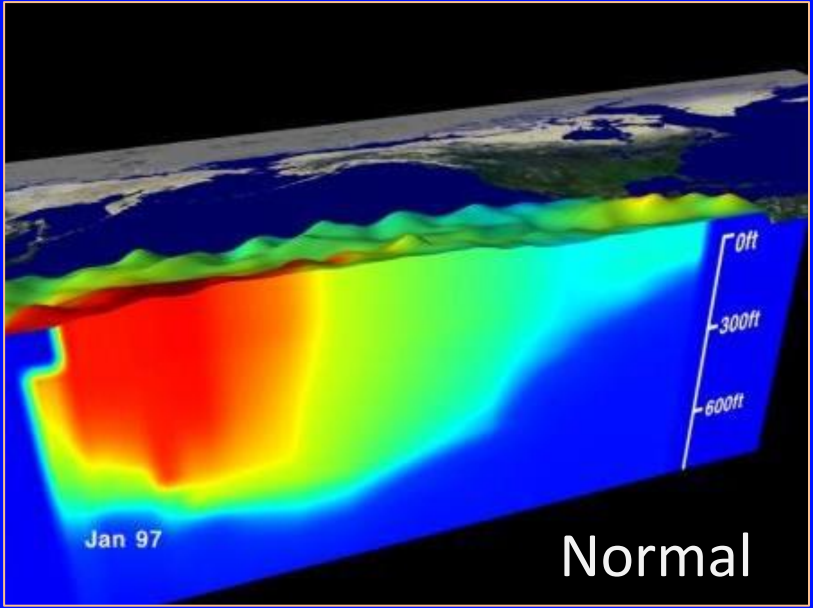
Note that trade winds and currents along the equator are NOT subject to Coriolis forces!

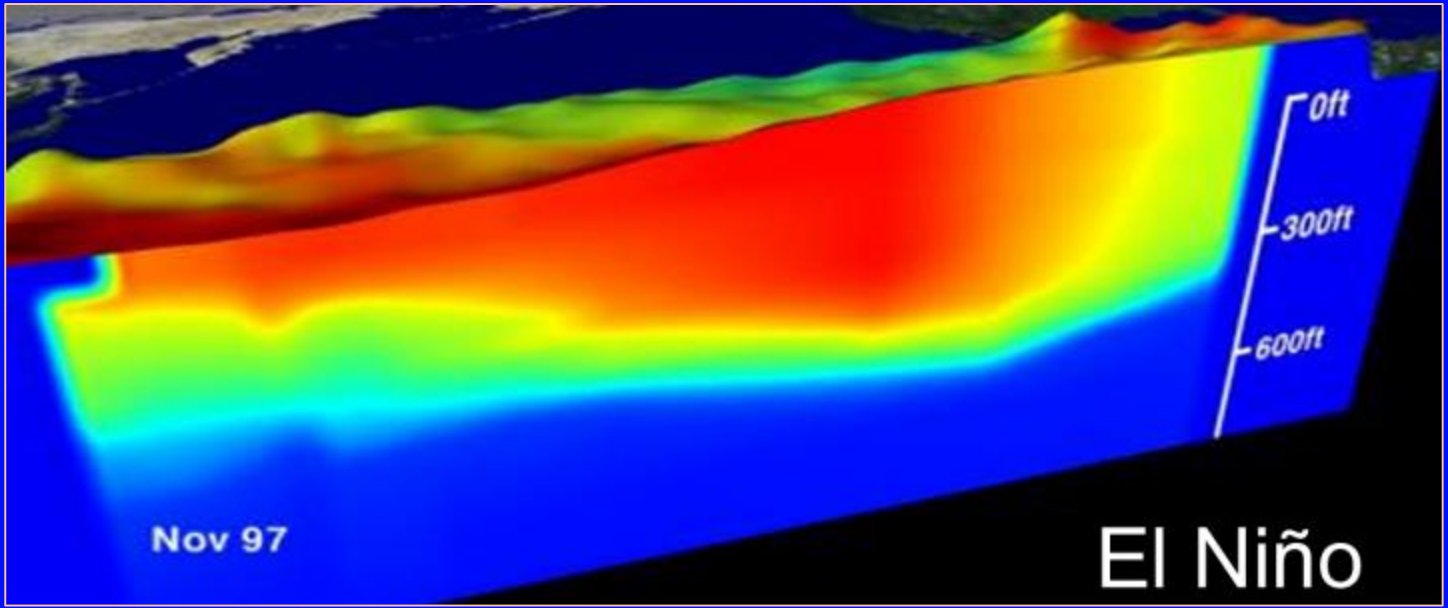


* **E**l **N**iño **S**outhern **O**scillation

ENSO Normal Status
(Side View)







ENSO Surface Height and Temperature Profiles

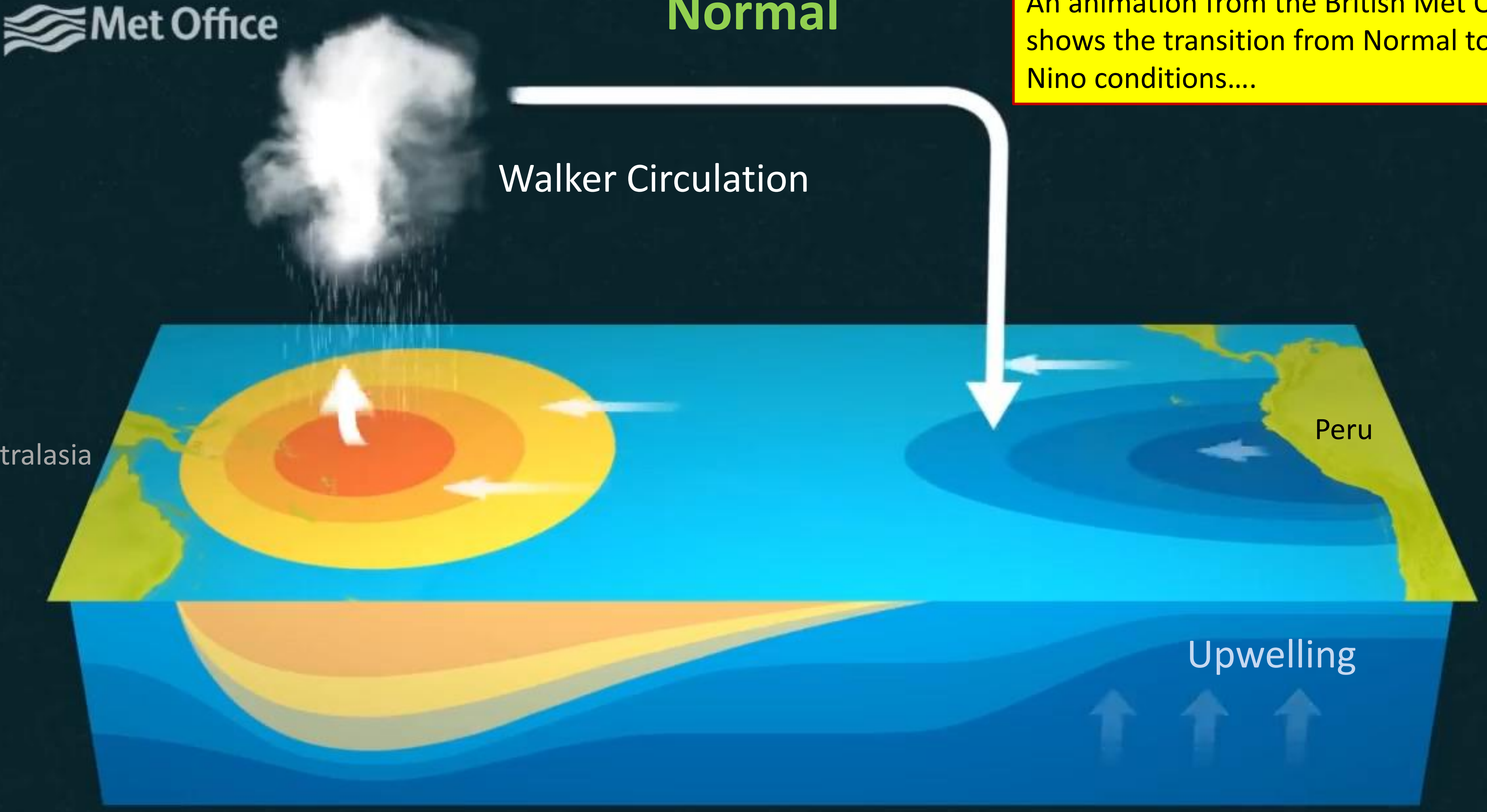
Ocean Surface Height
- *NASA TOPEX satellite*

Surface Temperature
- *NASA AVHRR Satellite Sensor*

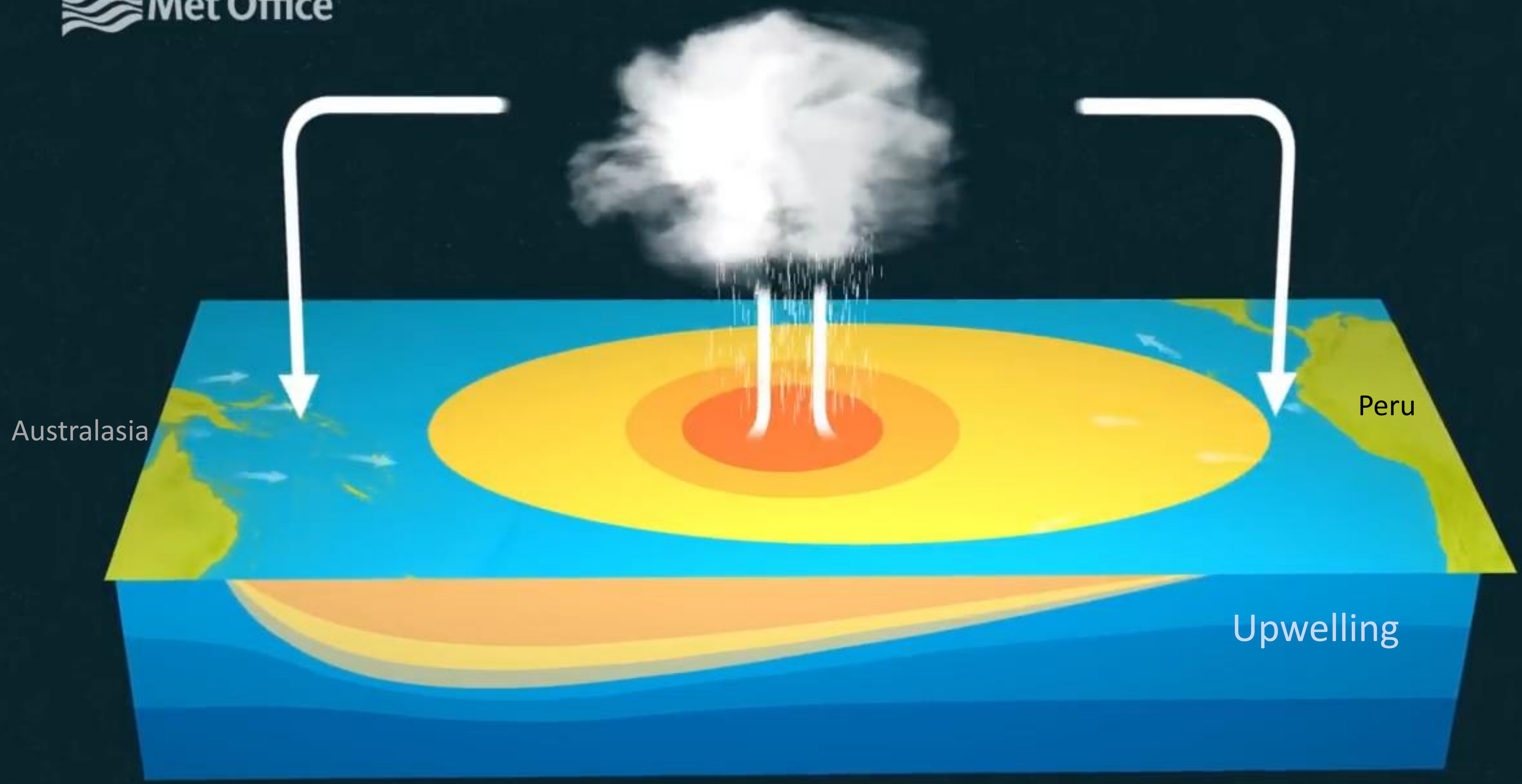
Subsurface Temperatures
- *NOAA TAO moored buoys*

Normal

An animation from the British Met Office shows the transition from Normal to El Nino conditions….



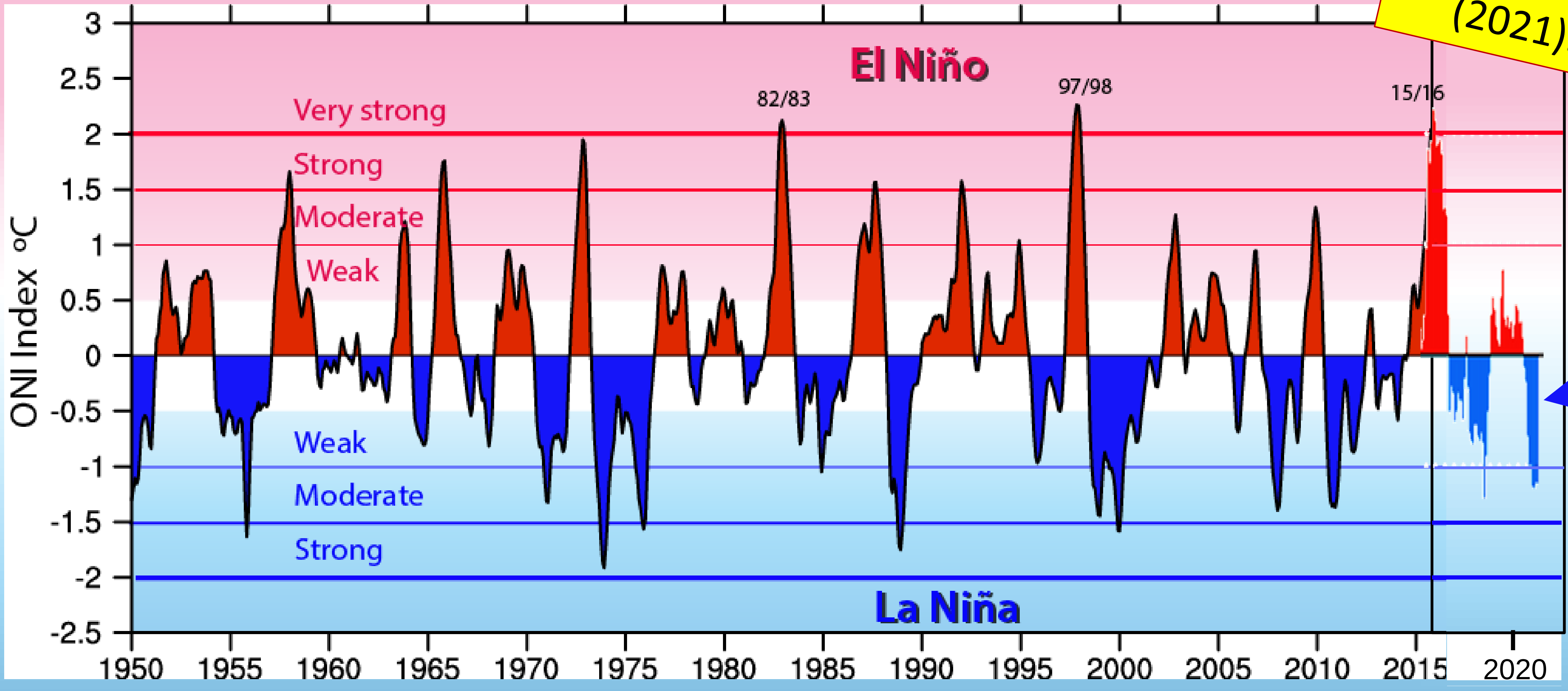
El Niño



ENSO Events are Quasi-Periodic

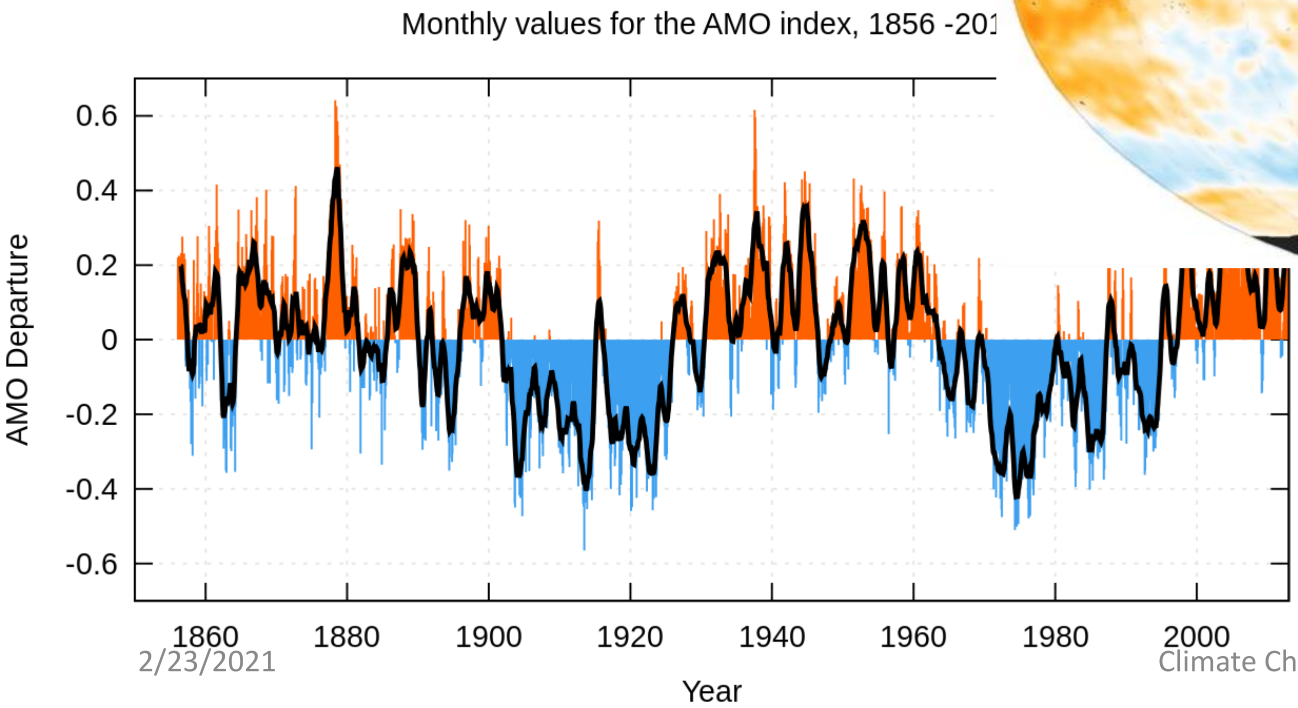
They tend to peak around Christmas time

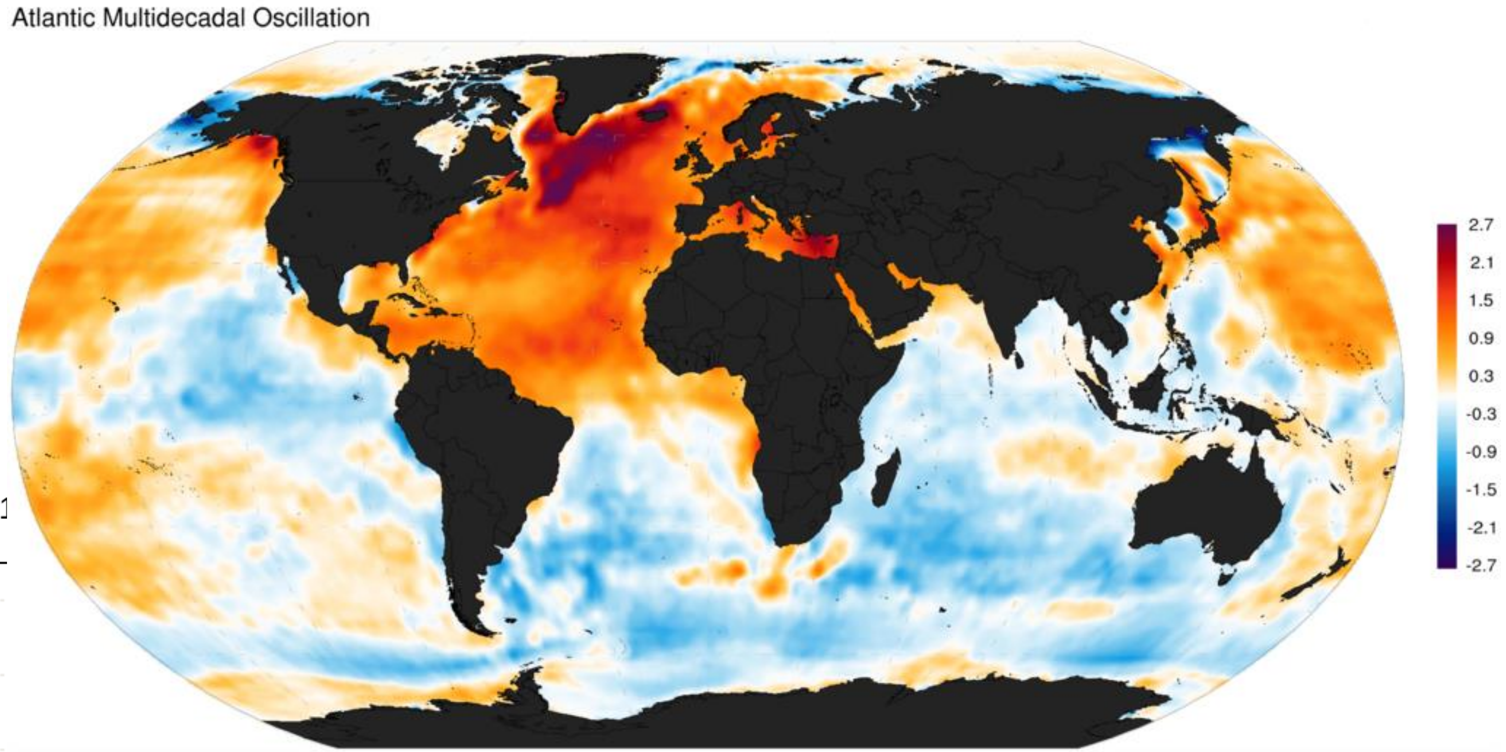
We're in a weak La Niña right now (2021)…



Atlantic Multidecadal Oscillation (AMO)

Surface Sea Temperature in non-tropical North Atlantic *with global trends removed*

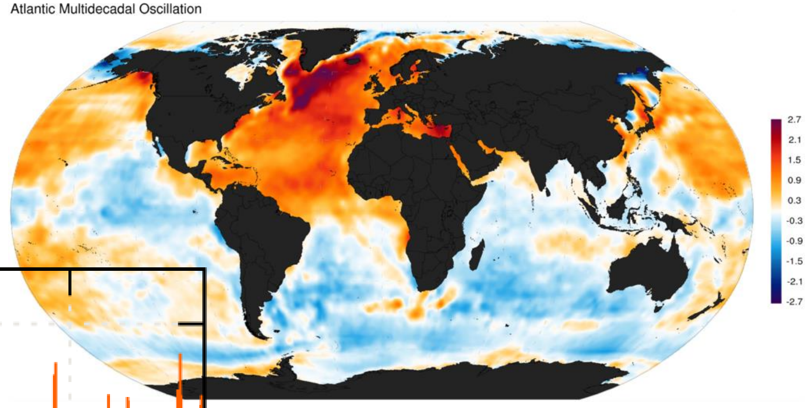




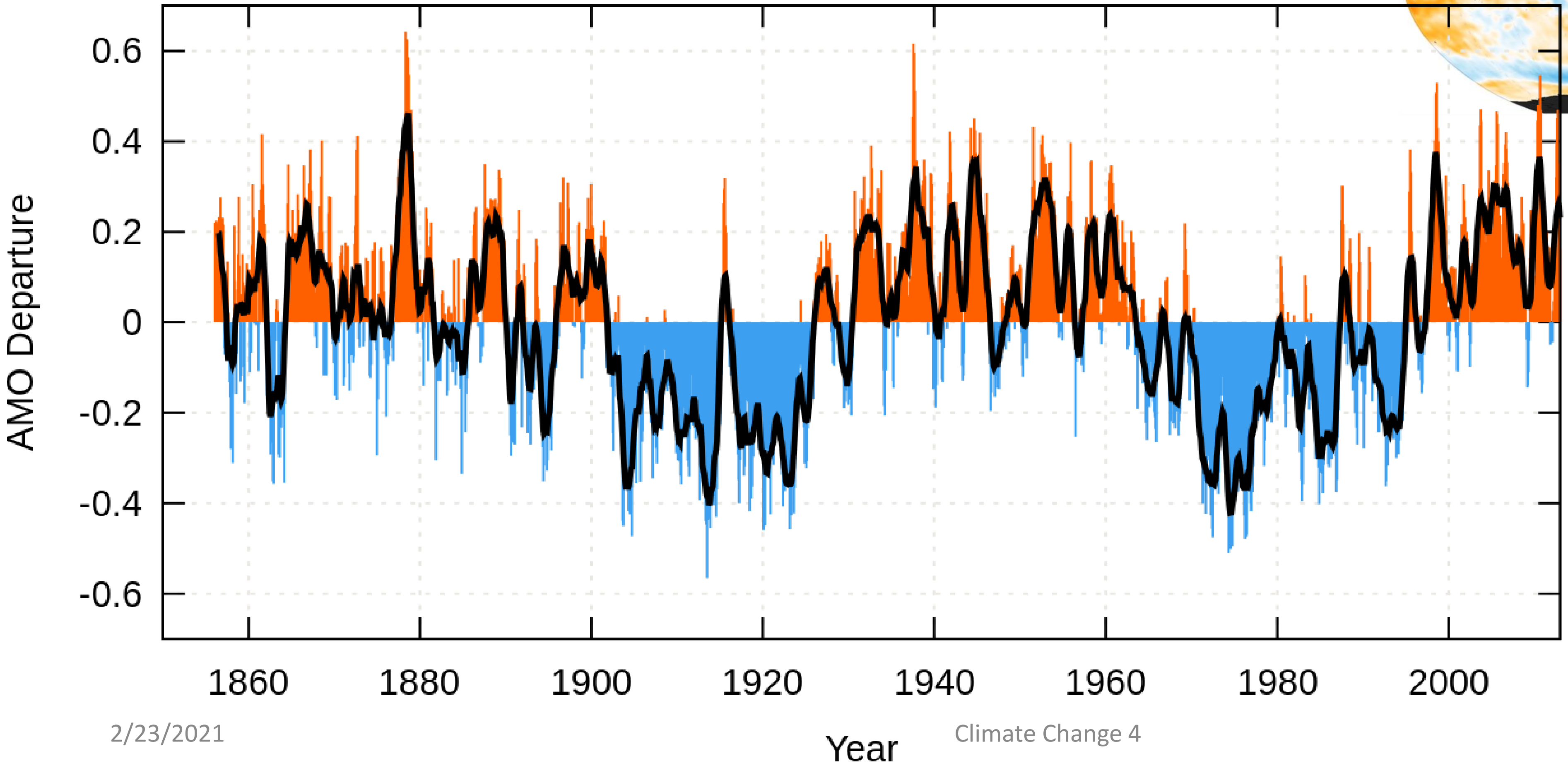
Note the weak ~50 year cycle. There are others like this around the world.

Atlantic Multidecadal Oscillation (AMO)

Surface Sea Temperature in
non-tropical North Atlantic
with global trends removed



Monthly values for the AMO index, 1856 -2013



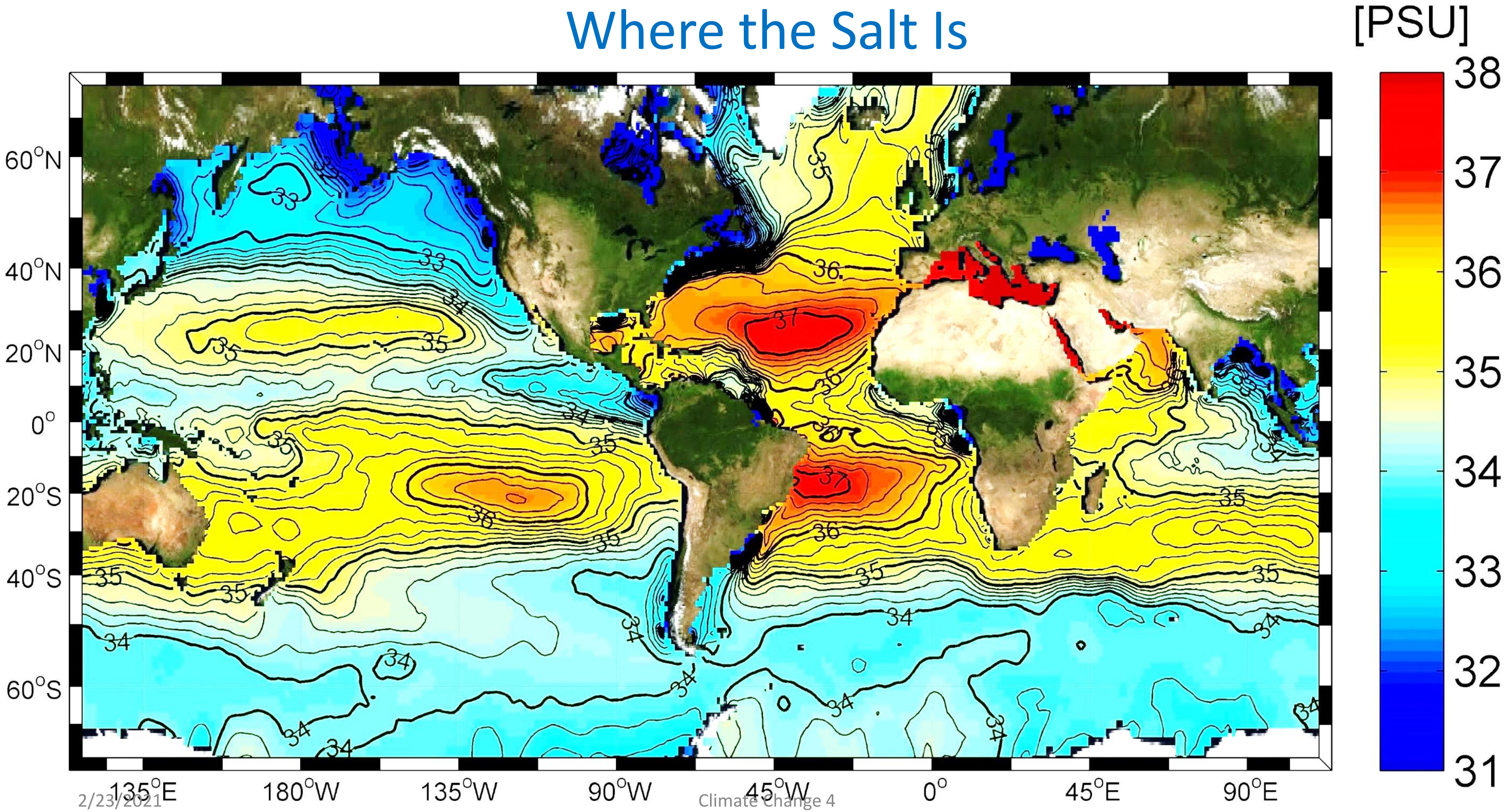
What Moves Ocean Water?

1. Winds
   – Modified by Coriolis Forces
   – Near the surface only

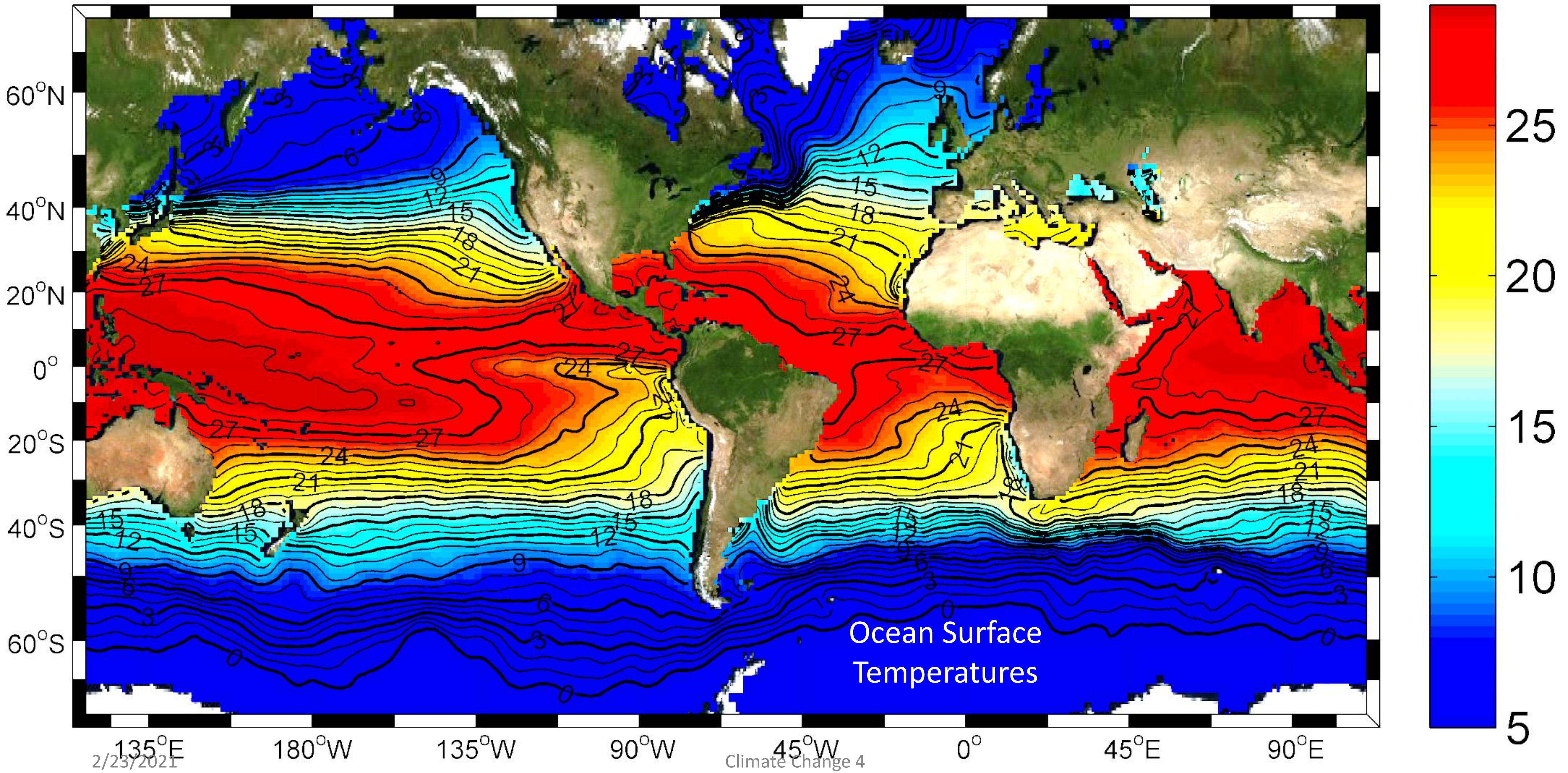
2. Density Differences
   – Colder = heavier
   – Saltier = heavier
   – “**Thermohaline** Circulation”

- *Or* Combinations of the two.

Where the Salt Is



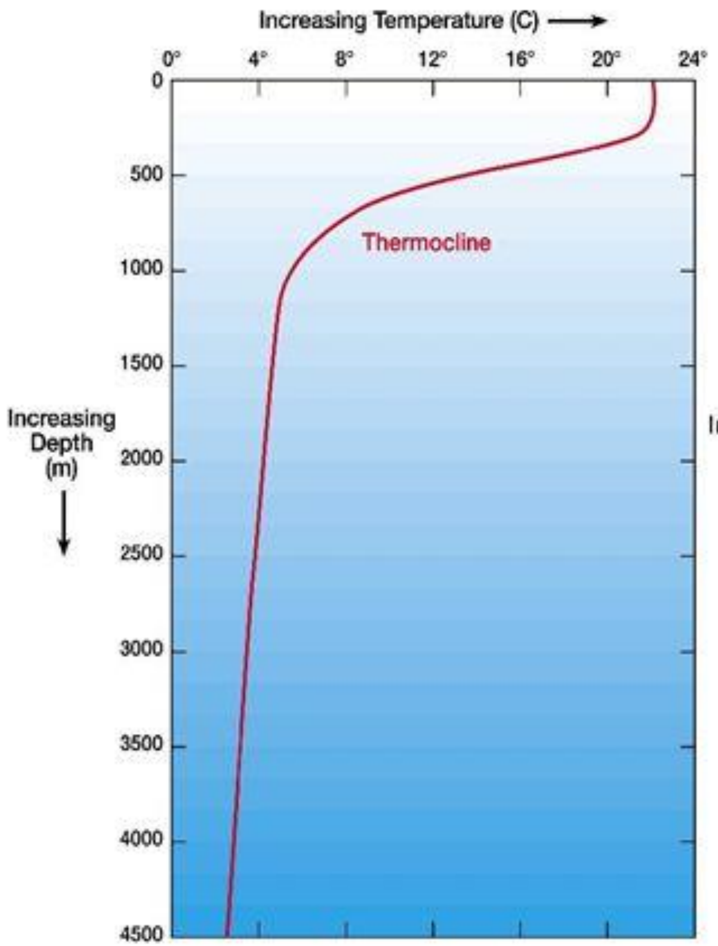
Where the Heat Is



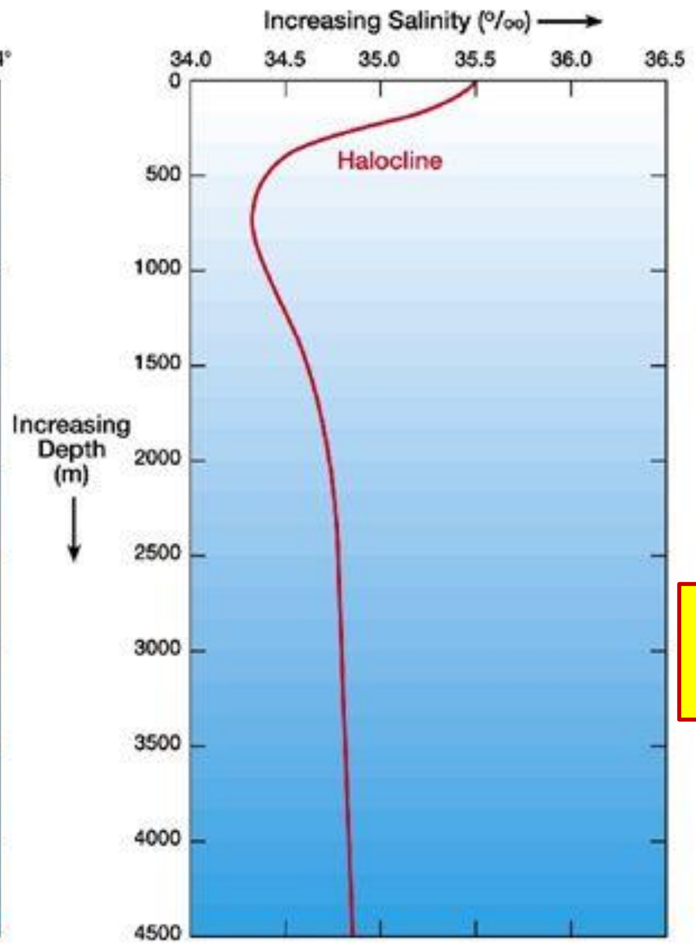
Depth Profiles

How do temperature and salinity contribute to density?

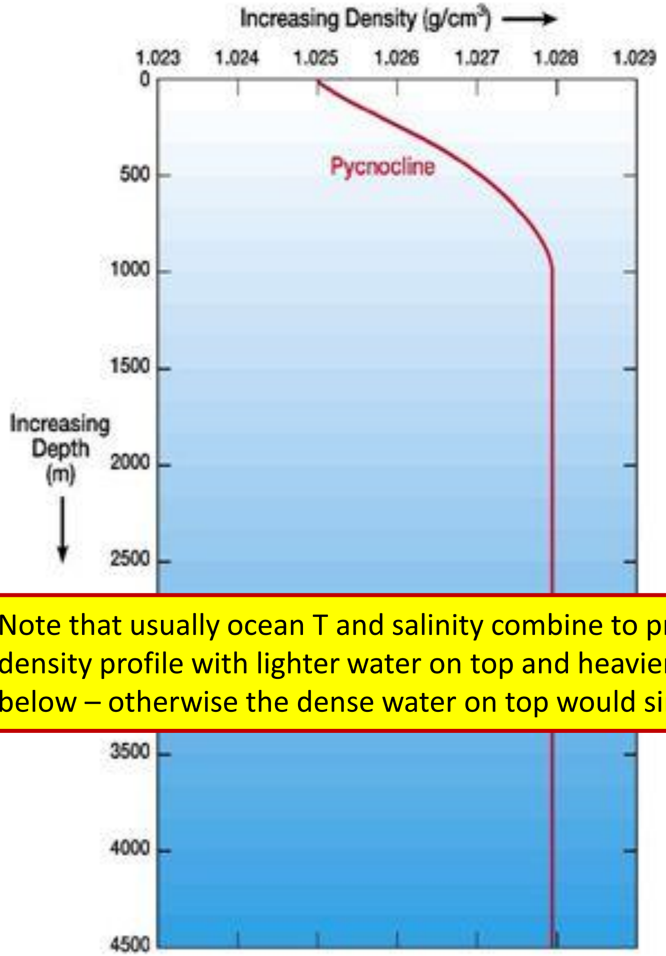
Temperature



Salinity



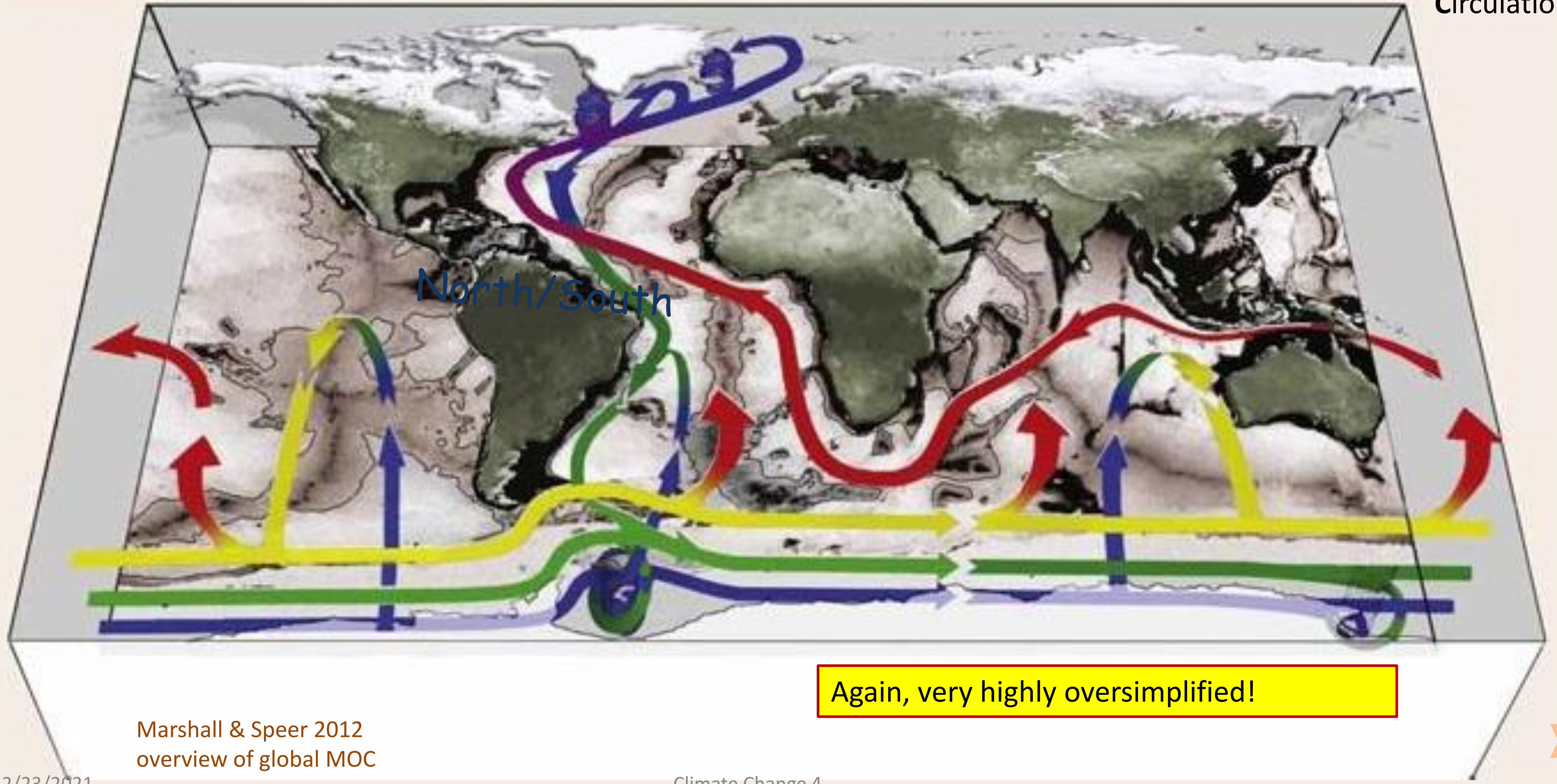
Density



Note that usually ocean T and salinity combine to produce a density profile with lighter water on top and heavier water below – otherwise the dense water on top would sink.

Global Thermohaline Circulation: MOC*

* **M**eridional **O**verturning **C**irculation



Again, very highly oversimplified!

Marshall & Speer 2012
overview of global MOC

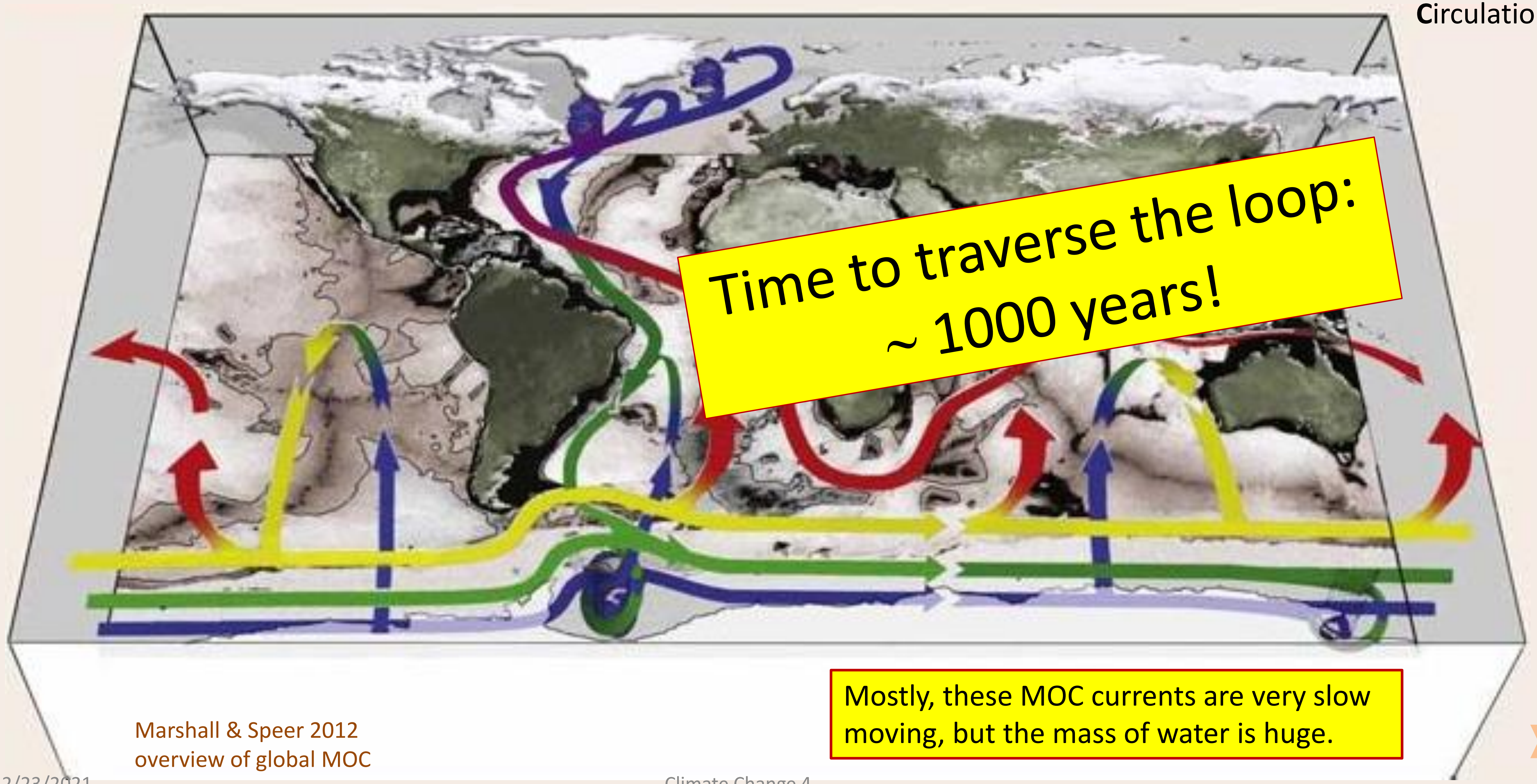
Global Thermohaline Circulation: MOC*

* **M**eridional **O**verturning **C**irculation

Marshall & Speer 2012
overview of global MOC

Global Thermohaline Circulation: MOC*

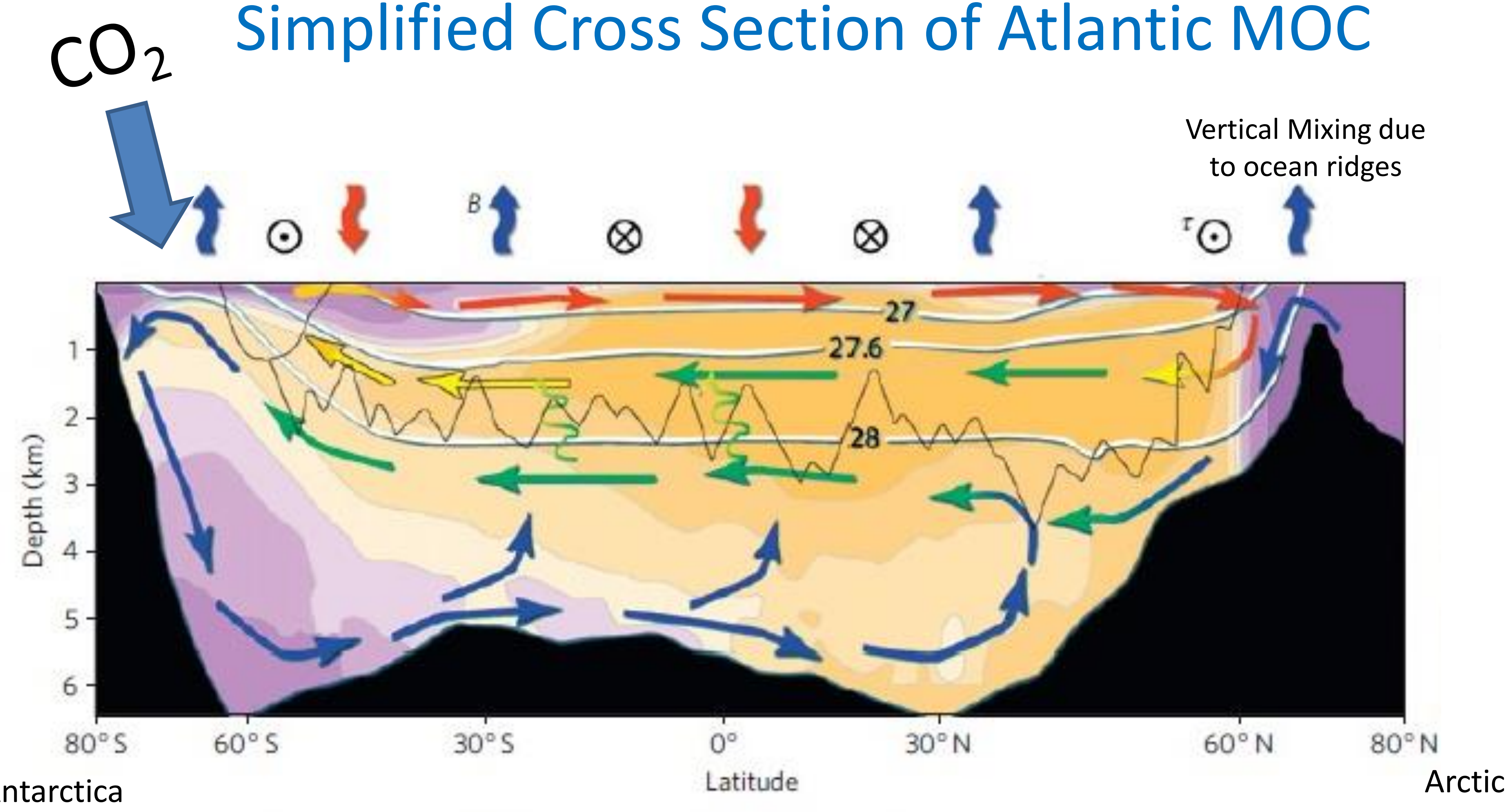
* **M**eridional **O**verturning **C**irculation



Mostly, these MOC currents are very slow moving, but the mass of water is huge.

Marshall & Speer 2012 overview of global MOC

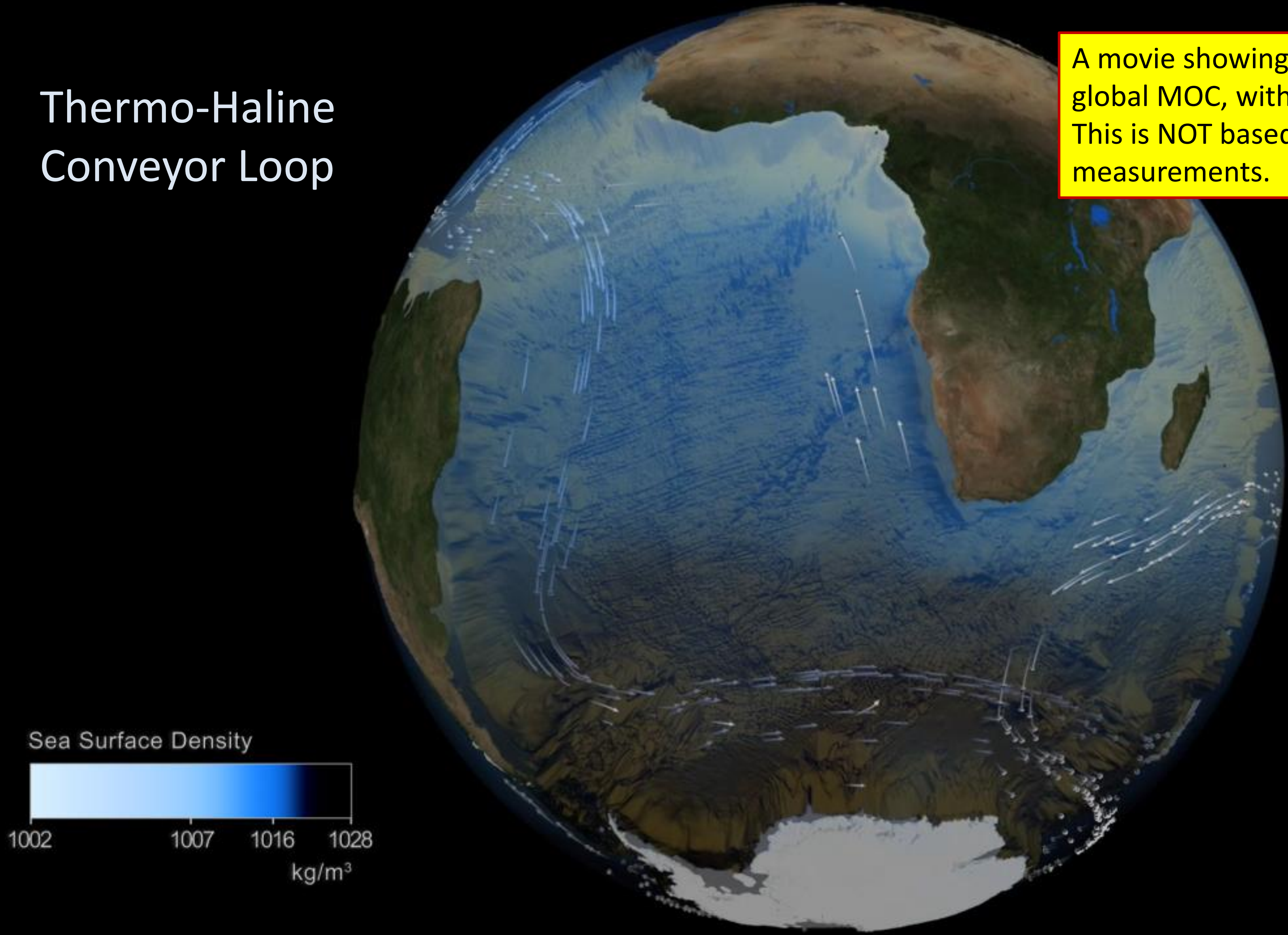
Simplified Cross Section of Atlantic MOC



Marshall & Speer
Nature Geoscience (2012)

Thermo-Haline Conveyor Loop

A movie showing general features of the global MOC, with lots of artistic license. This is NOT based much on detailed measurements.



NASA Visualization Studio

Hollywood Tackles the AMOC*….

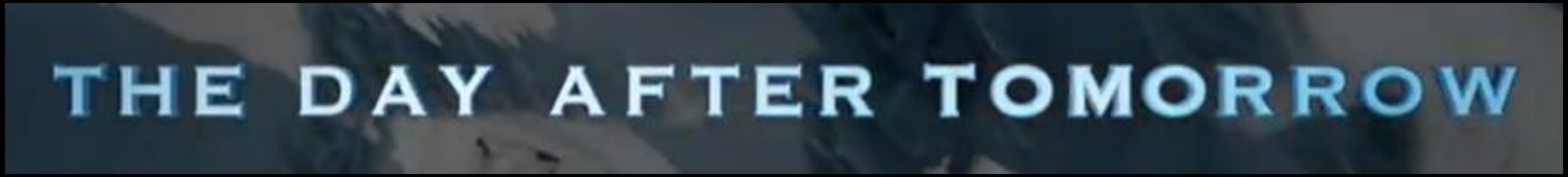
* Atlantic Meridional Overturning Circulation

Could the AMOC stop, plunging Europe and North Atlantic into freezing?

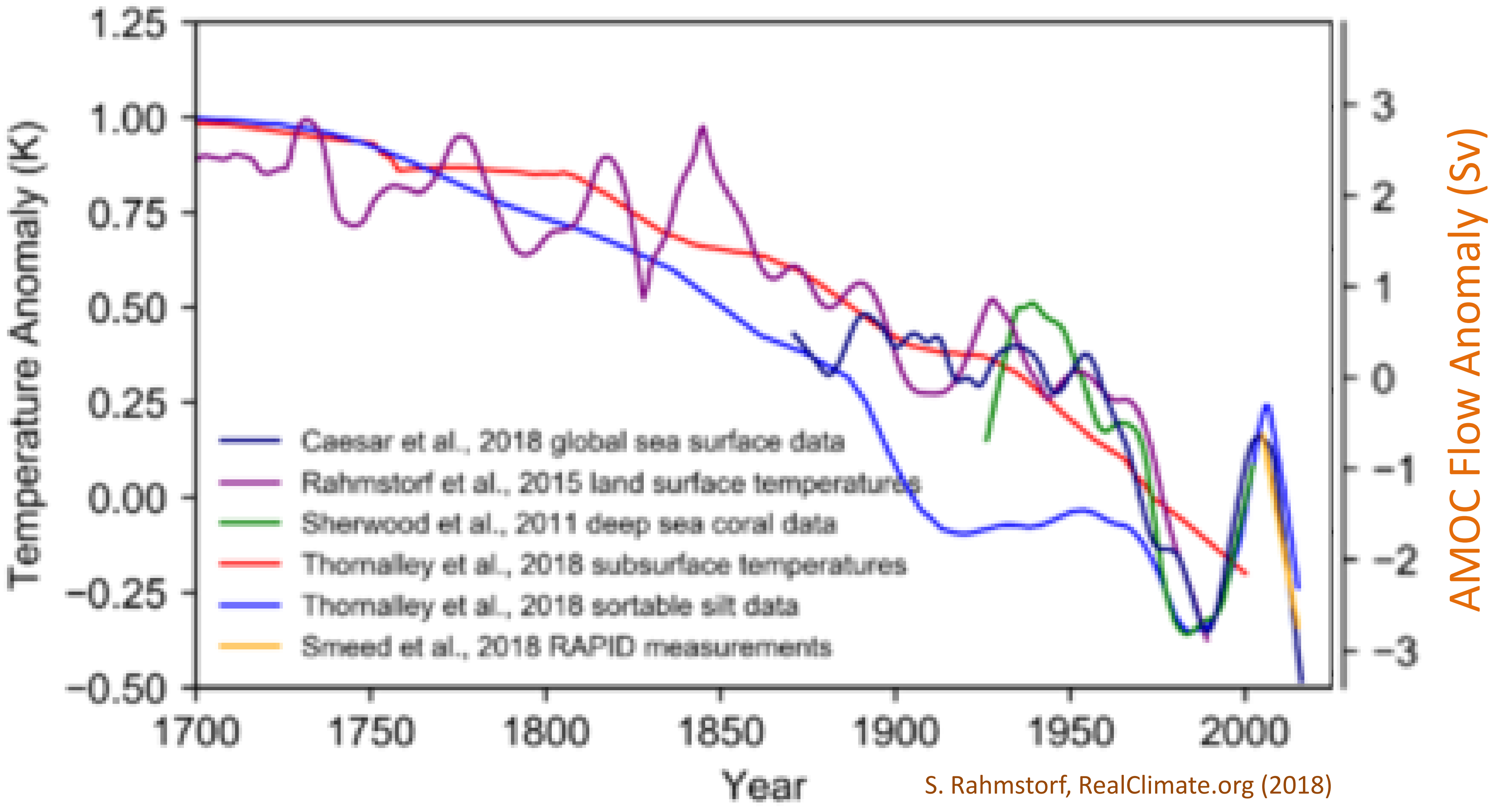
2004

…you recall what you said about how polar melting might disrupt the North Atlantic current?


"What can we do?"
"Save as many as you can…"

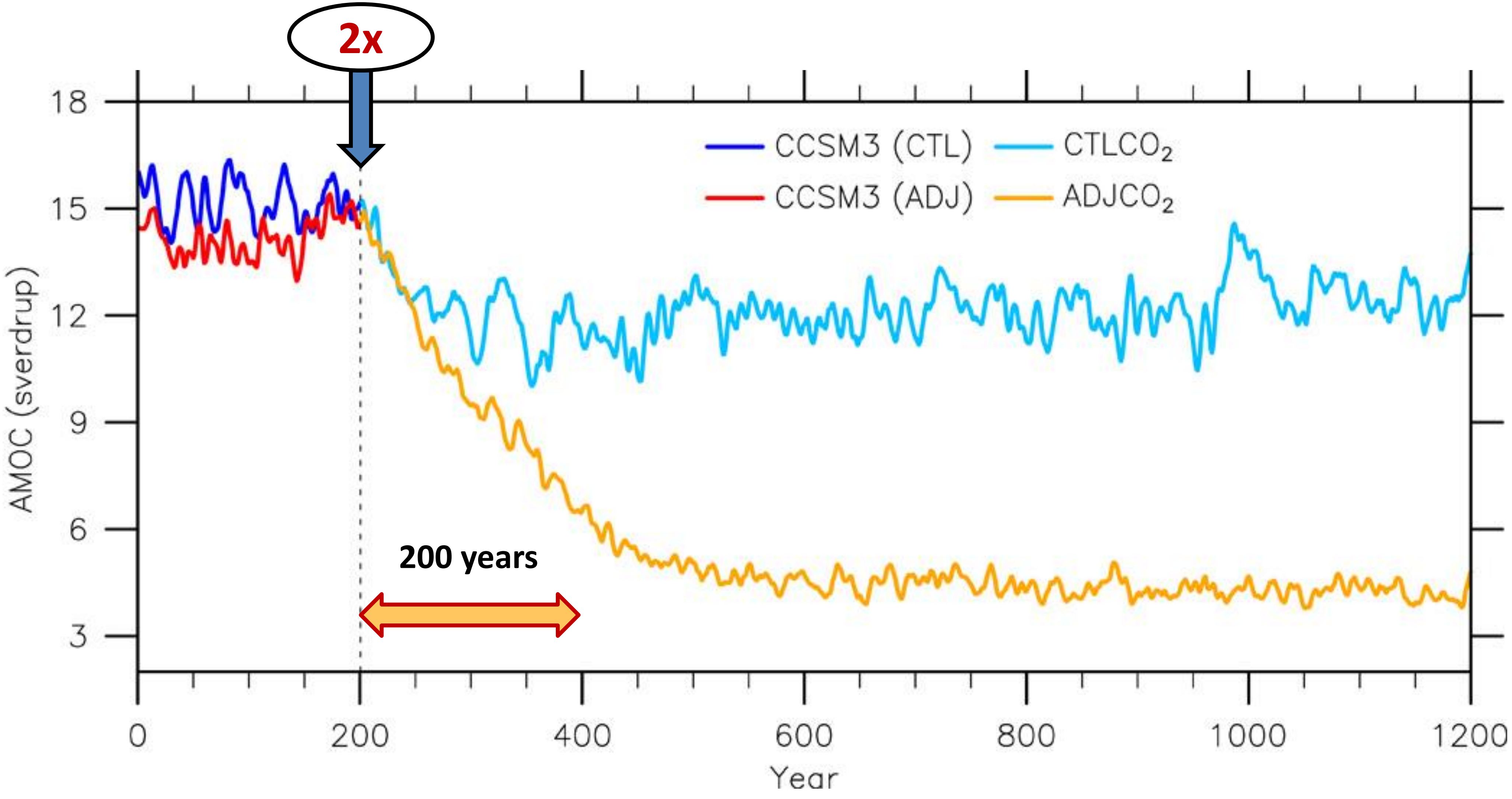

THE DAY AFTER TOMORROW

AMOC Has Decreased 3 Sverdrups (~15%) in 150 years



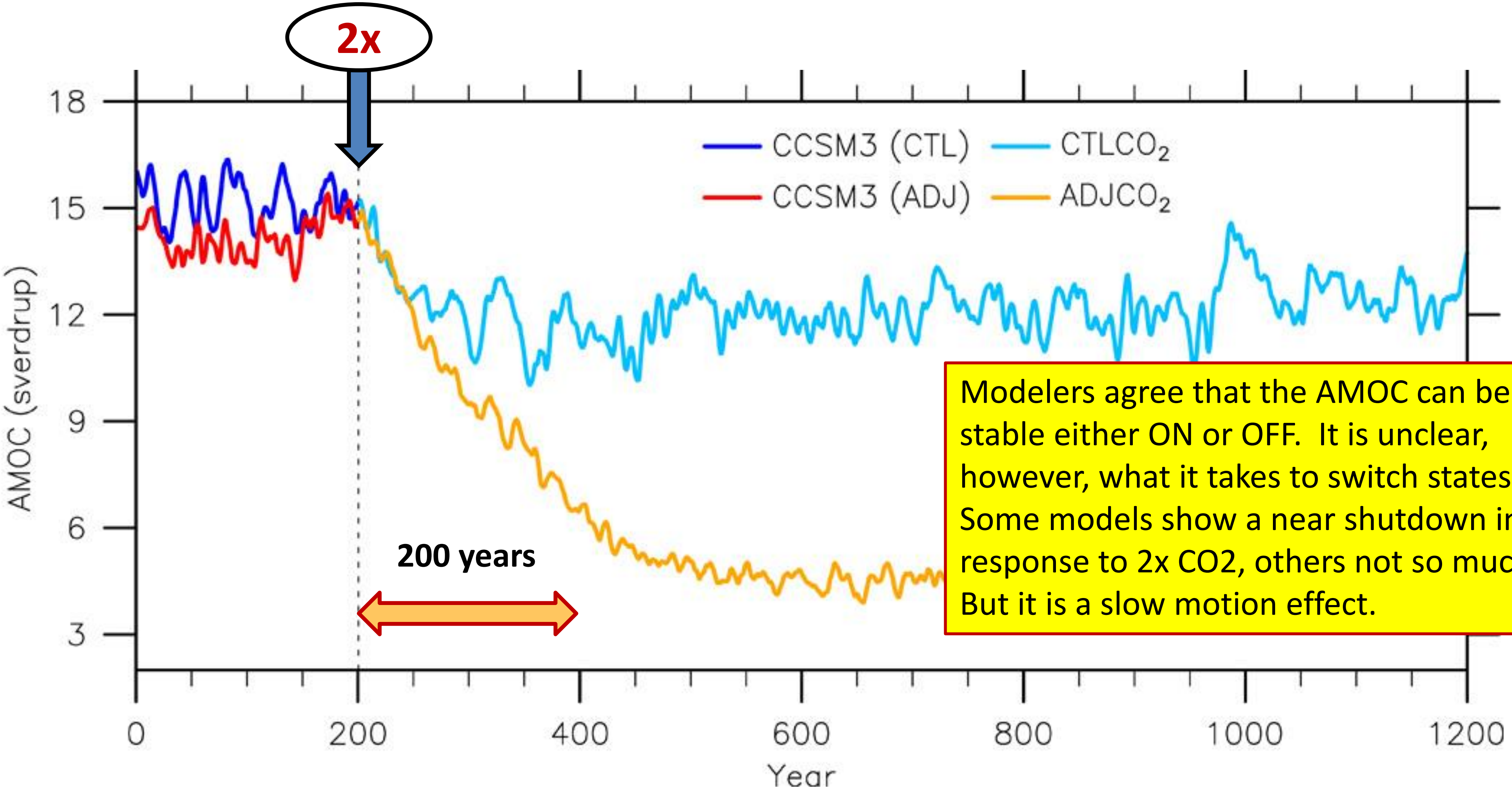
S. Rahmstorf, RealClimate.org (2018)

Sudden Doubling of CO_2 May or May not Trigger AMOC Collapse



Liu *et. al.* Sci. Adv. (2017)

Sudden Doubling of CO_2 May or May not Trigger AMOC Collapse

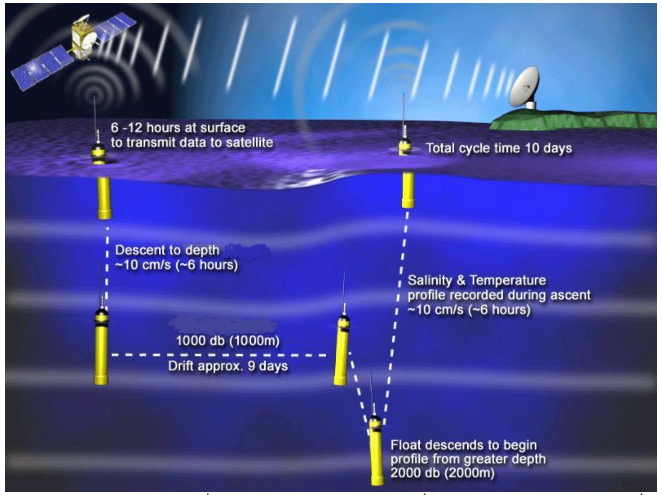


Modelers agree that the AMOC can be stable either ON or OFF. It is unclear, however, what it takes to switch states. Some models show a near shutdown in response to 2x CO2, others not so much. But it is a slow motion effect.

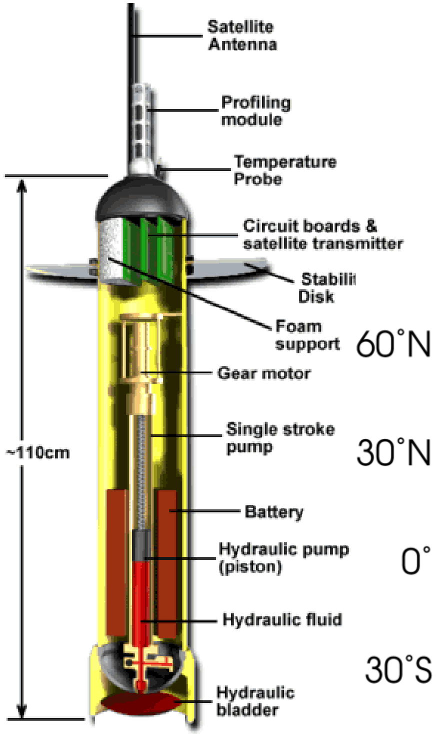
Liu *et. al.* Sci. Adv. (2017)

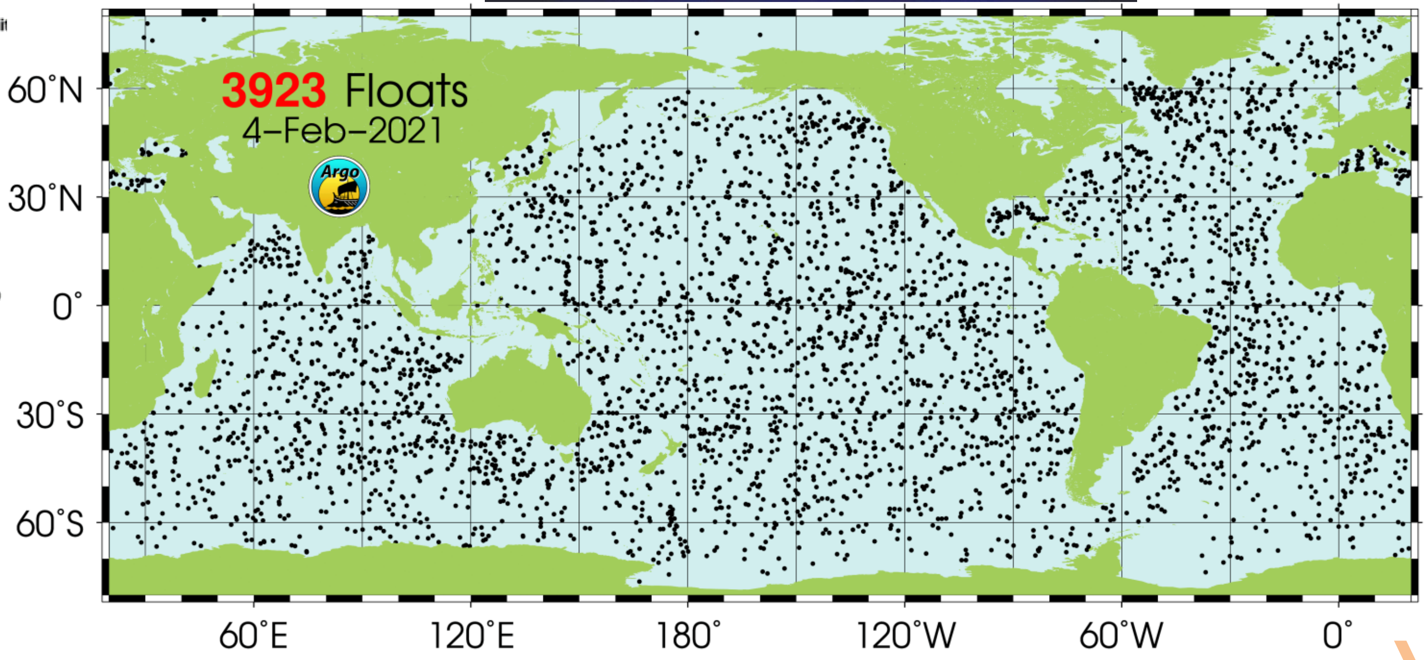
ARGO: Free Floating Ocean Data Reporting

International project headquartered at UC San Diego. Named after Jason's ship.



- Dive 0-2000 m deep
- 10 day cycle
- Temperature, Salinity, Velocity
- All data publicly available
- Use satellite 2-way communications
- Each Float:
  - 4-5y battery life
  - ~150 cycles
  - $15K



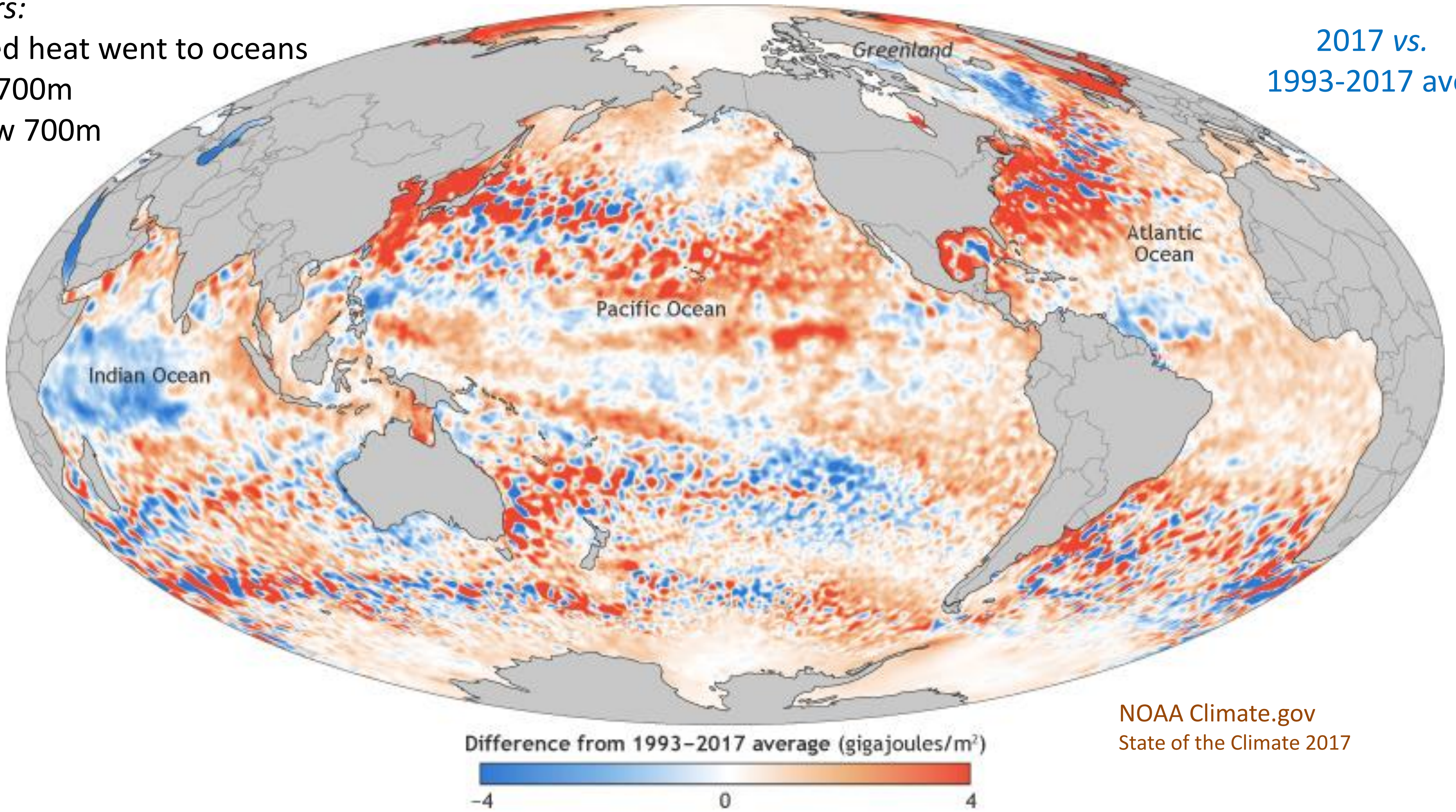


Changes in Heat Content of Upper 700 m of Oceans

Over last 50 years:

- >90% of added heat went to oceans
  - 63% upper 700m
  - ~ 30% below 700m
- Remainder:
  - Land
  - Air
  - Ice Caps

2017 *vs.*
1993-2017 ave.



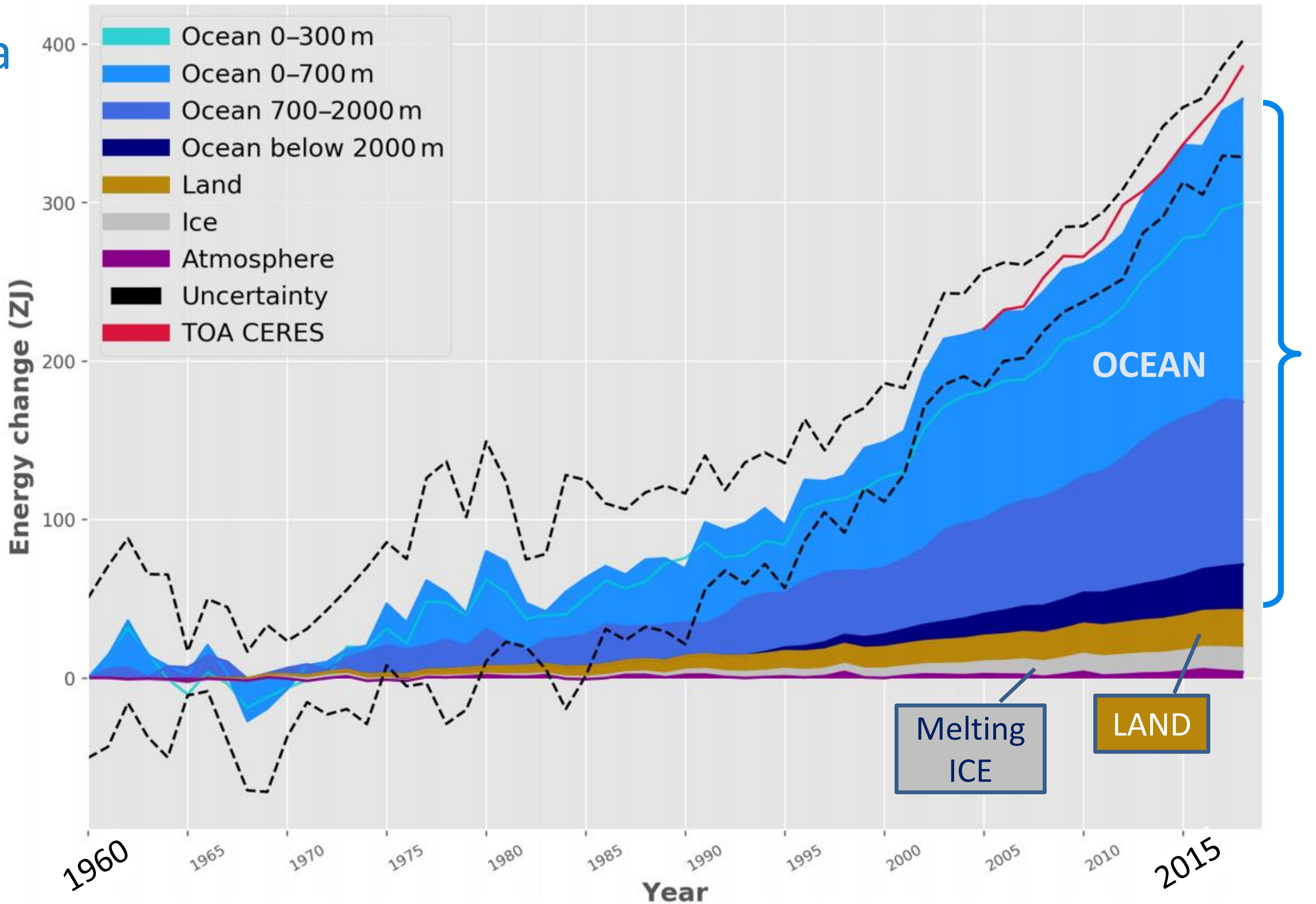
NOAA Climate.gov
State of the Climate 2017

Where Did the Extra Heat Trapped by Greenhouse Gases Wind Up?

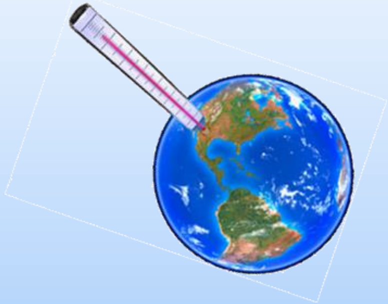
1960--2019

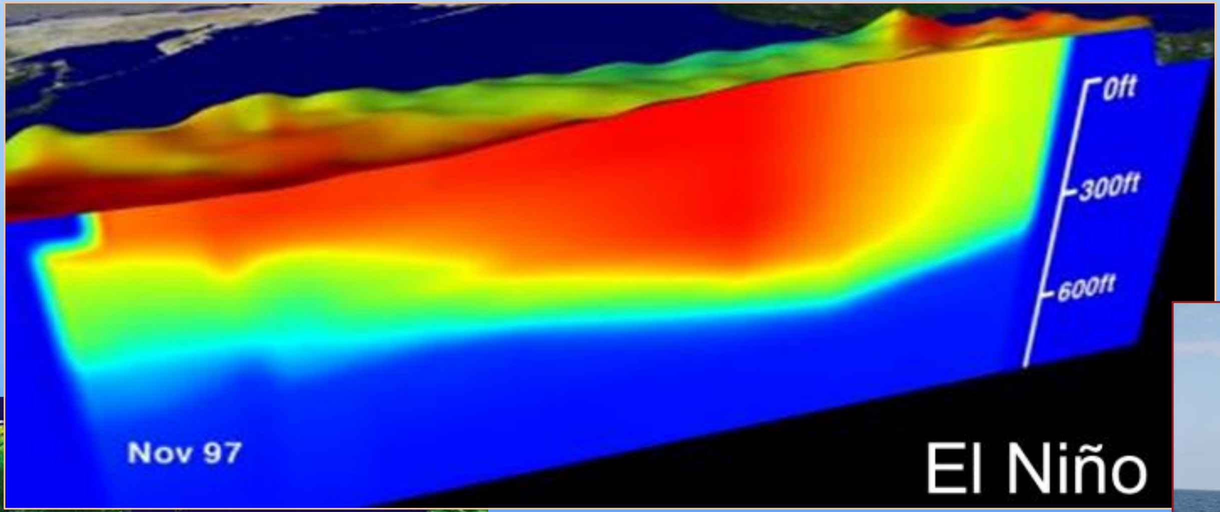
Almost all of it went into heating up the ocean, mainly the upper layers.
But for this, the Land would have heated far more.

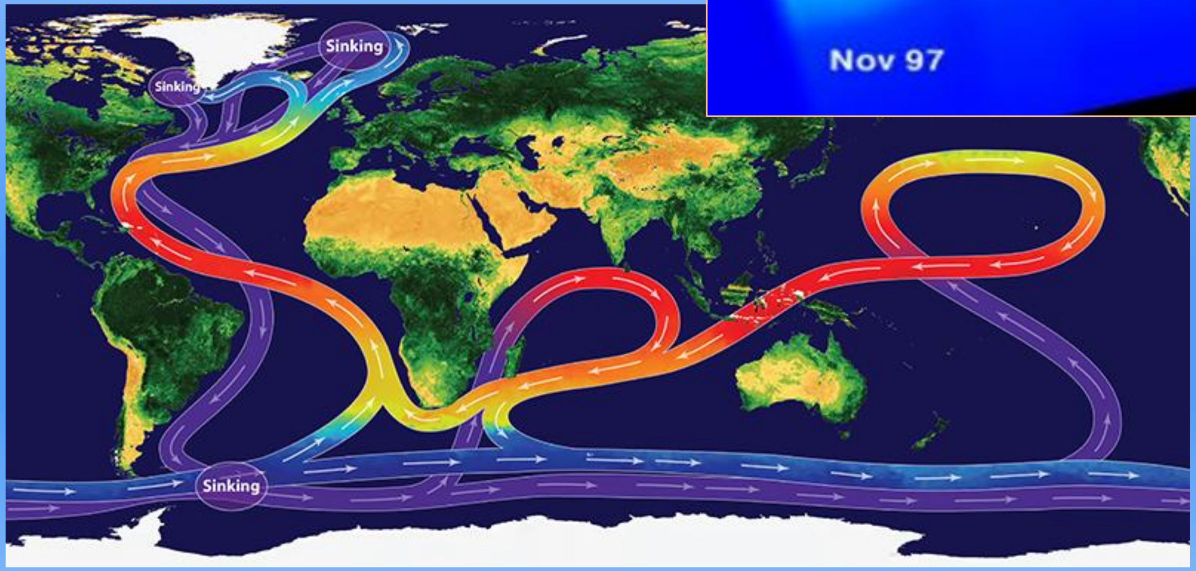
Heat stored in the Earth system: where does the energy go?
Karina von Schuckmann *et. al.*
Earth Syst. Sci. Data, **12** (2020)



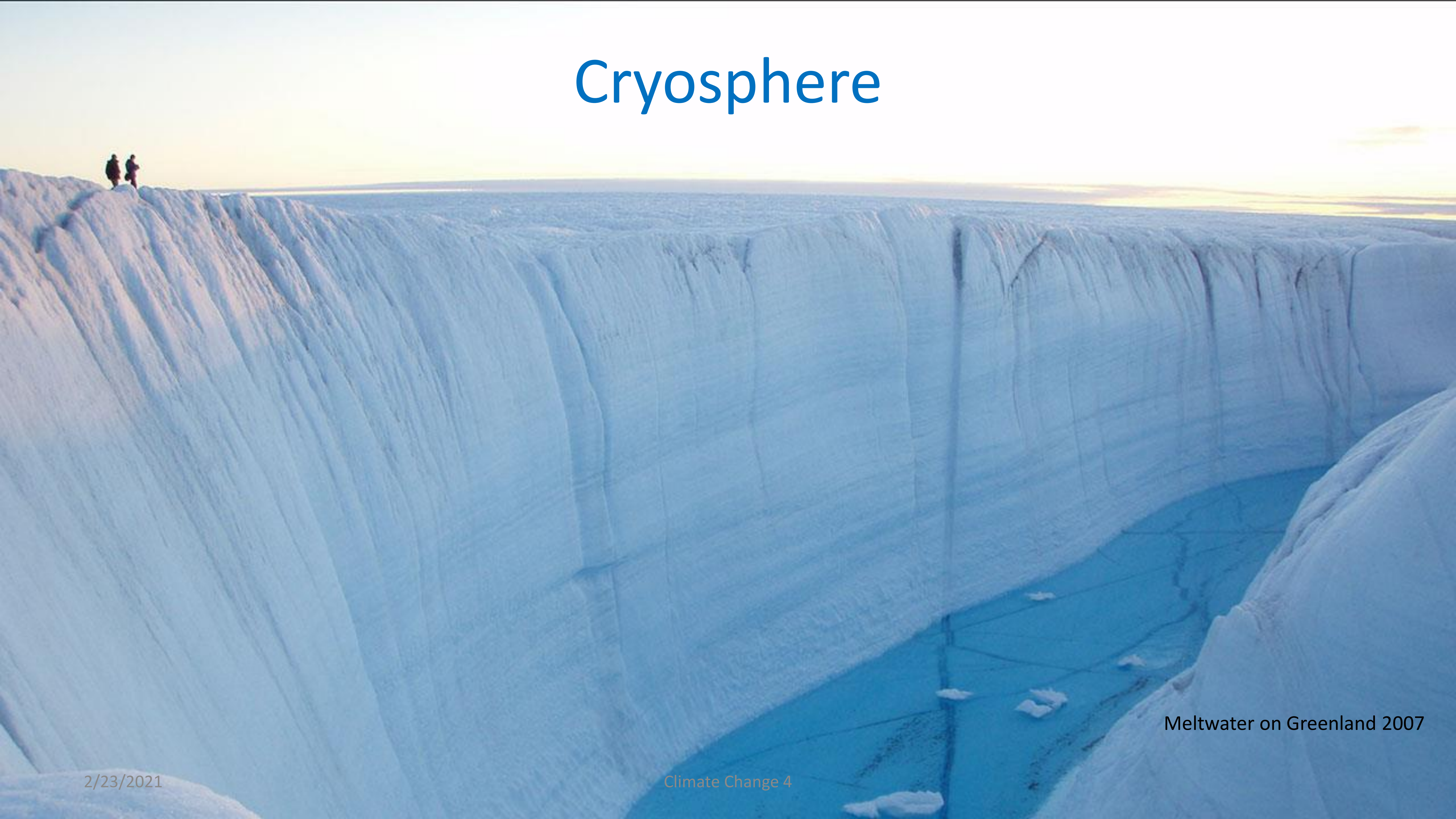
Questions about Ocean Circulation







Cryosphere

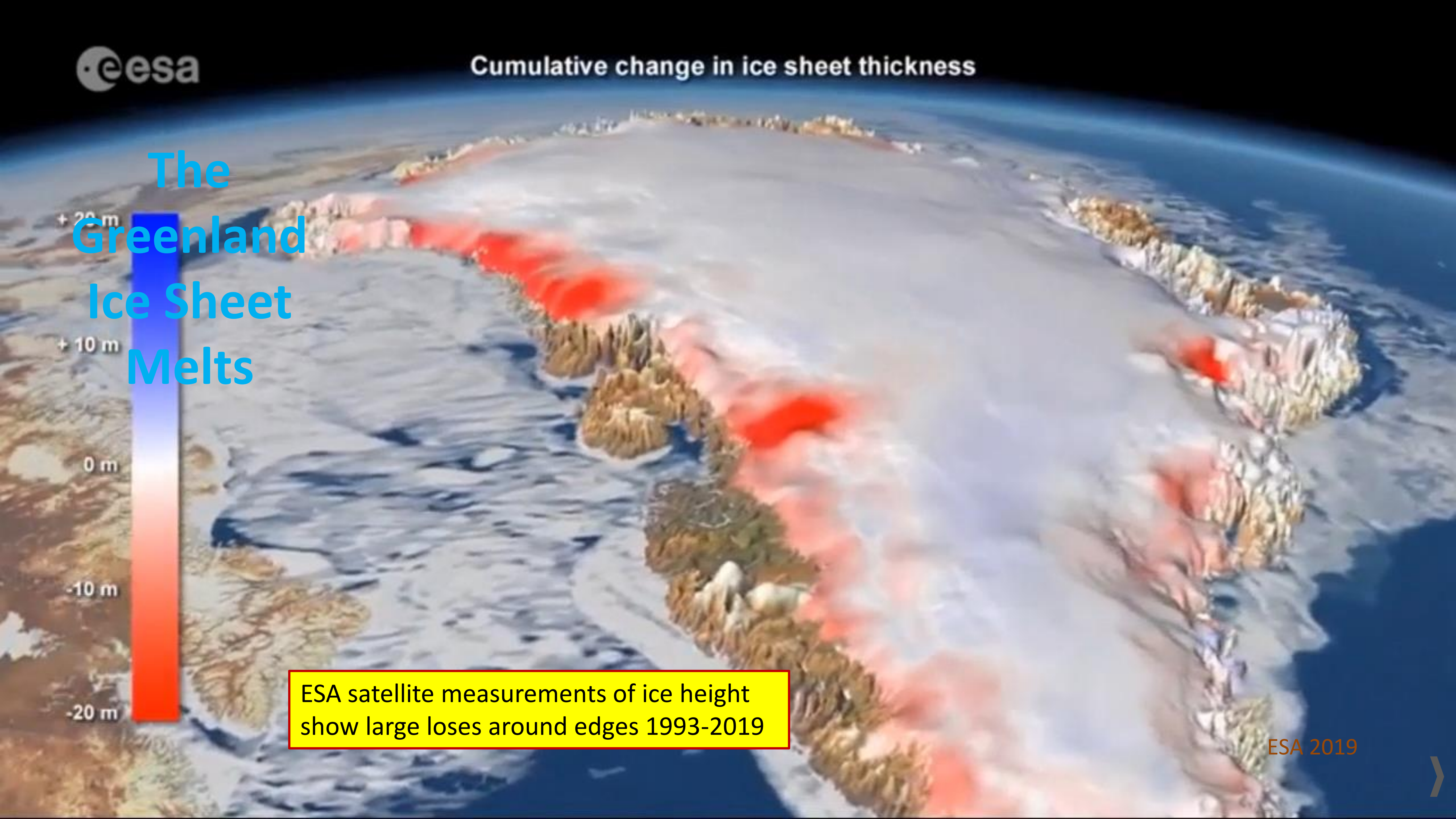


Meltwater on Greenland 2007

Arctic Albedo

Melting artic ice produces a huge Positive Feedback from Albedo changes, amplifying any Radiative Forcing.

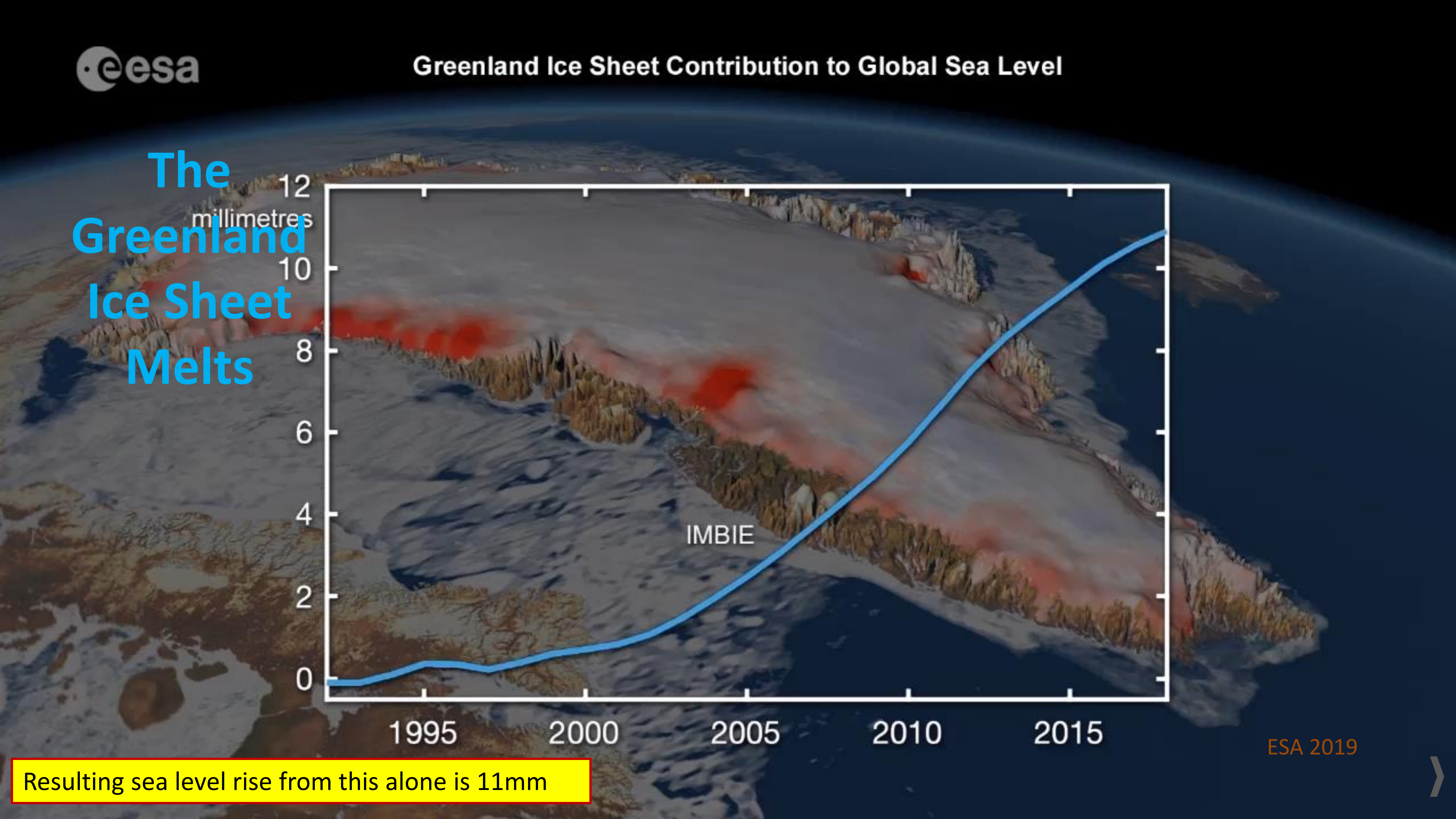
The Greenland Ice Sheet Melts



ESA satellite measurements of ice height show large loses around edges 1993-2019

ESA 2019

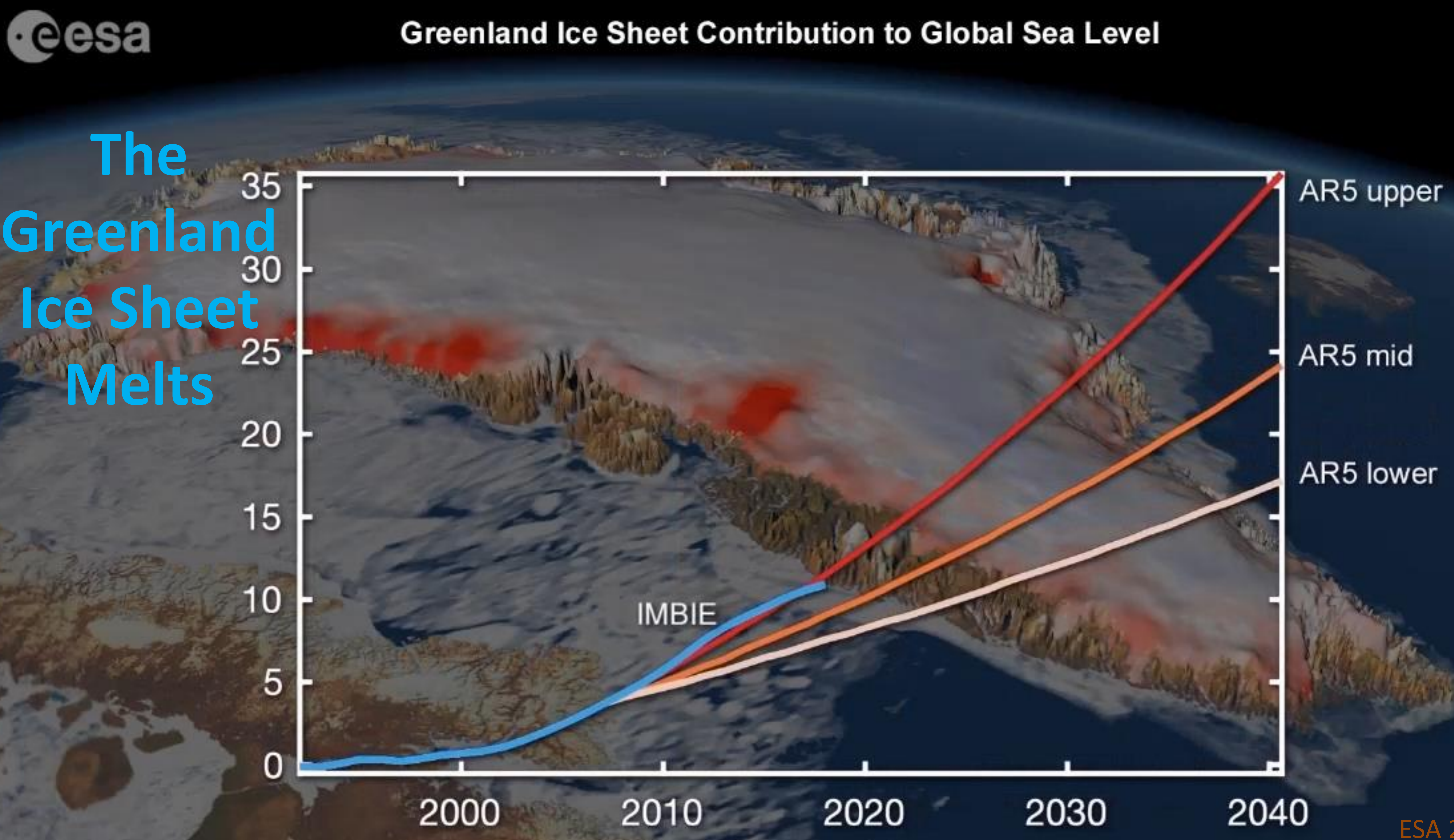
The Greenland Ice Sheet Melts



ESA 2019

Resulting sea level rise from this alone is 11mm

The Greenland Ice Sheet Melts



ESA 2019

Measurements are closest to the 2011 IPCC “upper” forecast scenario.

Arctic Sea Ice 1984 to 2019

A Movie showing artic floating sea ice extent from 1984-2019, with different ages of ice indicated by color. White is 4 year or older ice, initially covering 2.5 million km2.

NASA 2019

Arctic Sea Ice 1984 to 2019

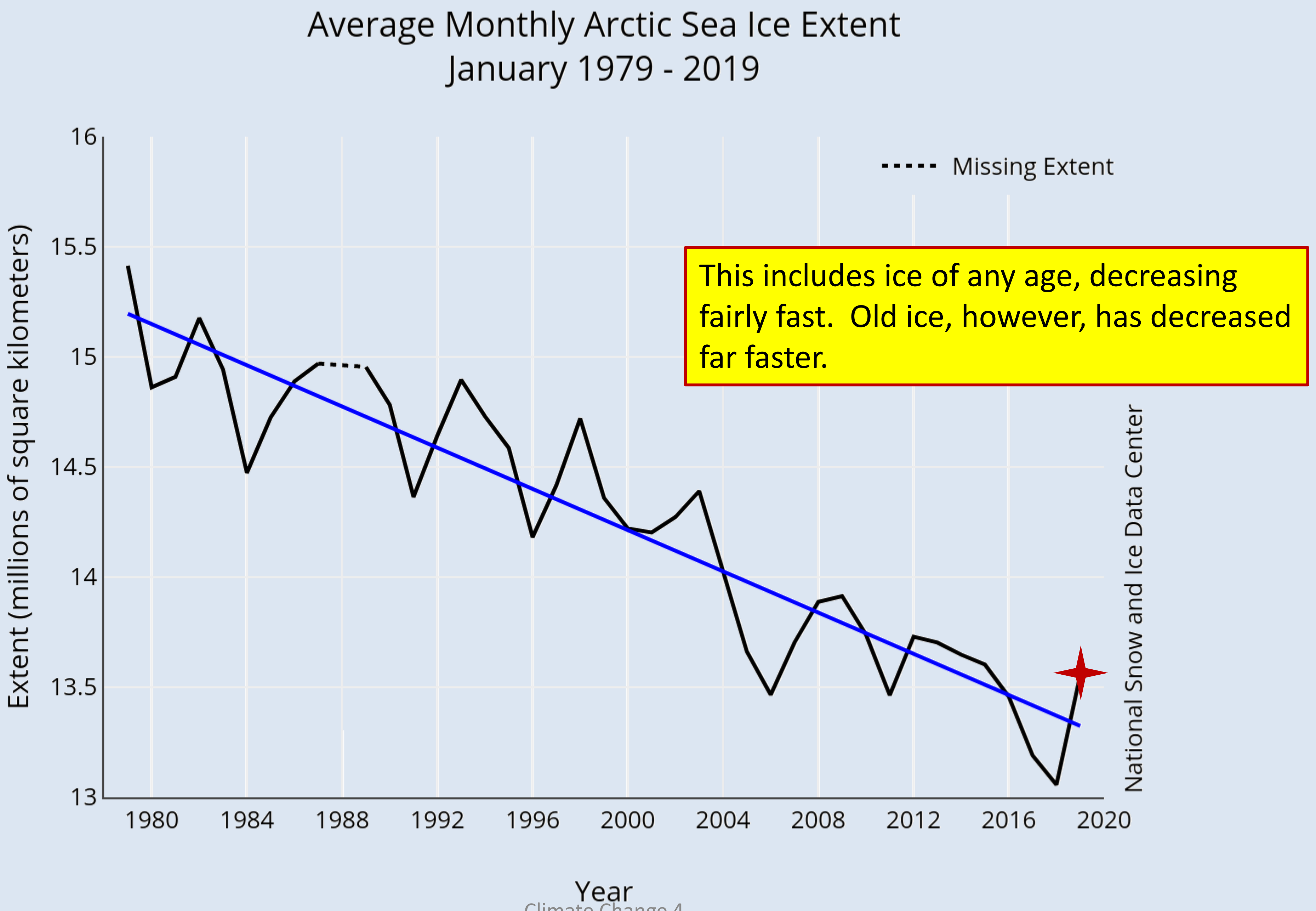
By winter 1994 there is 1.8 million km2 of old ice. Note that new ice covers Hudson Bay, the Bering sea, and elsewhere.

NASA 2019

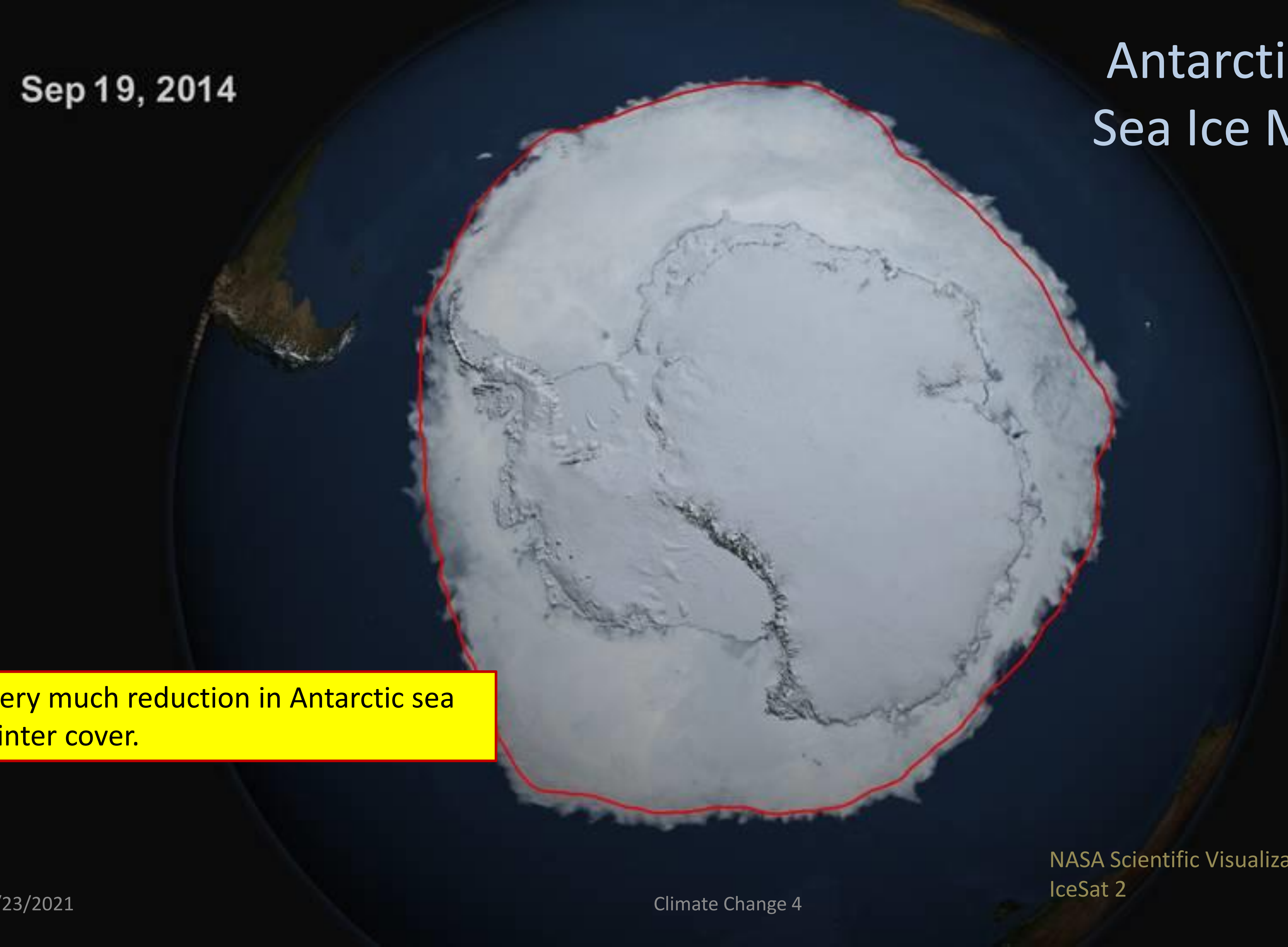
Arctic Sea Ice 1984 to 2019

By end of summer 2019, the 4 year ice is nearly all gone, although during the winter there is still substantial new ice cover.

NASA 2019

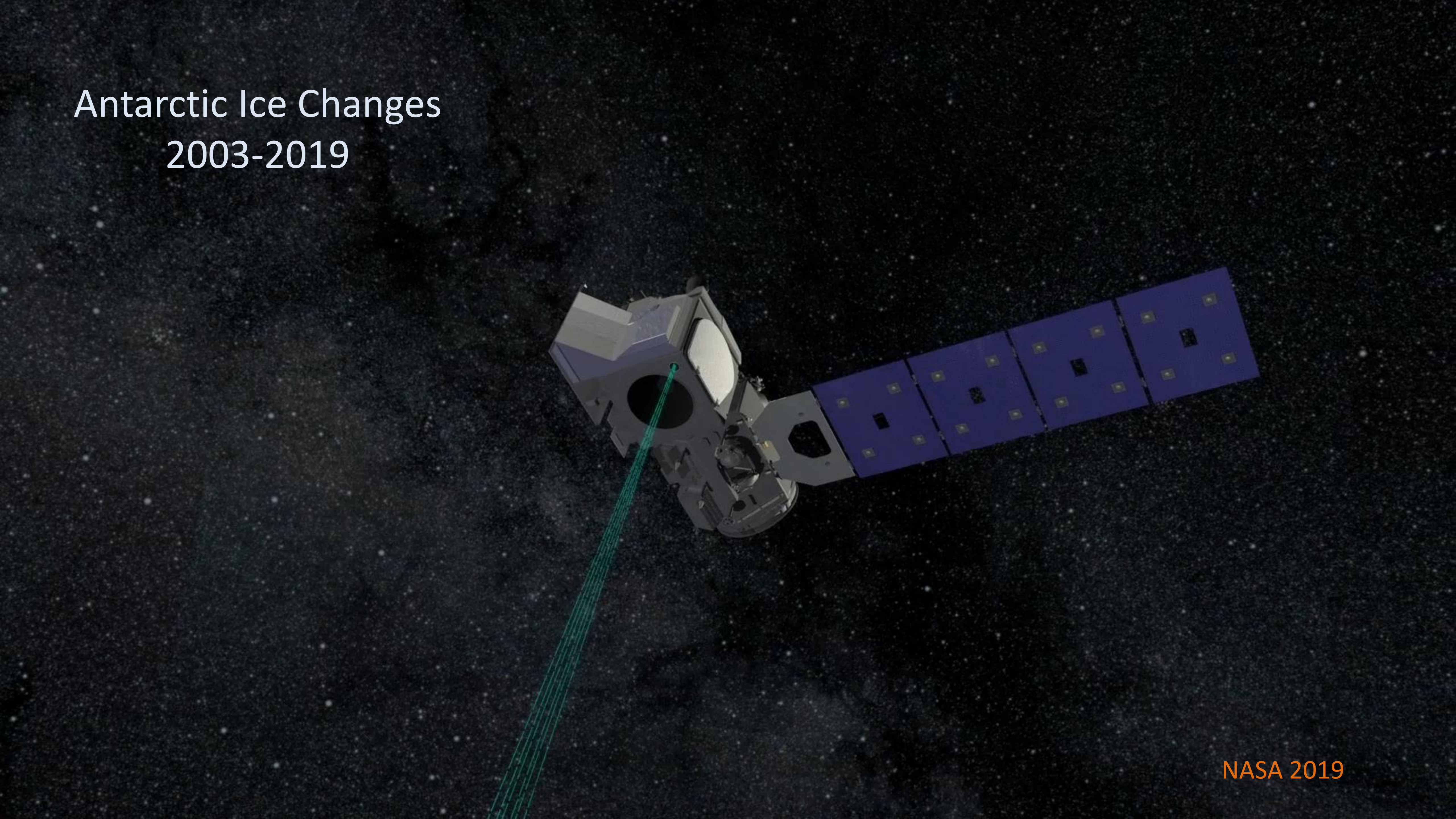

Average Monthly Arctic Sea Ice Extent
January 1979 - 2019
Extent (millions of square kilometers)
16
15.5
15
14.5
14
13.5
13
1980
1984
1988
1992
1996
2000
2004
2008
2012
2016
2020
Year
Missing Extent
National Snow and Ice Data Center
This includes ice of any age, decreasing fairly fast. Old ice, however, has decreased far faster.

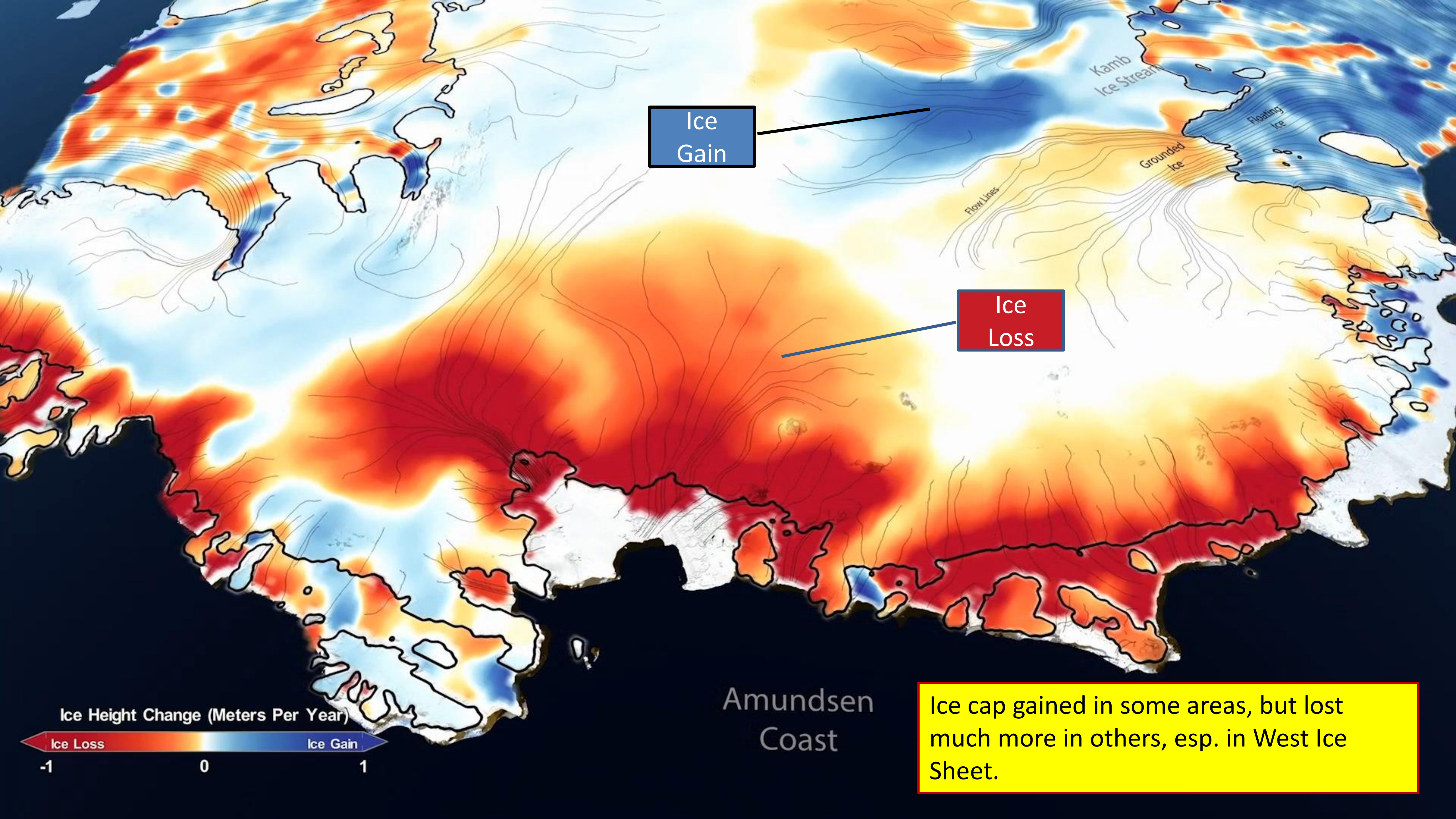
Antarctic Winter Sea Ice Maximum



Not very much reduction in Antarctic sea ice winter cover.

NASA Scientific Visualization Studio (2014)
IceSat 2

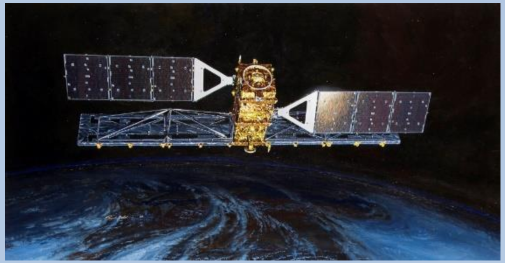

Antarctic Ice Changes
2003-2019
NASA 2019



Ice cap gained in some areas, but lost much more in others, esp. in West Ice Sheet.

Ice Flows in Antarctica

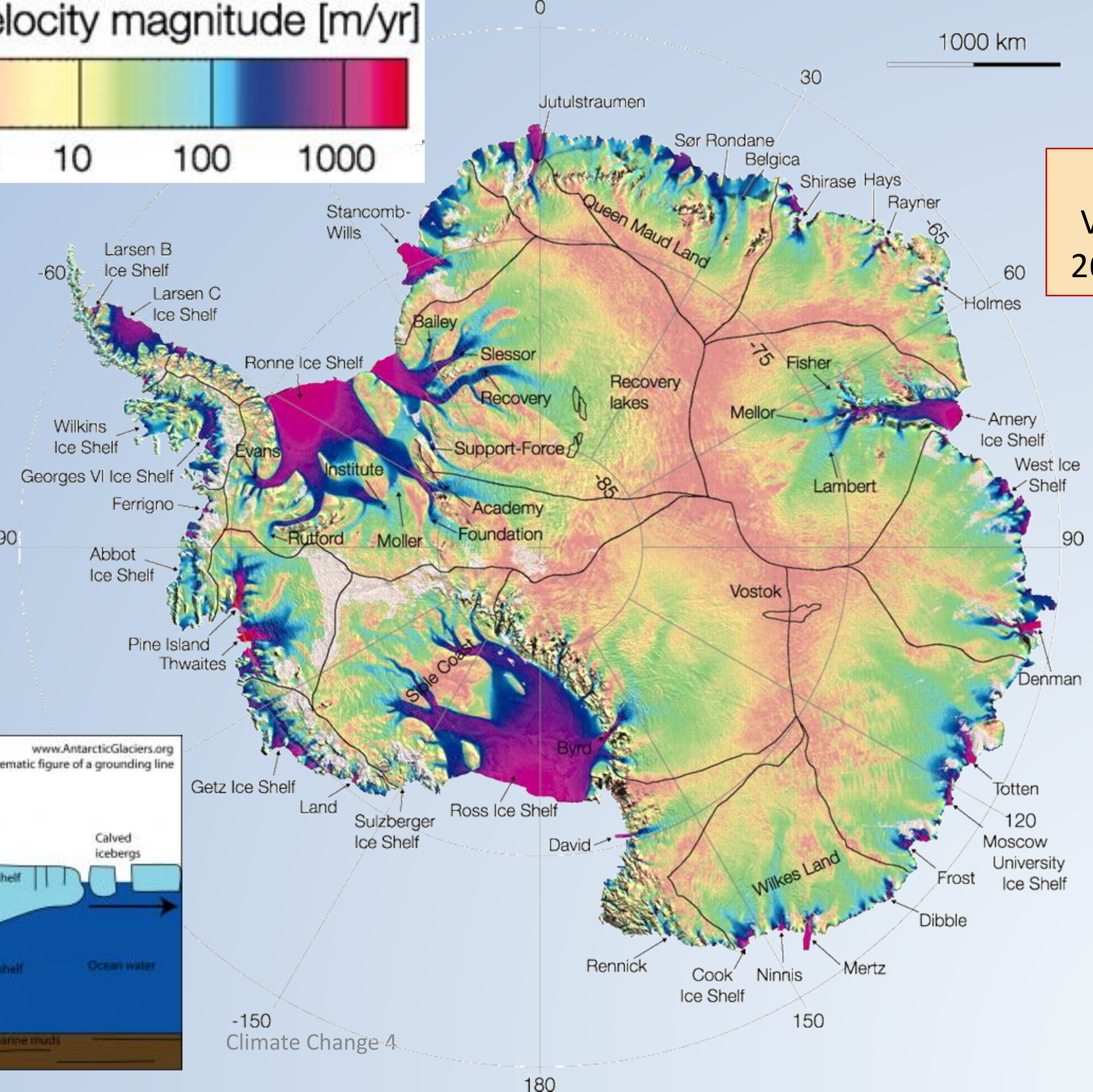
(Measured 2007-2009)



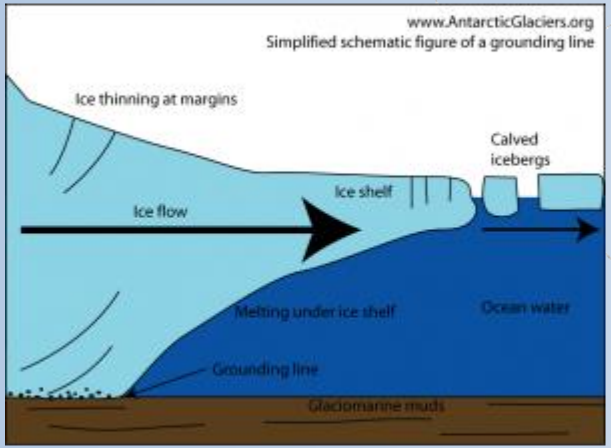
Satellite Radar Interferometry:

Radarsat 1 & 2, Envisat ASAR, ALOS

Rignot et. al. 2011

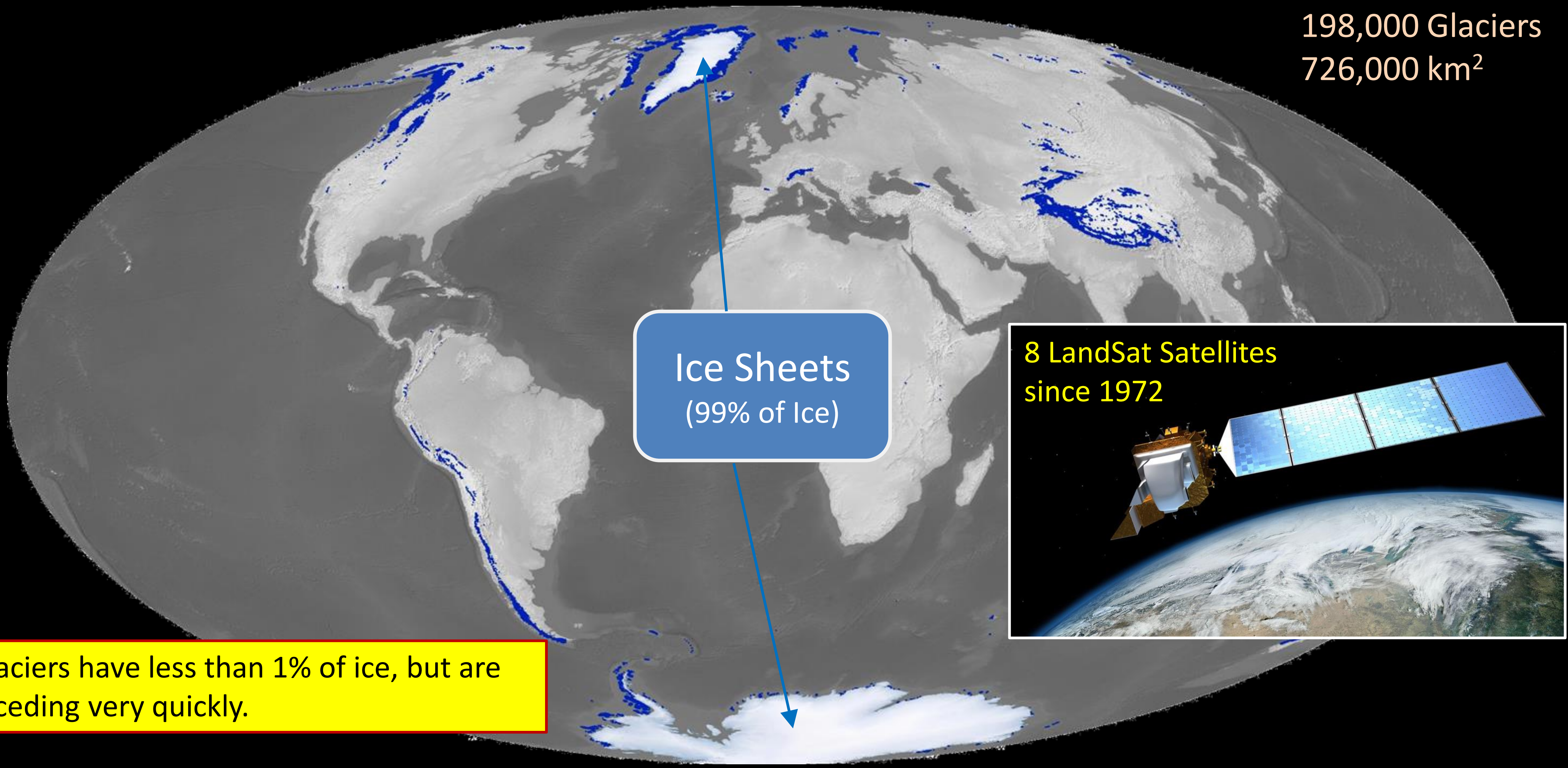


Ice Volume: 26 M km^3



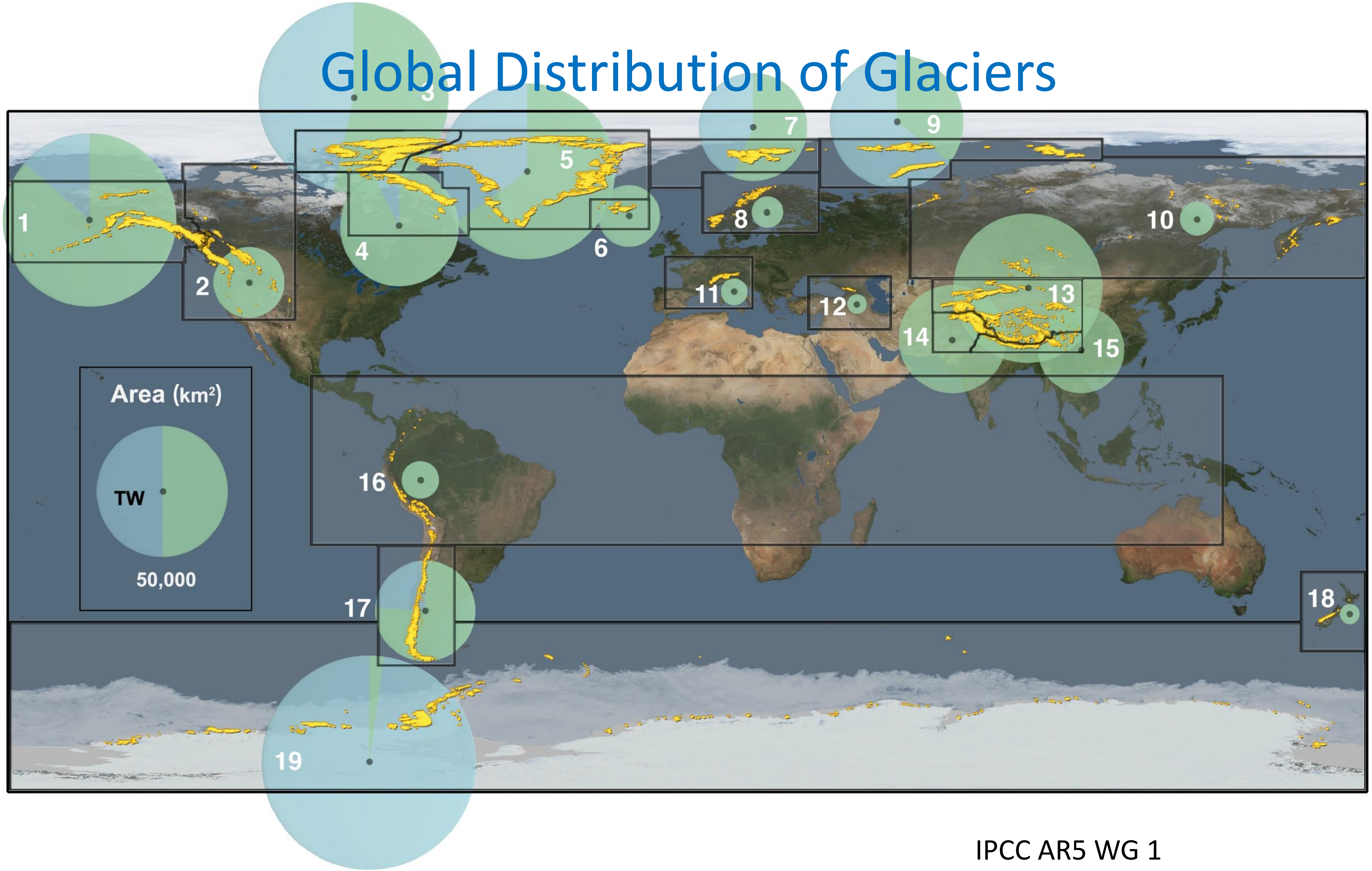
Randolph Glacier Inventory

198,000 Glaciers
726,000 km^2



Glaciers have less than 1% of ice, but are receding very quickly.

Global Distribution of Glaciers



IPCC AR5 WG 1

Biosphere

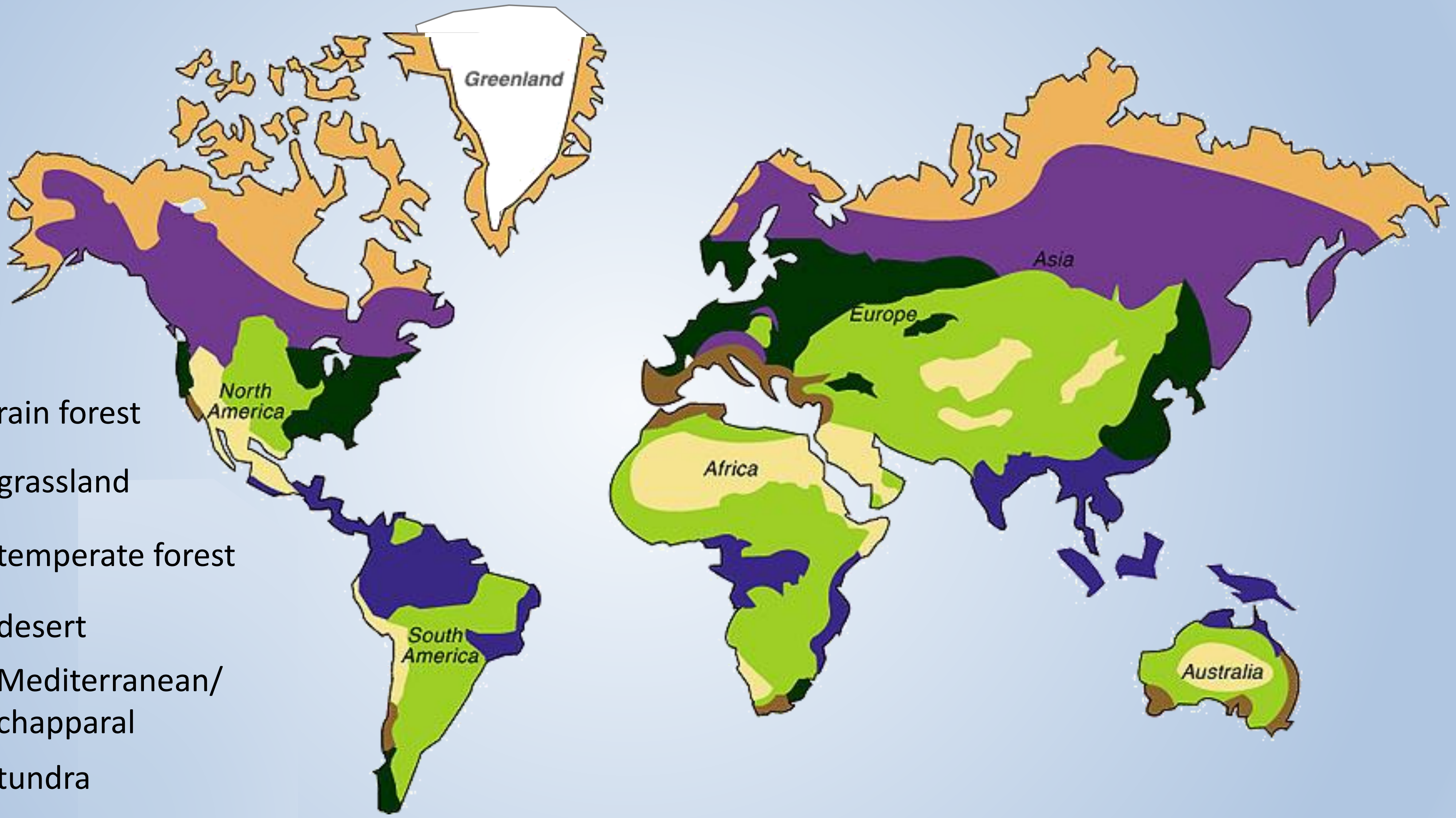
Mostly, the Biosphere must itself adapt to climate…

Biospheric Drivers of Climate:

- Oxygenization of the Atmosphere
  - ~500 Million Years Ago
  - Cyanobacteria in oceans

- Deposition of fossil fuels
- Partial regulation of CO_2
  - Photosynthesis (CO_2 removal)
  - Respiration (CO_2 emission)
  - Carbon sequestration in biomass
  - CO_2 & CH_4 release in decomposition
  - Marine organisms fix dissolved CO_2
- Albedo Effects
- Aerosol generating emissions
- Effects of vegetation on water cycle

Biomes



rain forest

grassland

temperate forest

desert

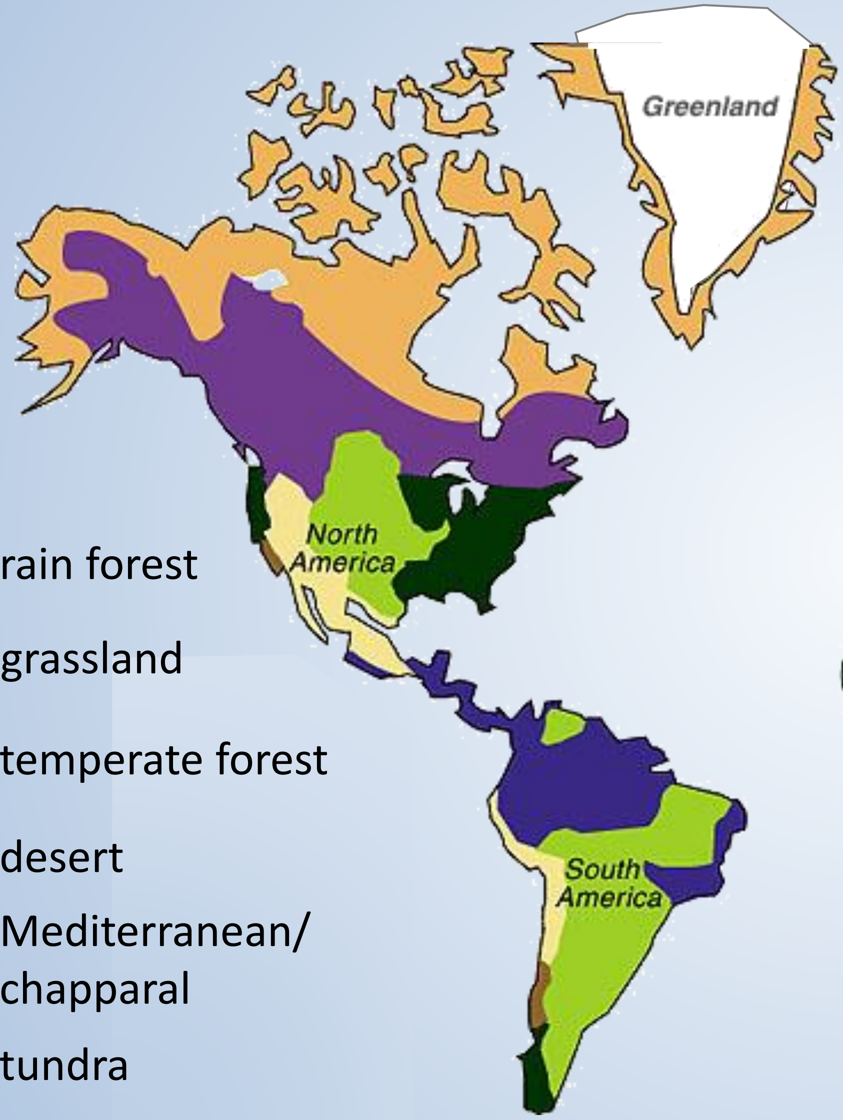
Mediterranean/ chapparal

tundra

taiga

Biomes

Permafrost Melting:
Methane & CO_2 Release



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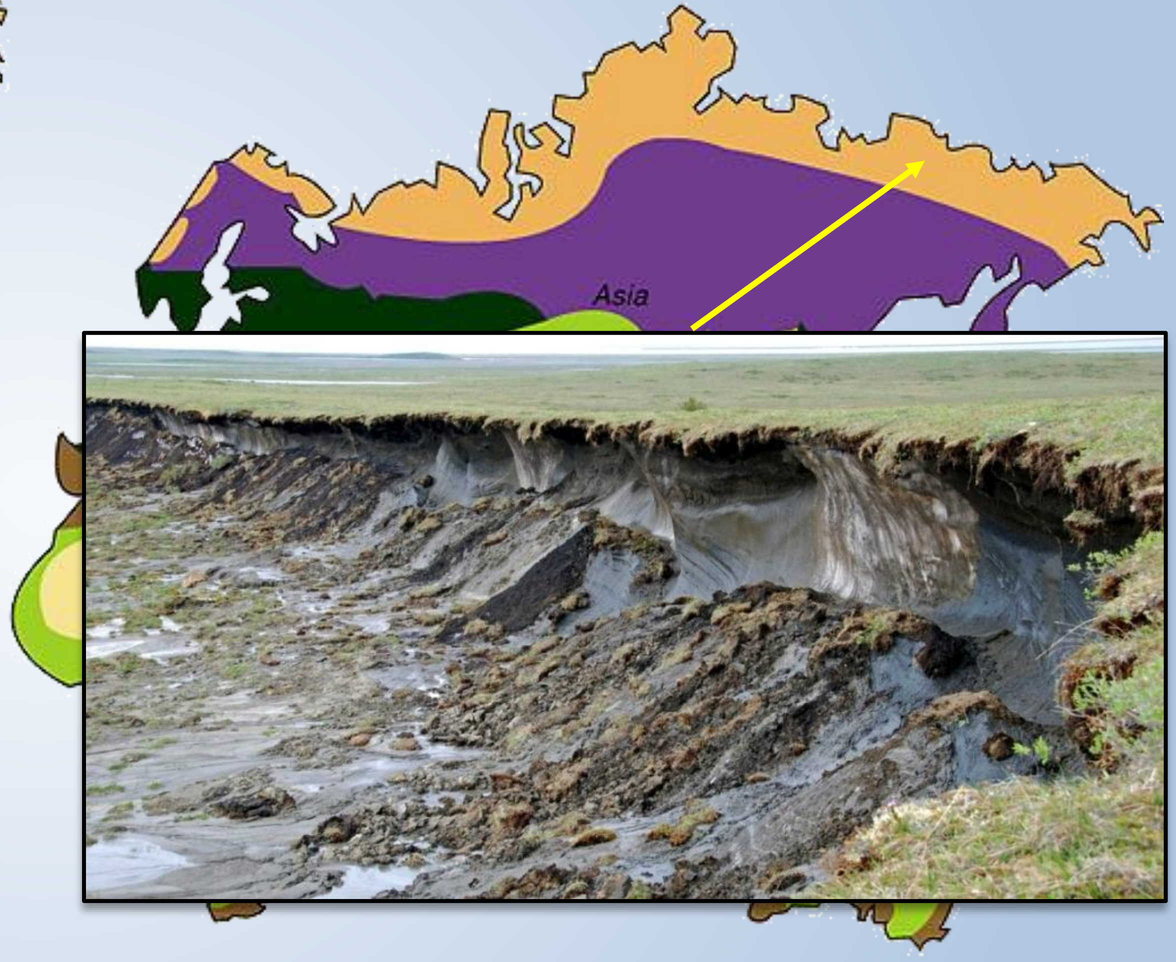
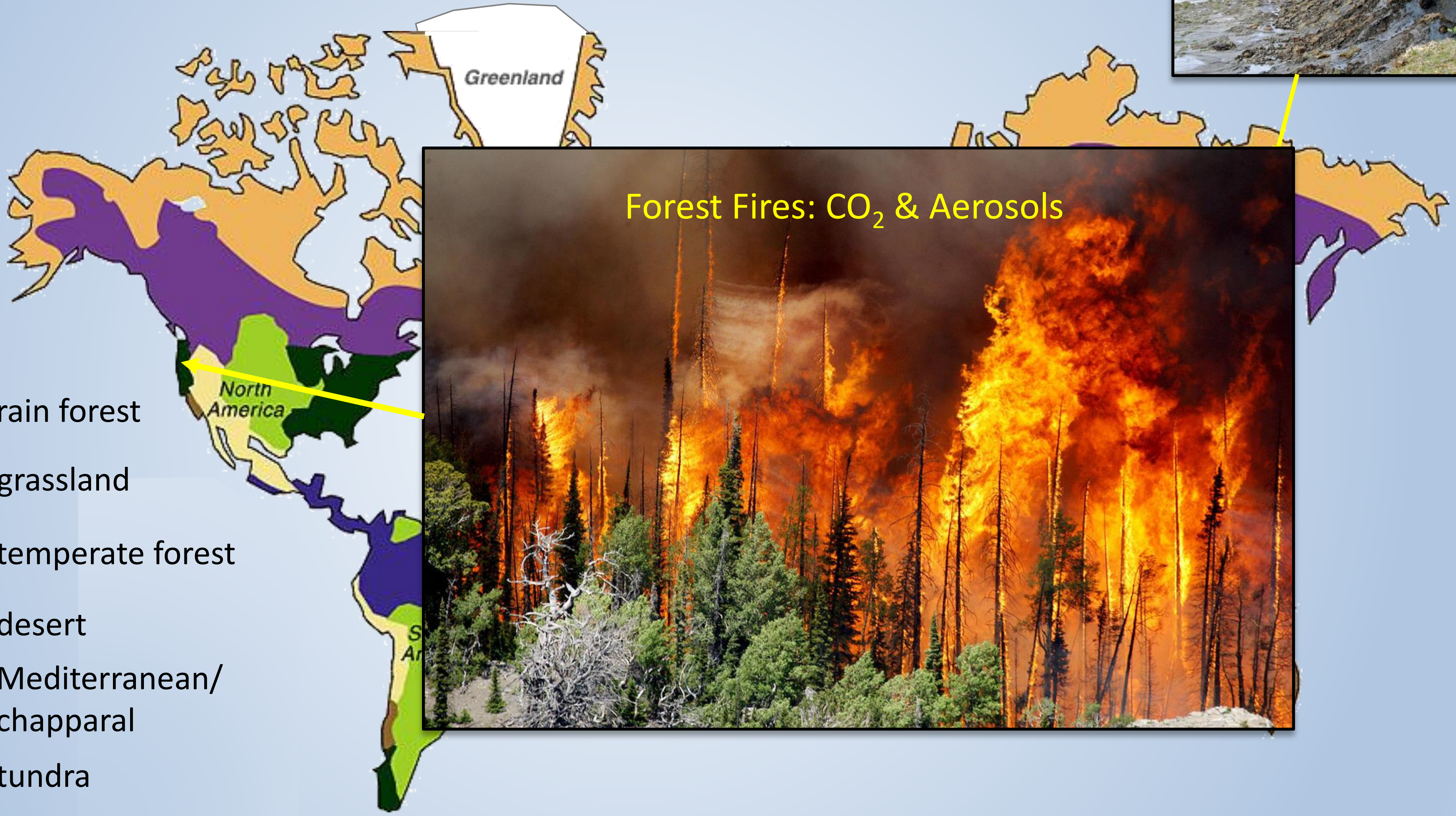
- tundra
- taiga



Biomes

Permafrost



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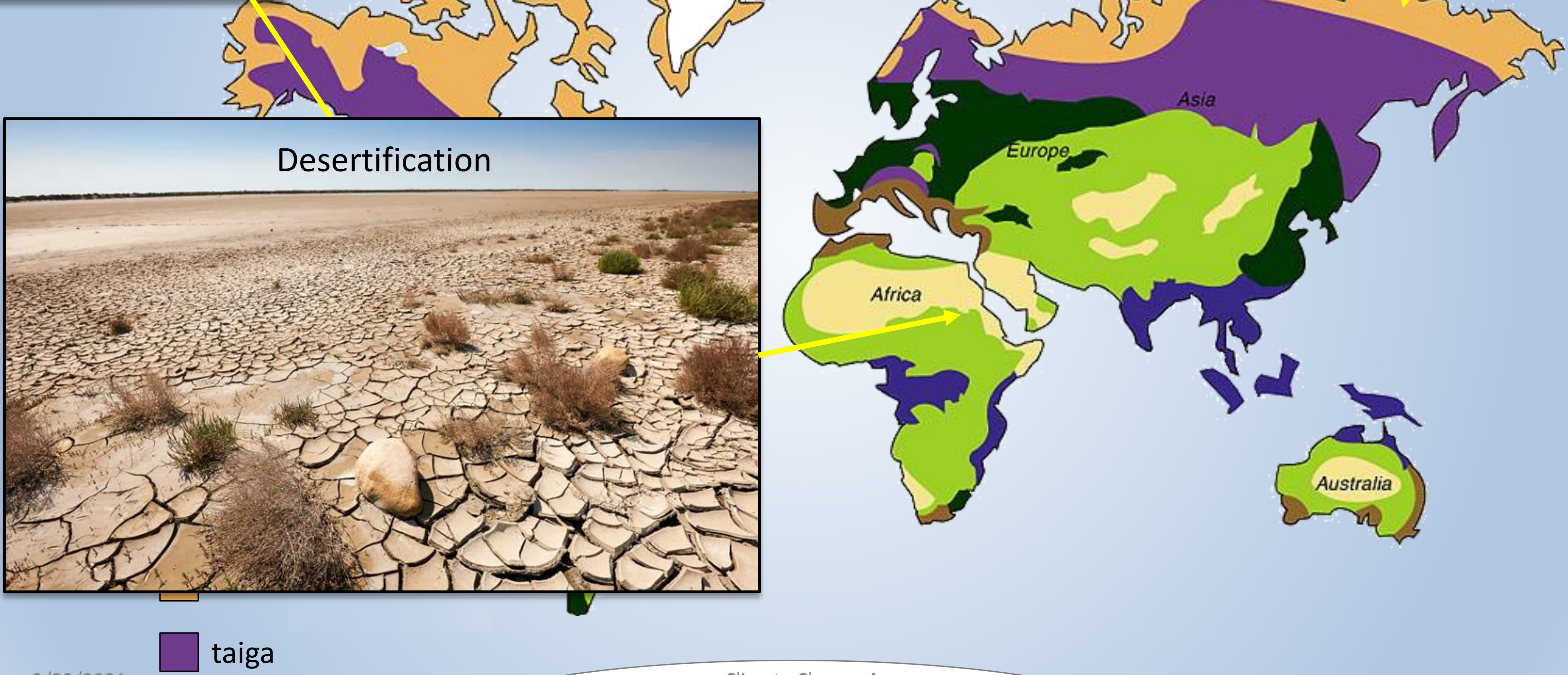
Biomes

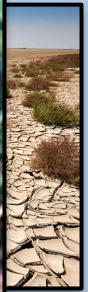
Permafrost



Biomes

Permafrost

Desertification



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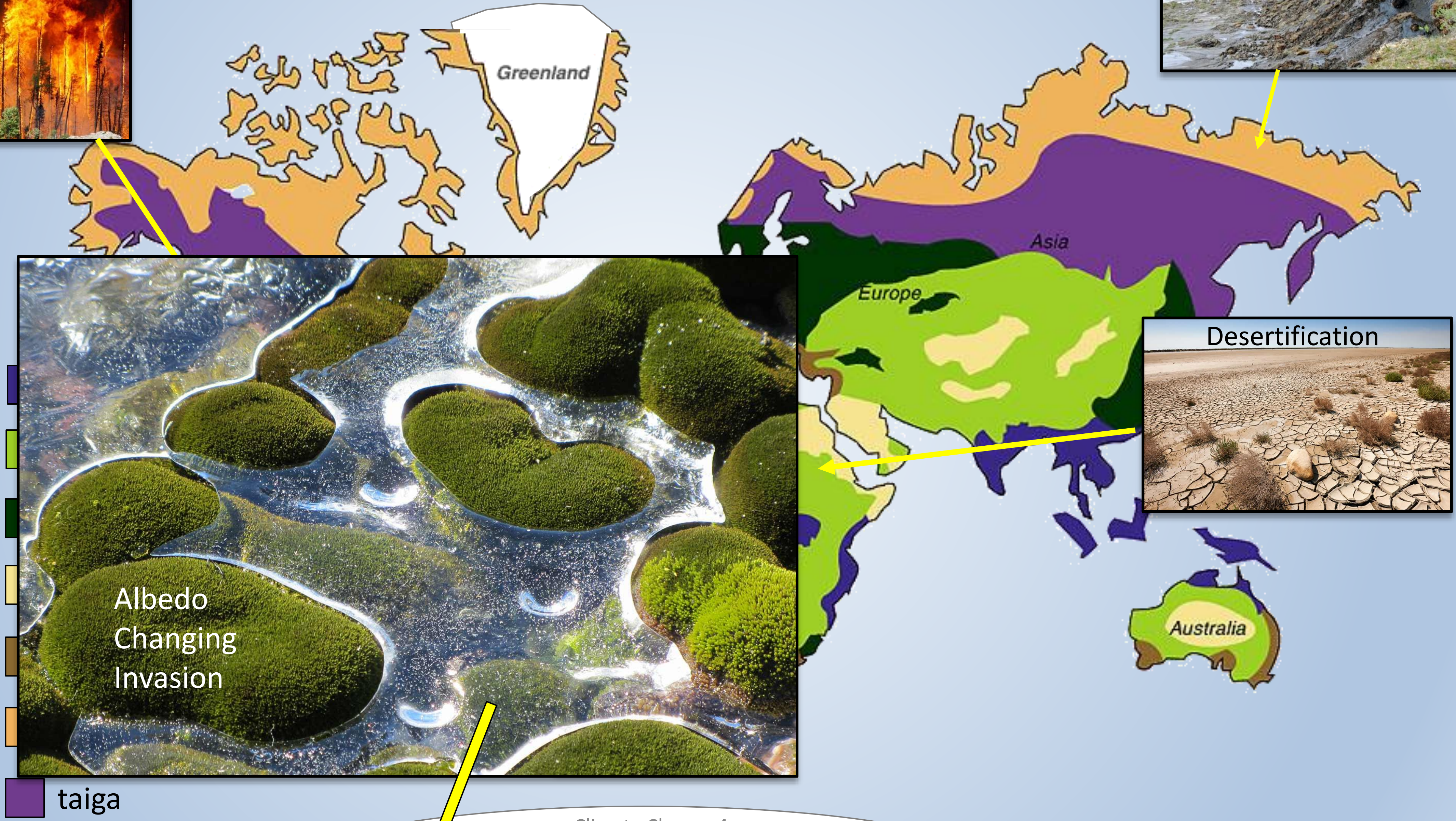
Biomes

Permafrost

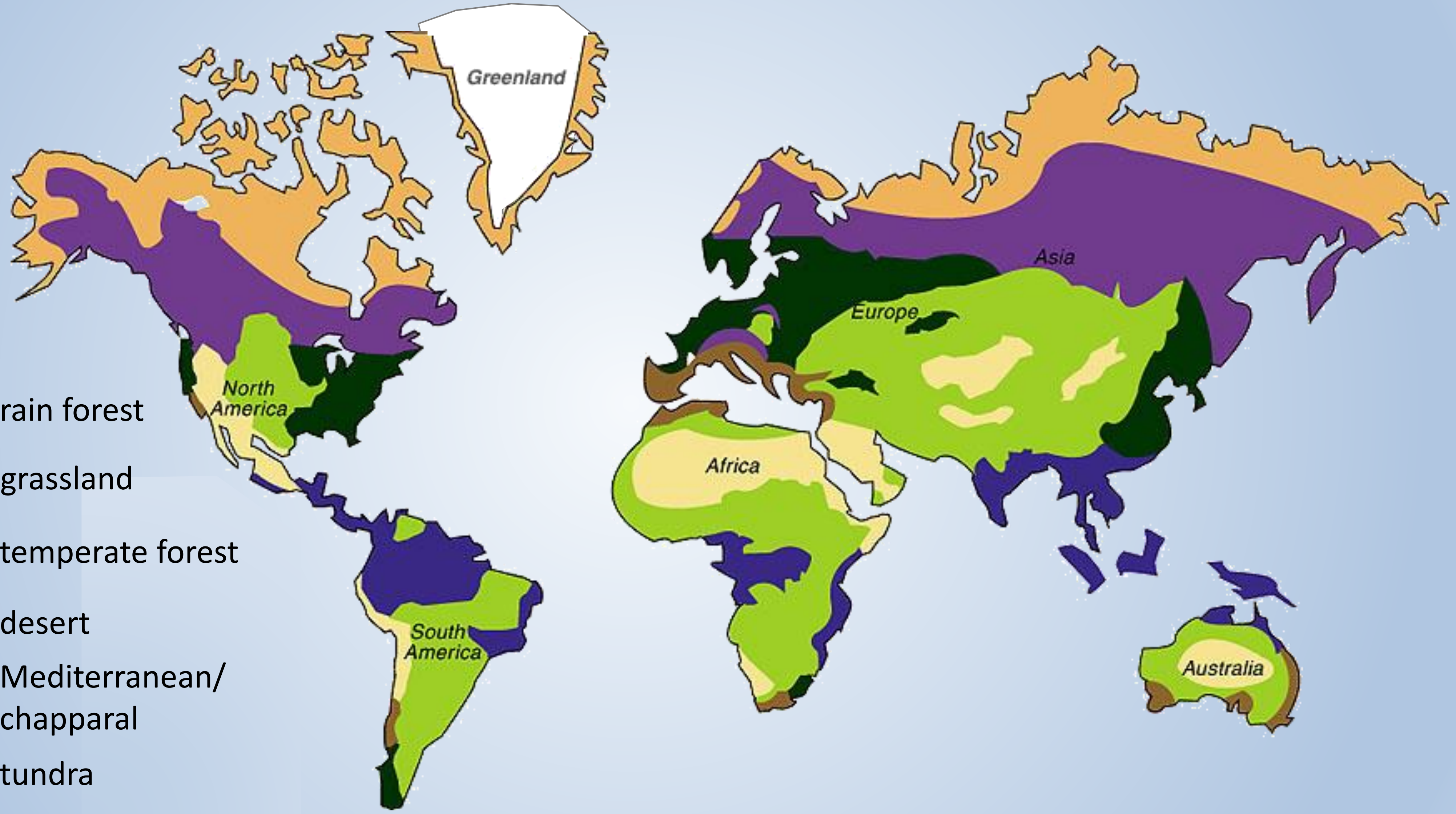


Biomes

Permafrost

Moss
Spread

Biomes



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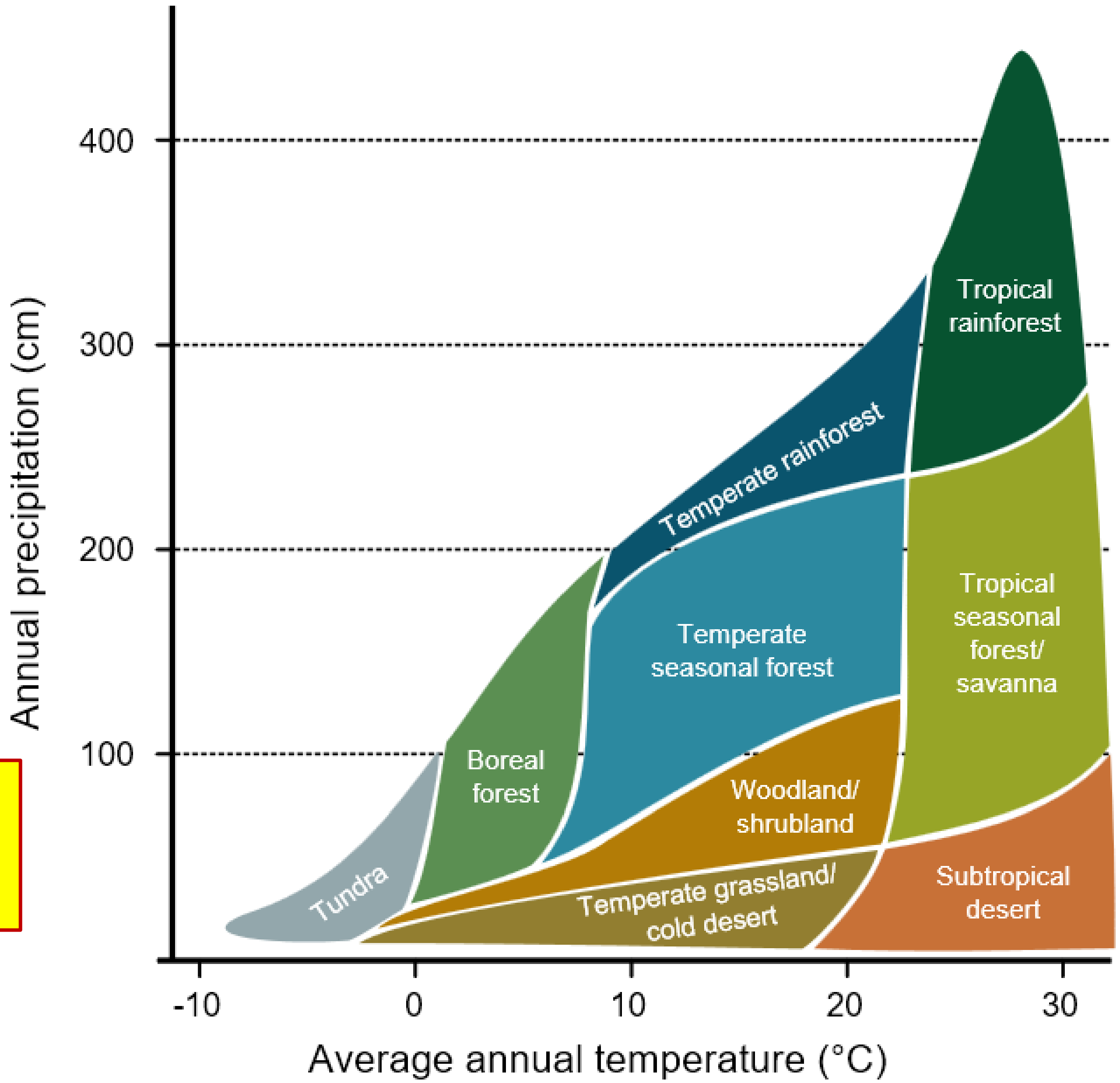
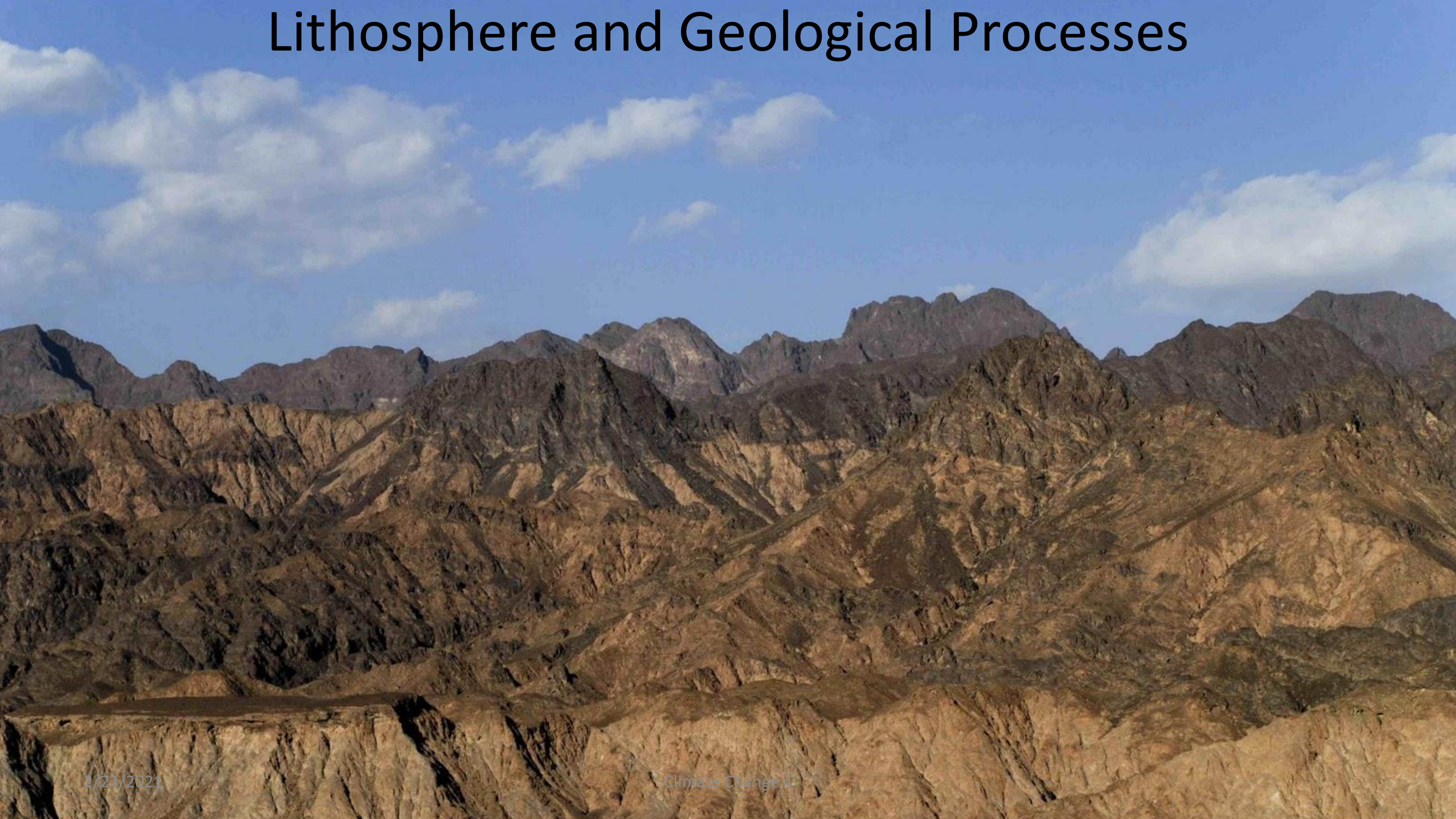
Biomes Dependent mainly on Temperature and Precipitation



As regional climates (Temperature and Precipitation) change, biome boundaries must adjust.

Lithosphere and Geological Processes

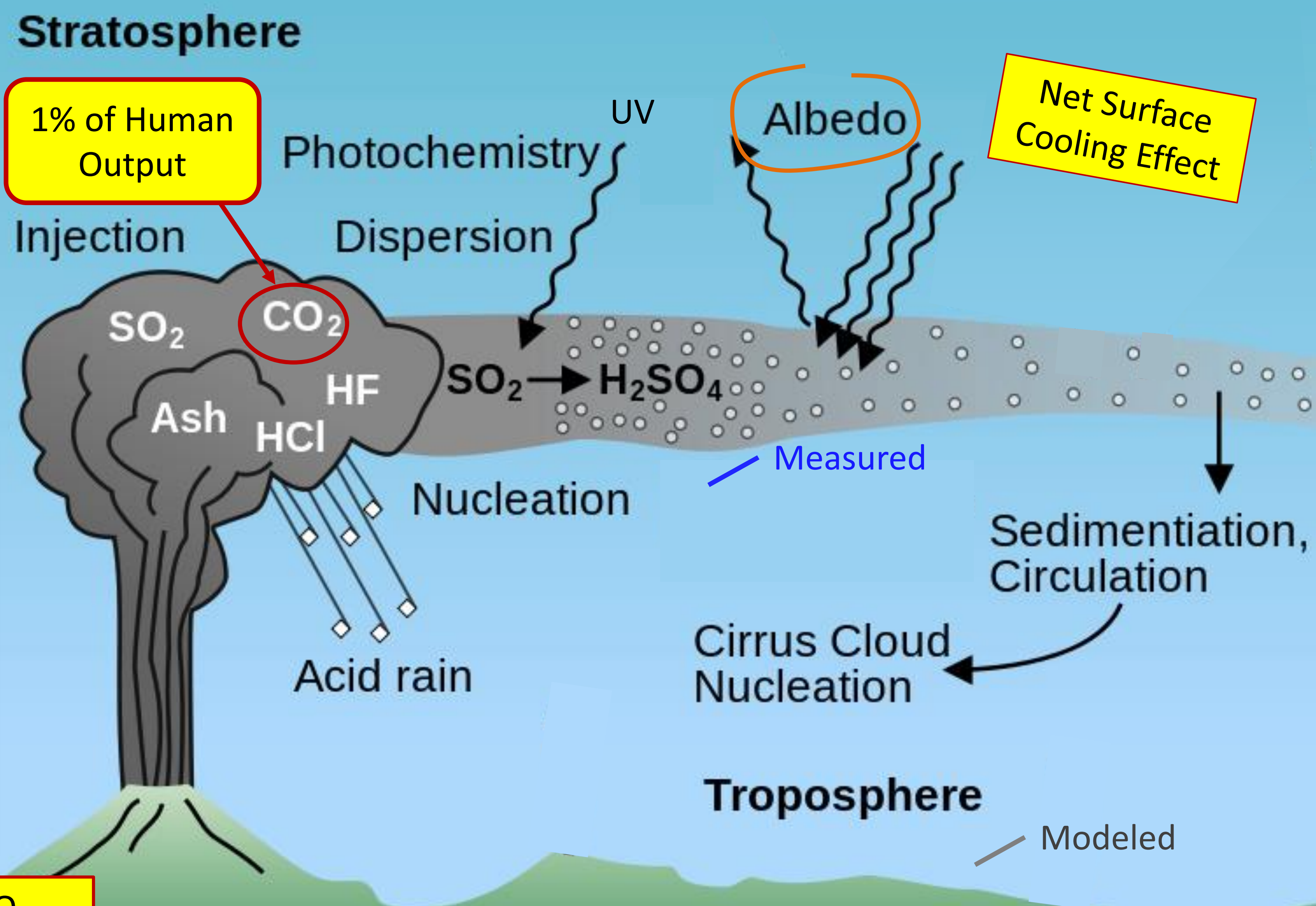


Mount Pinatubo Eruption

Philippines
June 12, 1991

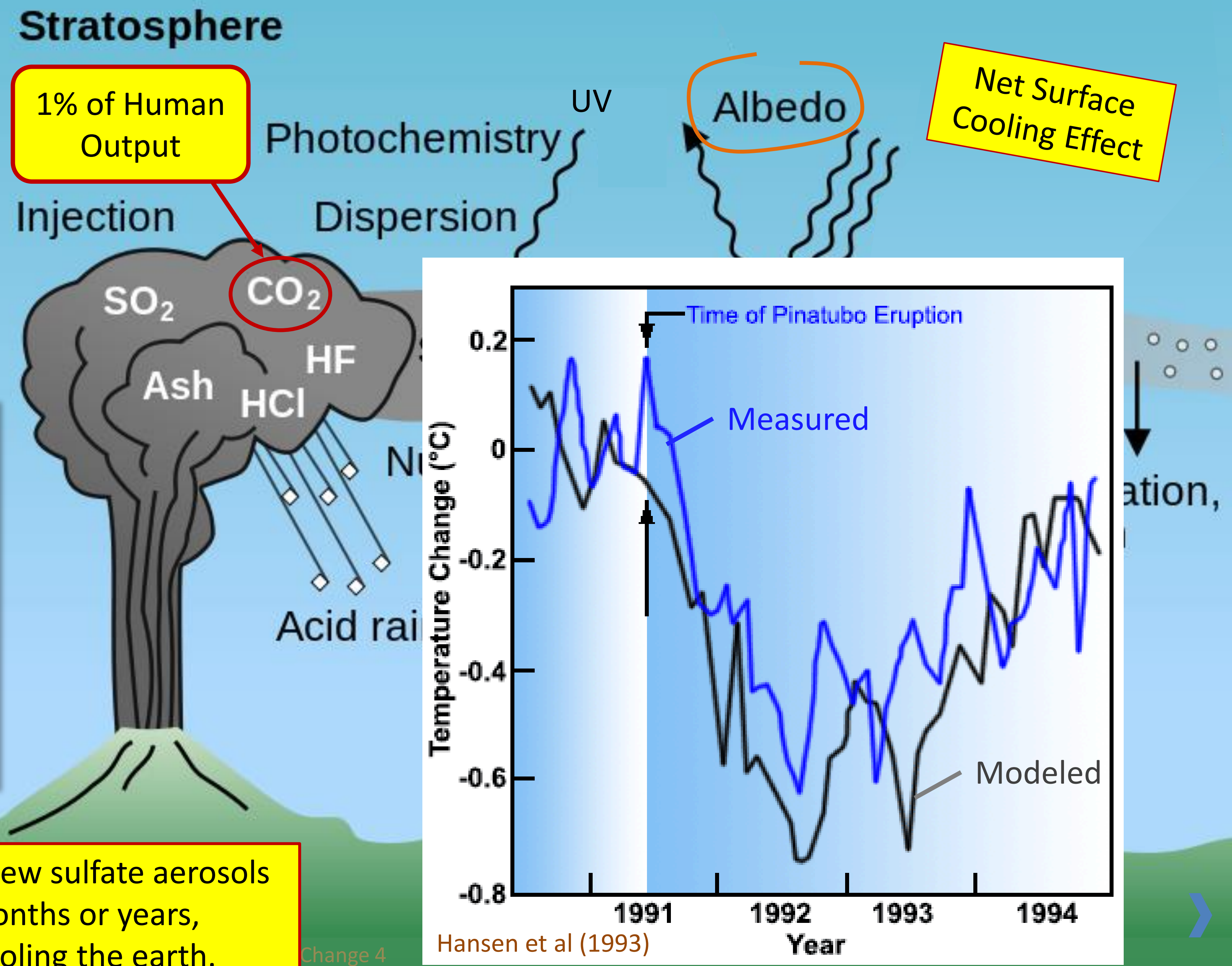
A few large eruptions ("Stratovolcanoes") break through tropopause and reach stratosphere

USGS



Volcanos large and small supply the CO_2 needed to make up sinks in the sea and keep CO_2 levels steady. But human sources of CO_2 are 100x larger!

Major Volcanic eruptions spew sulfate aerosols into the Stratosphere for months or years, changing the Albedo and cooling the earth.



Major Volcanic eruptions spew sulfate aerosols into the Stratosphere for months or years, changing the Albedo and cooling the earth.

99.9% of Earth's Carbon is in Rocks:

Mostly Limestone


Anthro

What are the human impacts on climate?

- Greenhouse Gas Generation
  - CO_2
    - Fossil Fuel Burning
    - Industrial processes
    - Land Use
  - Methane CH_4
  - N_2O
  - Freons
- Aerosol Generation
- Land Use

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We're playing with only **~0.01%** of Earth's carbon….

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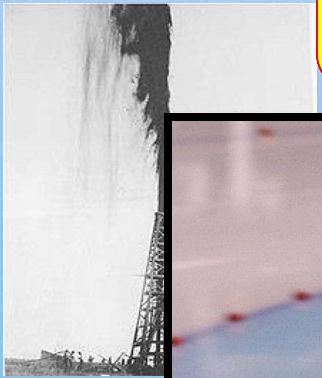
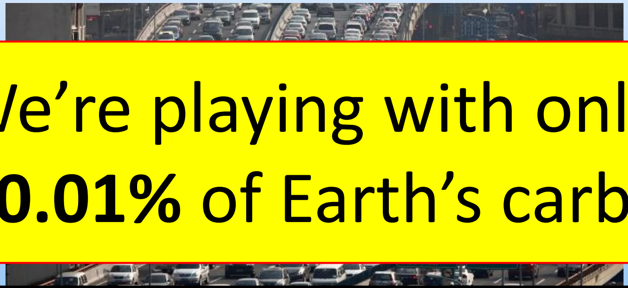
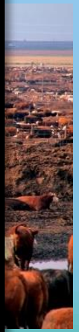




We're playing with only **~0.01%** of Earth's carbon....

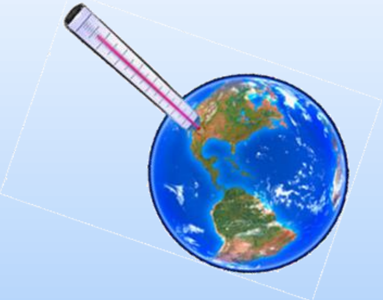


But we're adding it very, very quickly....

What are the human impacts on climate?

- Greenhouse Gas Generation
  - CO_2
    - Fossil Fuel Burning
    - Industrial processes
    - Land Use
  - Methane CH_4
  - N_2O
  - Freons
- Aerosol Generation
- Land Use

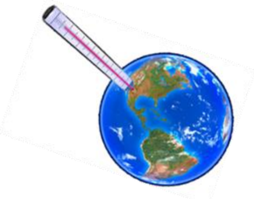
Questions about



- Cryosphere
- Biosphere
- Lithosphere
- Anthrosphere

Other stuff?

Course Outline



1. Building Blocks: Some important concepts
2. Our Goldilocks Earth: a Radiative Balancing Act
3. The Role of the Atmosphere: Greenhouse Gases & Clouds
4. **Global Circulation and Dynamics of the Earth System:**
   Oceans, Atmosphere, Biosphere, Cryosphere, People, Lithosphere
5. Natural Variability of the Climate, short and long term. Ice Ages
6. Carbon Dioxide and other Greenhouse Gases: where do they come from, where do they go, how are they regulated?
7. Impacts and Future Projections for Global Warming -- Uncertainties
8. Amelioration Strategies. The Climate debate. Policy options.