Dynamics of the Atmosphere and Ocean II

Chapter 1: The Atmosphere and Ocean: the Big Picture

1.1] The Atmosphere: an Overview

- Here we will present a top-down view of the atmosphere, what controls its thermal structure and its dynamics.
- Specifically we will look at the following:

A. energy sources

B. thermodynamics

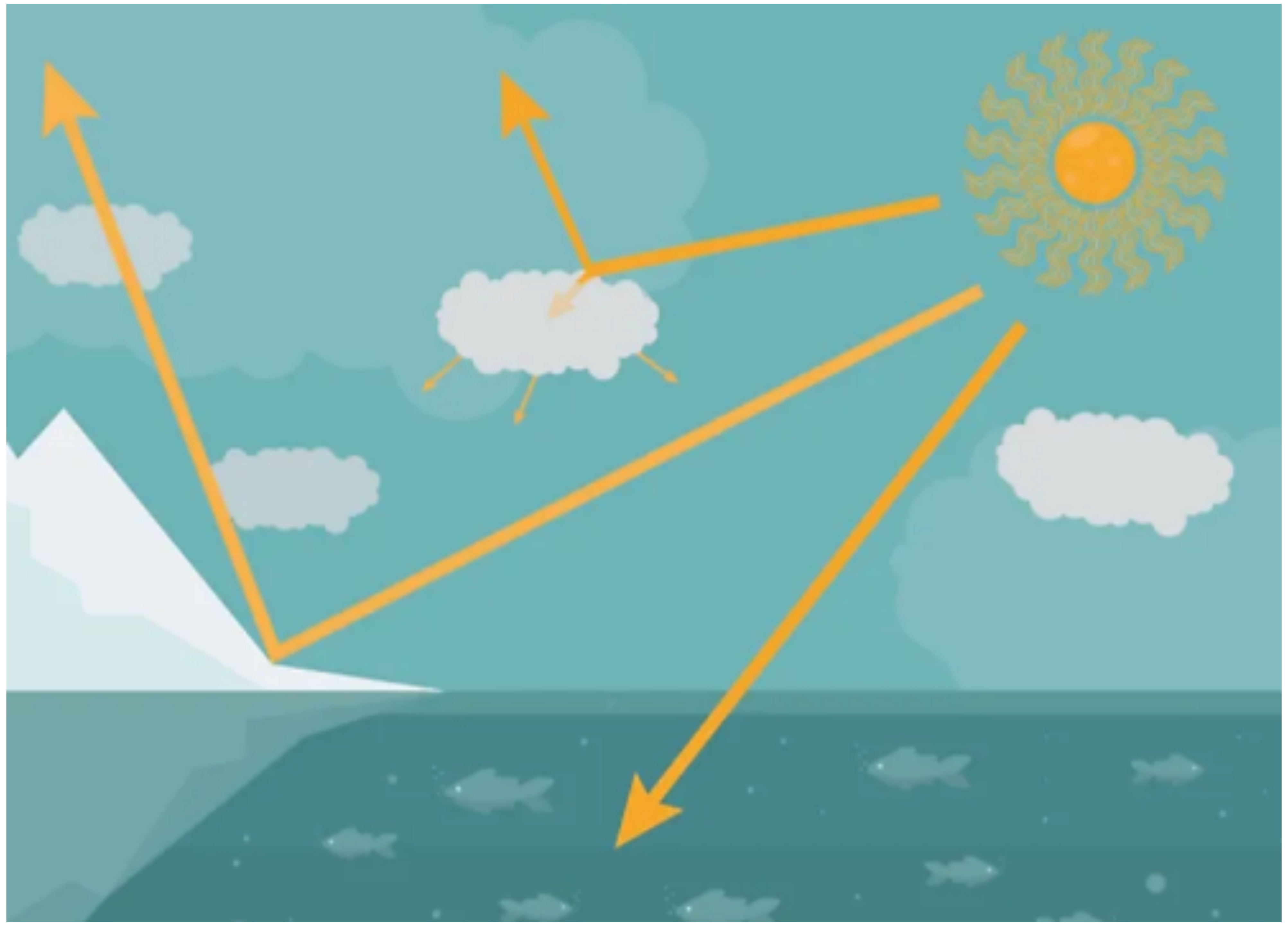
C. influence of the Earth's rotation

D. fluid dynamics

E. other considerations

A) Energy Sources - radiation and the albedo

- Ultimately, virtually all the energy driving our weather and climate originates from the sun.
  - *One exception is the effect of the moon on driving tides, which are important for ocean mixing … more on this later.*
- The flux of energy from the sun is 1370 W/m^2.
- About 30% of this input is reflected directly back out to space by reflection from the Earth's atmosphere (eg cloud tops) and surface (eg ice).
- The remaining 70% either heats the land and water or is absorbed directly in the atmosphere (eg by ozone).



A) Energy Sources - angle of incidence

- A surprising number of people think that it is warmer at the equator than the poles because the sun is closer to the equator.

- Of course this is completely wrong. The distance from the Sun to the Earth is 1.5×10^8 km whereas the radius of the Earth is just 6.4×10^3 km; the difference in distance to the poles and to the equator is negligible.

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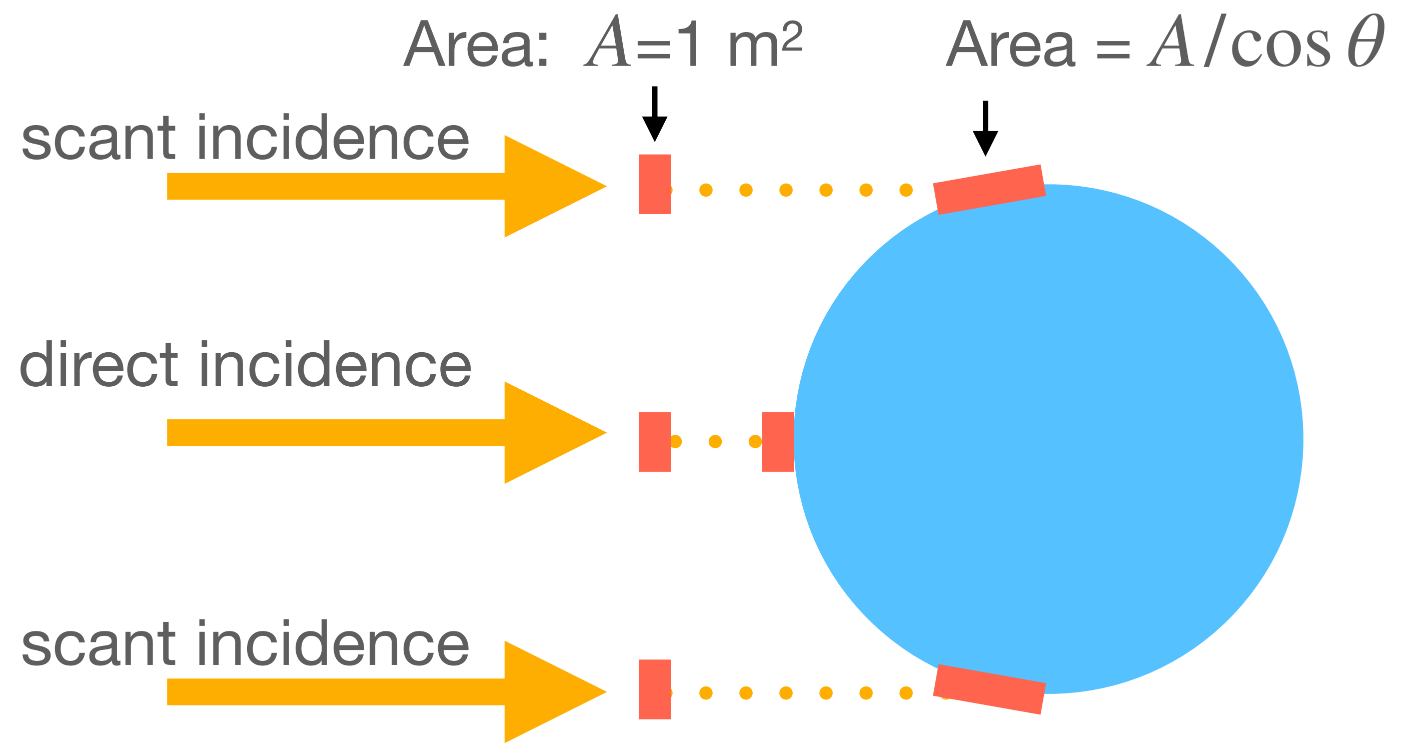

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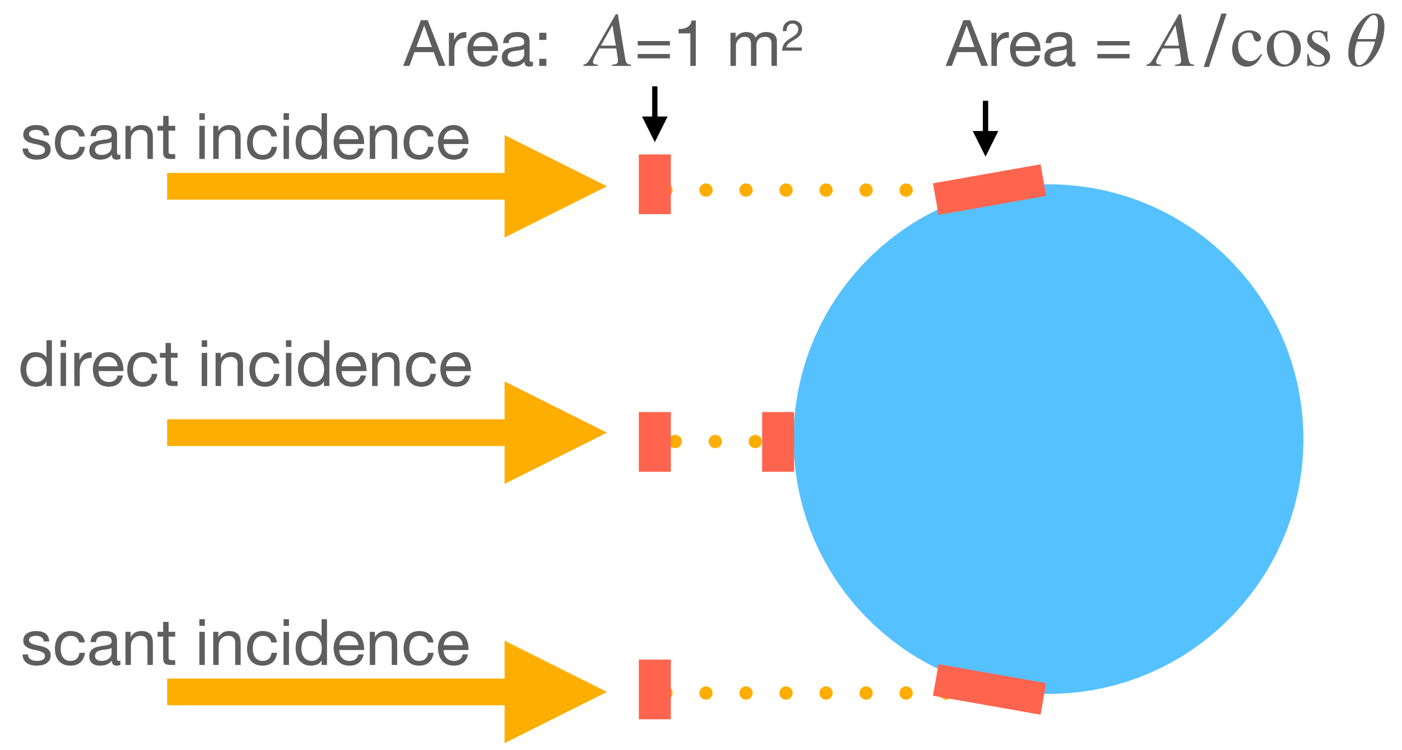
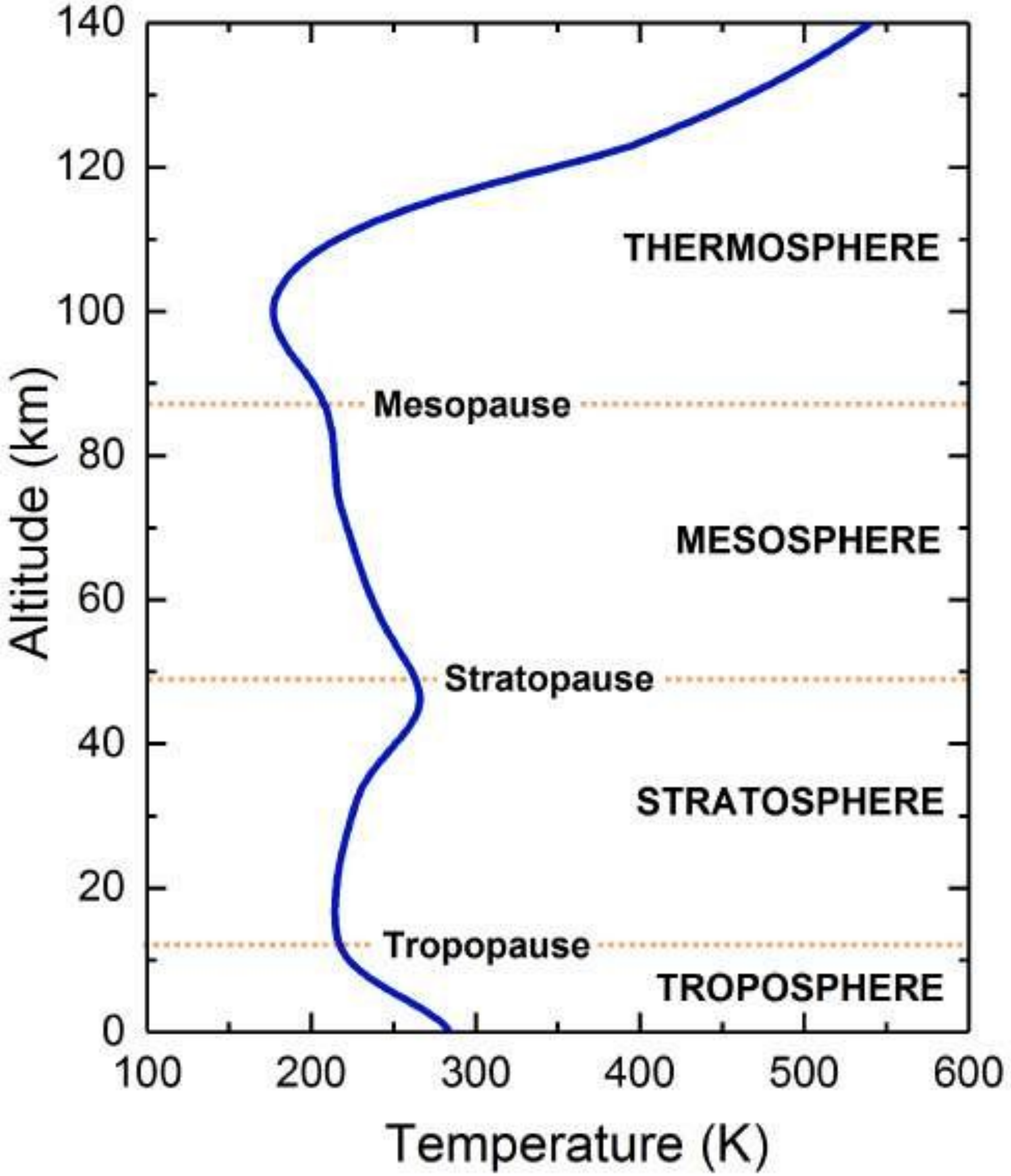


- Sunlight reaching the poles arrives at a scant angle, so the incident energy is spread out over a wider area.

- Sunlight crossing normal to $A = 1$ m^2 that hits the Earth at latitude θ is spread over an area $A/\cos\theta$. So the incident power is reduced to $1370\cos\theta$ W.

B) Thermodynamics: layers of the atmosphere

- A combination of chemistry (determining light absorption by different gases) together with thermodynamics gives rise to the observed thermal structure of the atmosphere.
- The 3 important “layers of the atmosphere are
  - the troposphere
  - the stratosphere
  - the mesosphere



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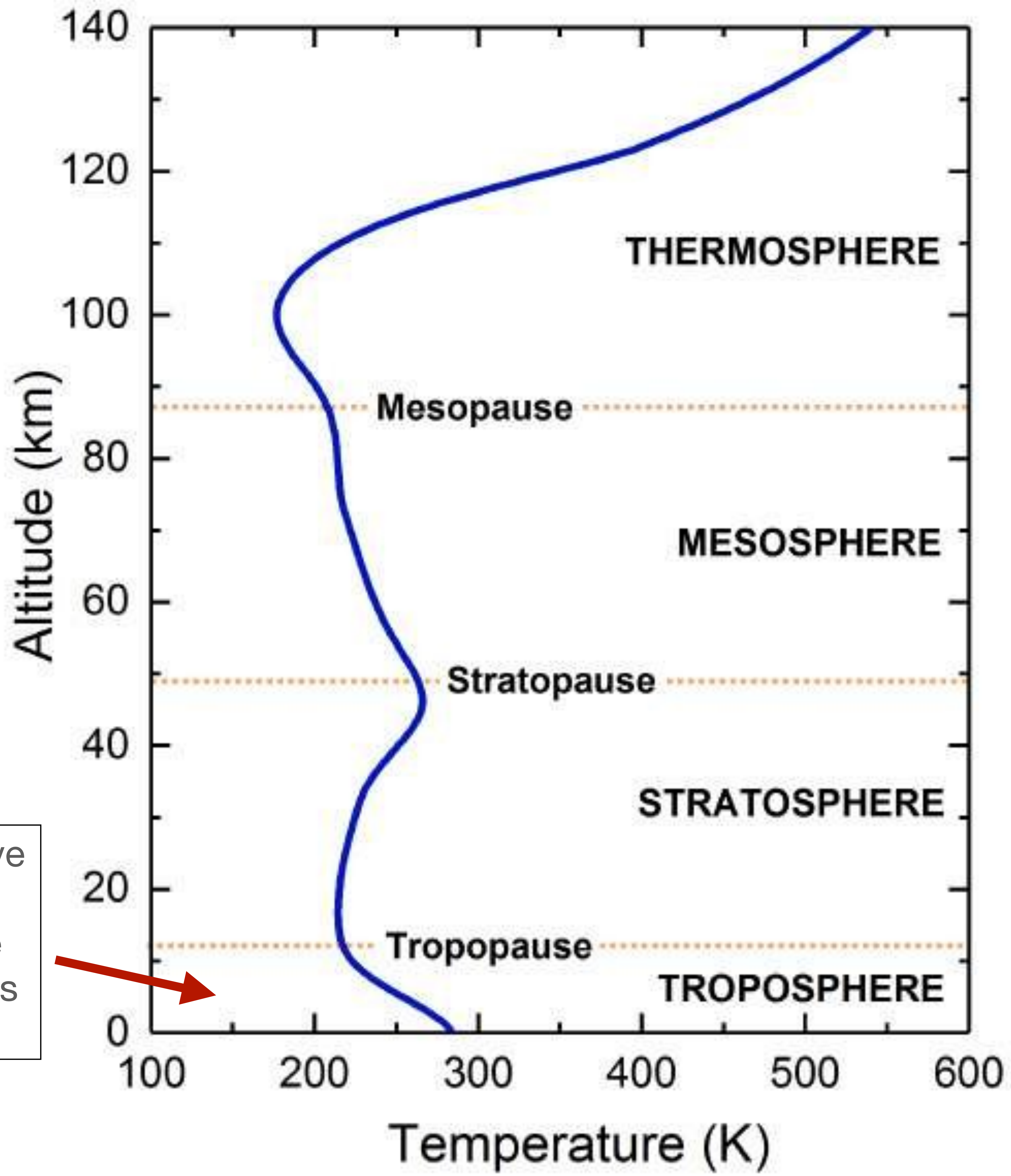
Cools with height because rising air cools as it expands in lower pressure



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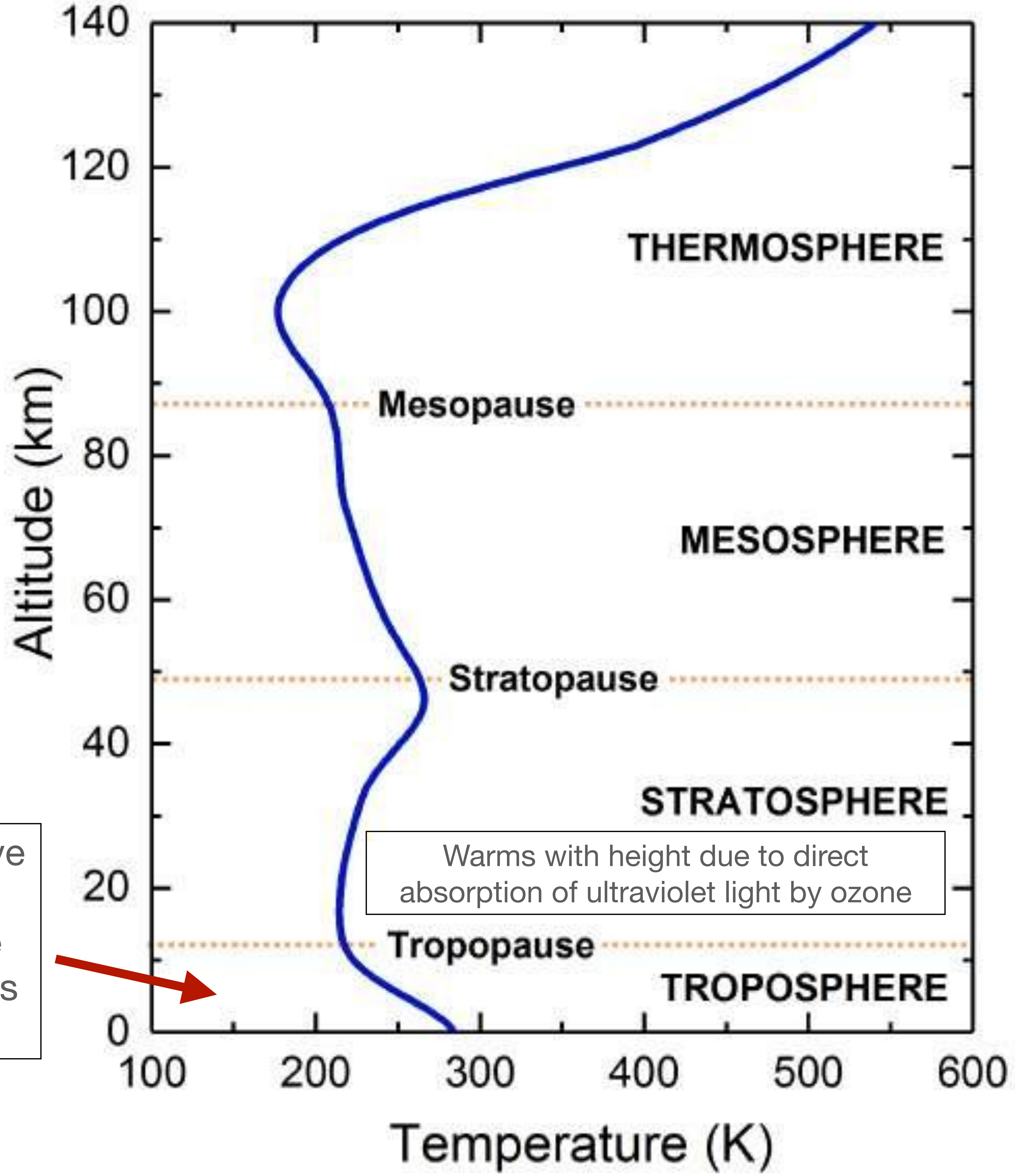

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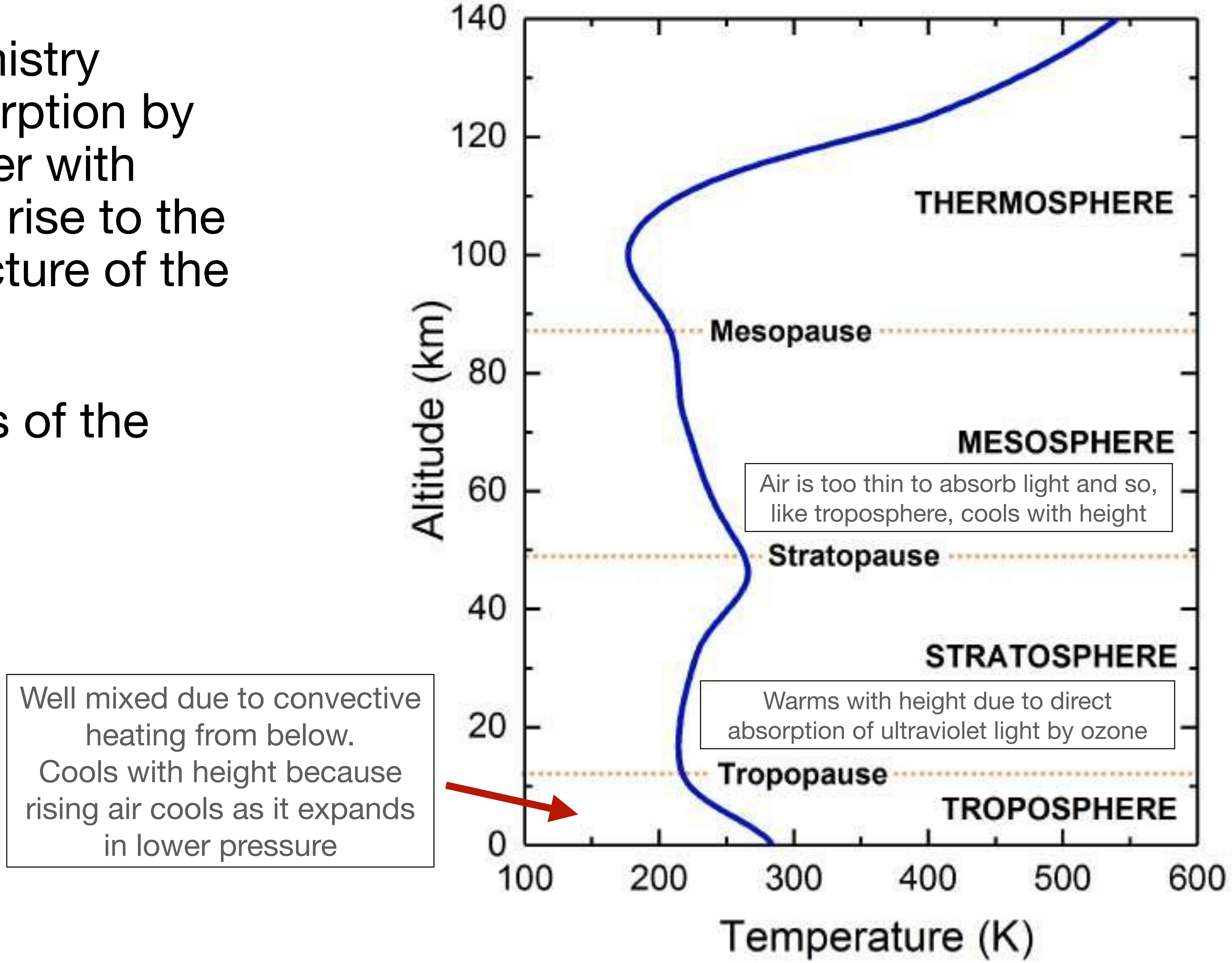

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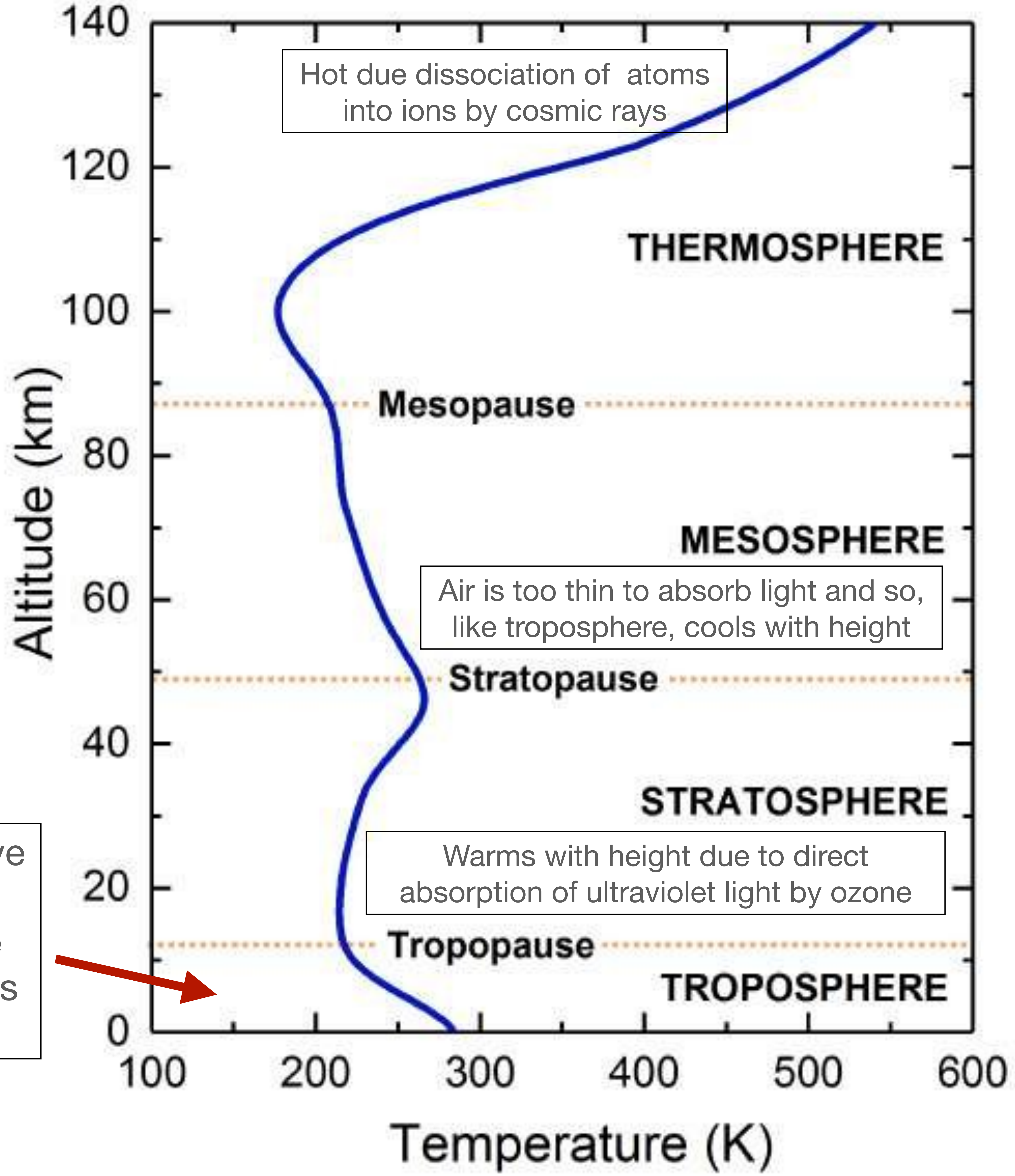
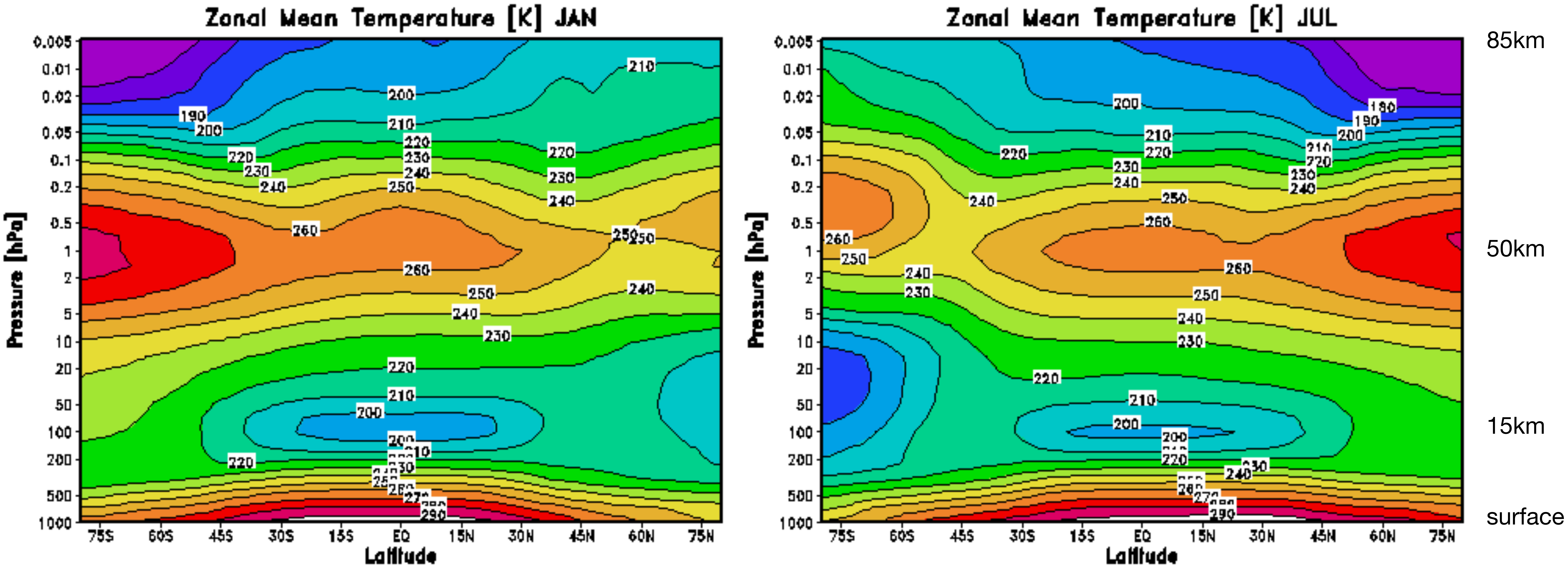


B) Thermodynamics: latitude and seasonal dependence

- The temperature in the troposphere is hottest at the equator.
- Around the stratopause, temperatures are warmer toward the summertime pole.
- But coldest temperatures are at summertime pole near mesopause.



COOL WARM COOL COOL WARM COOL

[sparc-climate.org]

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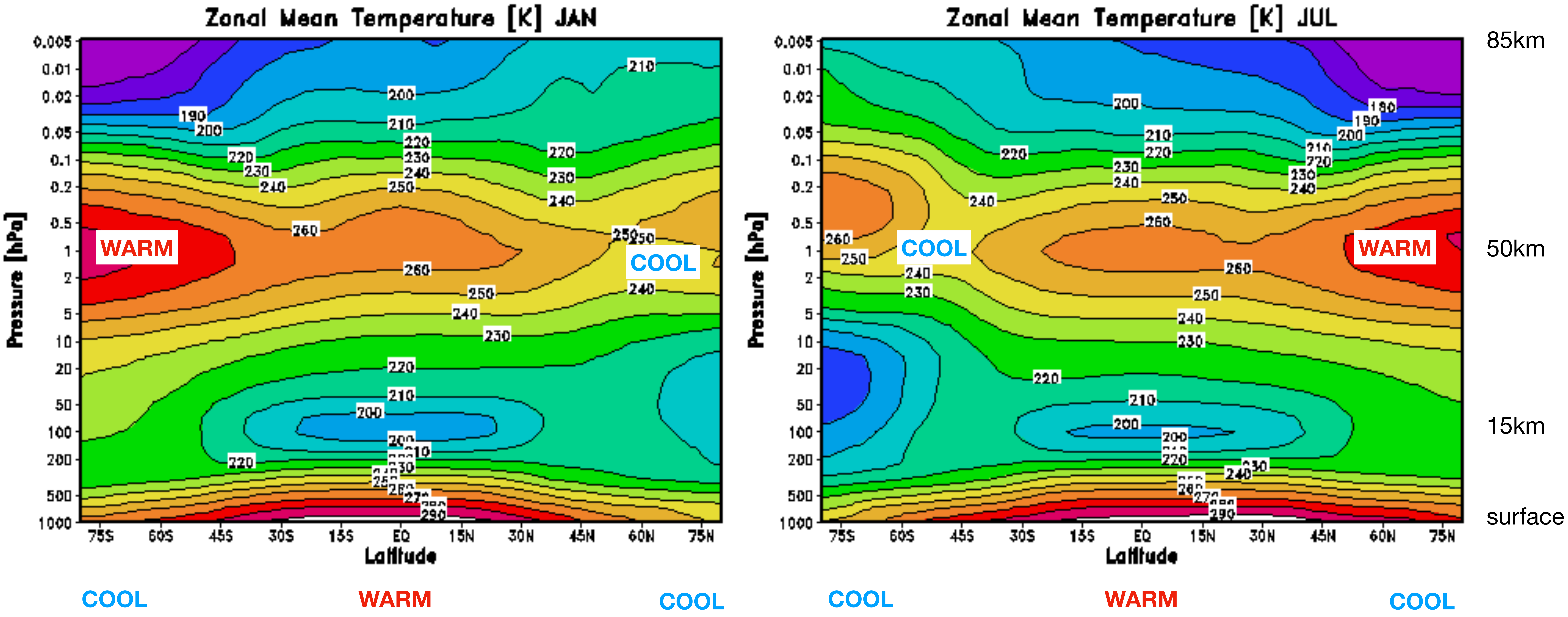

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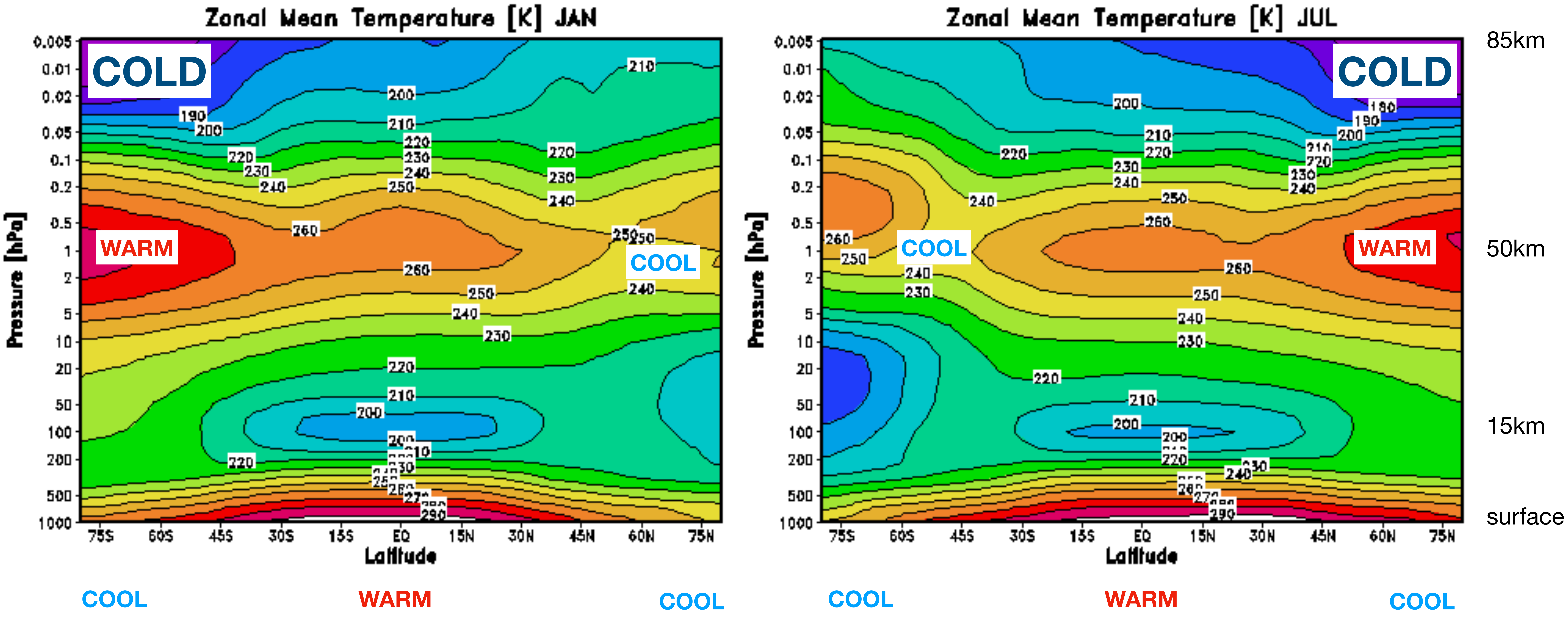

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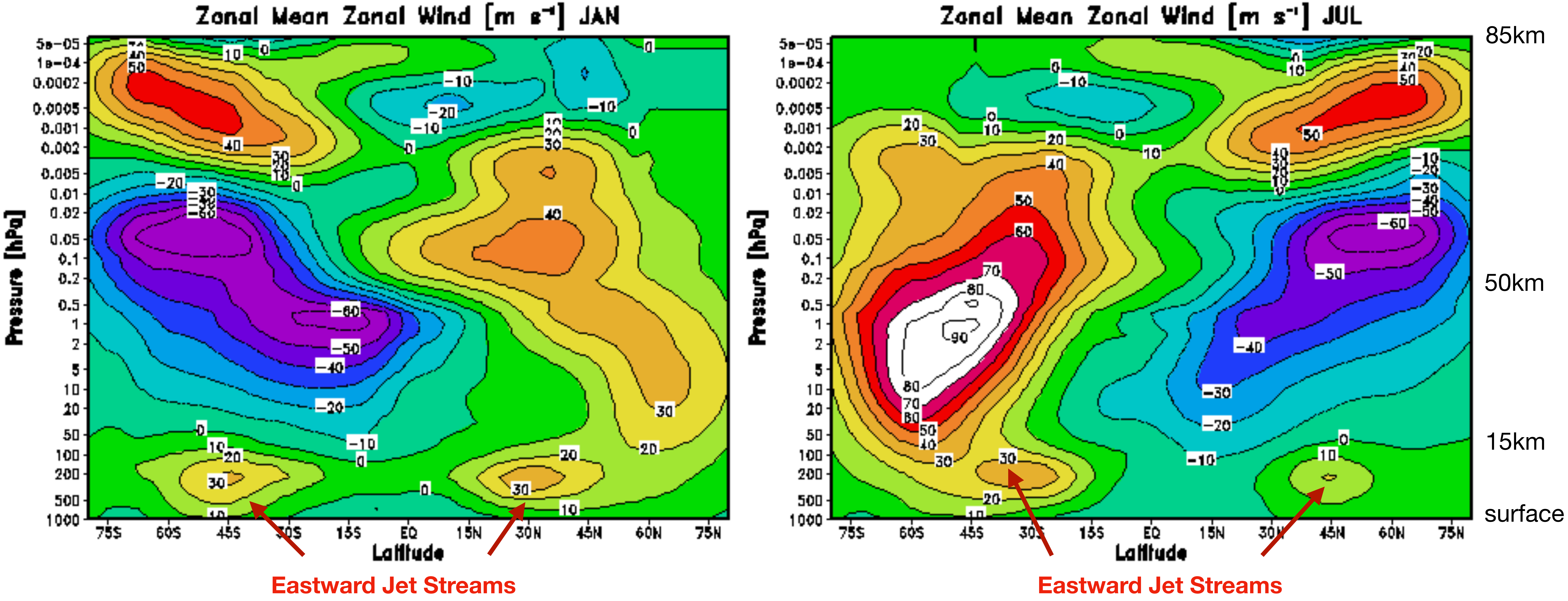
C) The Earth's Rotation

- Rotation deflects horizontal motion rightward in NH and leftward in SH.
- So warm air near equator spreading poleward is deflected to form "jet streams".



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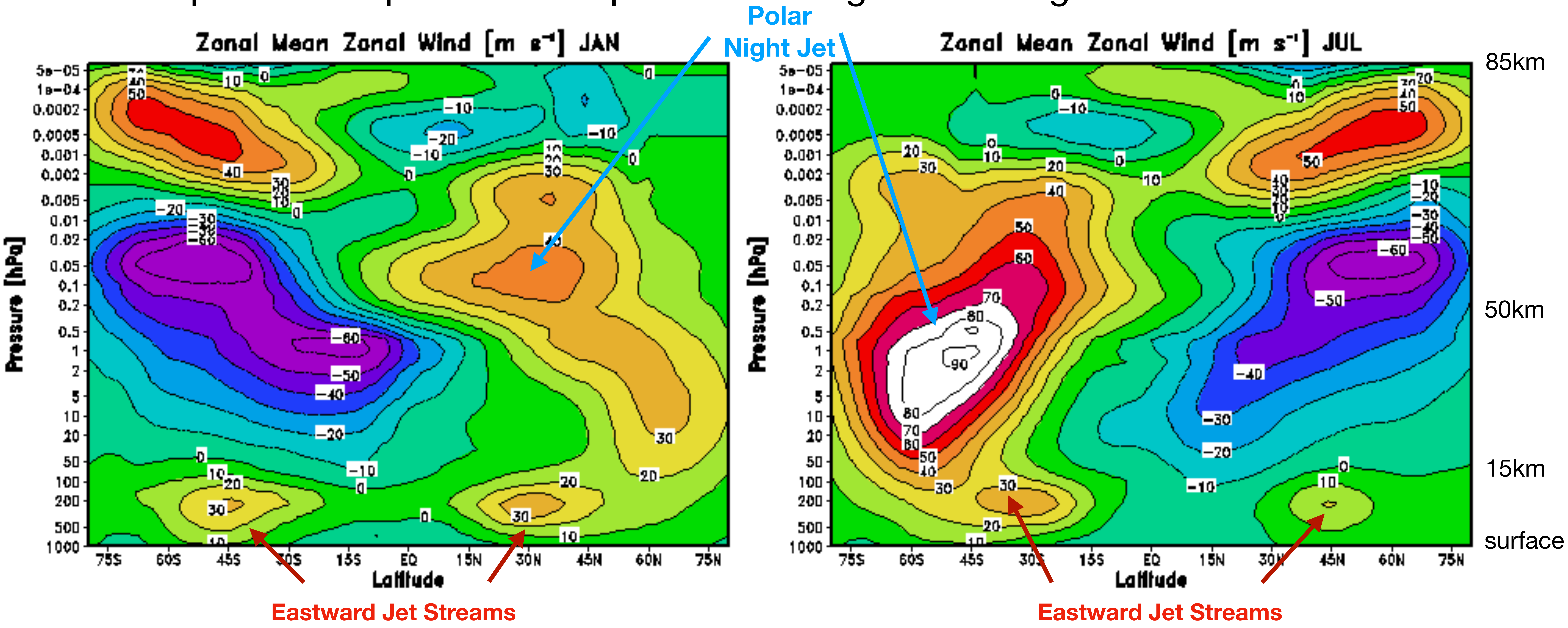
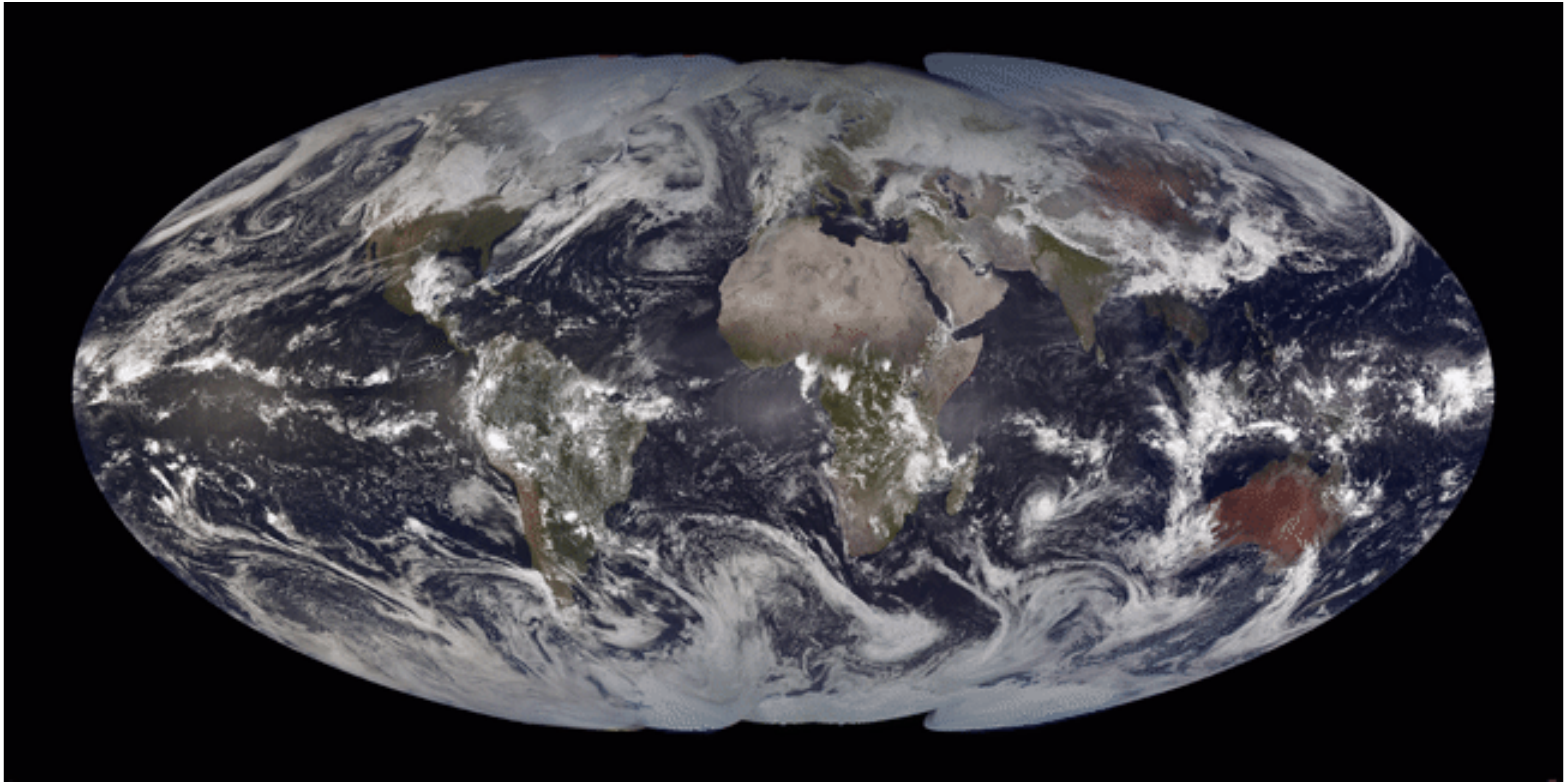
- In middle atmosphere, winds change from westward to eastward from summer to winter poles in response to temperature changes with height.



D) Fluid Dynamics: motion visualized by clouds



Successive snapshots of Earth at noon each day from March 6 - April 6, 2019

D) Fluid Dynamics: scales of motion

- So far we have been showing average profiles of temperature and winds (averaged going around lines of latitude).

- In reality weather occurs on length scales varying from 1000 km (synoptic weather patterns) to less than 1 mm (turbulence).
- Likewise, the time for evolution varies, being on the order of a week for synoptic-scale motion, on less then seconds for turbulence.

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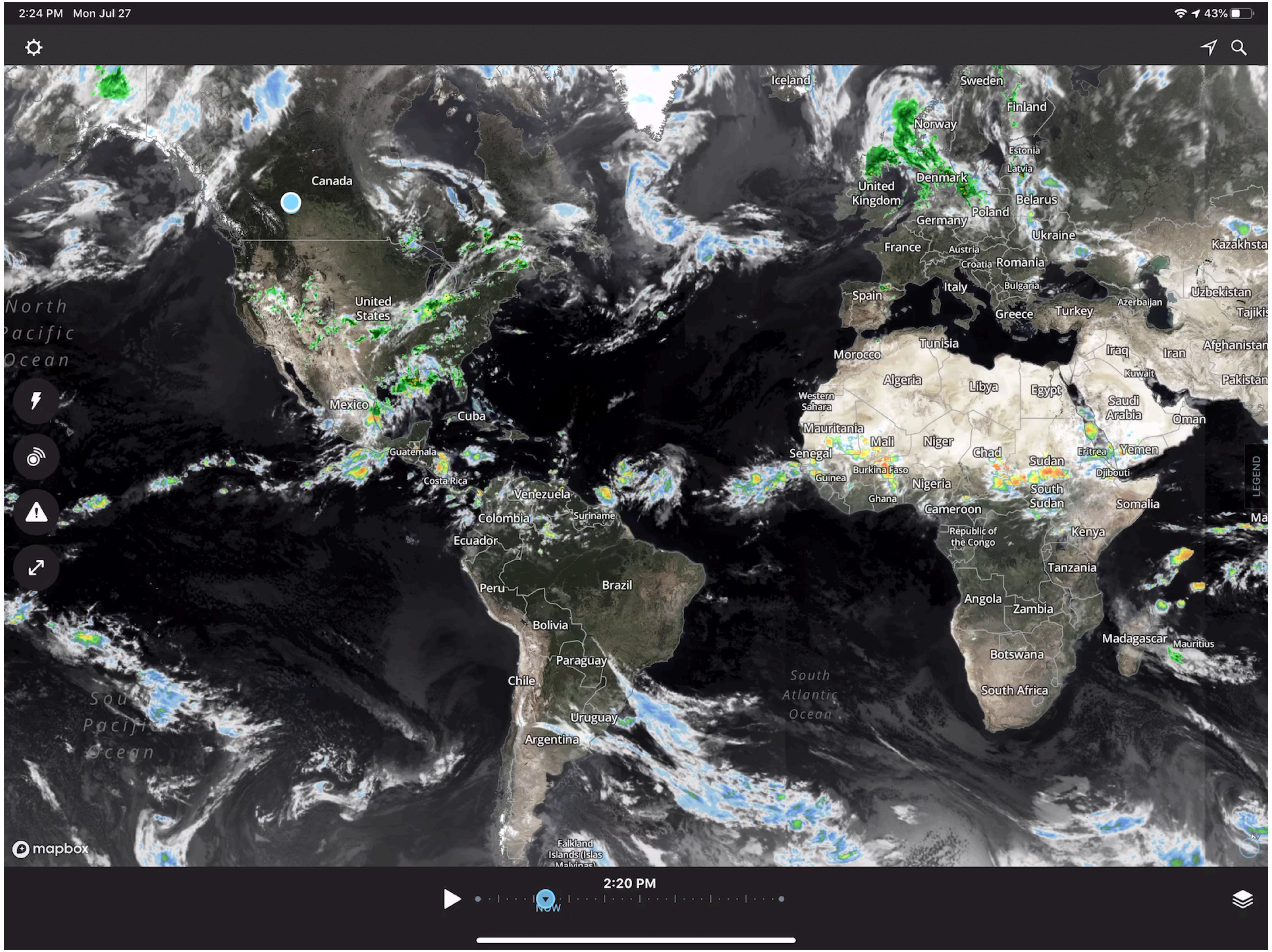
- Likewise, the time for evolution varies, being on the order of a week for synoptic-scale motion, on less then seconds for turbulence.
- For weather, the important scales are
  - Synoptic scales (100 - 1000 km)
  - Mesoscales (10 - 100 km)
  - Microscales (<100 m)

D) Fluid Dynamics: the Earth’s weather on July 27, 2020



This video was made using a screen recording of the “Storm Radar” app

D) Fluid Dynamics: vortices and waves

- In the movie, clouds did a wonderful job of revealing motion from cyclonic (vortical) motion of the synoptic scale flows, to streaks associated with fronts.
- Another focus in the course will be on waves that propagate within the atmosphere, since these play an important role in vertically transporting energy and momentum.
- Atmospheric waves are everywhere and range in scales from the microscopic to synoptic scale.

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- Atmospheric waves are everywhere and range in scales from the microscopic to synoptic scale.

- If moisture conditions are right, the waves can be visualised by clouds where moist air at the crests rises and cools causing condensation, and the droplets evaporate at the troughs where the air descends and warms up.
- They are particularly dramatic when forming over mountains to form "lenticular clouds" … a visualization of "internal gravity waves".

E) Other Considerations

- Besides the energetics, thermodynamics and fluid dynamics discussed so far, there are several other factors that significantly affect the weather:
  - Boundary conditions
    - surface roughness
    - heat reservoirs (eg water vs soil vs vegetation)
  - Moisture
    - heat release by condensation
    - heat absorption by evaporation
  - Aerosols (eg dust, pollution)
    - these partially block sunlight
    - Also act as nucleation sites for water droplets in clouds
  - etc ….

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  - etc ….
- **This course will <u>not</u> consider these factors, instead focusing on synoptic and mesoscale dynamics as well as consideration of atmospheric waves across wide-ranging scales.**

1.2] The Ocean: an Overview

- Here we will follow the same approach for the ocean as for the atmosphere (with some modifications), looking at the following:

A. energy sources

B. thermodynamics

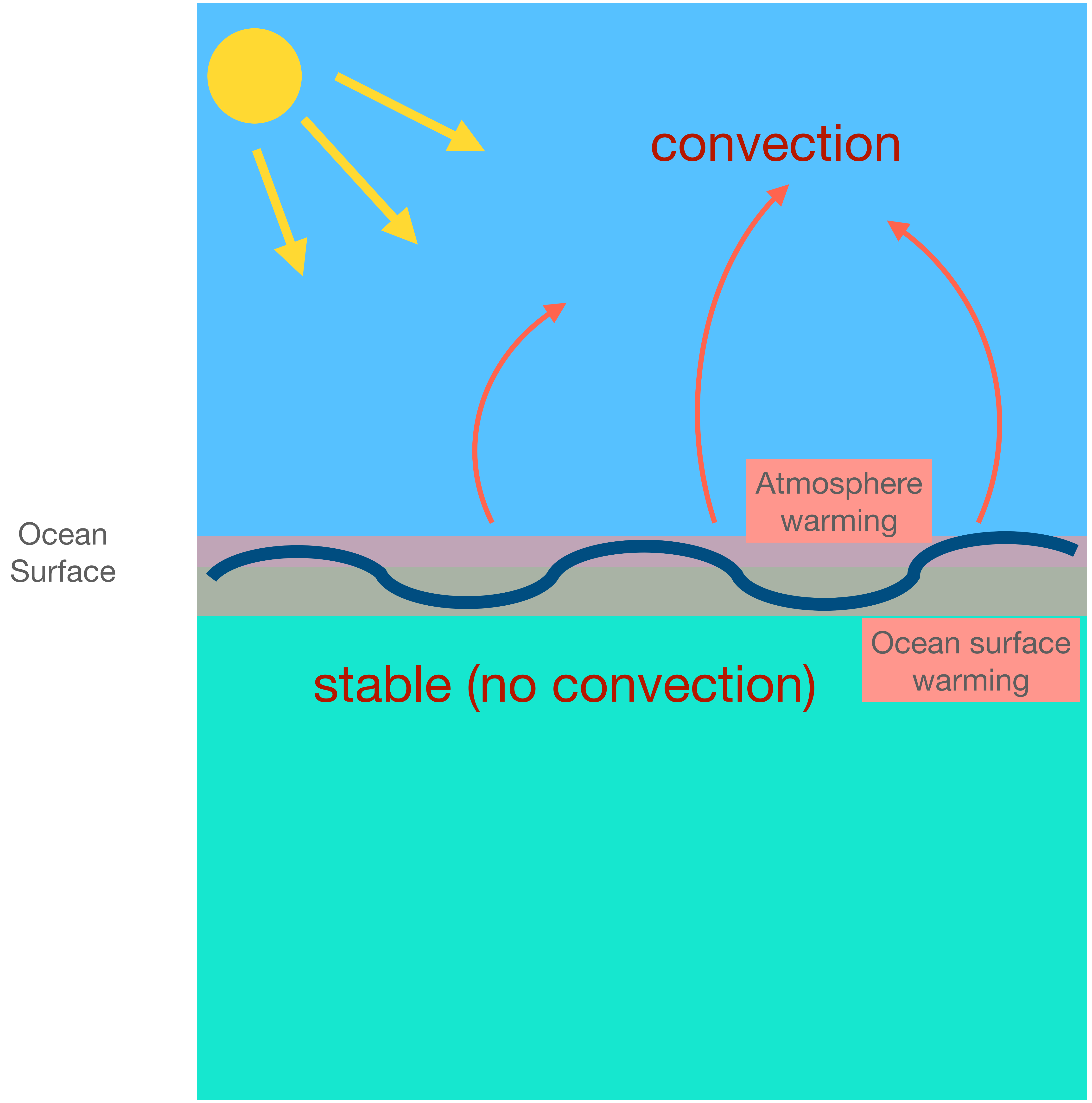
C. influence of the Earth’s rotation and side boundaries

D. fluid dynamics

E. other considerations

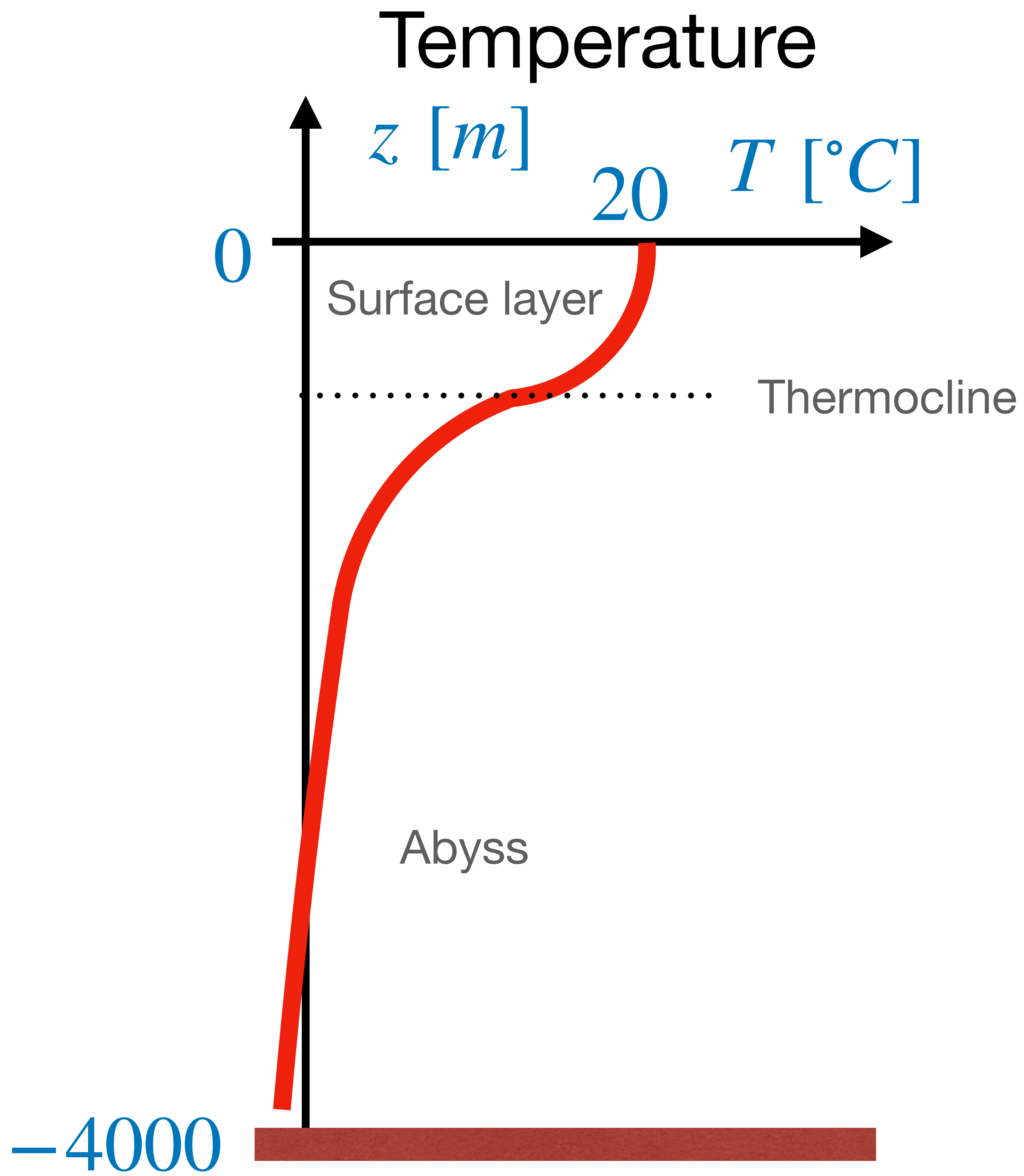
A) Energy Sources - thermal and mechanical forcing

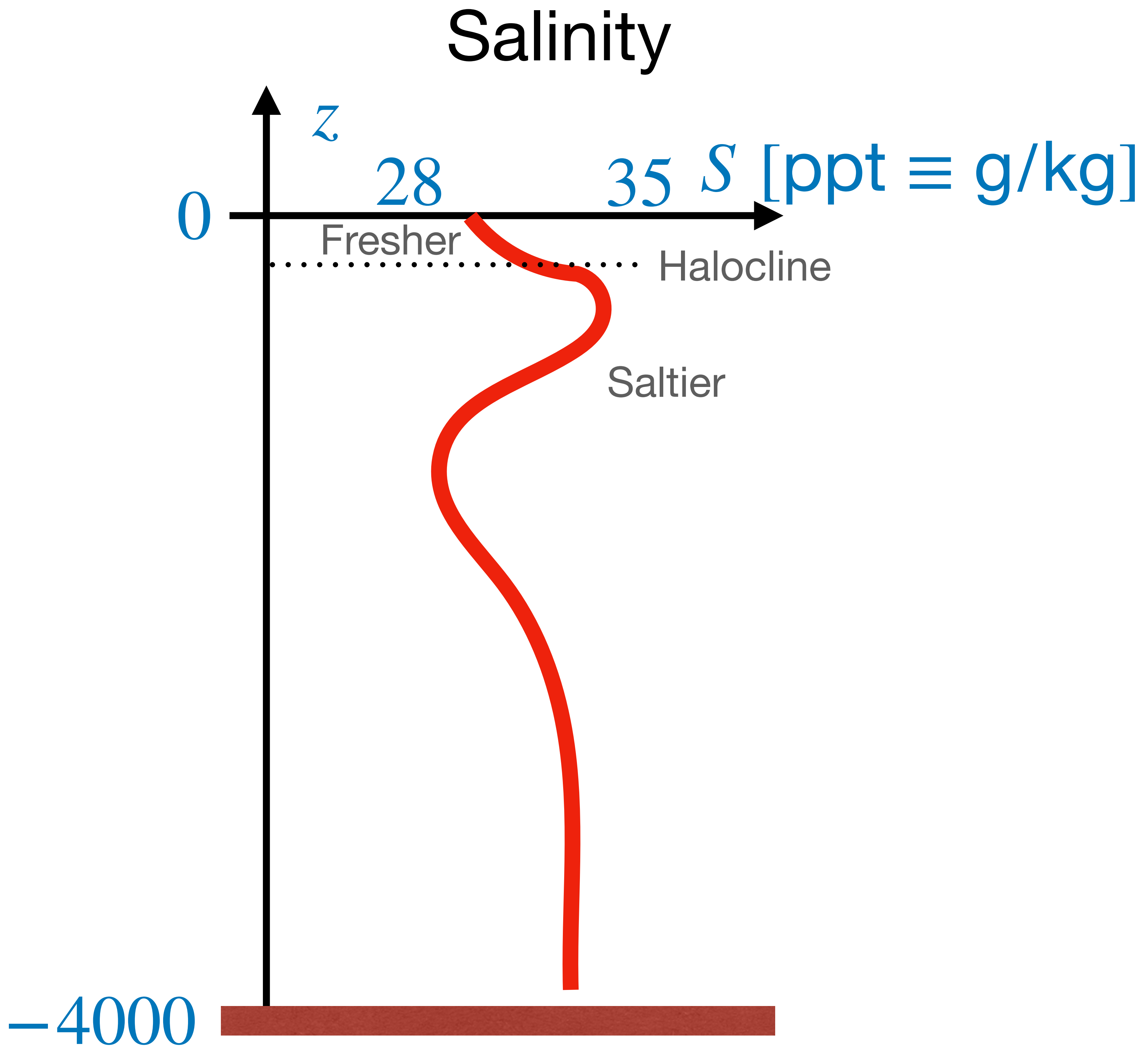
- As with the atmosphere, the ocean receives heat energy that warms the ocean most near the equator.
- As opposed to the atmosphere where surface warming causes convection, in the ocean, warming is stabilising: warmer water at the surface stays there.
- The primary drivers of motion in the ocean are due to
  - winds - driving motion at surface (20 TW goes in but 95% dissipated at surface)
  - tides - driving mixing at depth (3.5 TW goes in with about 2/3 dissipated in shallow seas)



B) Thermodynamics: temperature and salinity

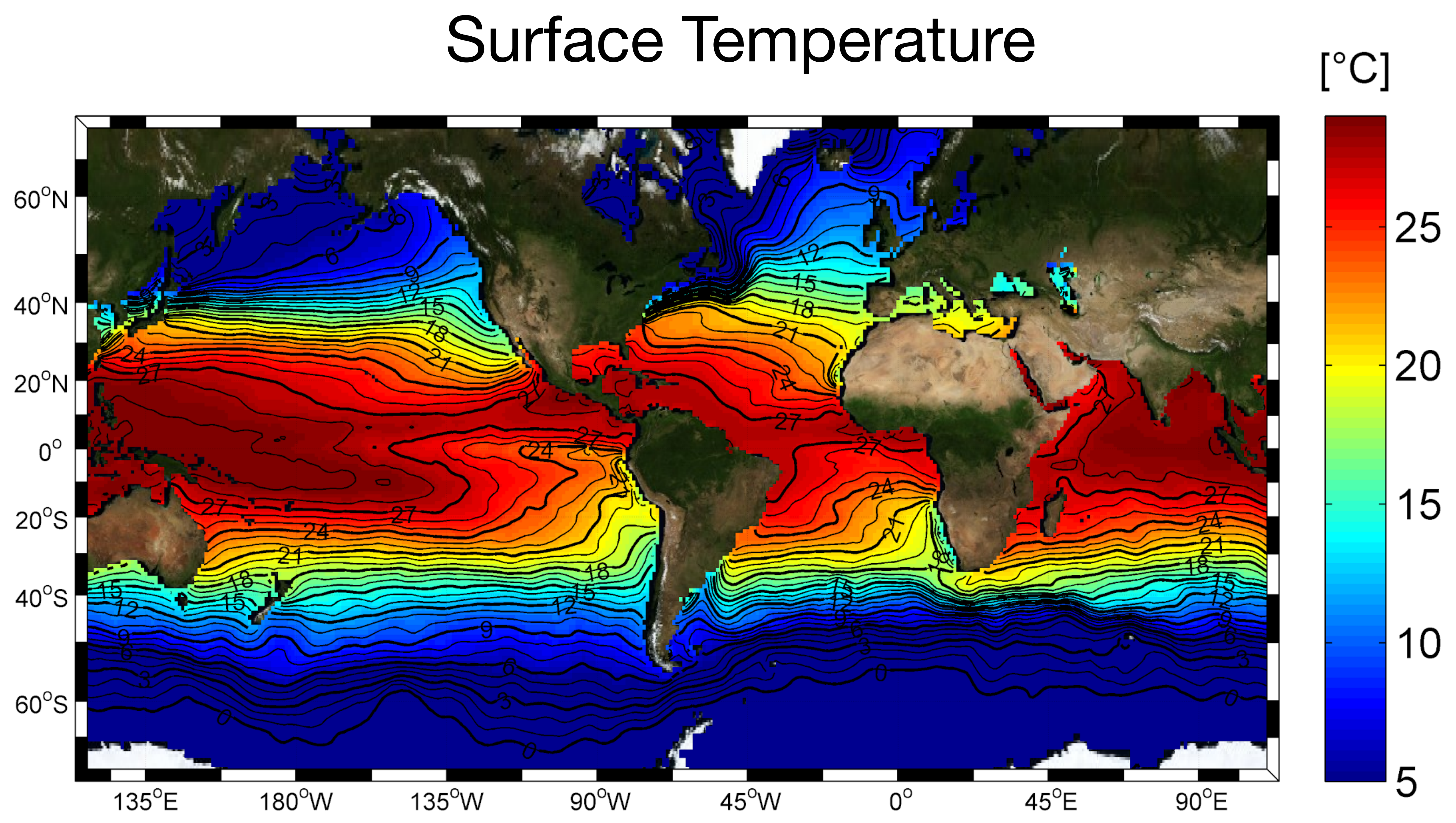
- The density of air depends primarily upon pressure and temperature.
- In the ocean, pressure is less important. But need to consider salinity as well as temperature





B) Thermodynamics: sea surface temperature and salinity

- As expected the surface is warmest about the equator.



[Source: World Ocean Atlas, 2005]

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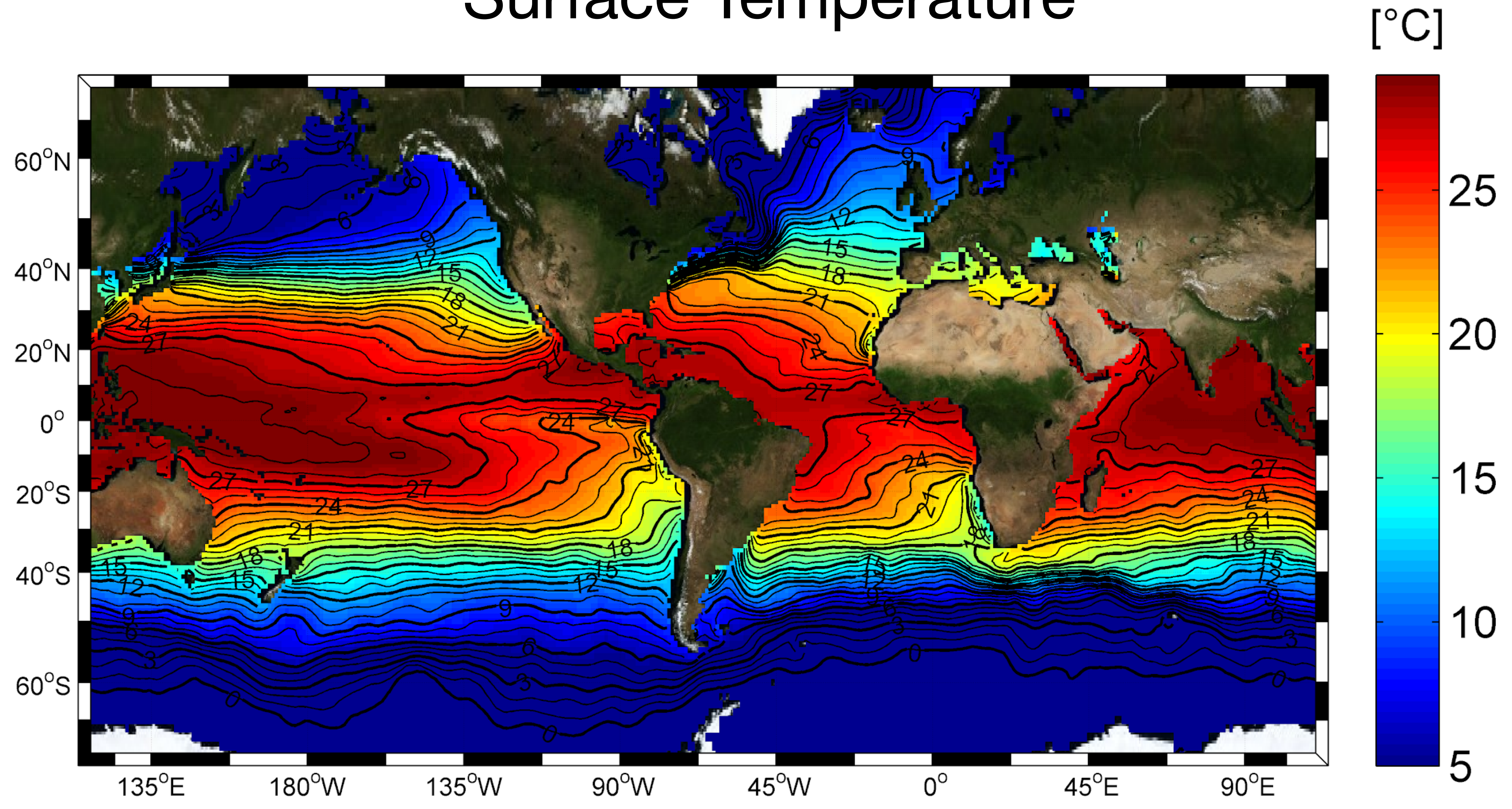
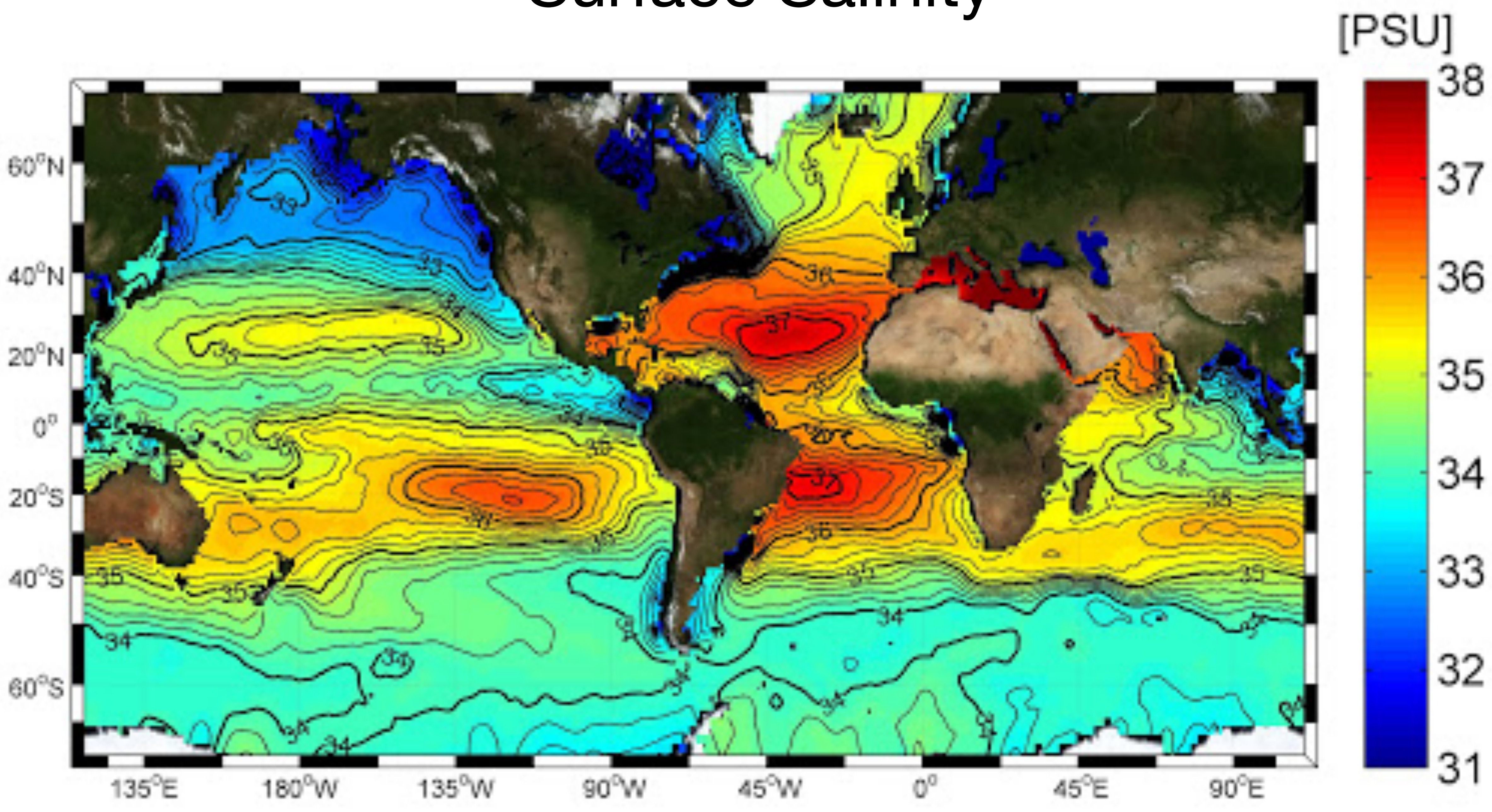
- Salinity can be larger due to evaporation and smaller due to rain (or ice melting toward poles)

Surface Temperature



Surface Salinity



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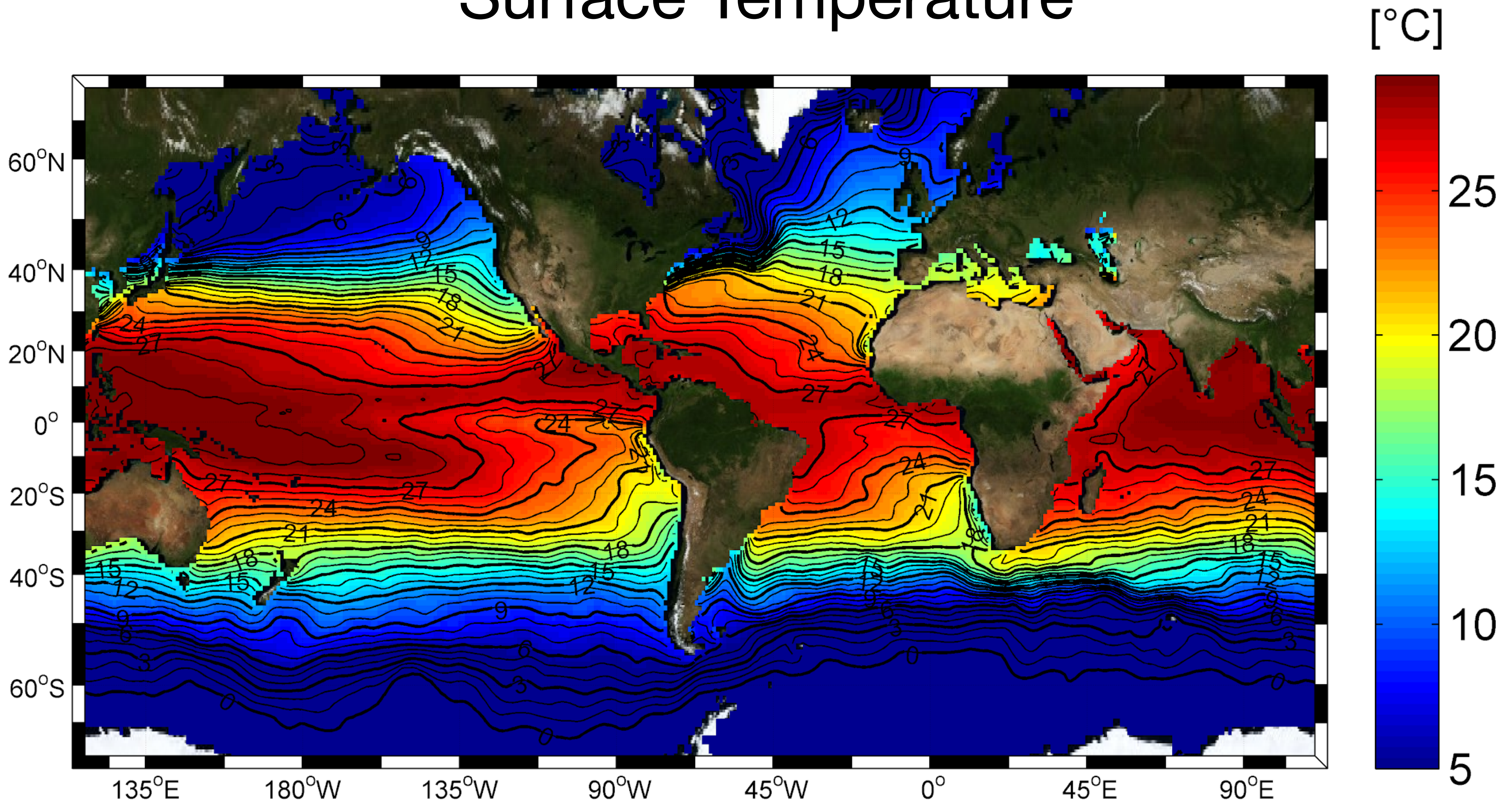
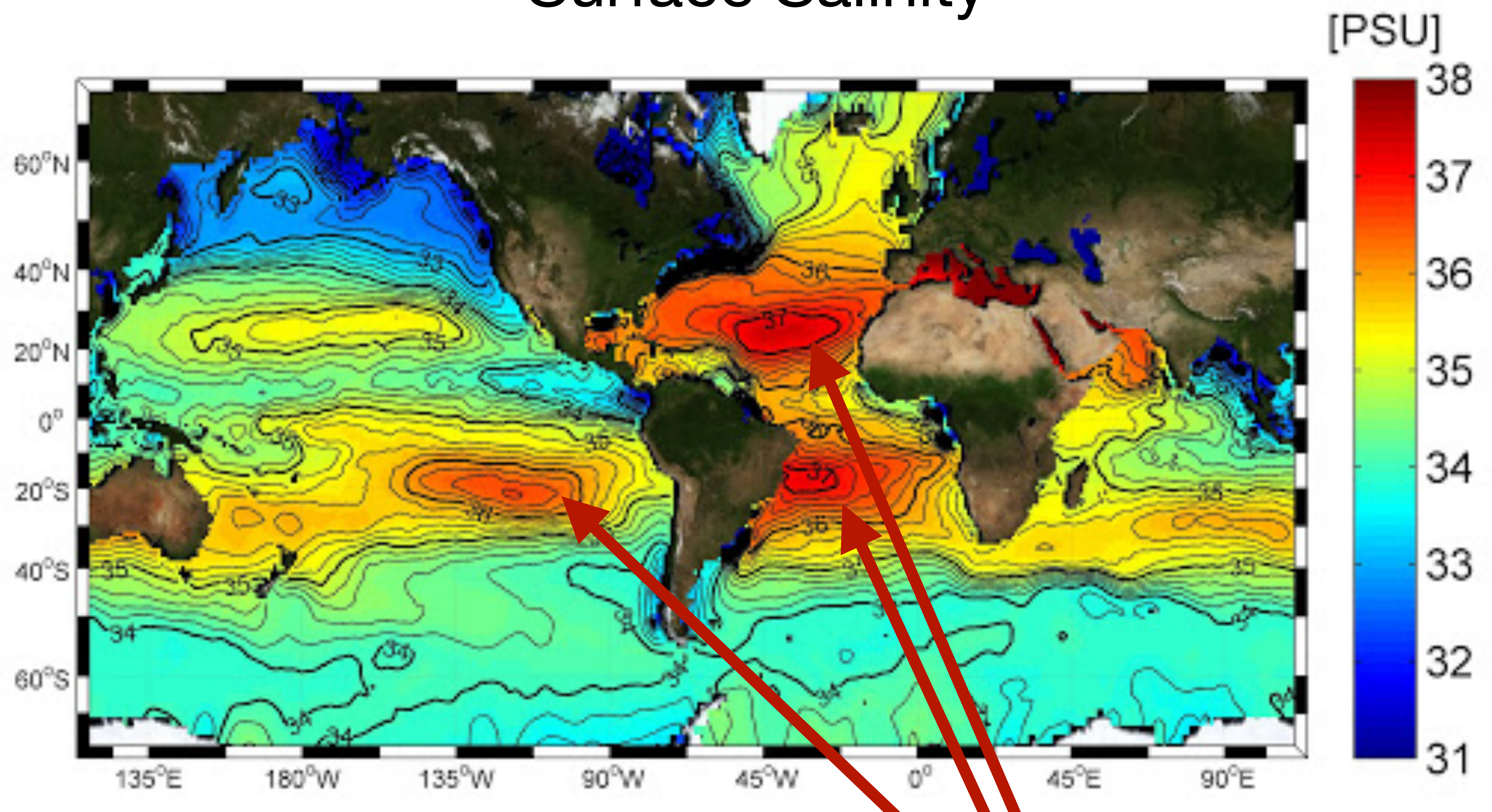


Surface Salinity



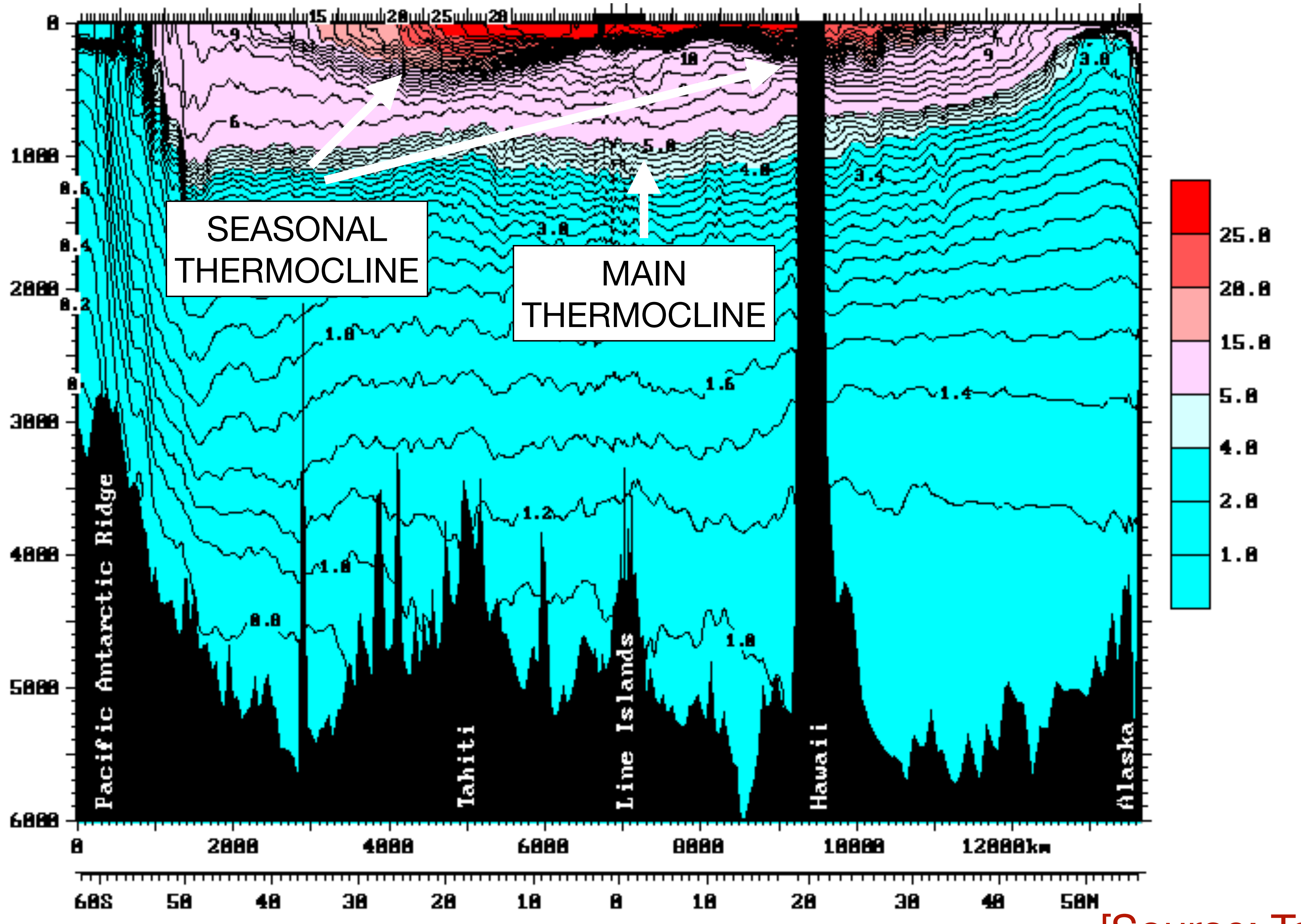
[Source: World Ocean Atlas, 2005]

Saltier because of evaporation, but not under equatorial storms

B) Thermodynamics: vertical cross-sections of temperature and salinity

- Generally the temperature becomes cooler with depth.

Temperature cross section at 150W

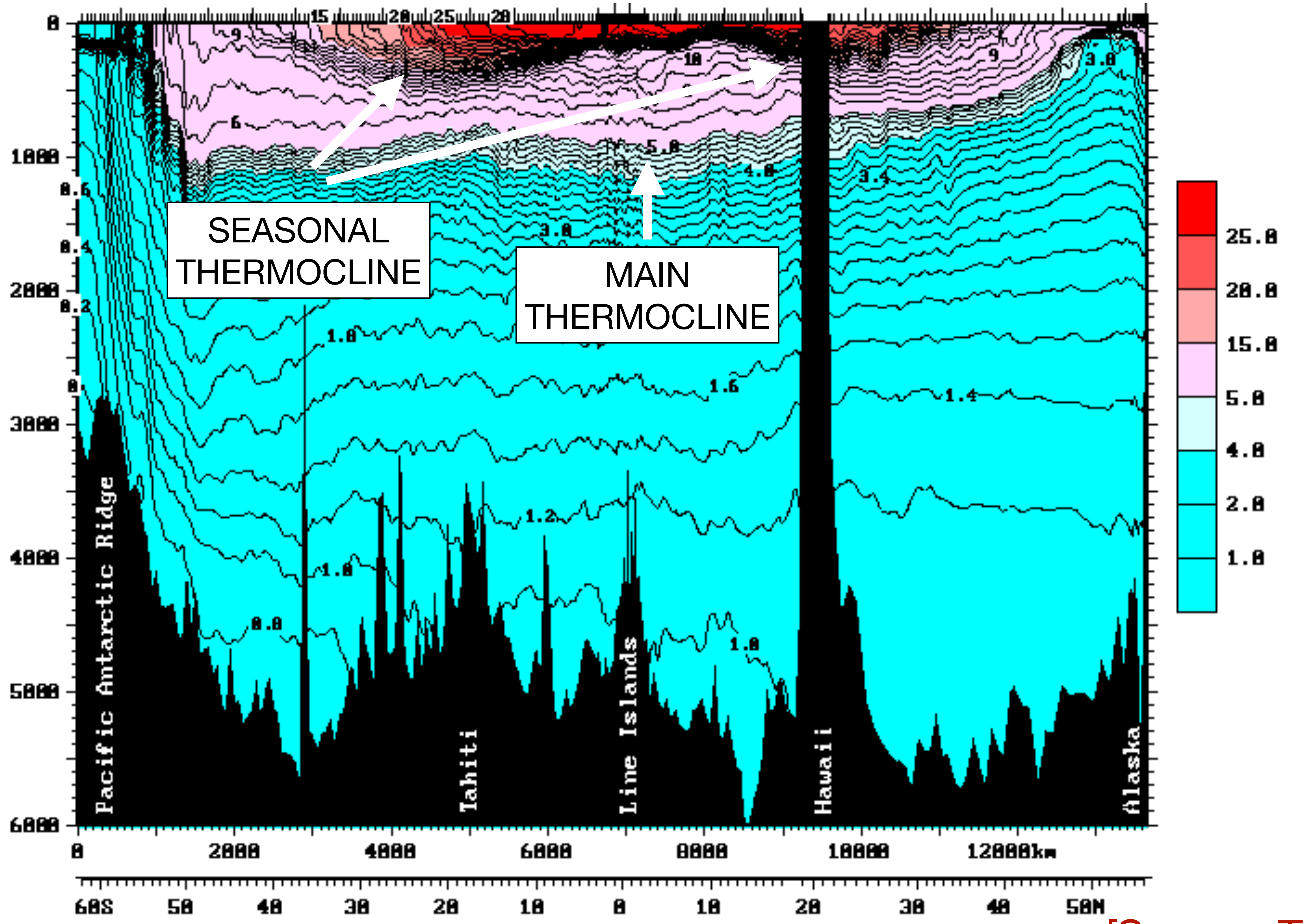


[Source: Talley et al (1991)]

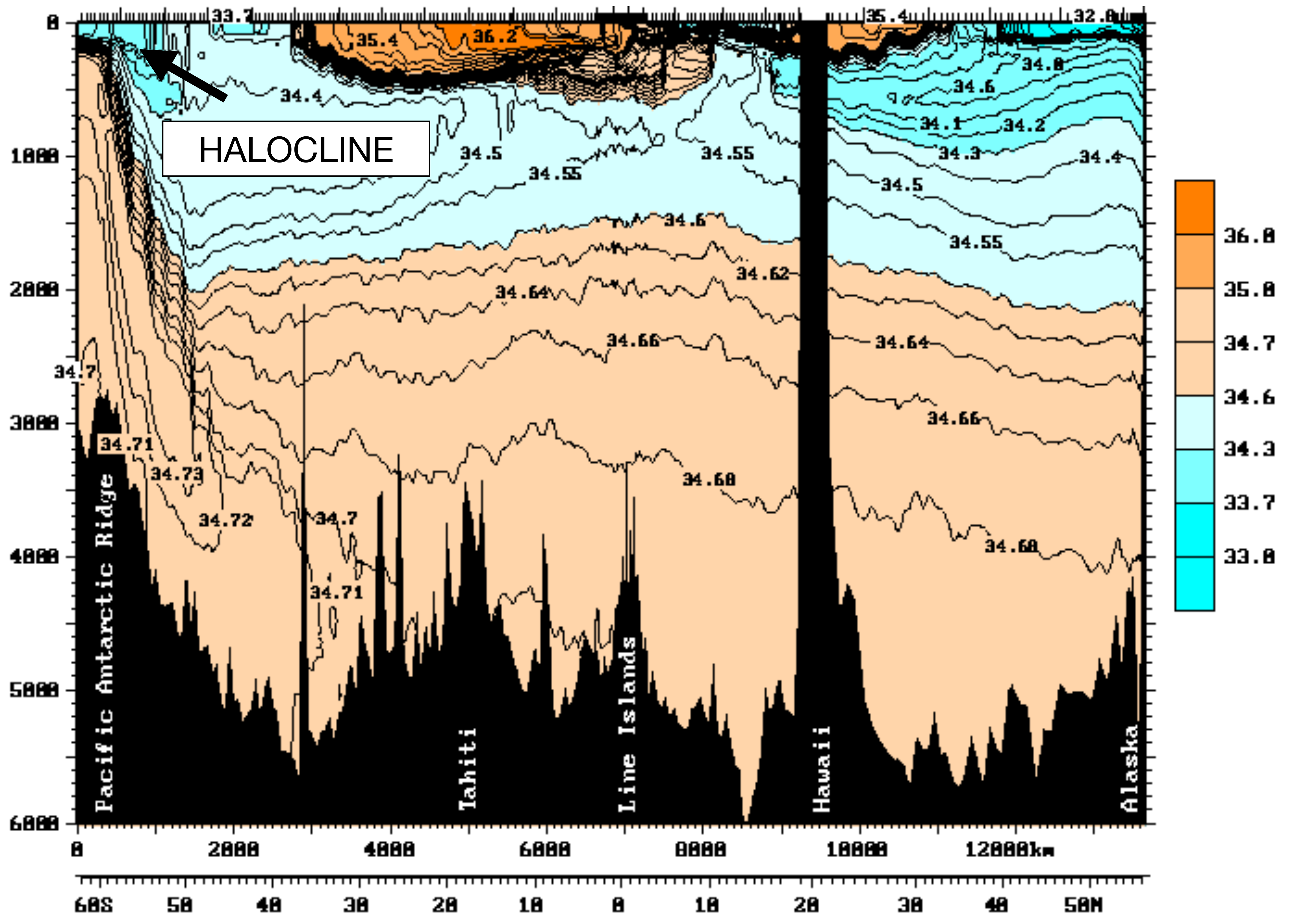
B) Thermodynamics: vertical cross-sections of temperature and salinity

- Generally the temperature becomes cooler with depth.
- Salinity can decrease and increase with depth; salty water needs to be warm enough so that it is less dense than fresher, cooler water below.

Temperature cross section at 150W



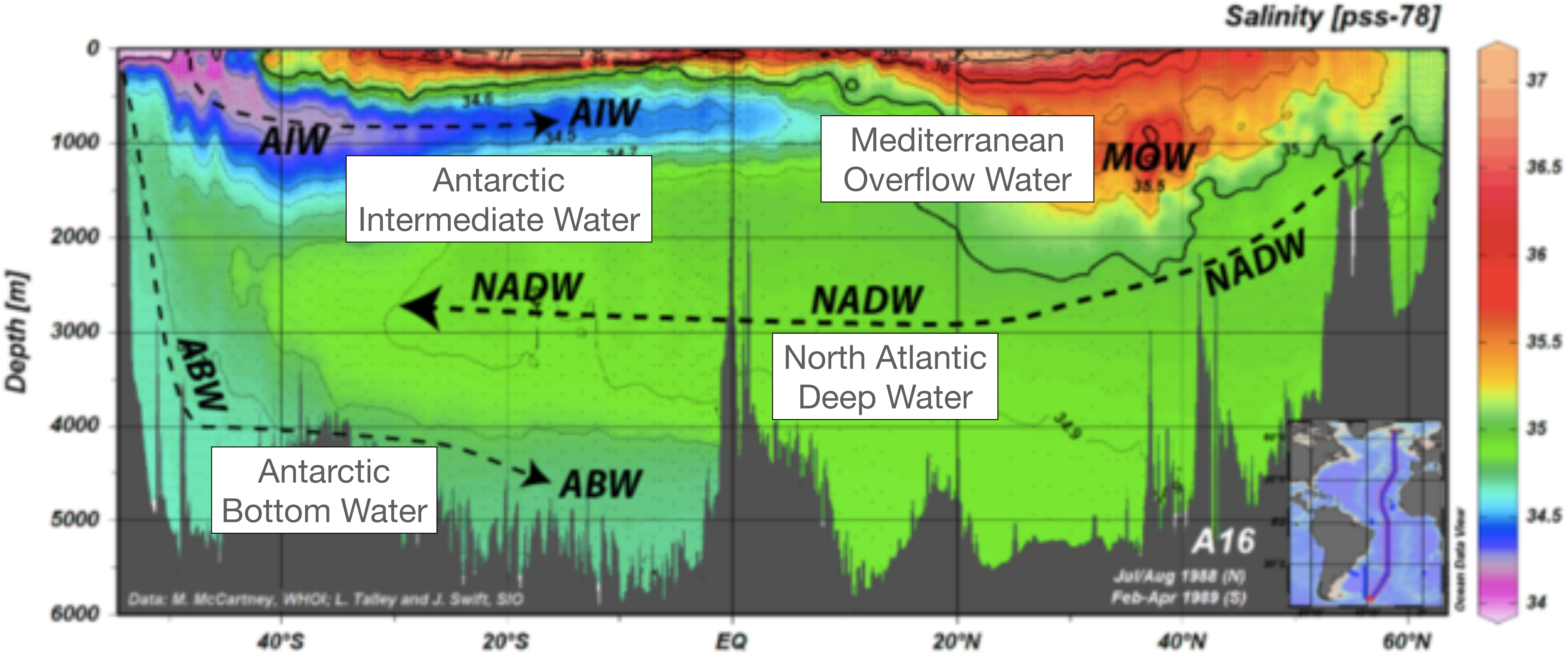
Salinity cross-section at 150W



[Source: Talley et al (1991)]

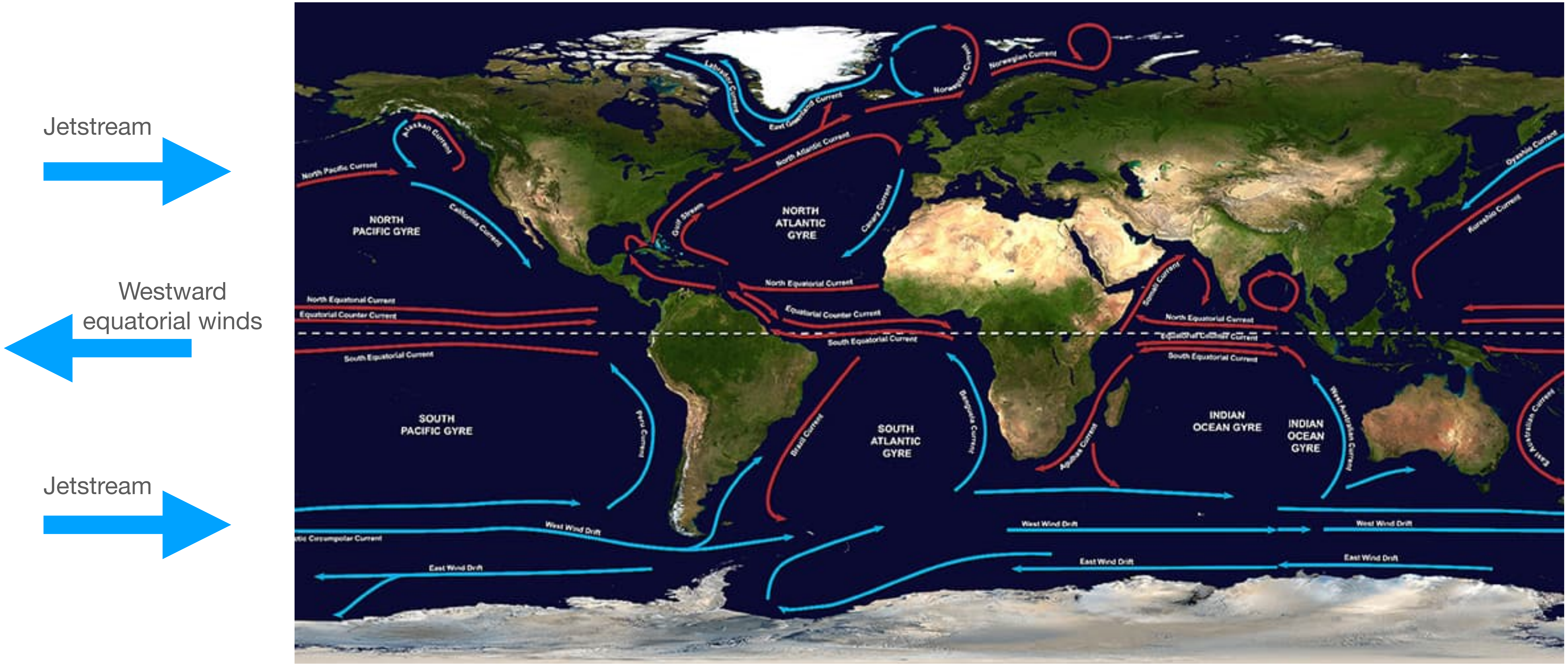
B) Thermodynamics: vertical cross-sections of temperature and salinity

- The combination of temperature and salinity determine the origin of water masses in the ocean. The Atlantic Ocean has been particularly well examined.



C) The Earth's Rotation: wind forcing and gyres

- In the open ocean surface currents are directly forced by winds - predominately eastward at midlatitudes and westward at the equator.



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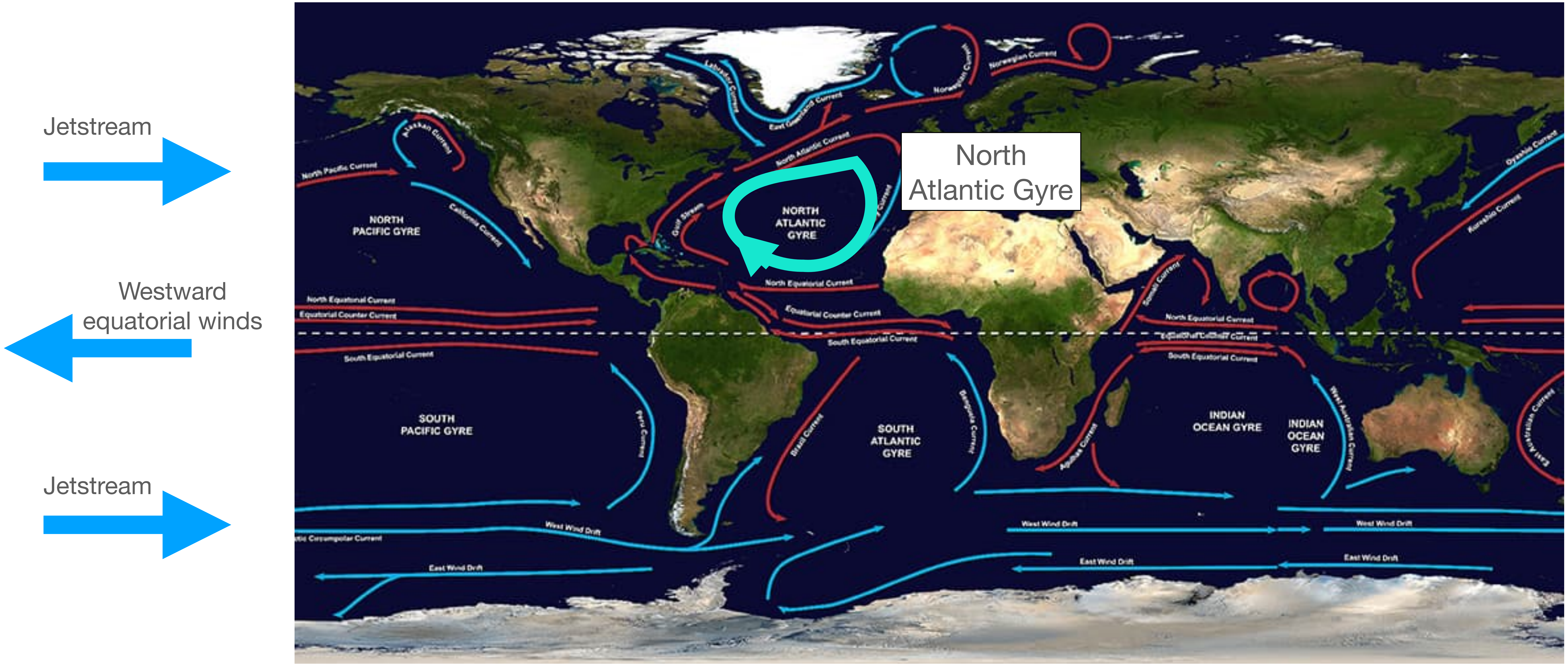

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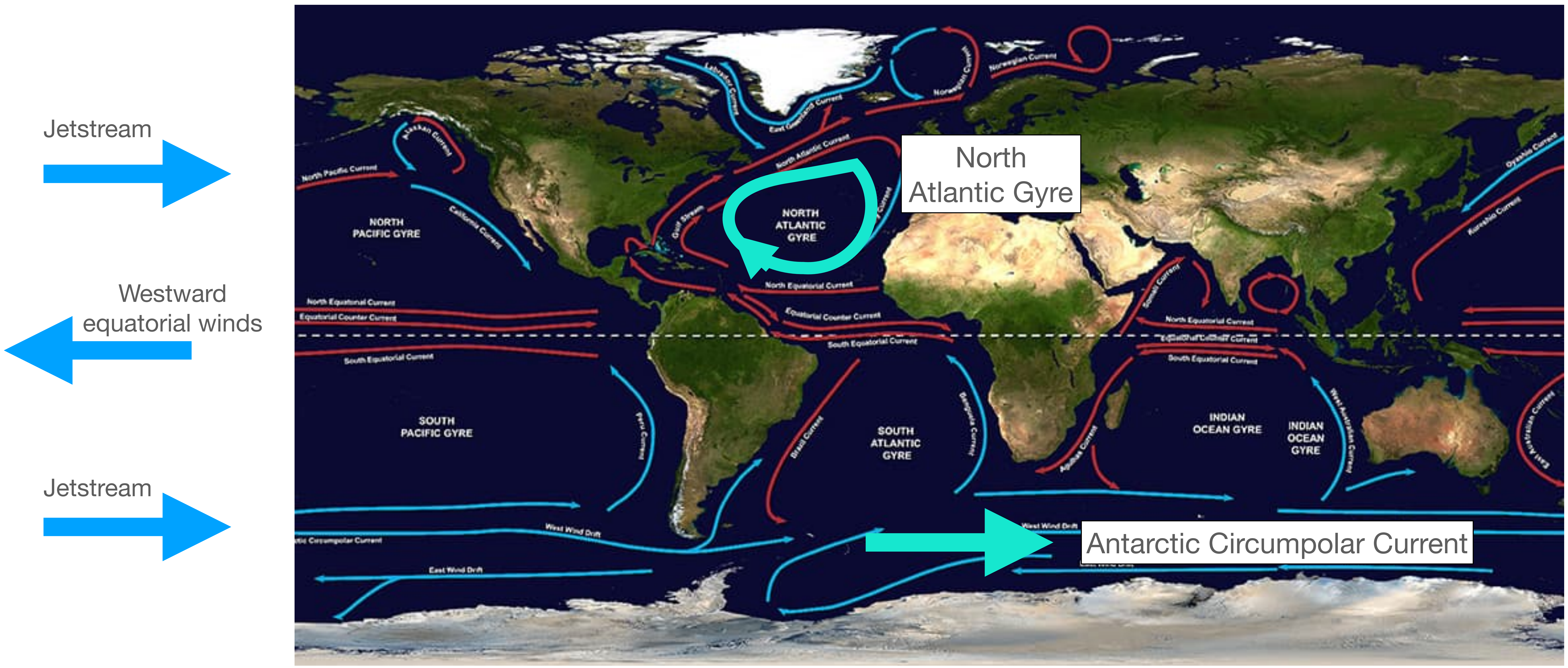
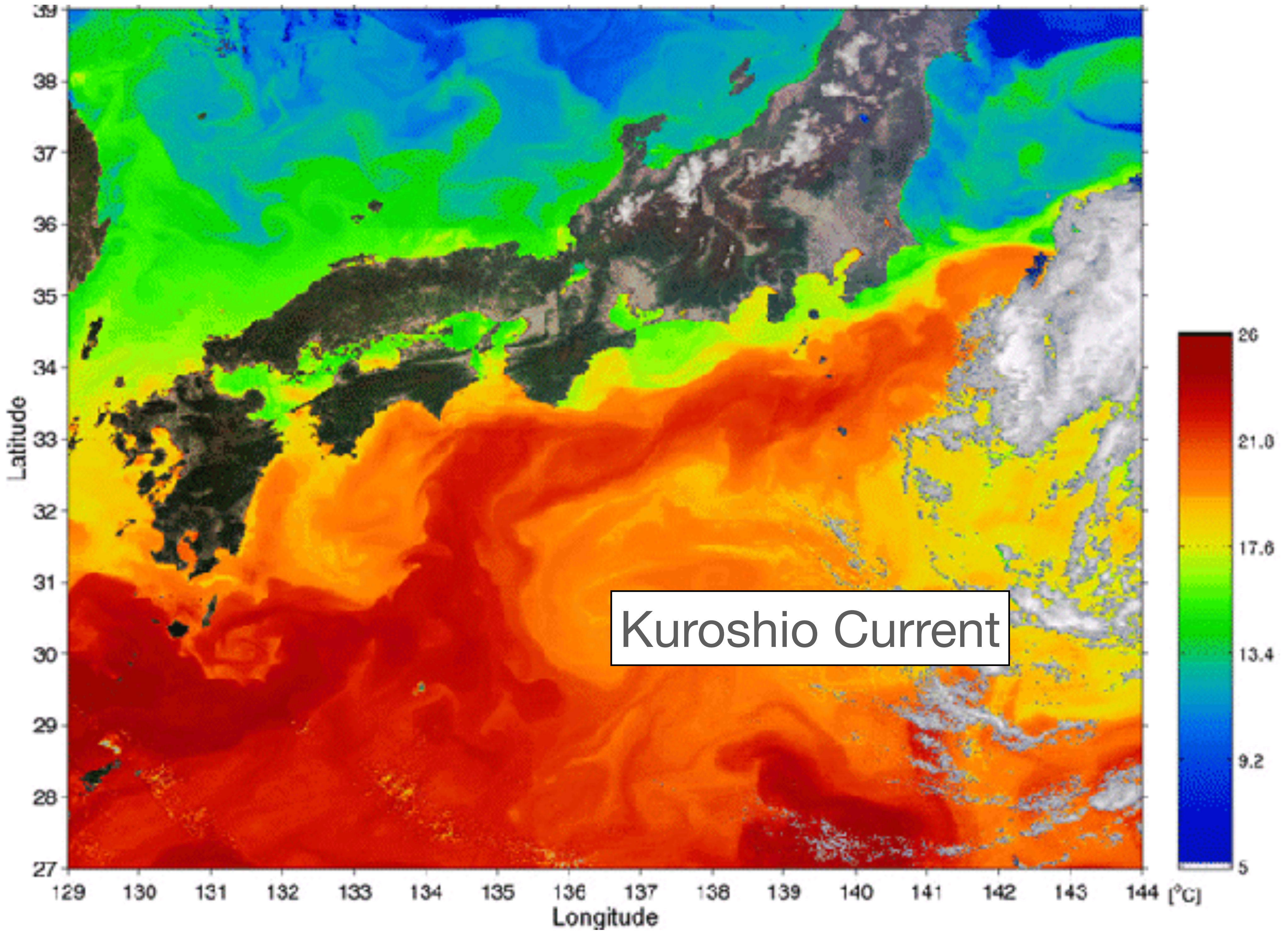
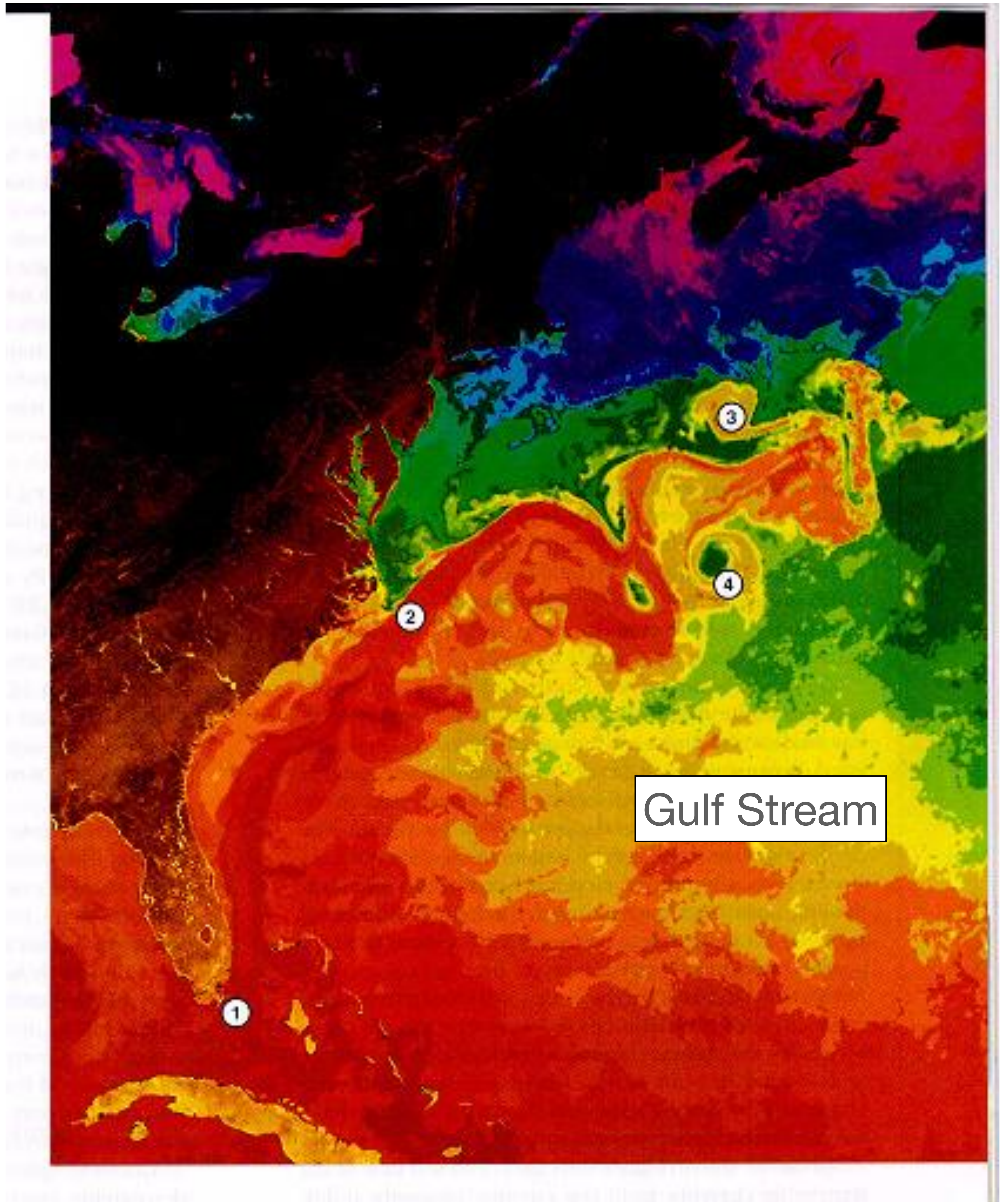
- Around Antarctica there is no barrier, giving the “Antarctic Circumpolar Current” (ACC)



C) The Earth's Rotation: western boundary currents

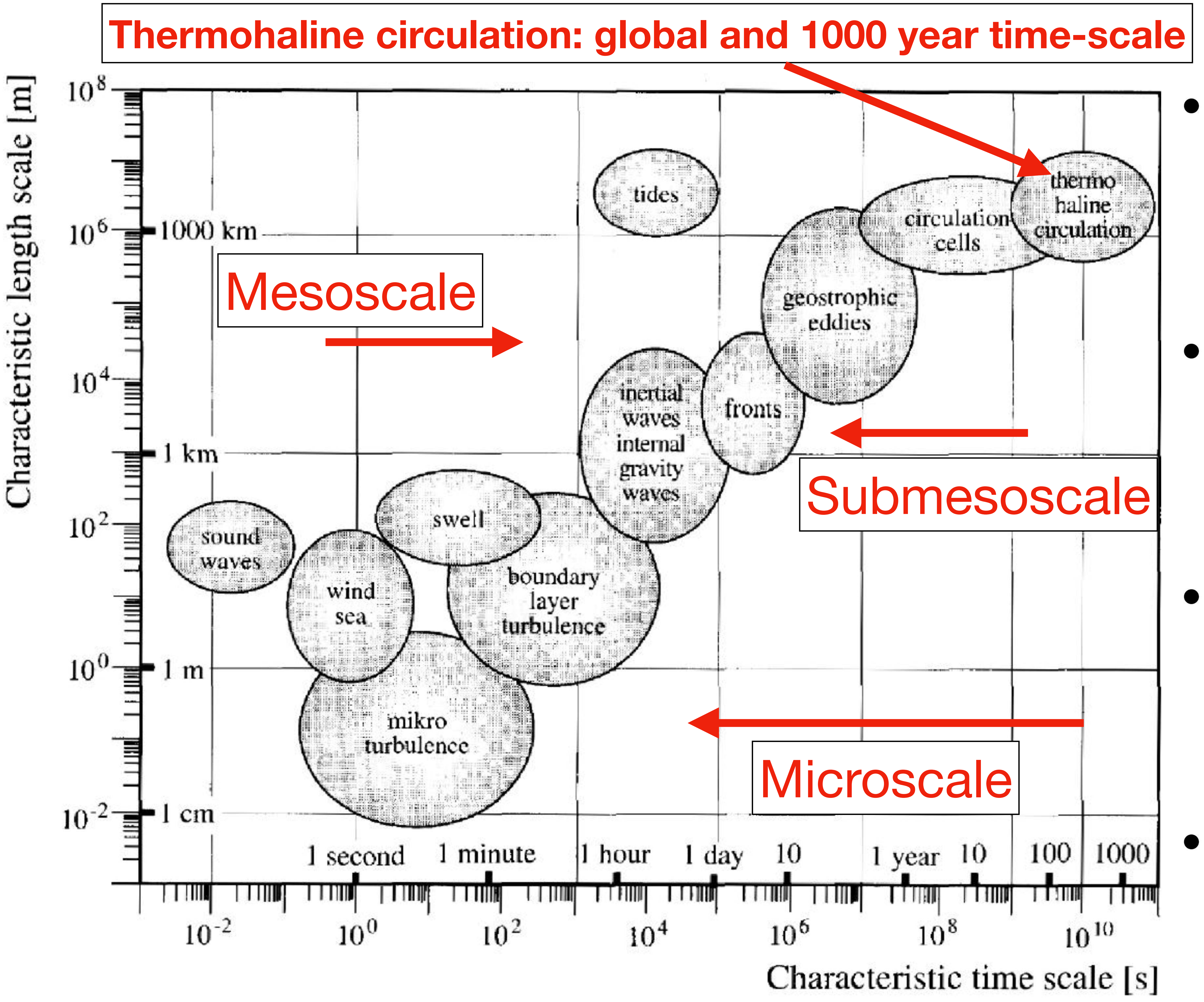
- A closer look reveals the presence of strong poleward currents occurring on the western sides of the ocean basins.   These lead to …
  - The Gulf Stream
  - The Kuroshio Current
  - The Agulas Current
  - The East Australian Current, etc





D) Fluid Dynamics: scales of motion

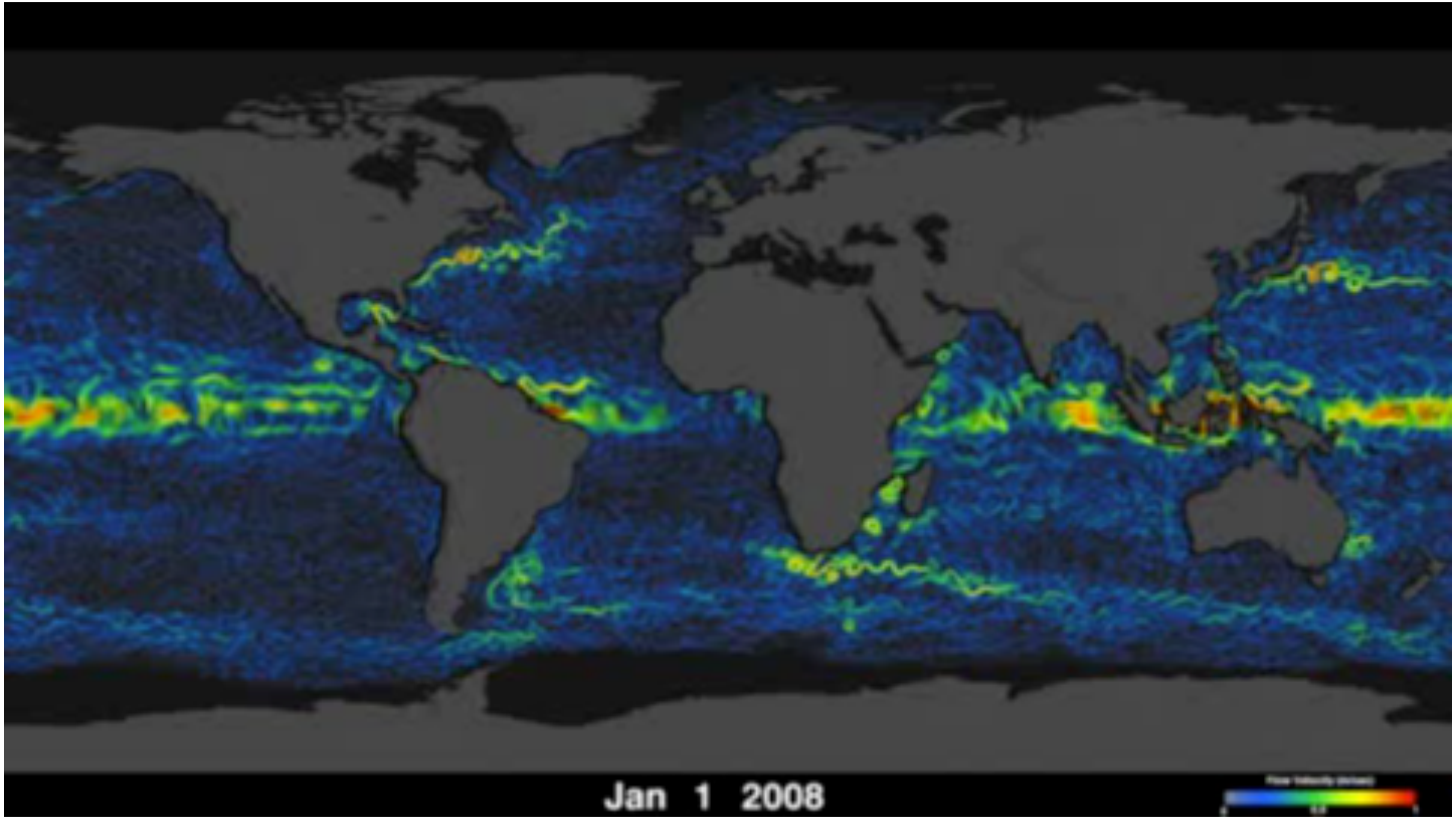
- As with the atmosphere, the actual motions occur on a wide range of space and time scales
- The equivalent of synoptic weather in the atmosphere (1000 km scale) is confusingly called the "mesoscale" (which is the same scale as the mesoscale in the atmosphere: 10-100 km).
- Below this is the "submesoscale", which includes fronts, and waves inside the ocean (<1 km - 10 km).
- Again, turbulence and dissipation occurs at the "microscale".



Burchard (2002)

D) Fluid Dynamics: surface flows observed by satellite in 2008

This video is a product produced by NASA and developed at **Earth and Space Research** by Kathleen Dohan



D) Fluid Dynamics: waves and mixing

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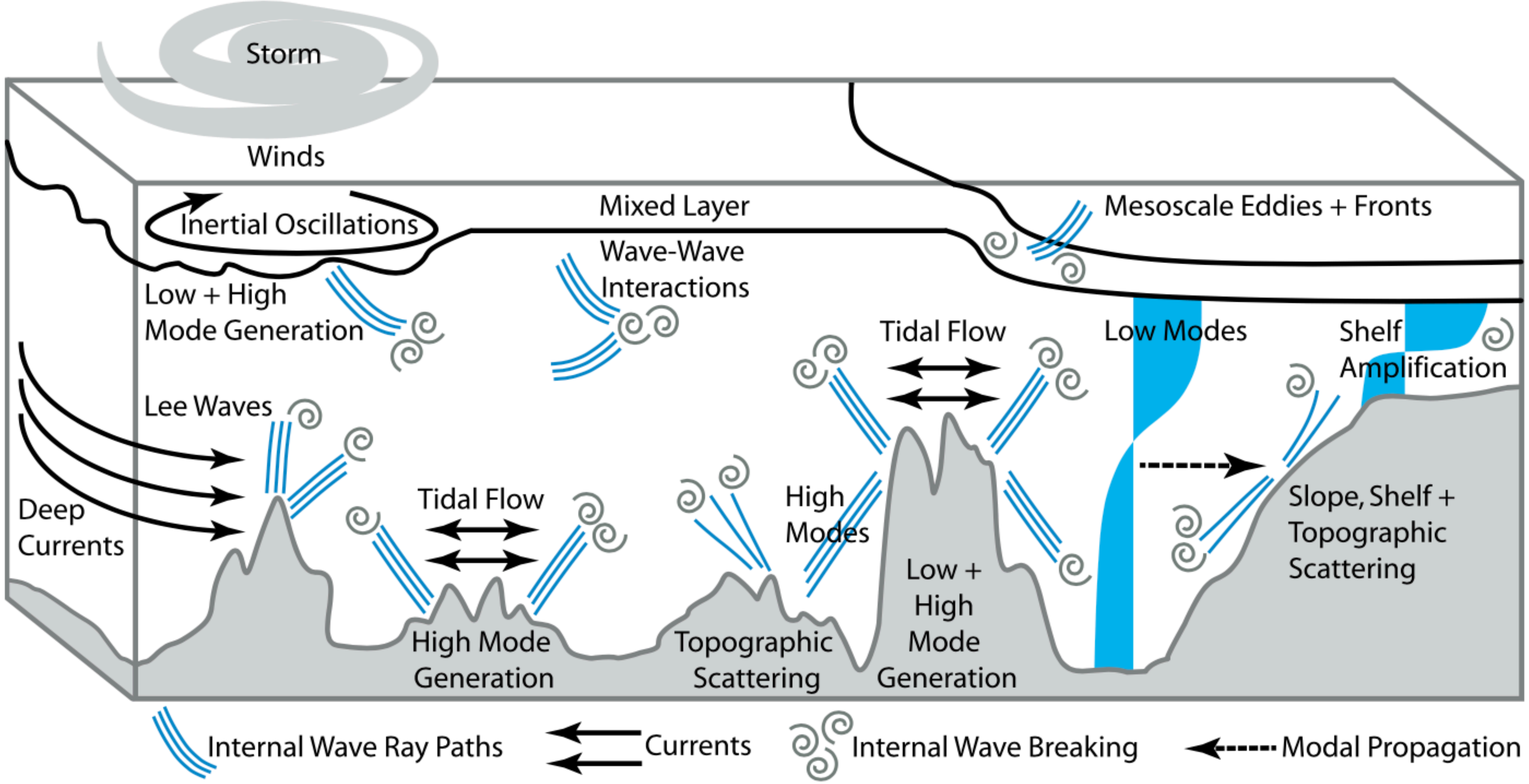
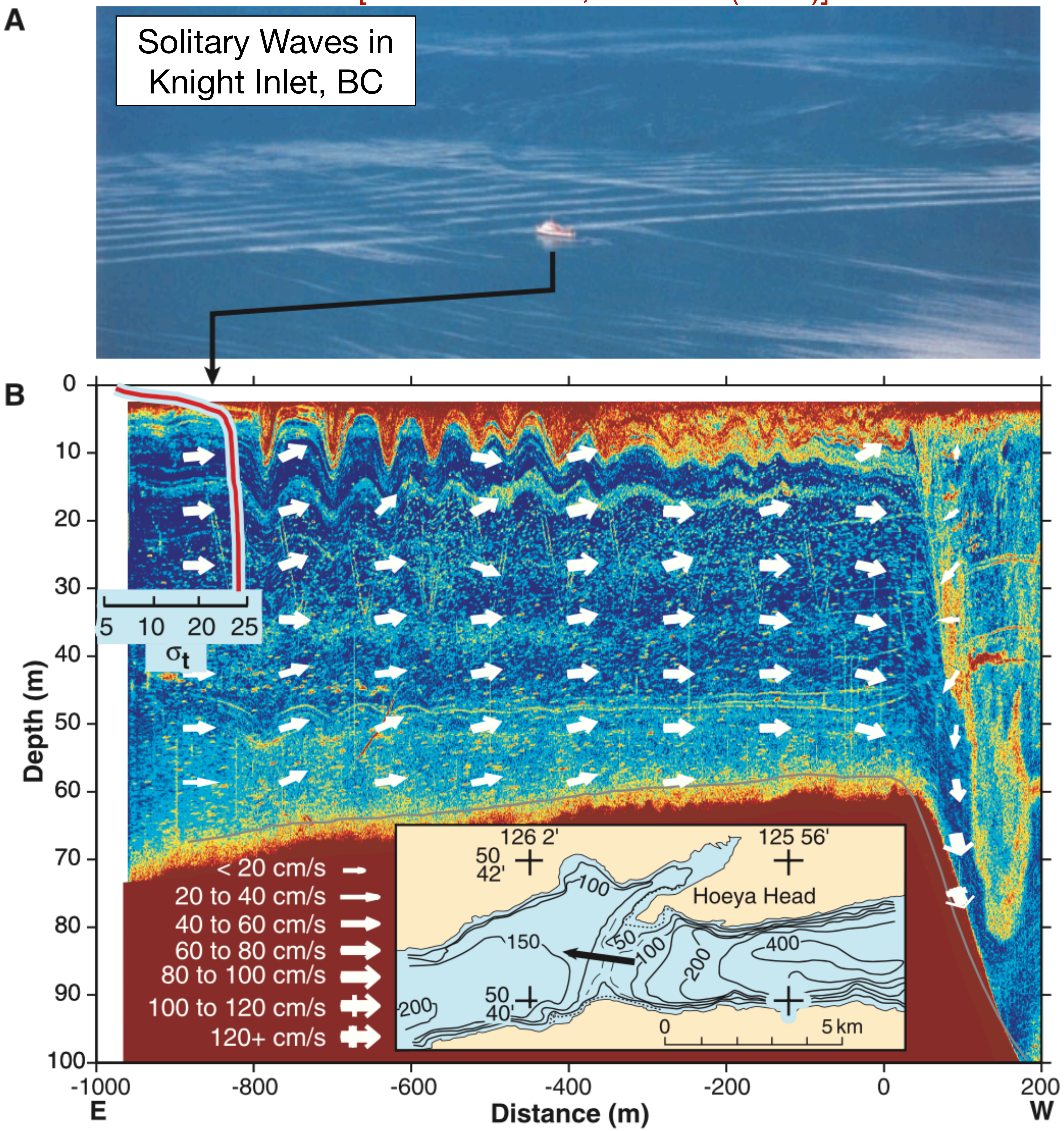


D) Fluid Dynamics: solitary waves

- In coastal regions, the tide can generate waves at the interface between hot and cold water. These sometimes steepen to form large amplitude "solitary waves".

[Farmer & Armi, Science (1999)]



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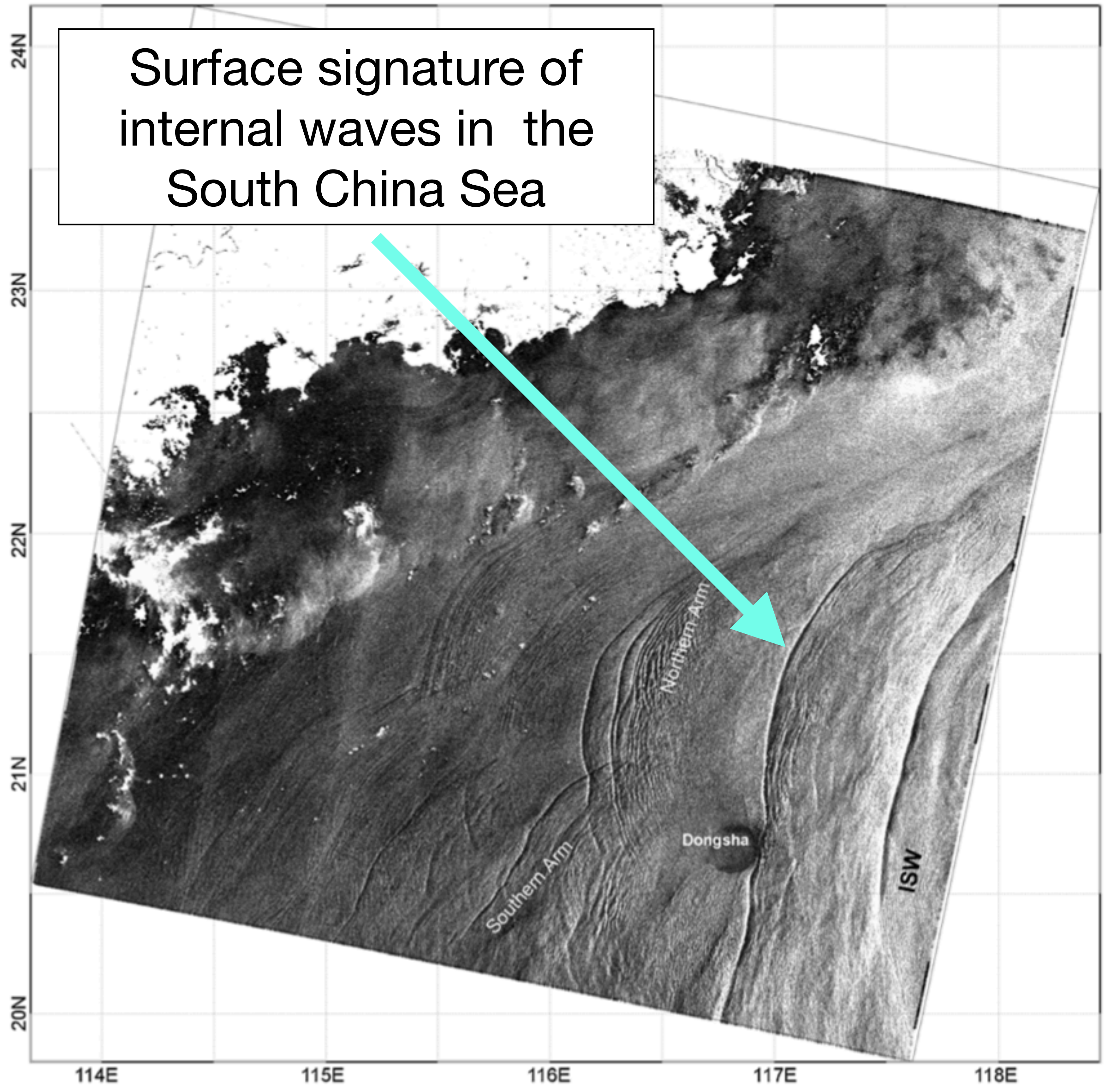

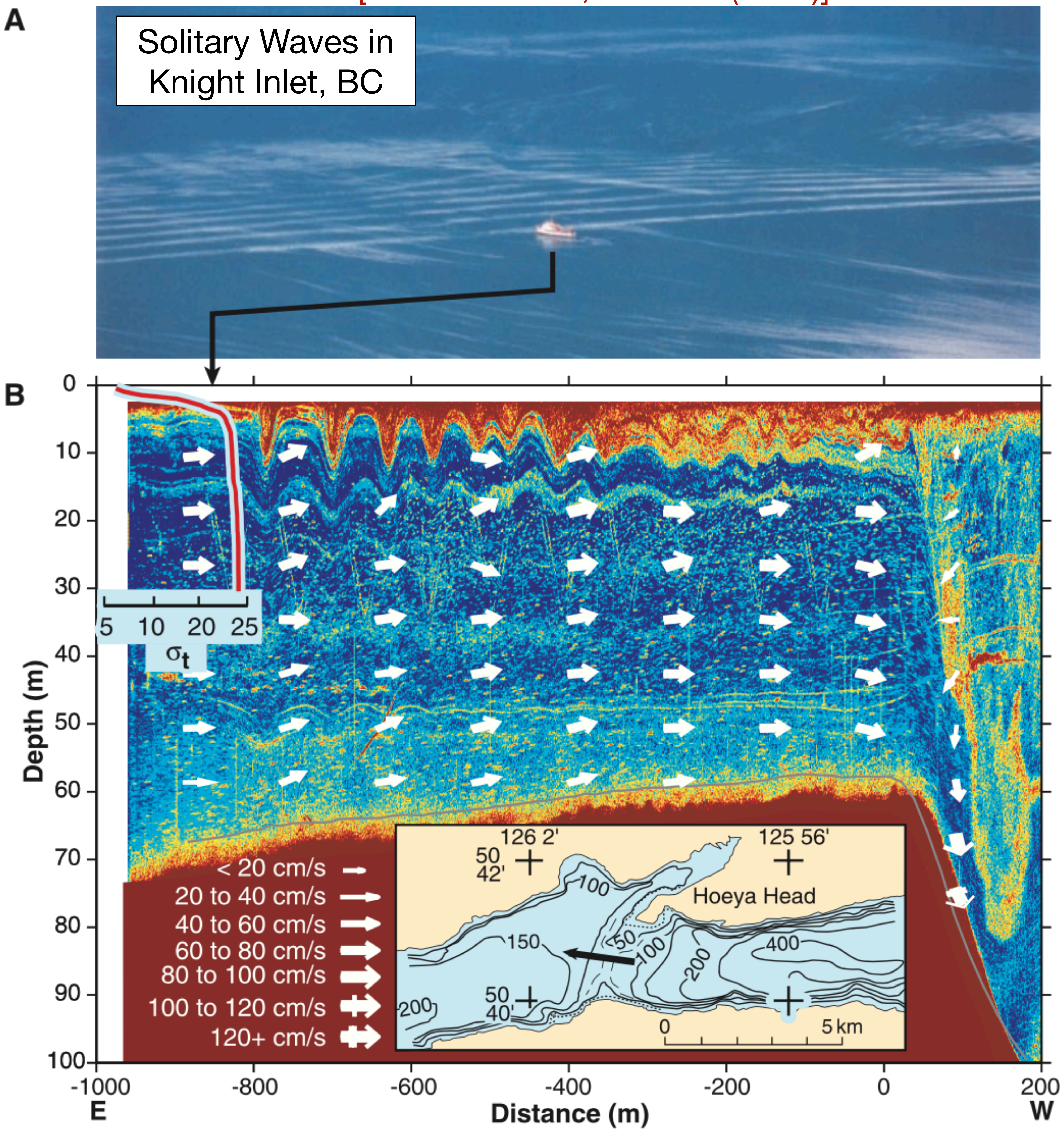

E) Other Considerations

- Besides the consideration of eddies, currents and waves, several other factors have an important influence on the evolution of the ocean:
    - Sea ice
        - freezing results in “brine rejection” making the water saltier
        - melting caps the ocean with fresher water.
        - removes influence of wind stress on wave generation and mixing
    - Biology
        - mixing by swimming sea life
        - inhibition of mixing by algal blooms
    - Atmosphere-ocean feedbacks
        - El-Nino and La Nina
        - South Asian monsoon
    - etc ….