GEF4400 “The Earth System”

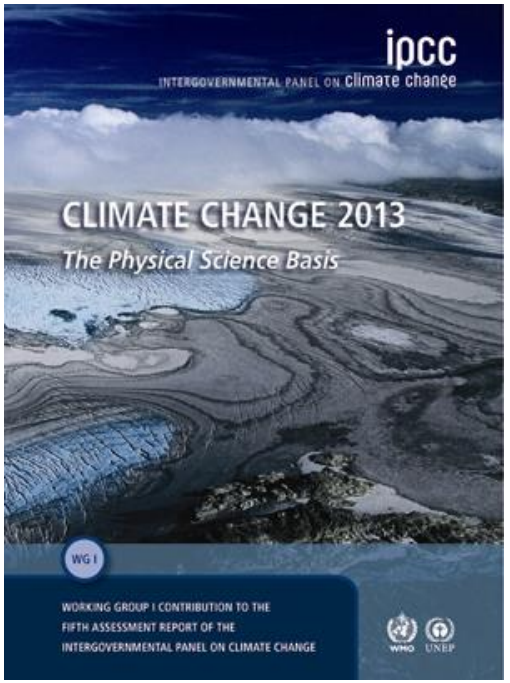
Prof. Dr. Jon Egill Kristjansson,

Prof. Dr. Kirstin Krüger (UiO)

Email: kkruegergeo.uio.no

- **Lecture/ interactive seminar/ field excursion**
  Teaching language: English
  Time and location: Monday 12:15-14:00
  Wednesday 10:15-12:00, CIENS Glasshallen 2.
- **Study program**
  Master of meteorology and oceanography
  PhD course for meteorology and oceanography students
- **Credits and conditions:**
  The successful completion of the course includes an **oral presentation (weight 50%)**, a **successful completion of the Andøya field excursion** (mandatory), a **field report**, as well as a final **oral examination (50%)**. Student presentations will be part of the

IPCC Chapter 3: **Observations: Ocean**

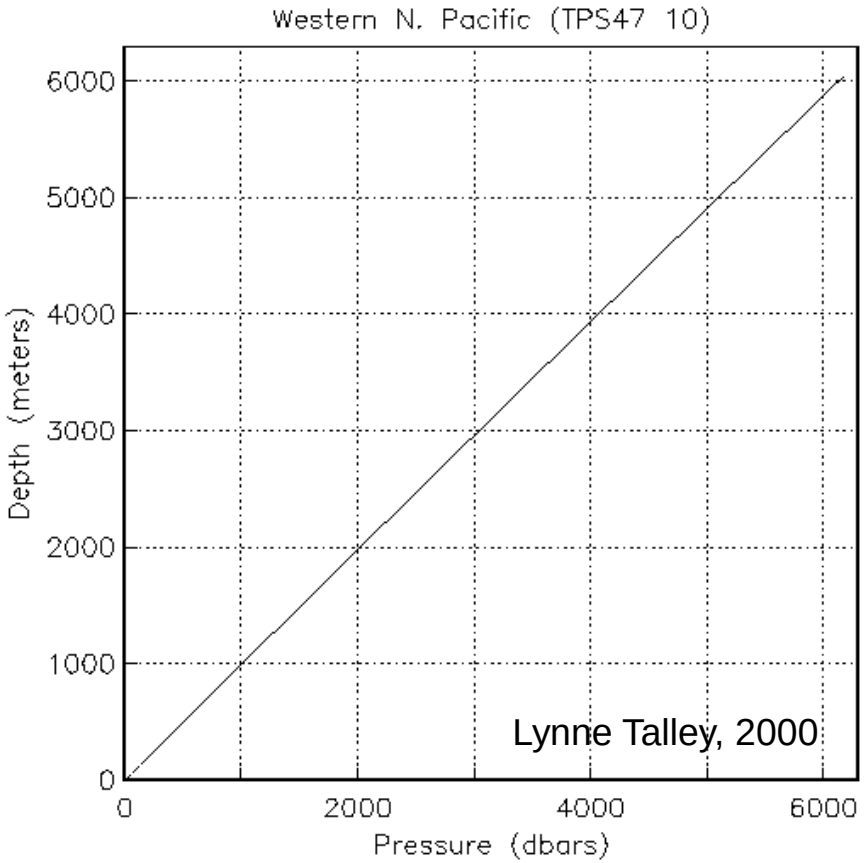


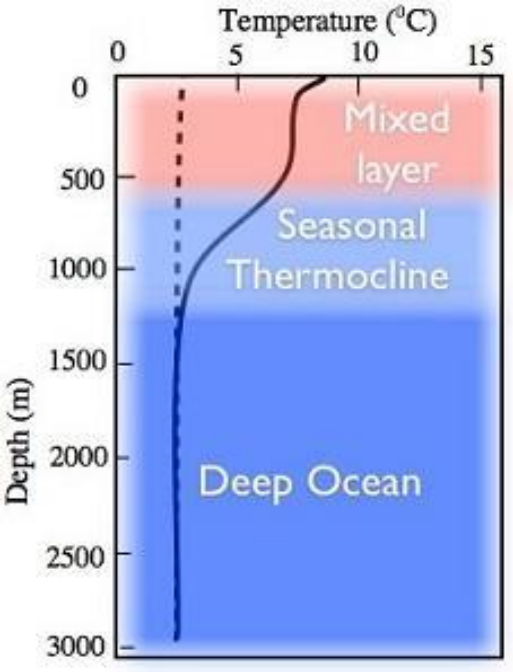
- Background
- Introduction *(Appendix 3A)*
- Ocean temperature and heat content *(Section 3.2)*
- Salinity and fresh water content *(Section 3.3)*
- Ocean surface fluxes *(Section 3.4)*
- Ocean circulation *(Section 3.6)*
- Sea level change *(Section 3.7)*
- Executive Summary *(Ch. 3)*

Rhein, M., et al., 2013: Observations: Ocean. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Background

Ocean vertical structure (Tropical Oceans)

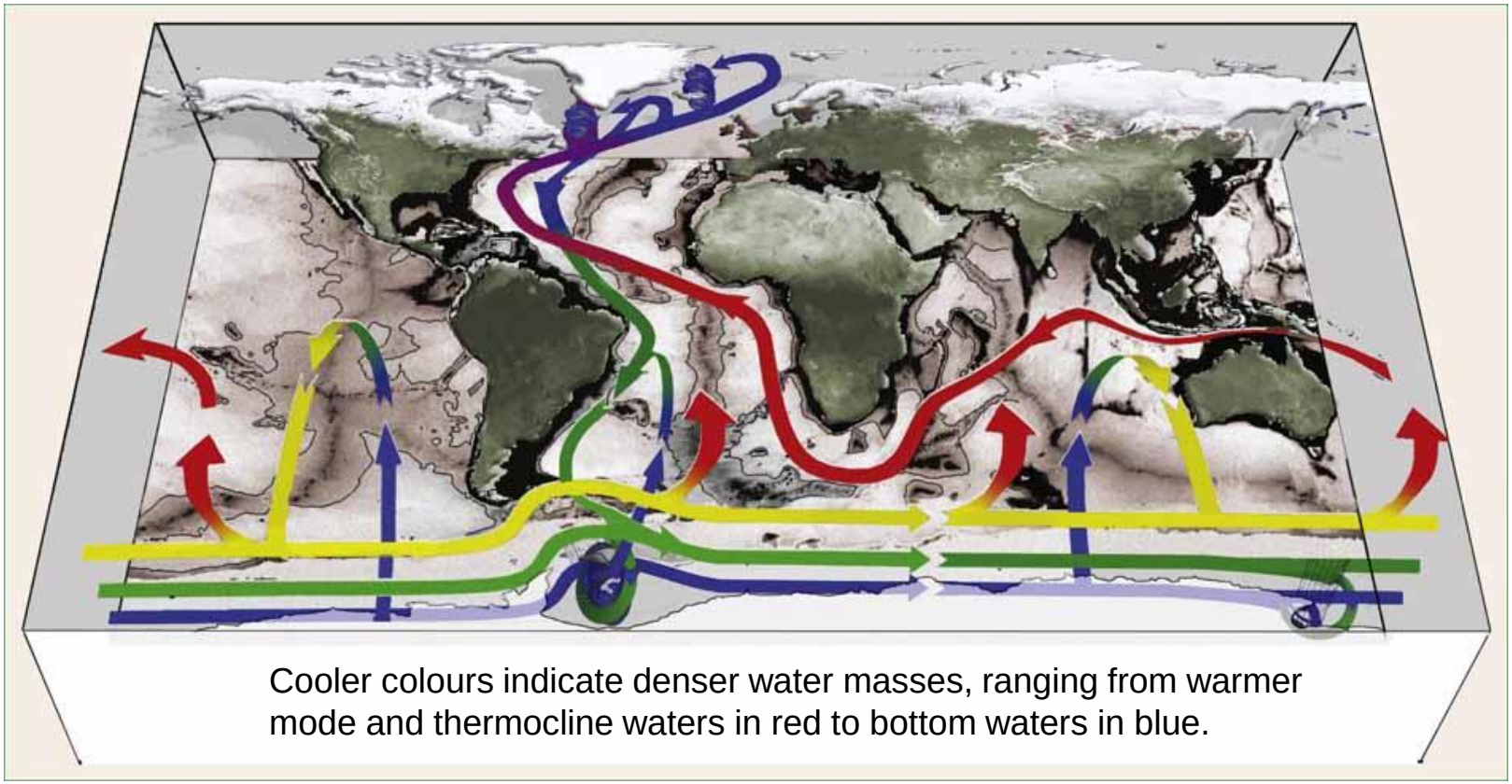




Ocean pressure is usually measured in decibars because the pressure in decibars is almost exactly equal to the depth in meters.

1 dbar = 10^-1 bar = = 10^4 Pascal = 100 hPa
Atmospheric pressure is usually measured in hPa; 1000 hPa = 1 bar = 10 dbar = 10^5 Pascal.

Ocean circulation



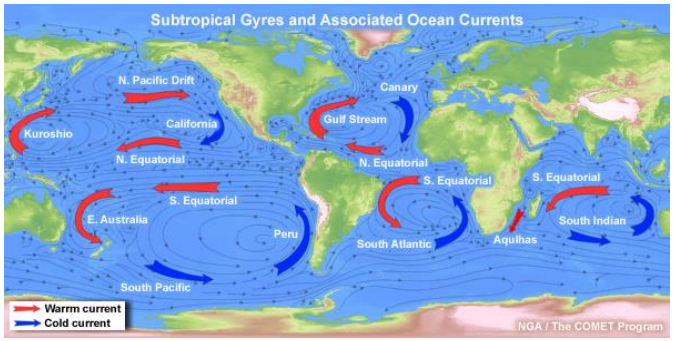
Cooler colours indicate denser water masses, ranging from warmer mode and thermocline waters in red to bottom waters in blue.

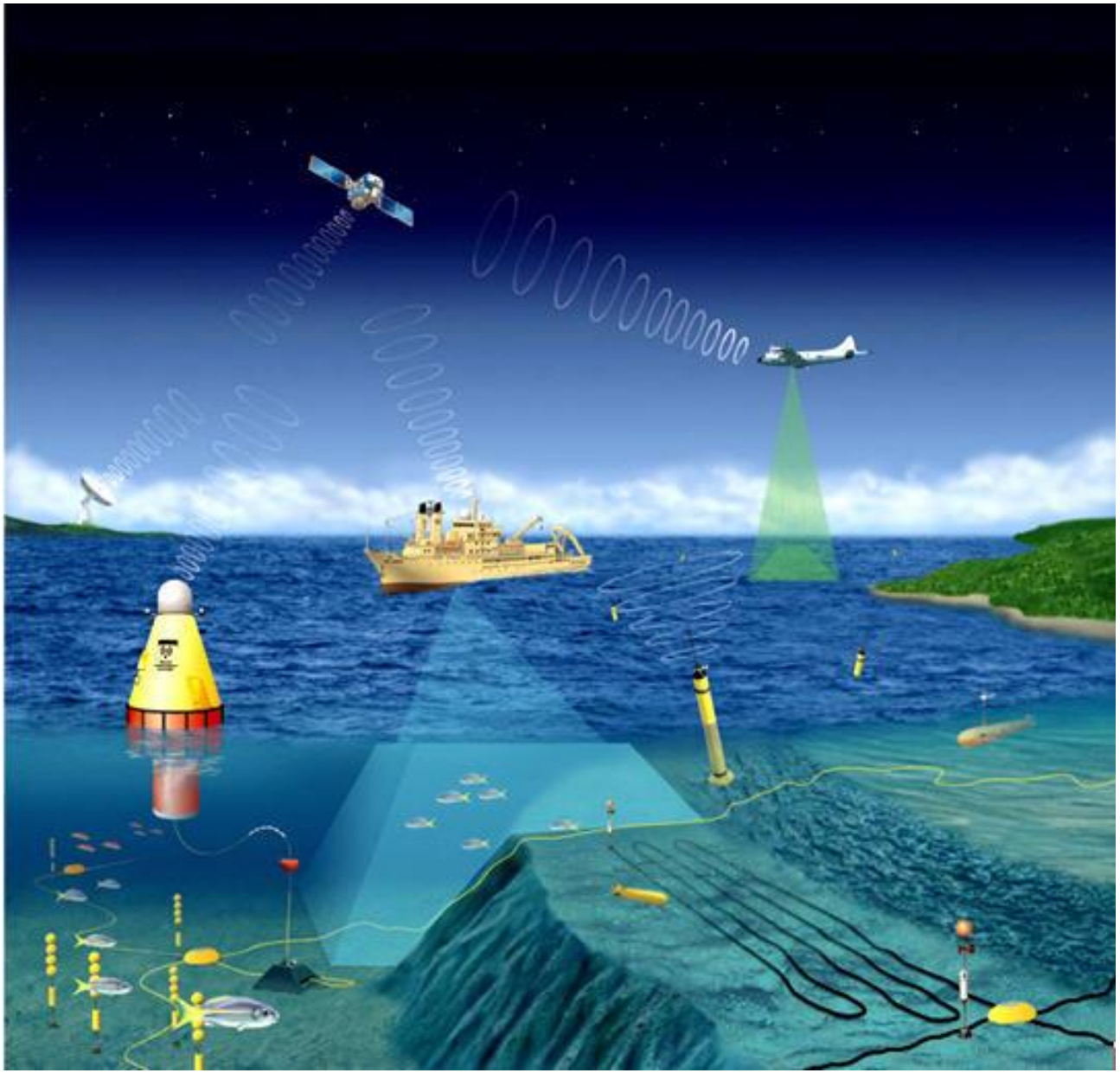
Marshall and Speer (2012, Nature)

Meridional Overturning Circulation (MOC) schematic driven mainly by the difference in heat, salinity, wind and eddies. In the early schematic of the conveyer belt analogy by Broecker (1991) the role for the Southern Ocean was neglected.

Surface Ocean Currents

- Surface ocean currents are **driven by** the circulation of **wind above surface waters**, interacting with **evaporation**, **sinking of cold water at high latitudes**, and the **Coriolis force** generated by the earth's rotation. **Frictional stress** at the interface between the ocean and the wind **causes the water to move in the direction of the wind**.
- Large surface ocean currents are a response of the atmosphere and ocean to the **flow of energy from the tropics to polar regions**.
- On a global scale, large ocean currents are constrained by the continental masses found bordering the three oceanic basins. **Continental borders cause** these currents to develop an almost closed circular pattern called a **gyre**.
- **Each ocean basin** has a **large gyre** located at approximately 30° North/South. The currents in these gyres are driven by atmospheric flow produced by subtropical high pressure systems.





Ocean observations

In-situ: buoys, Argo floats, gliders, mooring, ships, ROV

Remote sensing: satellite, aircraft, radar

Observed ocean properties

- Sea Surface Temperature (SST): satellite and in-situ
- Sea Surface Salinity (SSS): in-situ
- Sea surface wind (stress): satellite and in-situ
- Sea level height: satellite and in-situ
- Ocean current: in-situ
- Ocean colour (chlorophyll): satellite and in-situ
- Air-sea fluxes (Carbon): in situ
- Sea ice: satellite and in-situ

Introduction and Motivation to Chapter 3

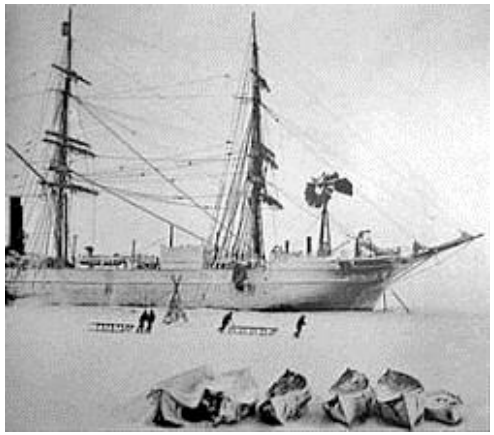
Why do we care about the Oceans influence on climate?

- Storing and transporting large amounts of **heat, freshwater, and carbon**; exchanging these properties with the atmosphere.
- **~93%** of the excess **heat energy stored in** the **ocean** over last 50 yrs;
- **>3/4** of total **exchange of water** (evaporation, precipitation) takes place **over** the **oceans**;
- **50 times more carbon** than in the atmosphere, presently **absorbing** about **30%** of **human emissions** of **carbon dioxide** (CO_2);
- **ocean changes** may result in climate feedbacks that either **increase or reduce** the **rate of climate change**;
- **large inertia** of the **oceans** means can provide a **clearer signal of longer-term change** than other components of the climate system.

→**Observations of ocean change** to track the **evolution of climate change**, and a relevant **benchmark for climate models**.

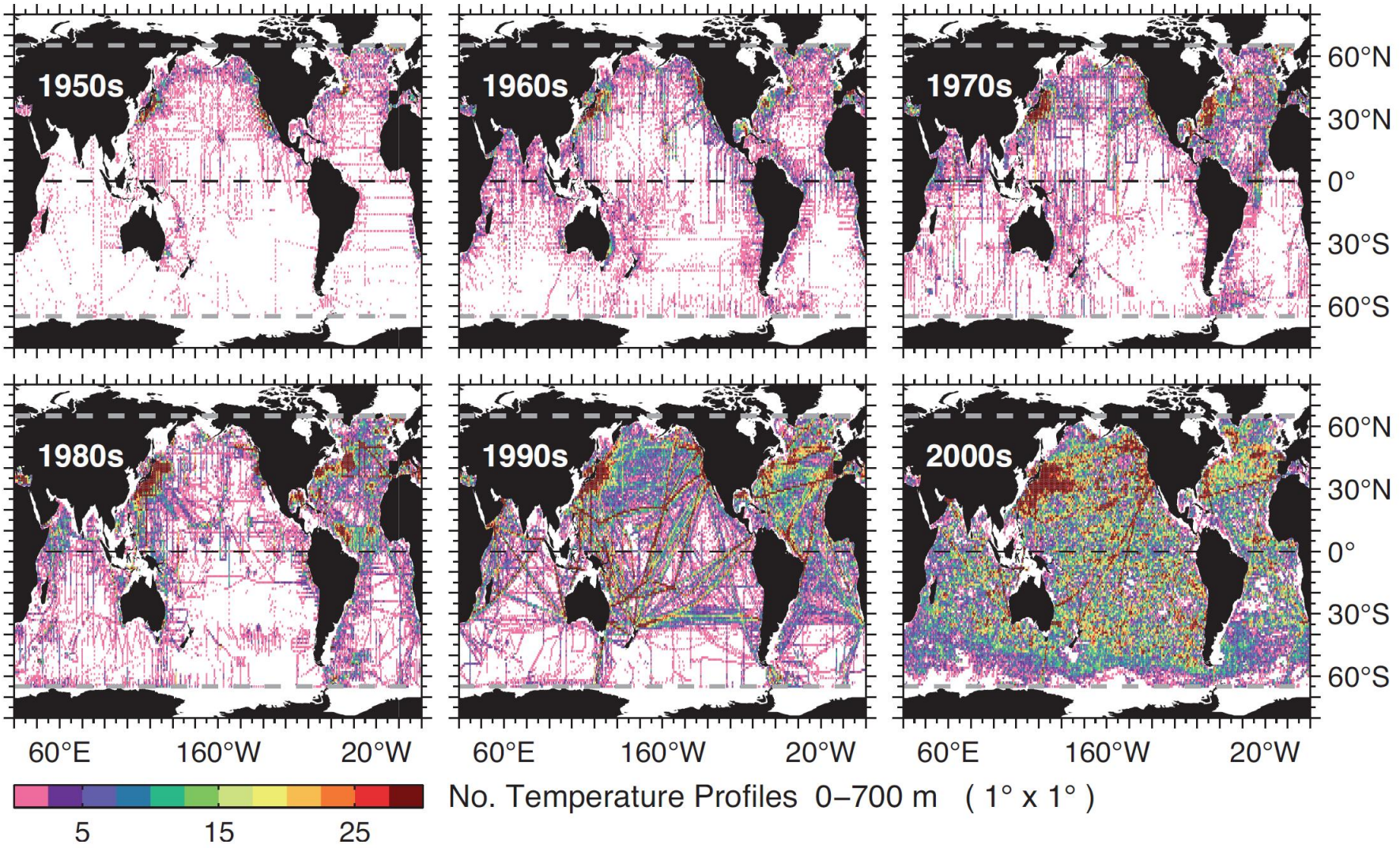
Oceanography expeditions

- Early oceanography expeditions in the 1870s (e.g. *Challenger* voyage around the world);
- Arctic and Antarctic explorations (1893 to 1912) with *Fram;*
- *Meteor* survey to the Atlantic in the 1920s;
- *Discovery* investigations to the Southern Ocean in the 1920s.

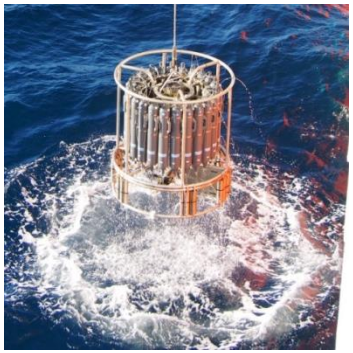


With the International Geophysical Year (IGY) in 1957/58 a more frequent sampling began.

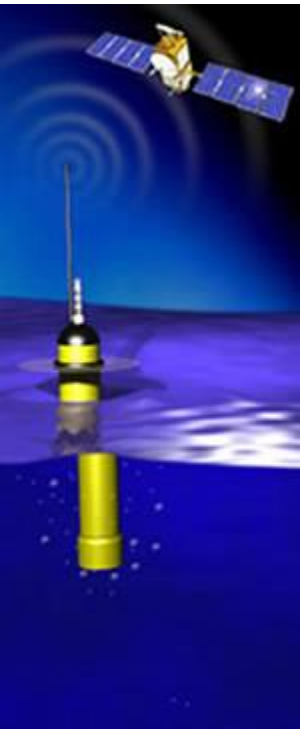
Ocean observations evolution



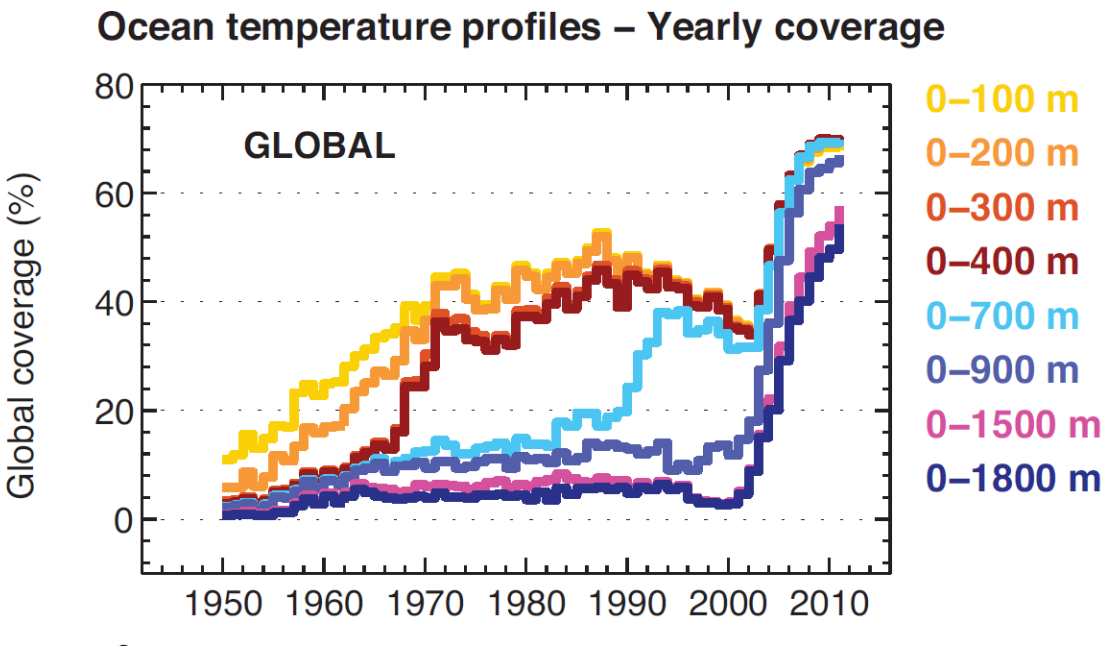
Ocean observations evolution



- Reversing thermometers and **Nansen bottles** from ships on stations
- 1960s: Conductivity-Temperature-Depth (**CTD**) casts with **Niskin bottles**
- 1950s-1970s: subsurface measurements with mechanical bathythermographs from slow moving ship
- >late 1960s: Expendable bathythermographs (**XBT**) from fast moving ships (until 400m depth; from 1990s up to 700m depth)
- Since 2000s: **Argo floats** sampling until 2000m depth; near global coverage by 2005
- Below 2000m depth from CTD ship stations



Ocean observations coverage



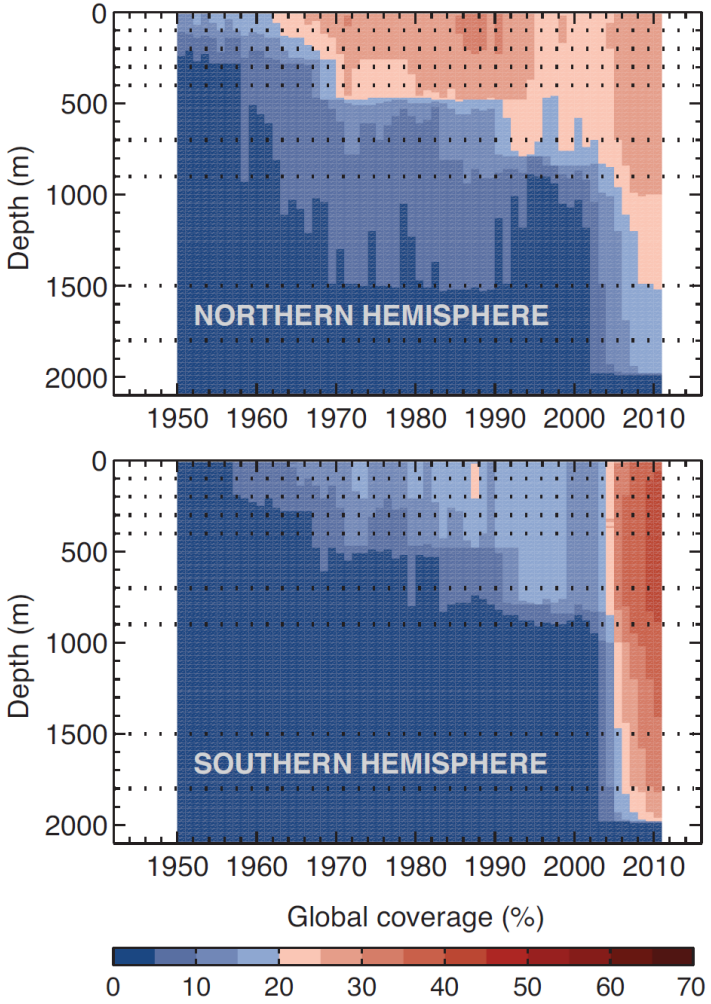


Figure 3.A.2 | (Top) Percentage of global coverage of ocean temperature profiles as a function of depth in 1° latitude by 1° longitude by 1-year bins (top panel) shown versus time. Different colours indicate profiles to different depths (middle panel). Percentage of global coverage as a function of depth and time, for the Northern Hemisphere. (Bottom panel) As above, but for the Southern Hemisphere.

Ocean observations improvements since AR4

Lack of long-term ocean measurements → documenting and understanding oceans changes is an ongoing challenge.

Since AR4, substantial progress has been made in improving the **quality** and **coverage** of **ocean observations**:

- Biases in historical measurements have been identified and reduced, providing a clearer record of past change.
- Argo floats have provided near-global, year-round measurements of temperature and salinity in the upper 2000 m since 2005.
- Satellite altimetry record is now >20 years in length.
- Longer continuous time series of the meridional overturning circulation and tropical oceans have been obtained.
- Spatial and temporal coverage of biogeochemical measurements in the ocean has expanded.

→Understanding ocean change has improved.

3.2 Ocean temperature and heat content

"Temperature is the most often measured subsurface ocean variable."

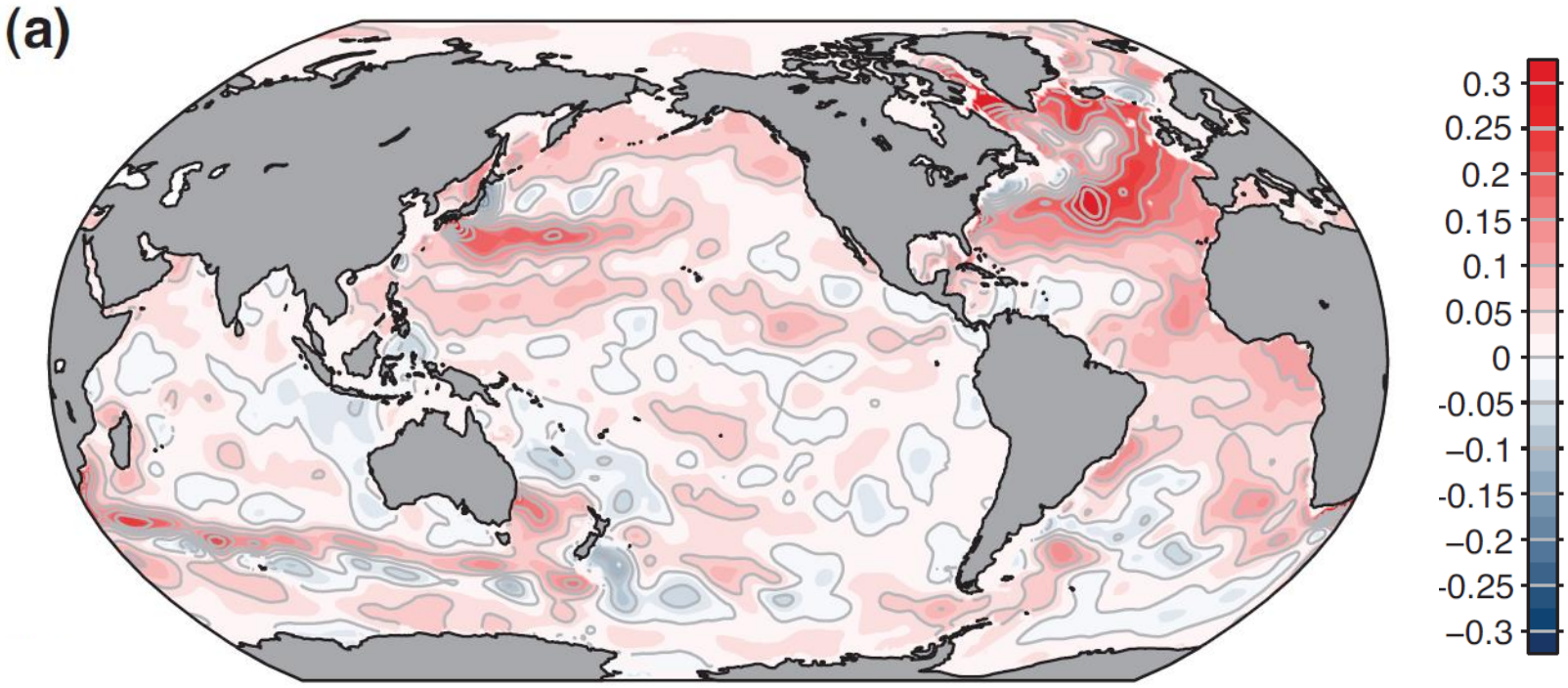
- How is the temperature in the shallow, medium and deep ocean changing?
- How is the ocean heat content changing?

$$H = \rho c_p \int_{h2}^{h1} T(z)dz$$

-H: Ocean heat content
-ρ: water density
-c_p: specific heat capacity for sea water
-$h_{1,2}$: ocean depth
-T: Temperature

Temperature trend 1971-2010
(deg C/decade)

0-700 m depth



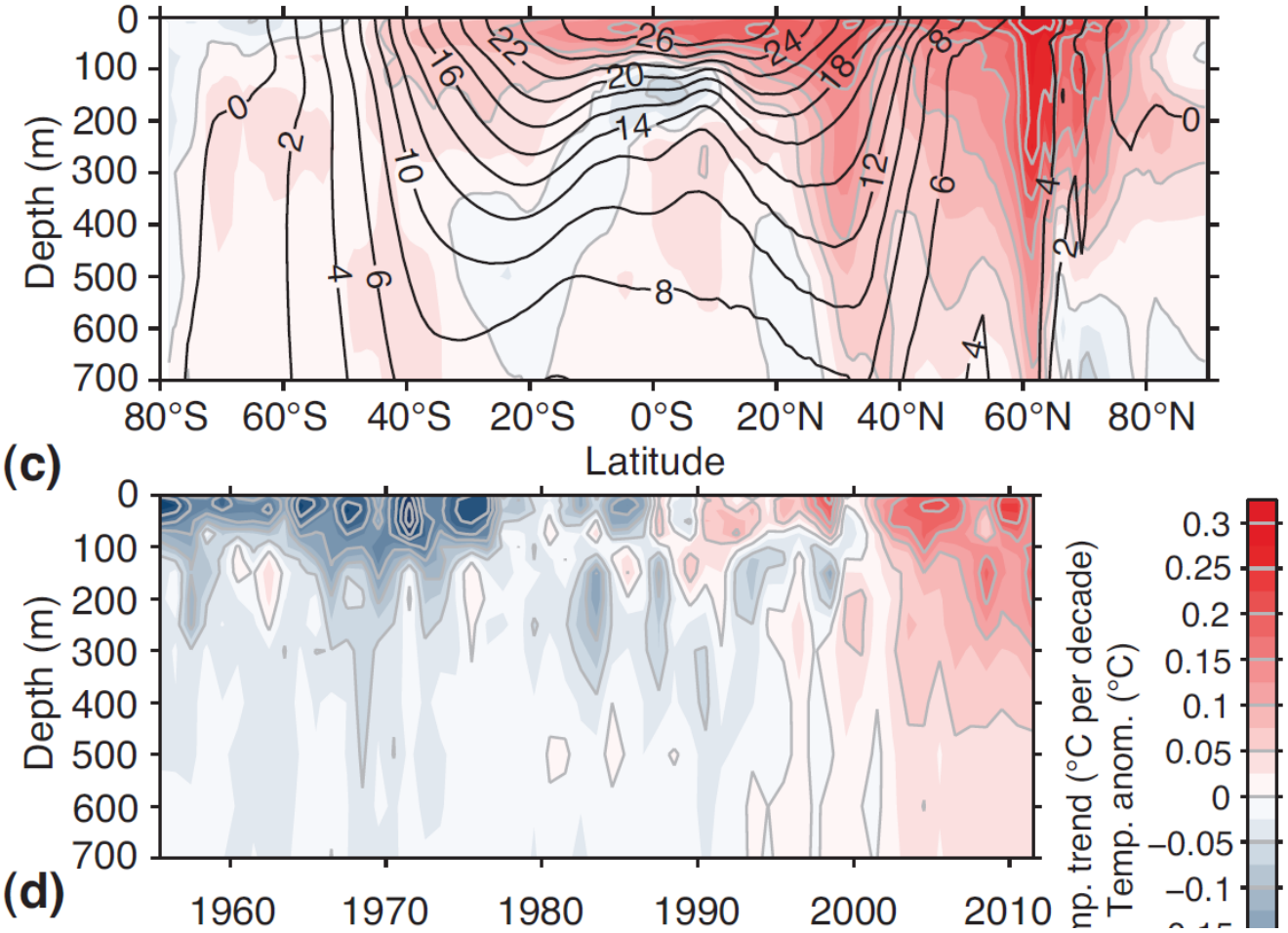
- Positive temperature change over most of the globe (Levitus et al., 2009).
- Warming is more prominent in the NH, especially the North Atlantic.
- This result holds in different analyses, using different time periods, bias corrections and data sources.

Temperature trend - Global

Temp trend
-mean temp

Temp anomaly
wrt 1971-2010

$-T_{0m} - T_{200m}$
-5yr run. mean



- Increased by ~0.25ºC from 1971 to 2010 (Levitus et al., 2009);
- corresponds to a 4% increase in density stratification;
- is widespread in all oceans north of 40°S.

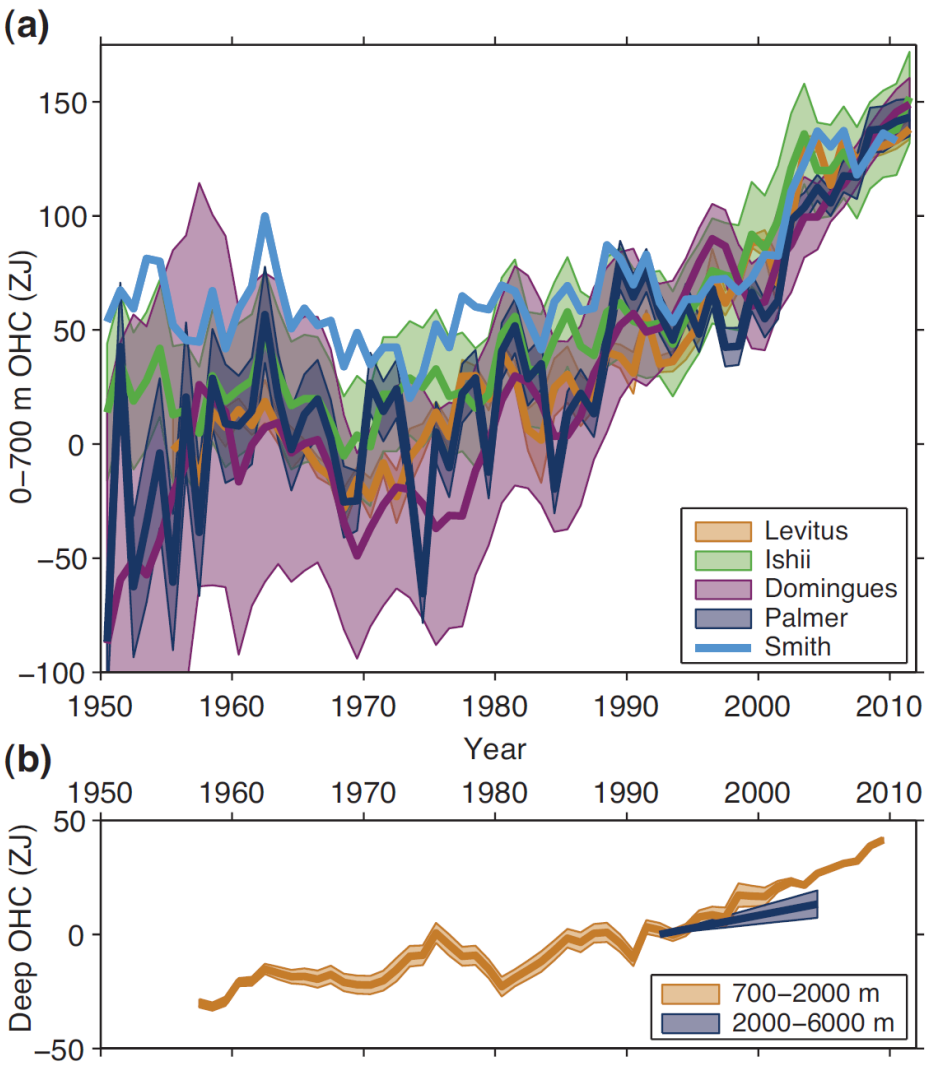
Why is the Northern Ocean warming stronger than the Southern Ocean?

- Discuss together

Ocean heat content (OHC)

0-700 m depth
(1σ std dev.)

700-2000 m
2000-6000 m



Global integrals of 0 to 700 m **upper OHC** estimated from Ocean temp. measurements show a **gain from 1971-2010.**

Increasingly uncertain for earlier years, especially prior to 1970.

Decreases few years following major volcanic eruptions (1963,1982,1991).

Slowing of the upper OHC between 2003 and 2010(?)

1 Zepta Joule (ZJ): 10^{21} Joules (=kg·m^2/s^2)

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GEF4400/9400 changed time schedule

Changed GEF4400/9400 time schedule during September and November 2015:

Mo 14.09.15, 12:15-14:00, Wed -

Mo. 21.09.15: 10:00-12:30, Wed -

Mo. 28.09.15: 10:00-12:30, Wed -

Mo. 02.11.15: 10:00-12:30, Wed 04.11.15 10:15-12:00

Mo. 09.11.15: 10:00-12:30, Wed 11.11.15 10:15-12:00

Mo. 16.11.15: 10:00-12:30, Wed 18.11.15 10:15-12:00

Mo. 23.11.15: 10:00-12:30, Wed 25.11.15 10:15-12:00

GEF4400/ GEF9400 topic presentations

Christine Smith-Johnsen

- 5.1: Polar amplification in the past (KK)
- 8.1: Has solar activity contributed significantly to global warming? (JEK)

Malte Ziemek

- 5.2: How do volcanic eruptions affect climate? (KK)

Susanne Foldvik (JEK)

- 4.2: Stability of the Antarctic ice sheet (JEK)

Charalampos Sarachidis

- 3.2: El Niño in the past, present and future (KK)

Hans Brenna

- - 6.2: Causes and relevance of oxygen minimum zones (KK)
- - 8.2: CO2 doubling (JEK)

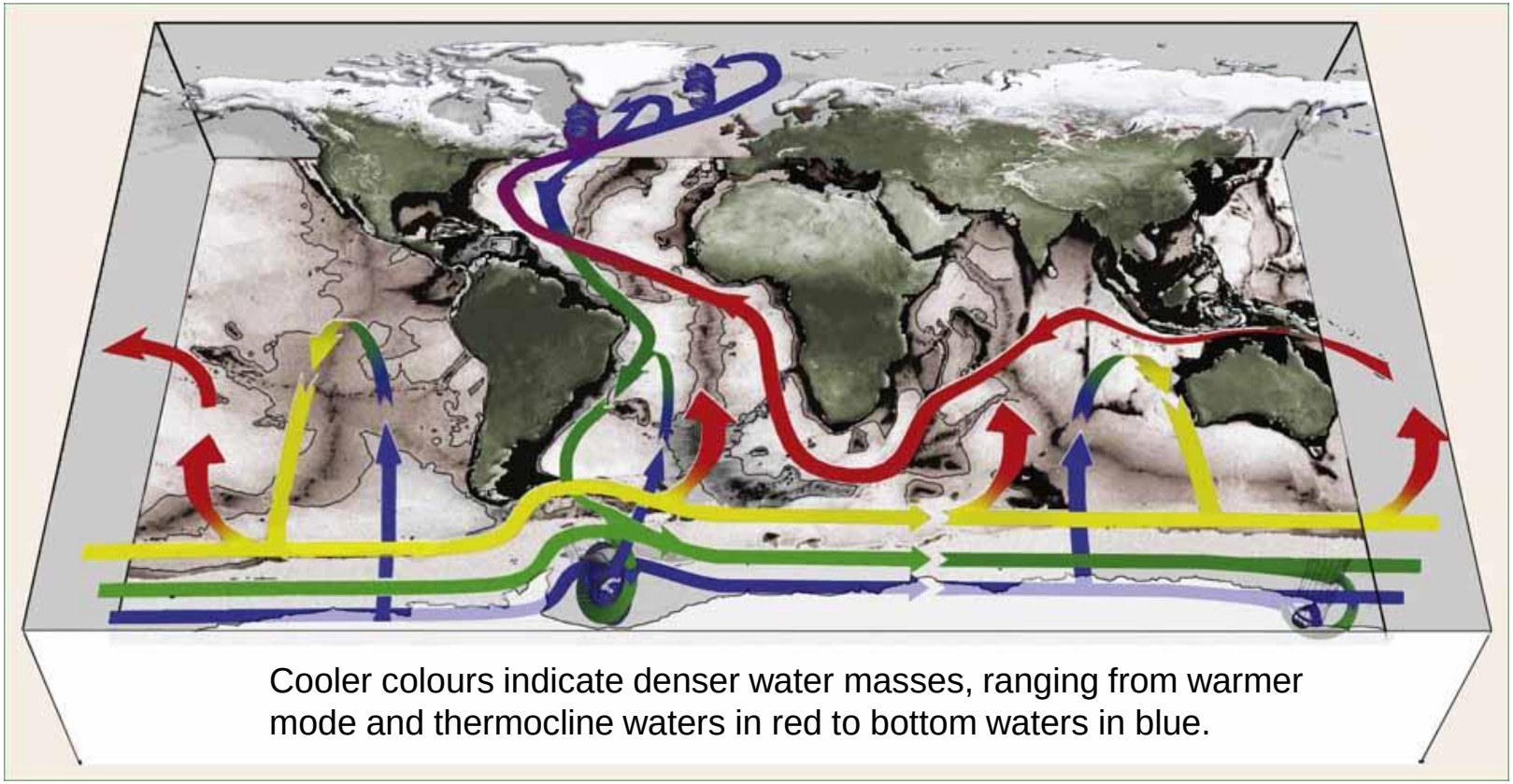
Sara Marie Blichner

- 7.1) What is the sign of the Cloud Feedback? (JEK)
  or
  7.2) Basic aspects of Aerosol-Cloud Interactions (JEK)

Suggested presentation time plan

Chapter 5: Paleo climate archives (KK)	Charalampos: El Nino? 28.09.2015	-
Chapter 7: Clouds and Aerosols	(JEK) 05.10.2015	Sara: tba 07.10.2015
Chapter 8: Radiative Forcing	(JEK) 12.10.2015	Christine: Solar activity 14.10.2015
Andøya	JEK 19.10.2015	JEK 21.10.2015
Chapter 8: Radiative Forcing	Susanne: AA ice sheet 26.10.2015	Hans: CO2 doubling 28.10.2015
Chapter 5 Paleo climate archives and Ch. 6: Biogeochemistry	Charalampos: El Nino 02.11.2015	KK 05.11.2015
Chapter 6: Biogeochemistry	Hans: Oxygen minimum zones 09.11.2015	KK 11.11.2015
Chapter 12: Long-term Climate Change	Christine: Polar Amplification 16.11.2015	KK 18.11.2015
Chapter 12: Long-term Climate Change	Malte: Volcano-Climate 23.11.2015	KK 25.11.2015

Ocean circulation



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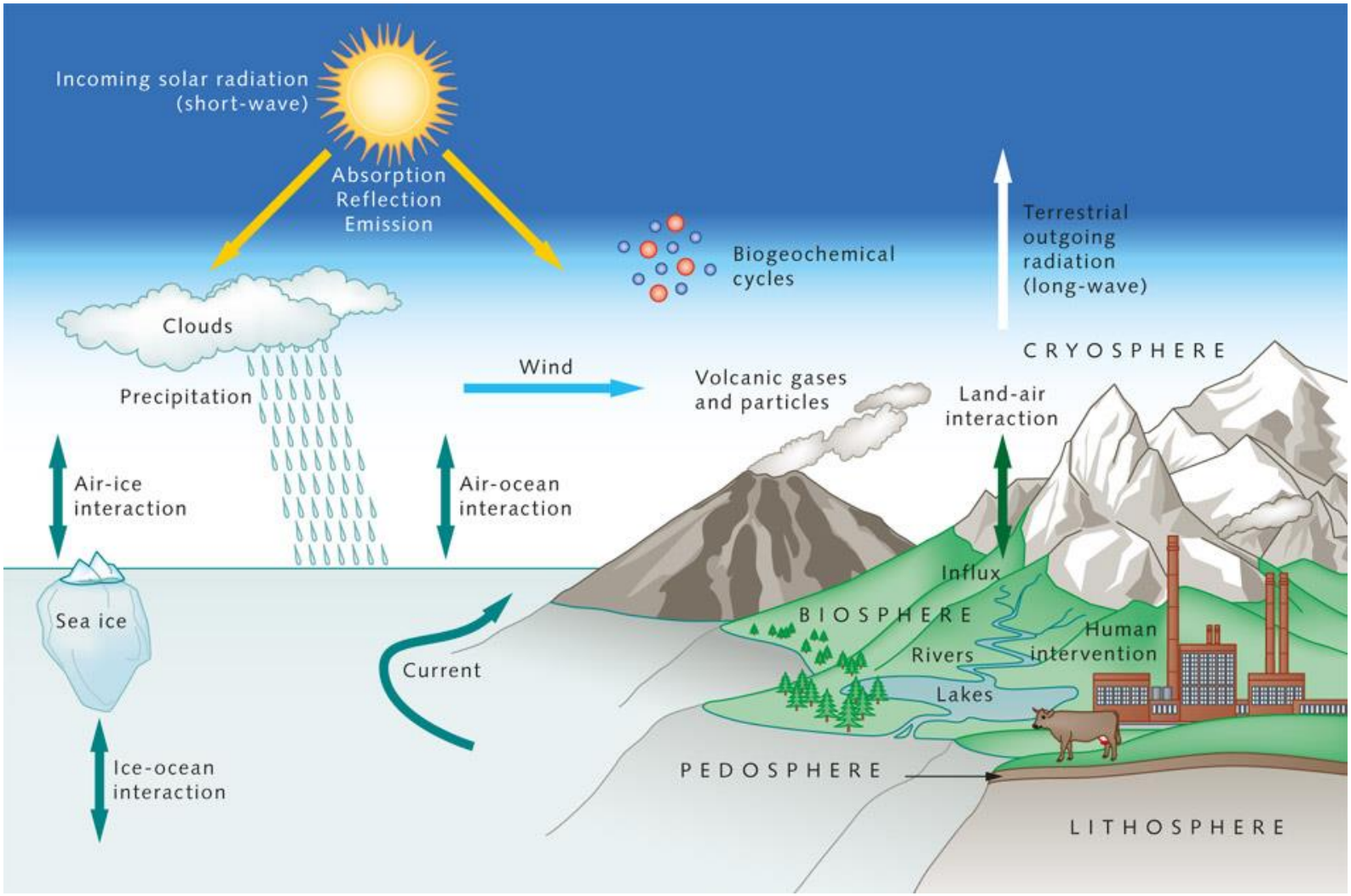
Ocean-atmosphere interactions



World Ocean Review (2010)

Ocean heat content (OHC)

0-700 m depth
(1σ std dev.)

700-2000 m
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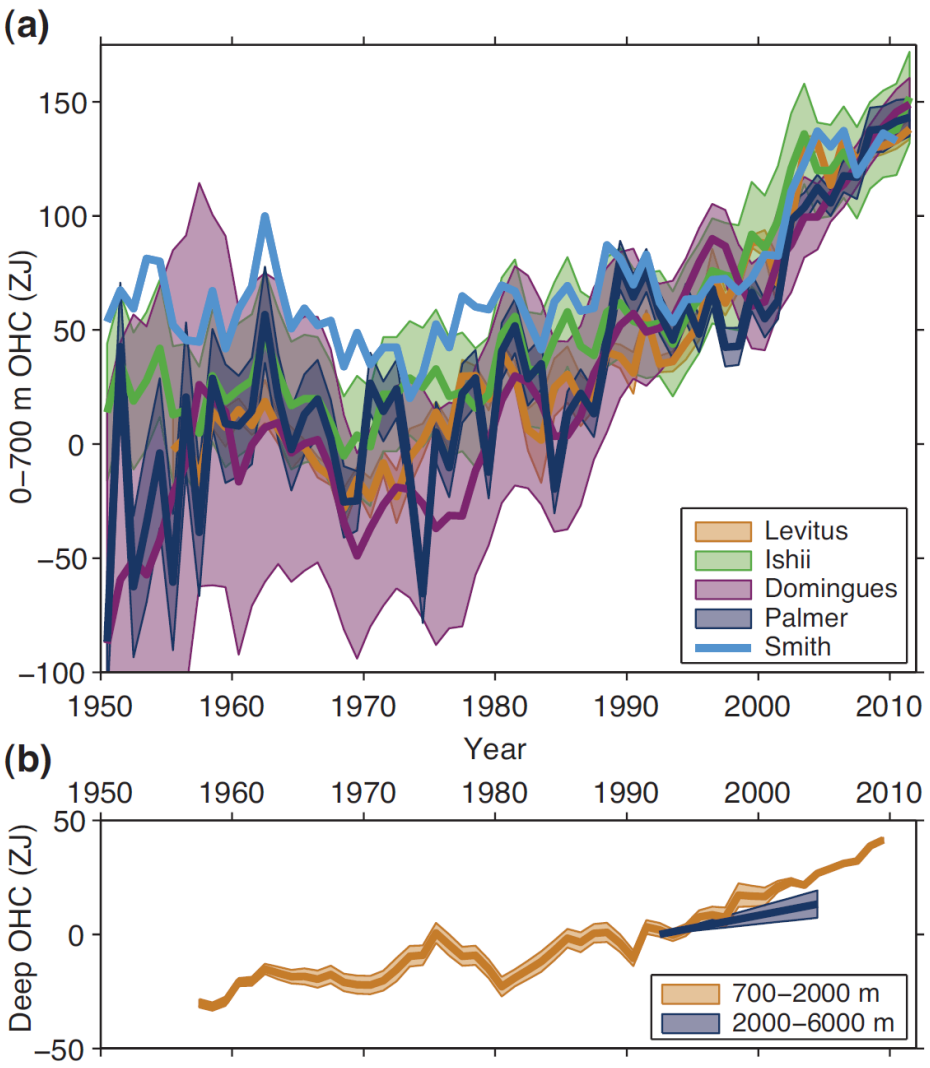

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Slowing of the upper OHC between 2003 and 2010(?)

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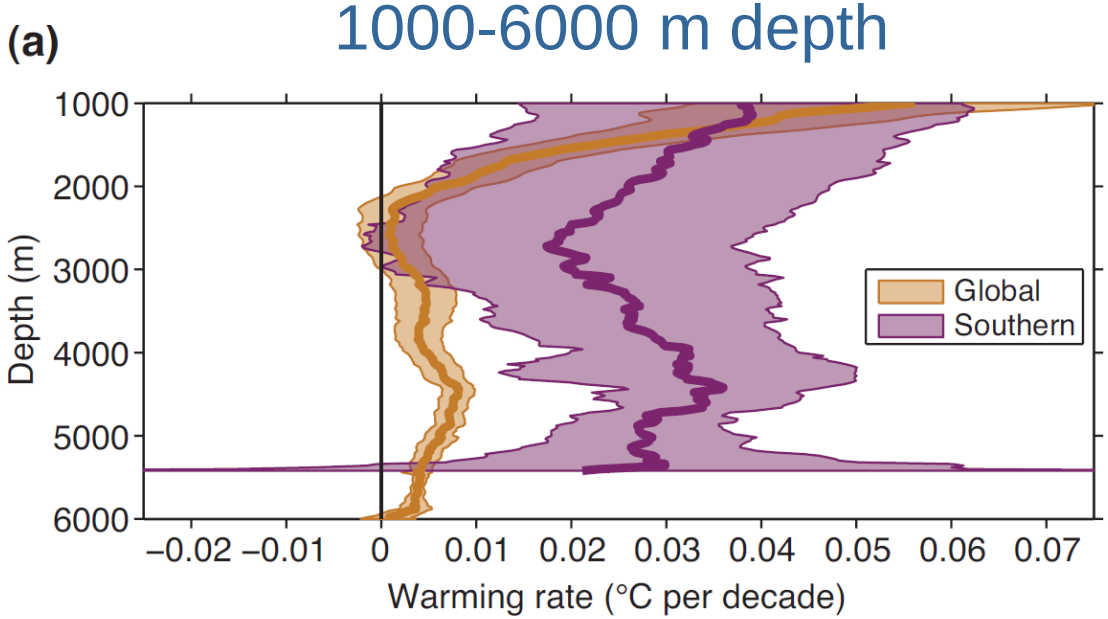
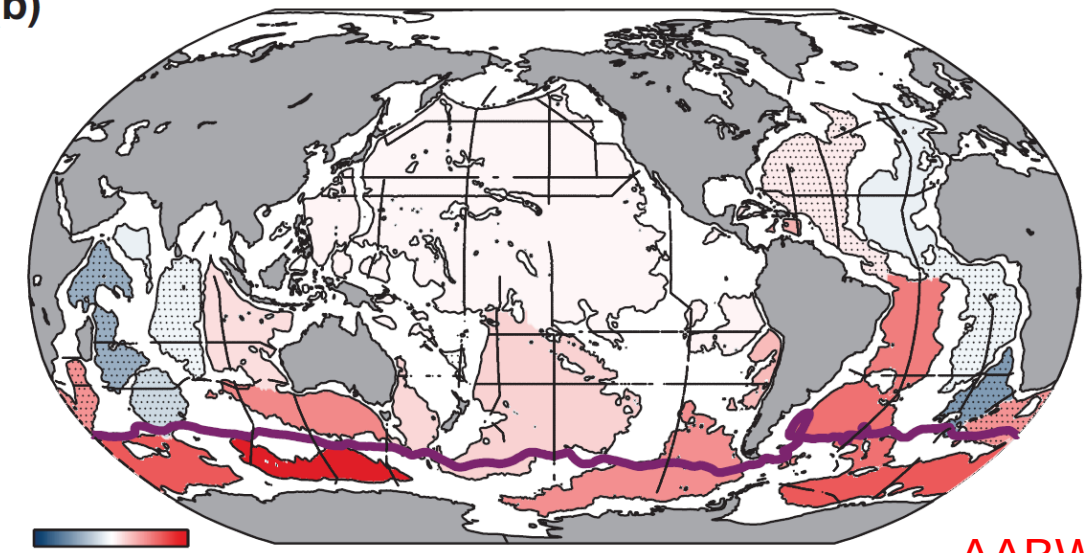
Warming rates for 1992-2005
(deg C/decade)

1000-6000 m depth



<4000 m depth

- No significant temperature trend between 2000-3000 m depth;
- <3000 m depth warming >0 is likely esp. in recently formed Antarctic Bottom Water (AABW);
- highest warming rates near 4500 m, usually near sea floor, where AABW influence is strongest.

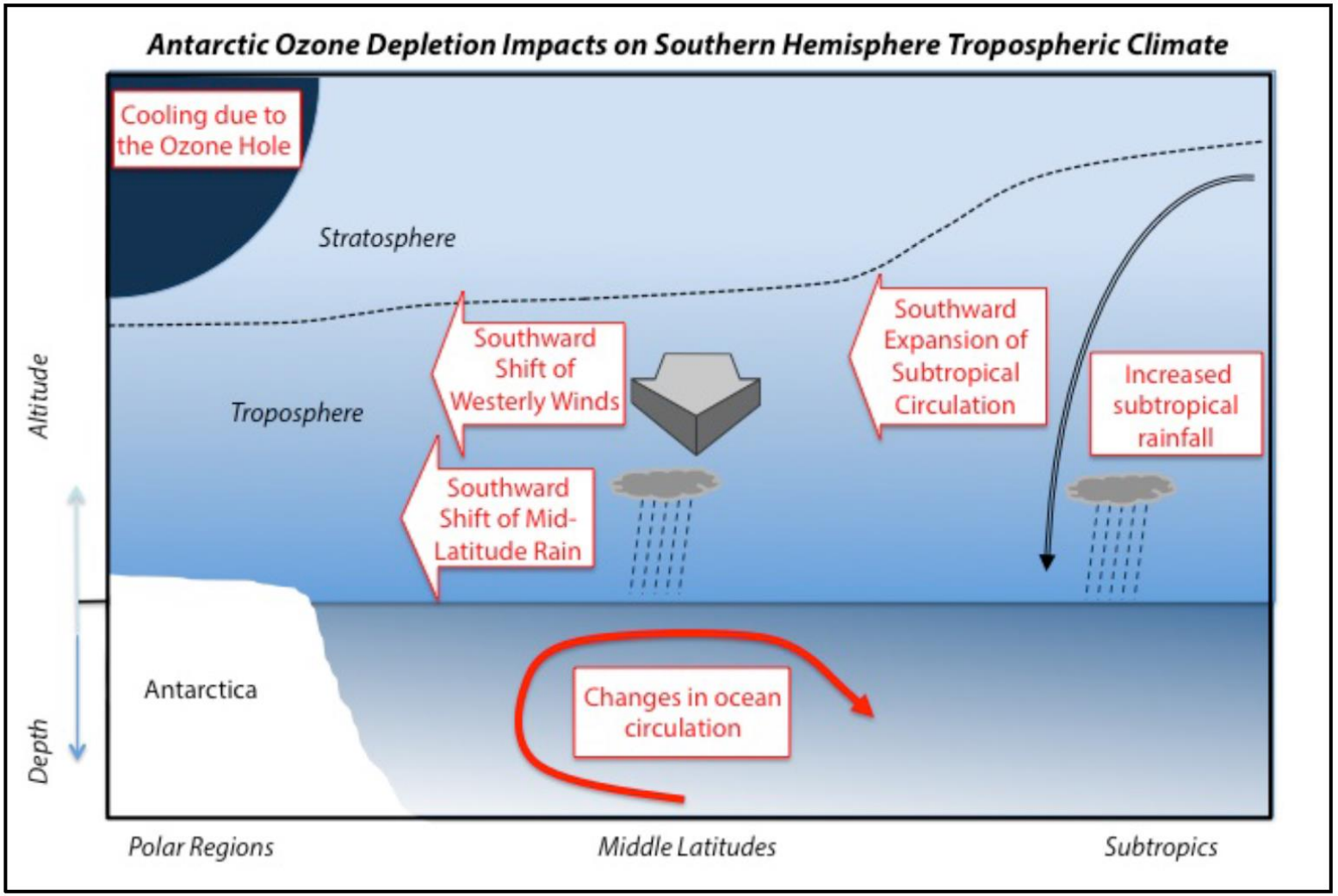


- Sub-Antarctic front
- Repeated oecanographic transects

AABW influence

Why is the AABW warming?

- Discuss together…
- …
- …

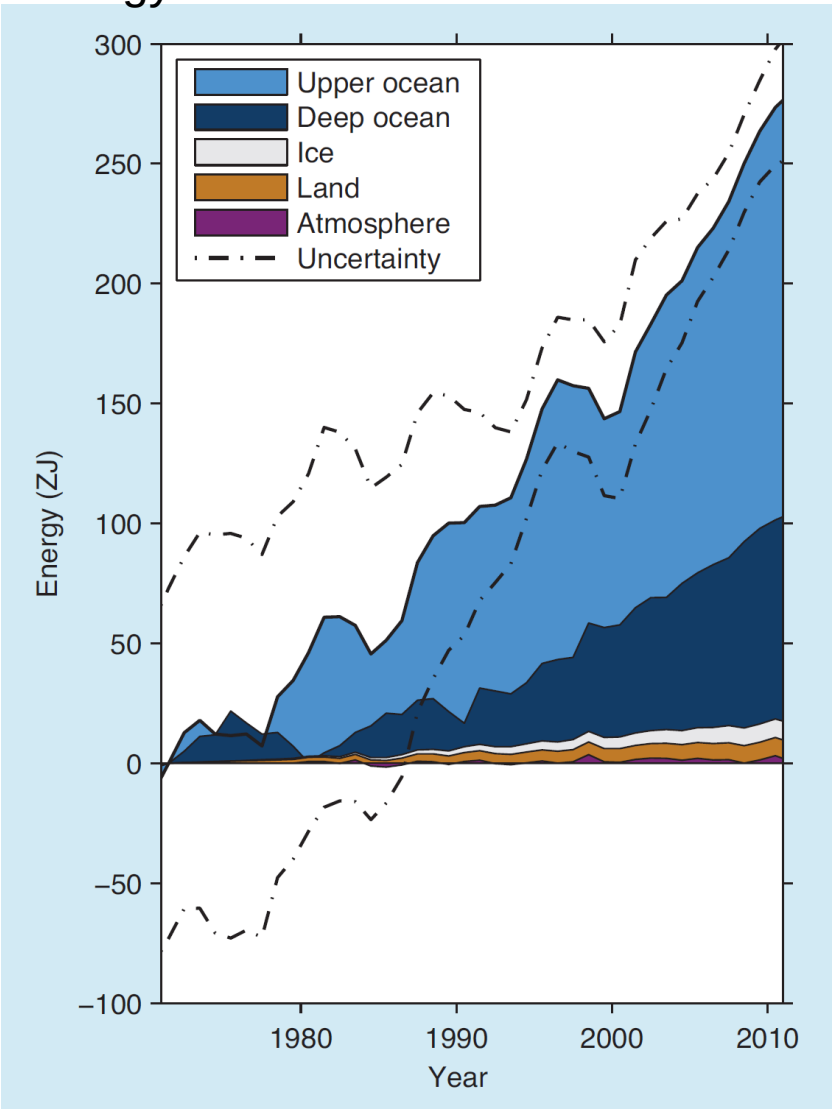


Stratospheric O_3 depletion > strengthening westerly winds (positive Southern Annular Mode) > increased surface wind stress > strengthening overturning circulation of the Southern Ocean

Chapter 4, WMO Ozone Assessment (2015)

Box 3.1 - Change in Global Energy Inventory

Energy accumulation relative to 1971



Estimated from satellite data since 1970:

Ocean warming dominates the total energy change inventory, accounting for ~93% from 1971 to 2010 (high confidence).

- The **upper ocean** (0-700 m) accounts for about 64% of the total energy change inventory.
- The **deep ocean** (below 700 m depth).
- Melting **ice** (including Arctic sea ice, ice sheets and glaciers) accounts for 3% of the total.
- Warming of the **continents** 3%.
- Warming of the **atmosphere** makes up the remaining 1%.

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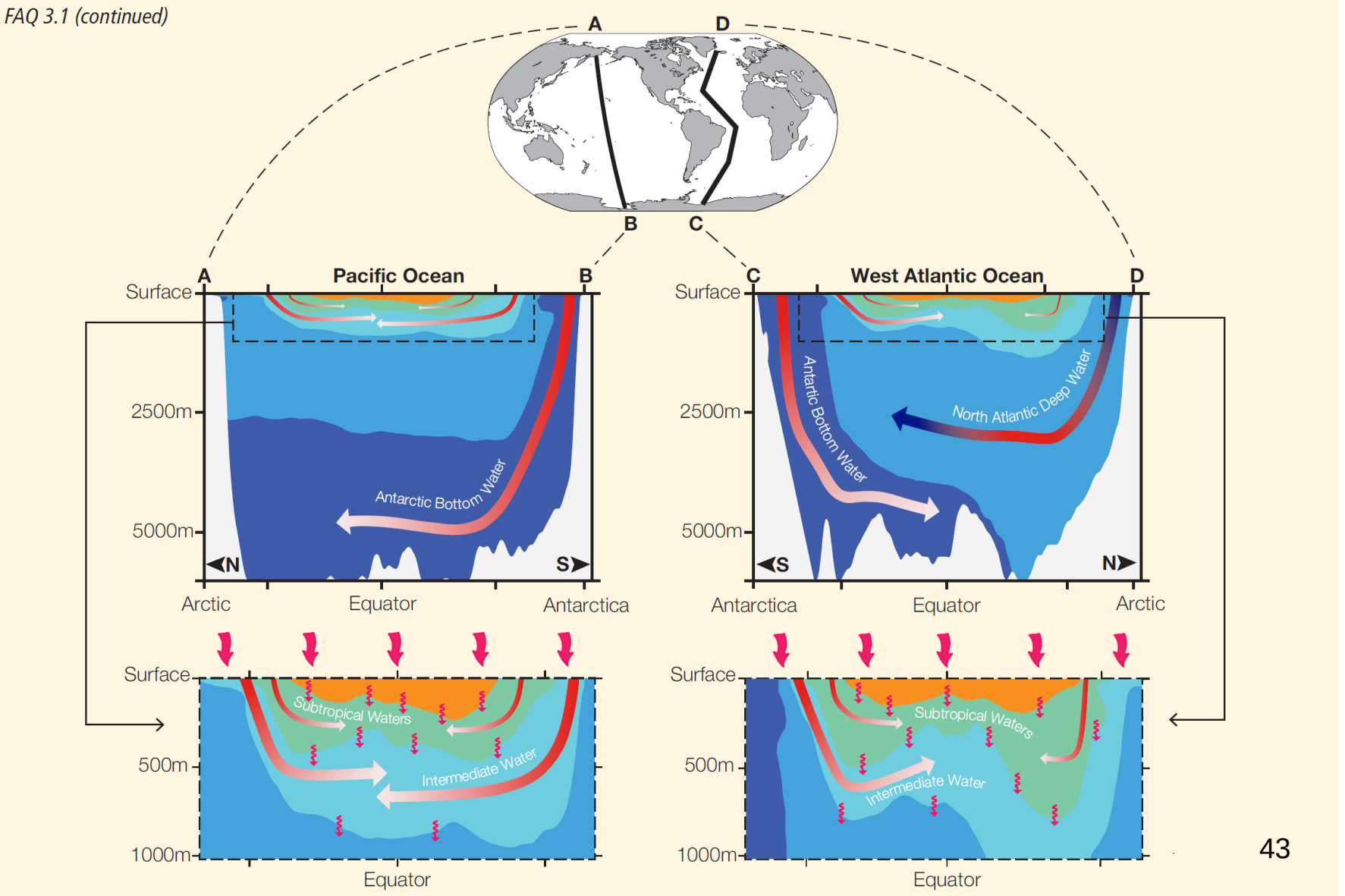
FAQ 3.1: Is the ocean warming?

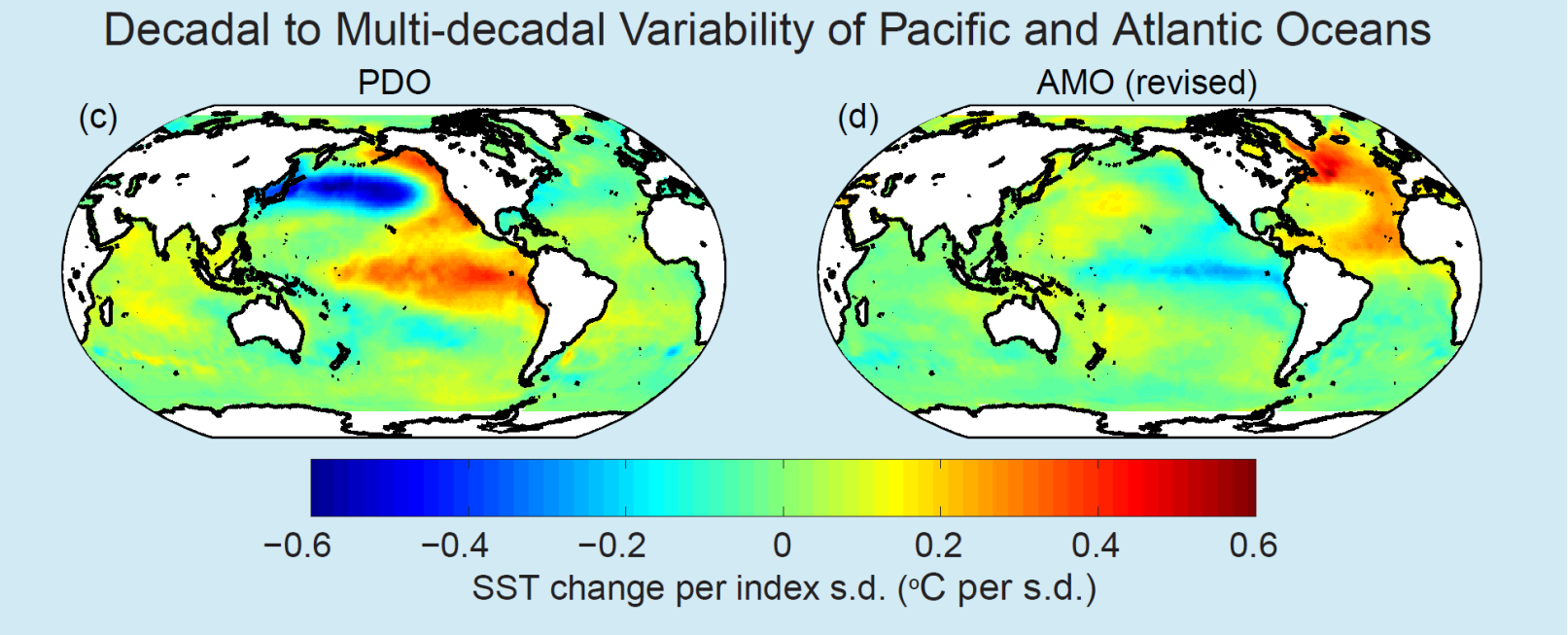
First, let's discuss in groups pro's and con's.

- **"Yes, the ocean is warming** over many regions, depth ranges and time periods,
- although **neither everywhere nor constantly**.
- The signature of warming emerges most clearly when considering global, or even ocean basin, averages over time spans of a decade or more.
- Ocean temperature at any given location can **vary** greatly with the **seasons**.
- It can also **fluctuate** substantially from **year to year -** or even **decade to decade -** because of variations in ocean currents and the exchange of heat between ocean and atmosphere."

FAQ 3.1: Is the ocean warming?

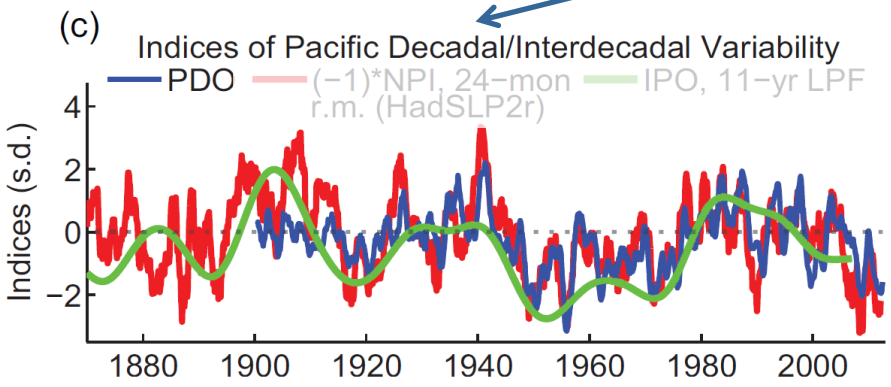


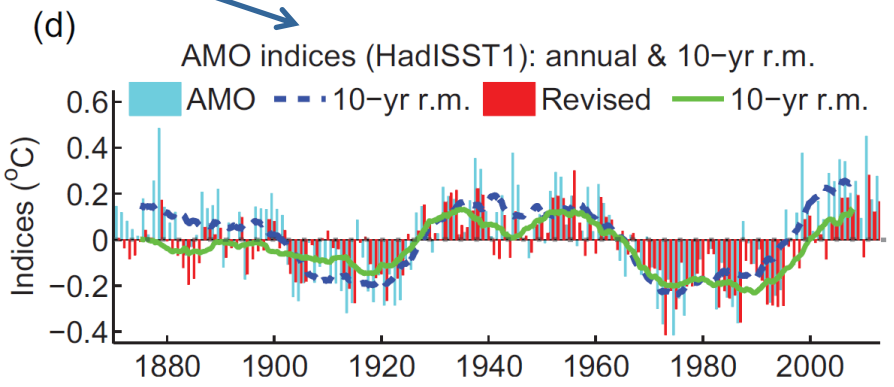
Box 2.5 - Patterns and Indices of Climate Variability – PDV (PDO) and AMV (AMO)

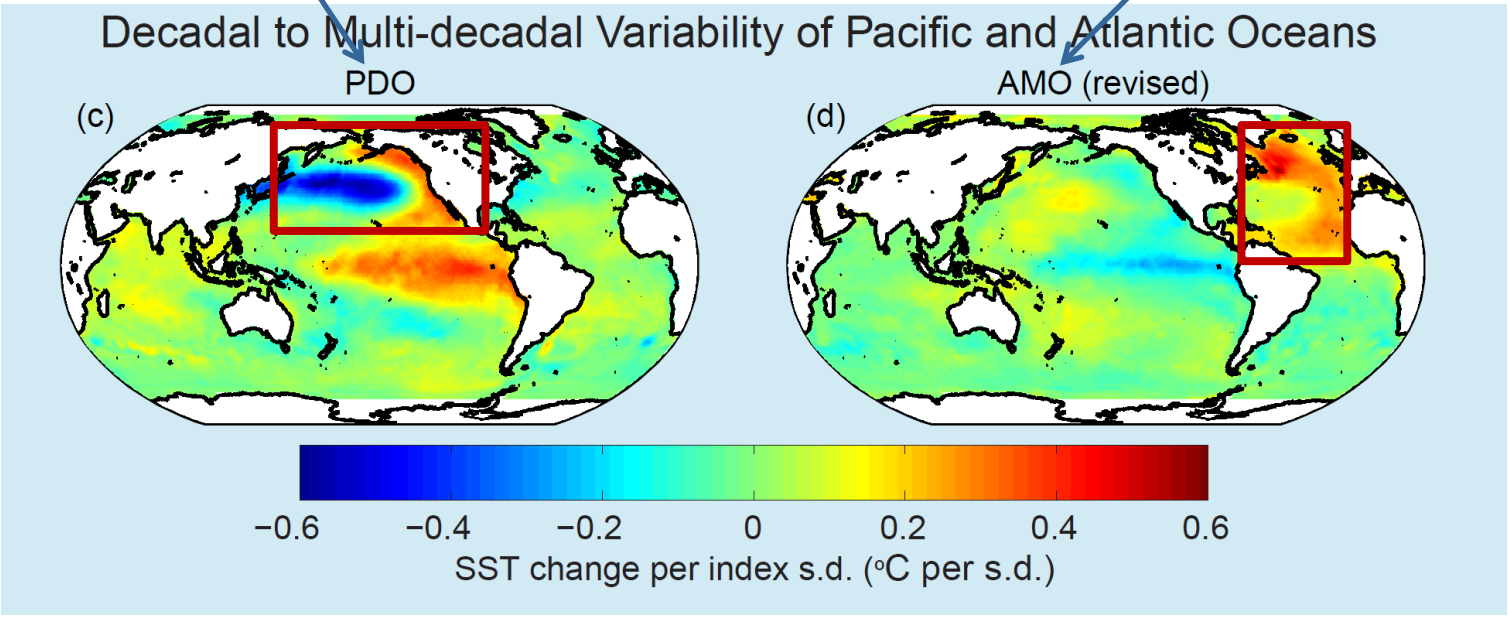


Pacific Decadal and Interdecadal Variability	Pacific Decadal Oscillation (PDO)	1st PC of monthly N. Pacific SST_a field [20°N–70°N] with subtracted global mean
	Inter-decadal Pacific Oscillation (IPO)	Projection of a global SST_a onto the IPO pattern, which is found as one of the leading Empirical Orthogonal Functions of a low-pass filtered global SST_a field
Atlantic Ocean Multidecadal Variability	Atlantic Multi-decadal Oscillation (AMO) index	10-year running mean of linearly detrended Atlantic mean SST_a [0°–70°N]
	Revised AMO index	As above, but detrended by subtracting SST_a [60°S–60°N] mean

Box 2.5 - Patterns and Indices of Climate Variability - PDV and AMV







HadISST: Hadley Centre Sea Ice and Sea Surface Temperature data set; Rayner et al (2003, *JGR*)

3.2 Conclusions - Temperature and Heat Content Changes

- "It is **virtually certain** that the **upper ocean** (above 700 m) **has warmed from 1971 to 2010**, and **likely** that it has **warmed** from the **1870s to 1971**. **Confidence** in the assessment for the time period **since 1971** is **high**.
- It is **likely** that the **ocean warmed between 700 and 2000 m from 1957 to 2009**, based on 5-year averages. It is likely that the **ocean warmed from 3000 m to the bottom from 1992 to 2005**, while no significant trends in global average temperature were observed between 2000 and 3000 m depth during this period.
- It is **virtually certain** that **upper ocean** (0 to 700 m) **heat content increased** during the relatively well-sampled 40-year period **from 1971 to 2010**.
- **Warming** of the **ocean** between **700** and **2000** m likely **contributed** about **30%** of the total **increase** in **global ocean heat content** (0 to 2000 m) between **1957 and 2009**.
- **Ocean warming dominates** the **global energy change inventory.**
- **Warming** of the **ocean accounts** for about **93%** of the **increase** in the **Earth's energy inventory** between **1971 and 2010 (high confidence**), with warming of the **upper** (0 to 700 m) **ocean accounting** for about **64%** of the total."