GEF4400 “The Earth System”

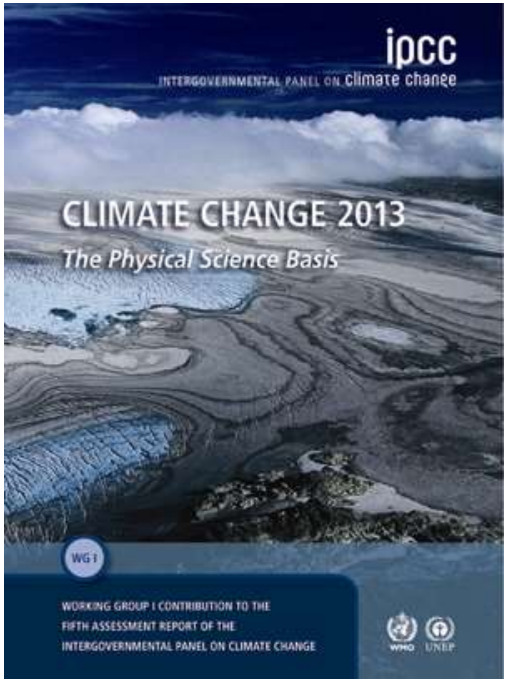
Prof. Dr. Jon Egill Kristjansson,

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

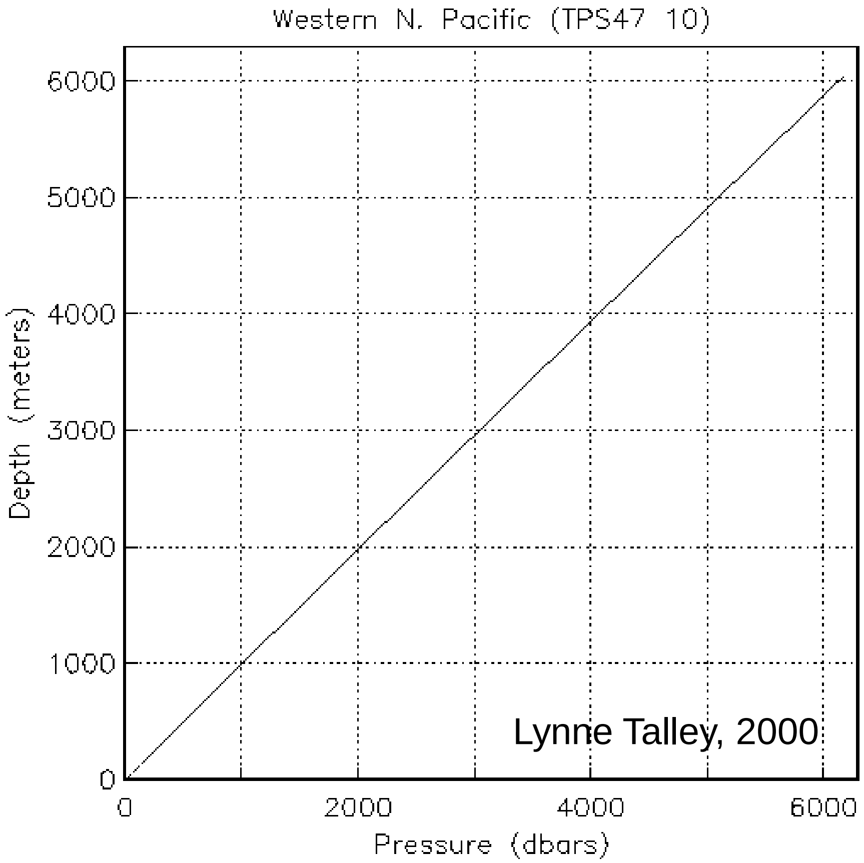


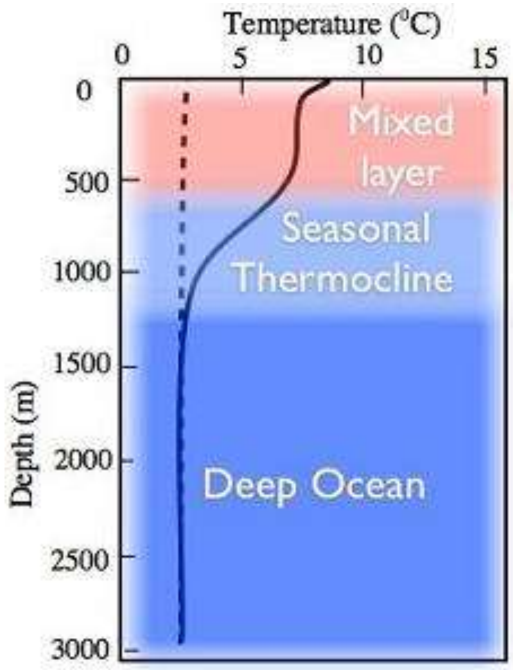
- Background
- Introduction *(Appendix 3A)*
- Ocean temperature and heat content *(Section 3.2)*
- Salinity and fresh water content *(Section 3.3)*
- Ocean surface fluxes *(Section 3.4)*
- Ocean circulation *(Section 3.6)*
- Sea level change *(Section 3.7)*
- Executive Summary *(Ch. 3)*

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)



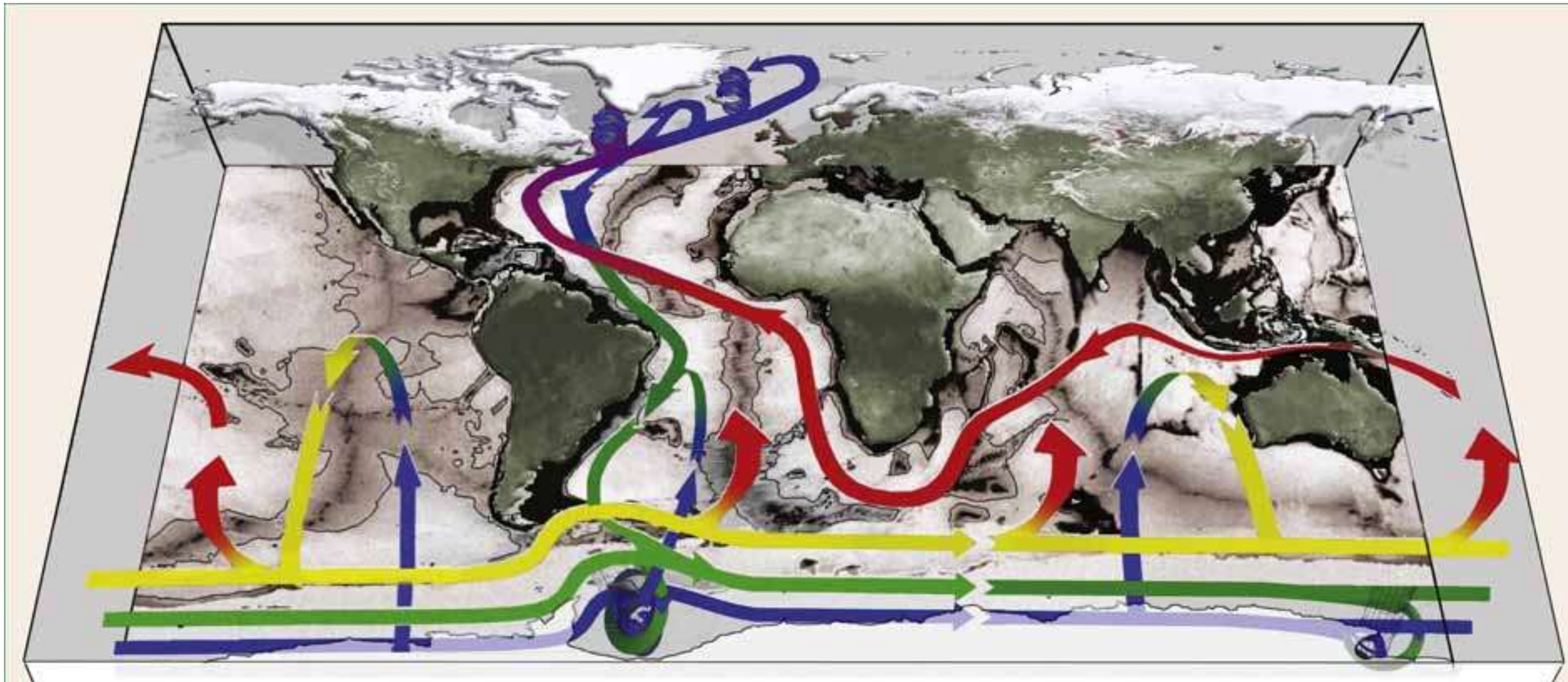


Ocean pressure is usually measured in decibars because the pressure in decibars is almost exactly equal to the depth in meters.

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



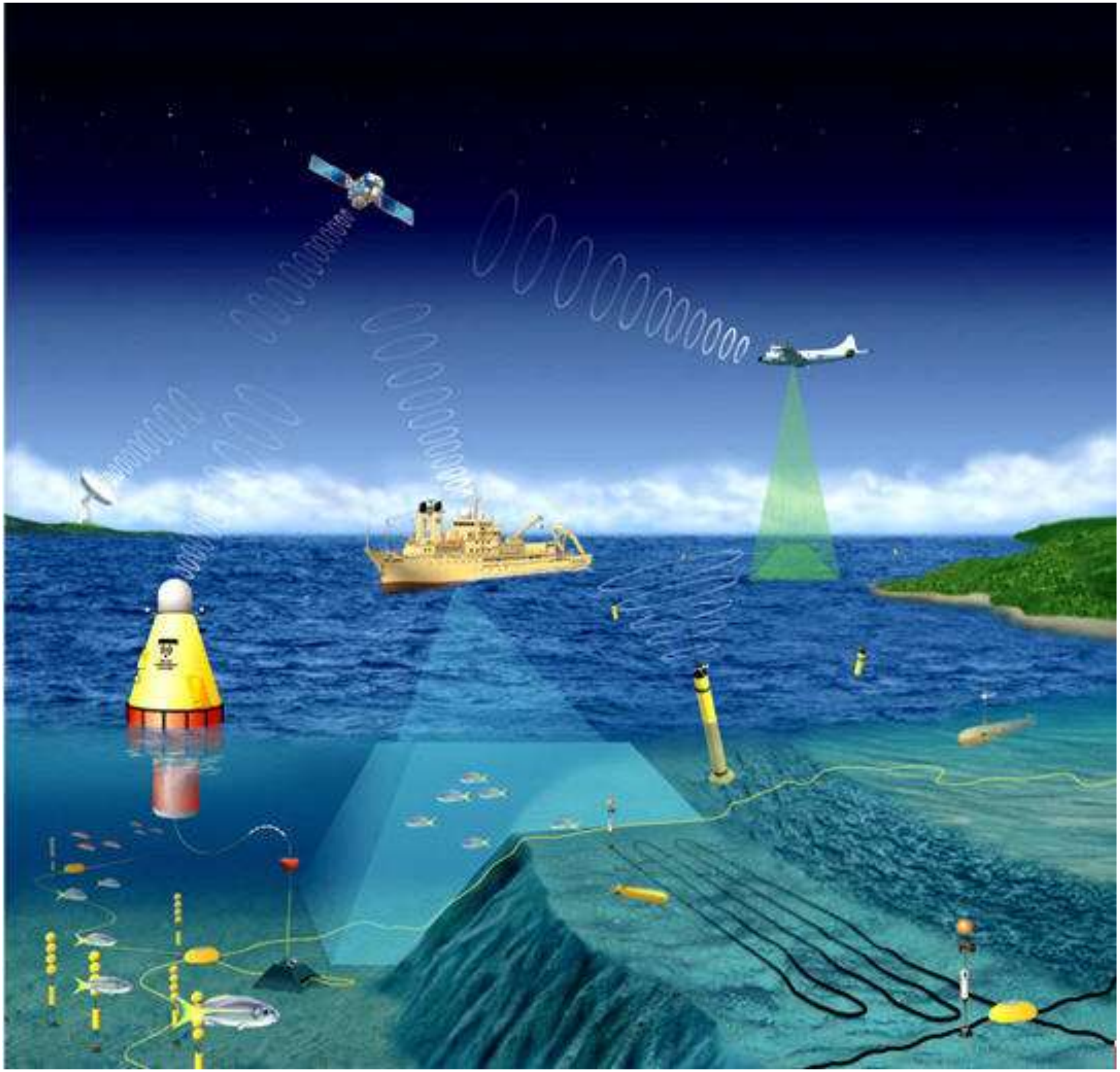
Cooler colours indicate denser water masses, ranging from warmer mode and thermocline waters in red to bottom waters in blue.

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

NOAA NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
UNITED STATES DEPARTMENT OF COMMERCE

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

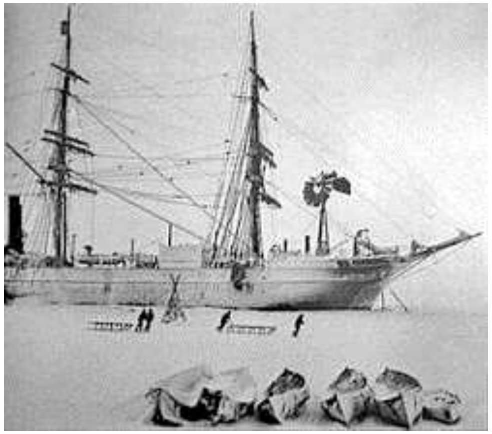
Why do we care about the Oceans influence on climate?

- 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**.

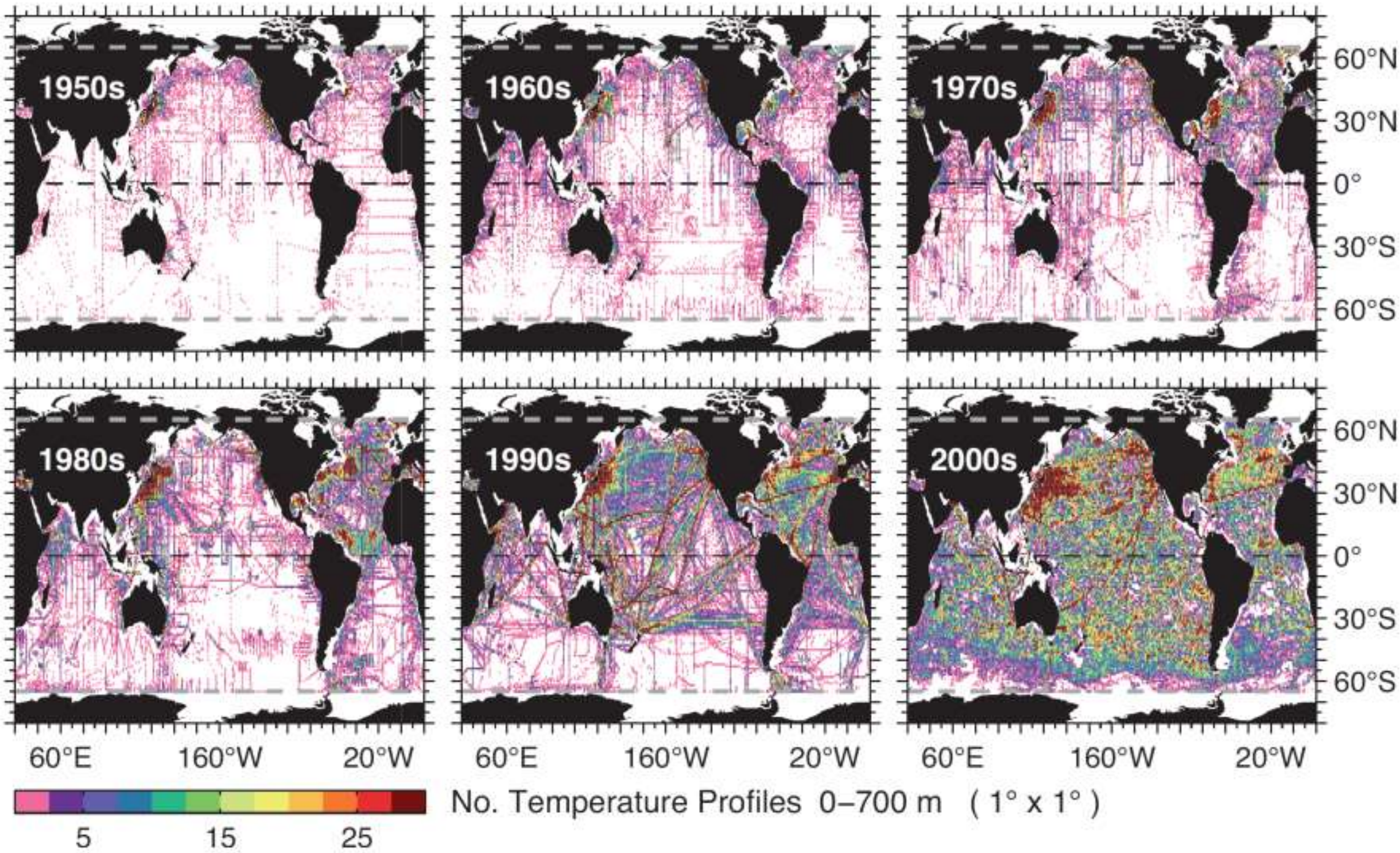
Oceanography expeditions

- 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



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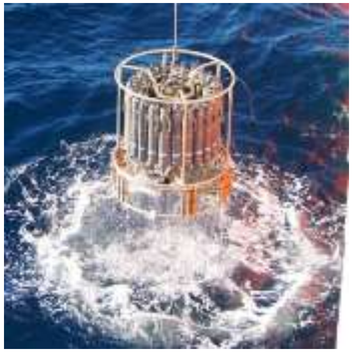
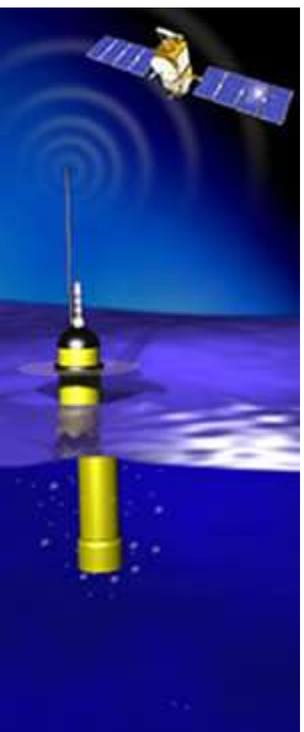




- Reversing thermometers and **Nansen bottles** from ships on stations
- 1960s: Conductivity-Temperature-Depth (**CTD**) casts with **Niskin bottles**
- 1950s-1970s: subsurface measurements with mechanical bathythermographs from slow moving ship
- >late 1960s: Expendable bathythermographs (**XBT**) from 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

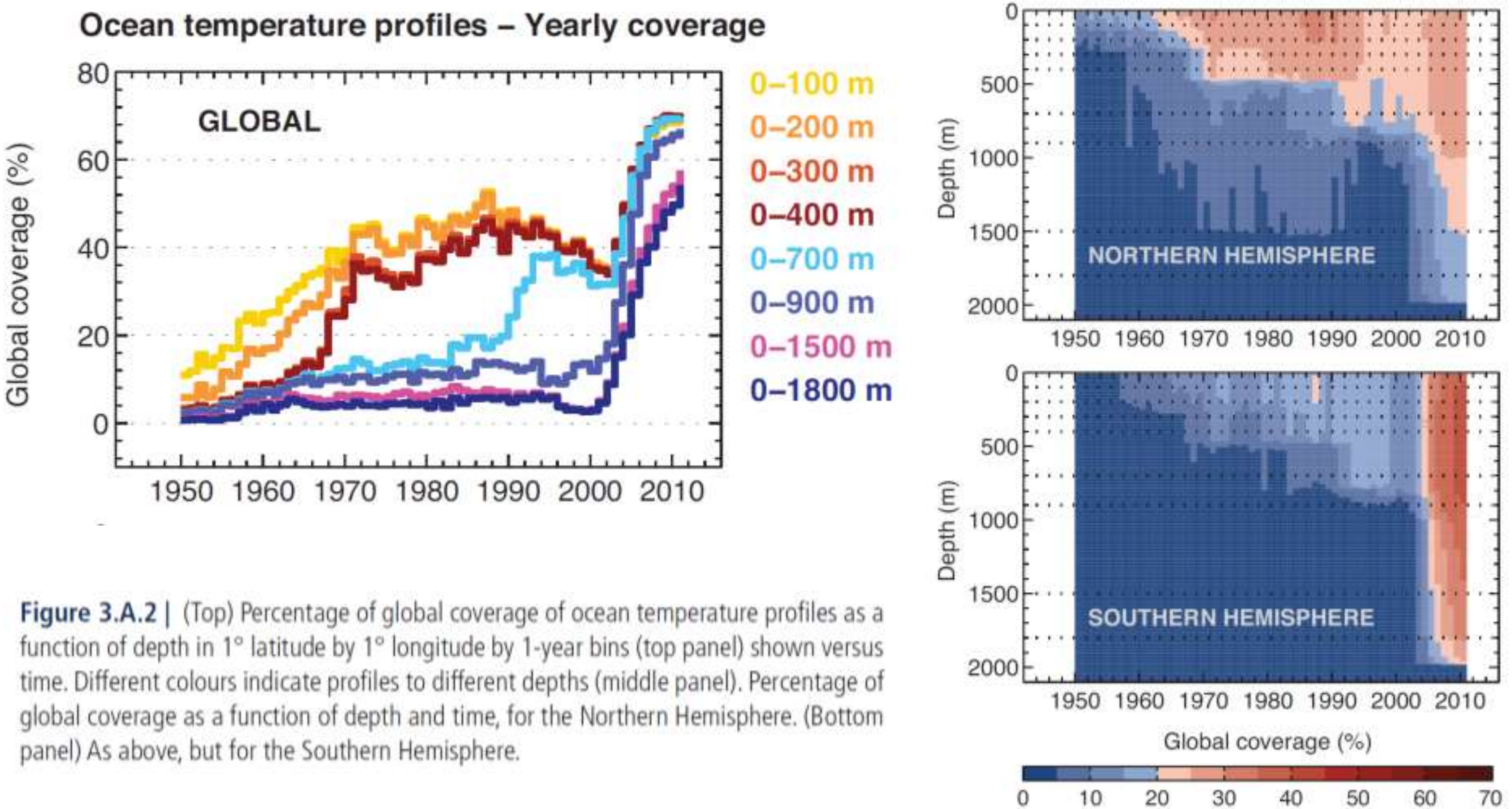


Figure 3.A.2 | (Top) Percentage of global coverage of ocean temperature profiles as a function of depth in 1° latitude by 1° longitude by 1-year bins (top panel) shown versus time. Different colours indicate profiles to different depths (middle panel). Percentage of global coverage as a function of depth 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."

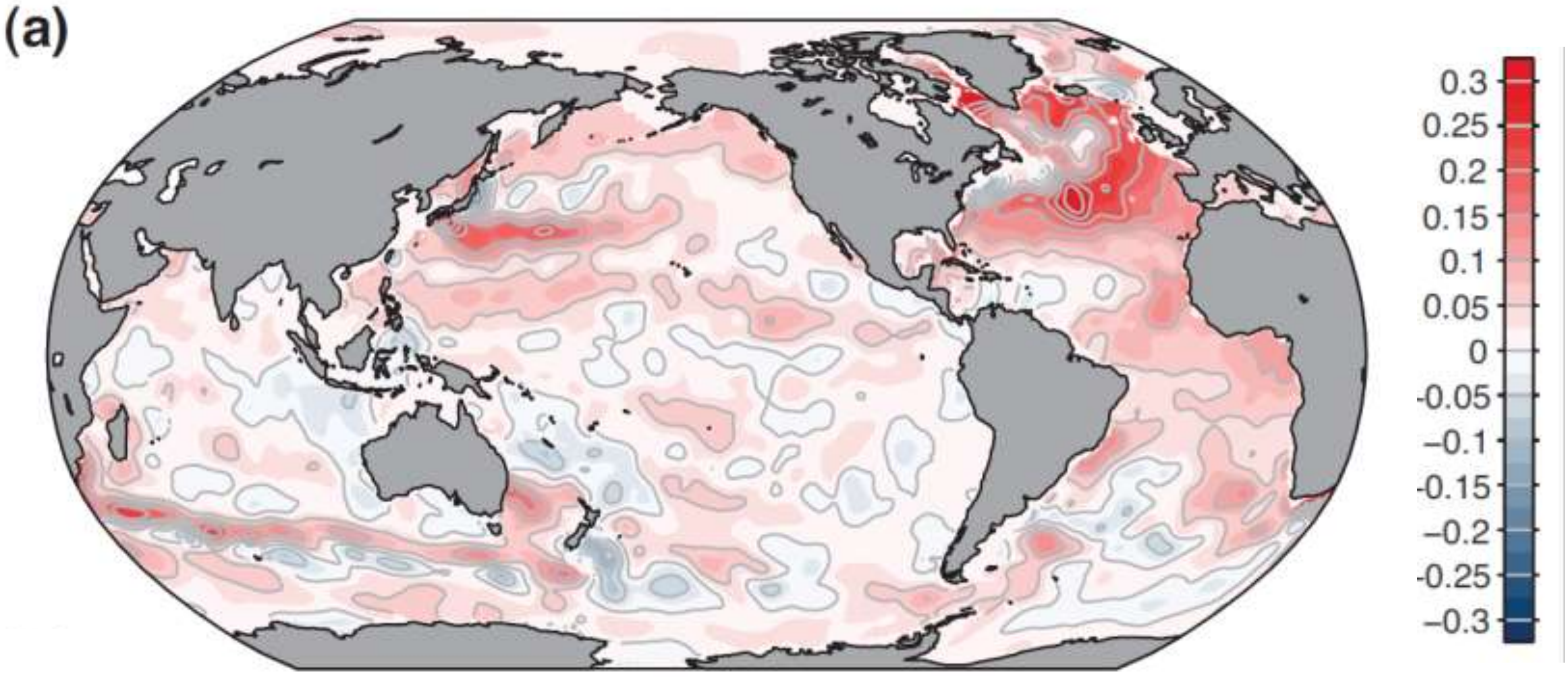
- How is the temperature in the shallow, medium and deep ocean changing?
- How is the ocean heat content changing?

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

-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



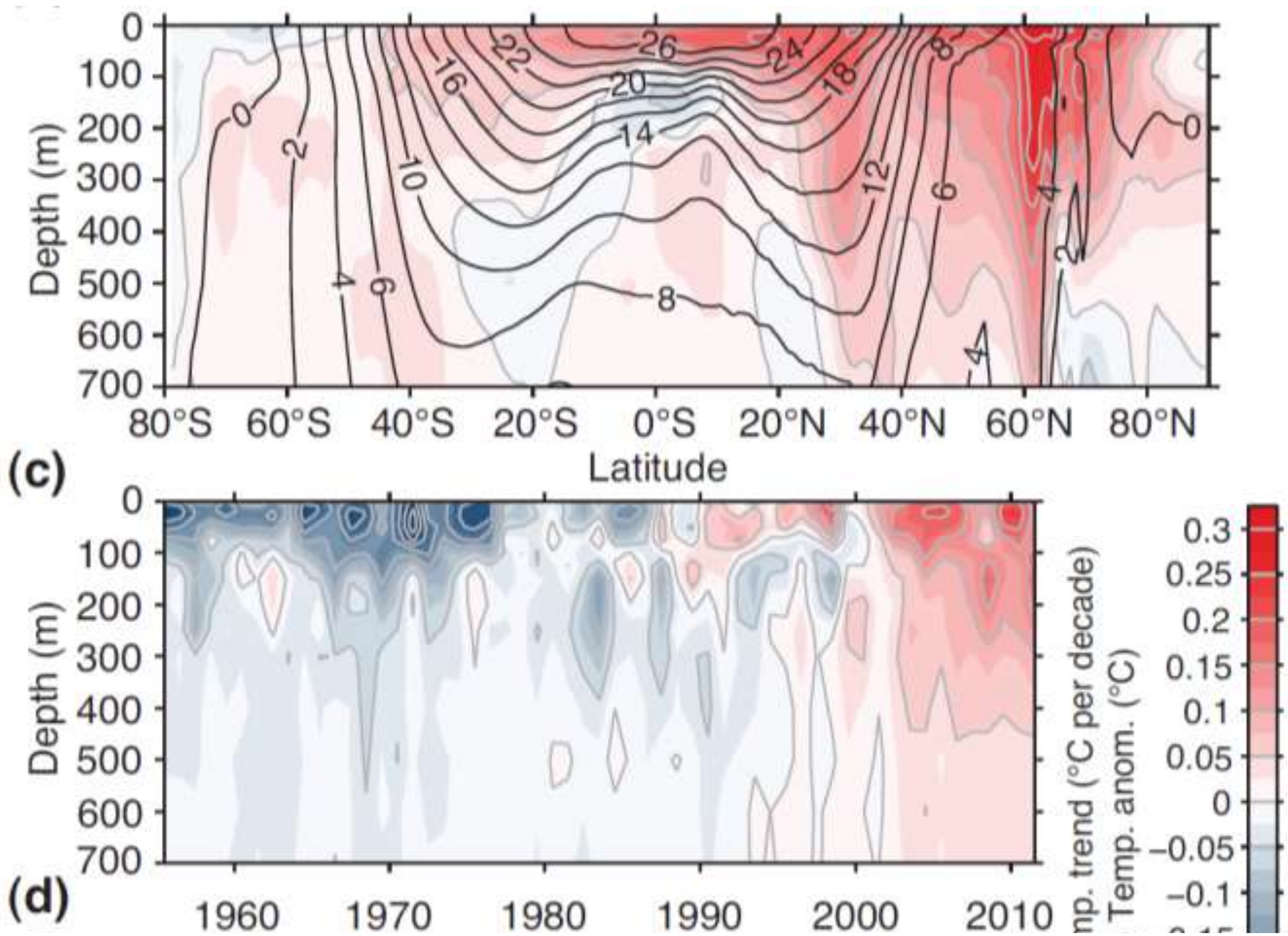
- Positive temperature change over most of the globe (Levitus et al., 2009).
- Warming is more prominent in the NH, especially the North Atlantic.
- This result holds in different analyses, using different time periods, bias corrections and data sources.

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.

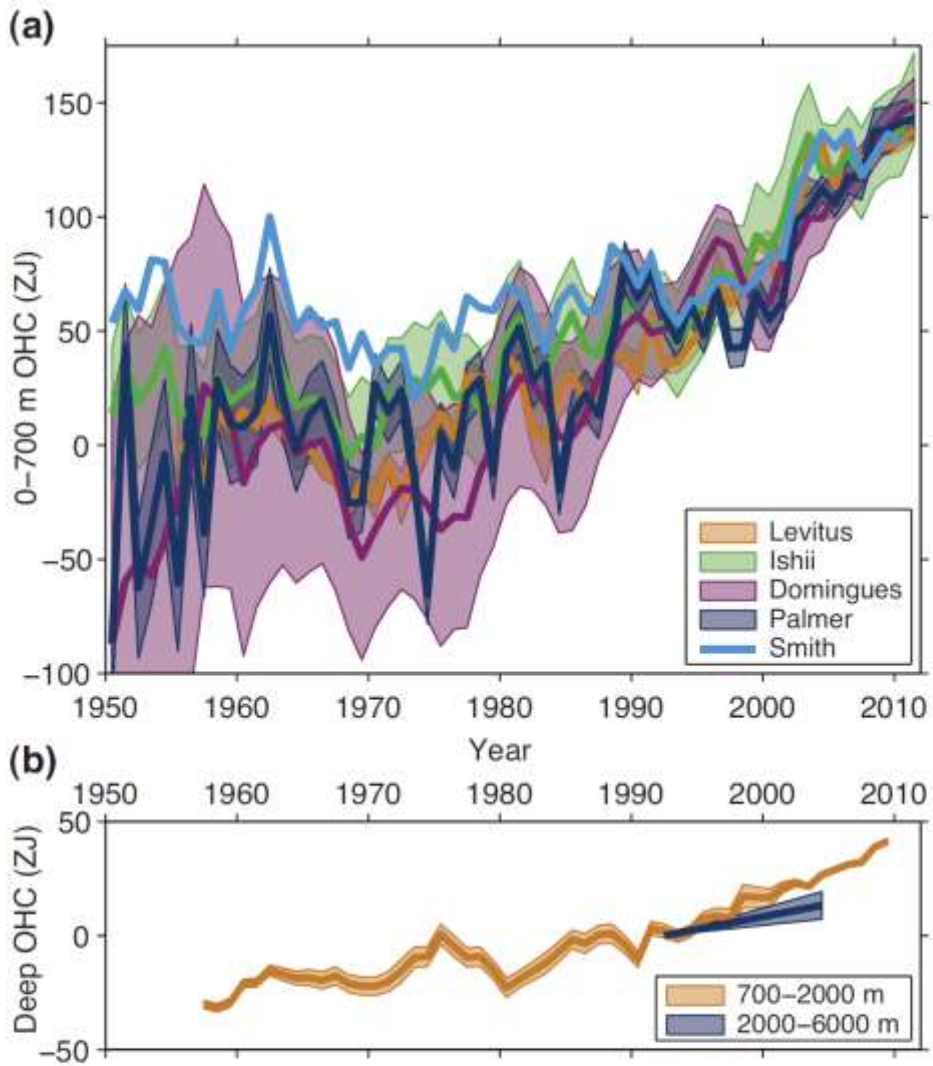
Why is the Northern Ocean warming stronger than the Southern Ocean?

- 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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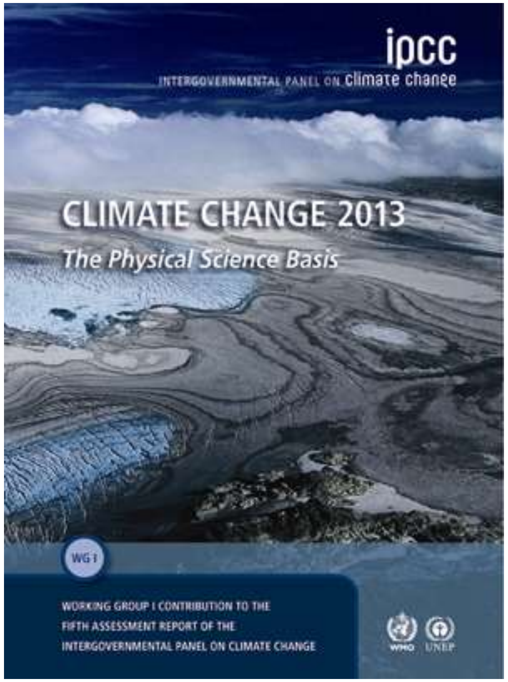

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GEF4400/9400 changed time schedule

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)	28.09.2015	-
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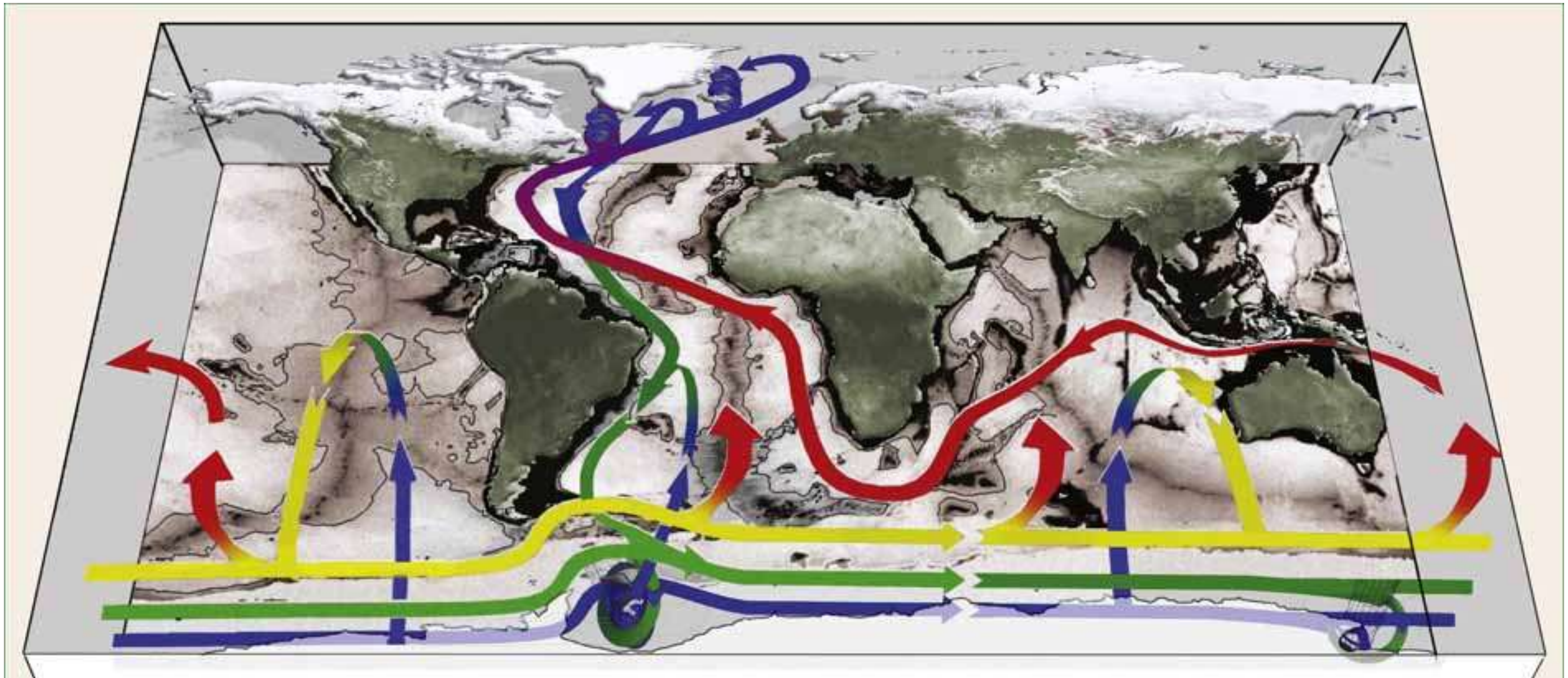
Ocean circulation



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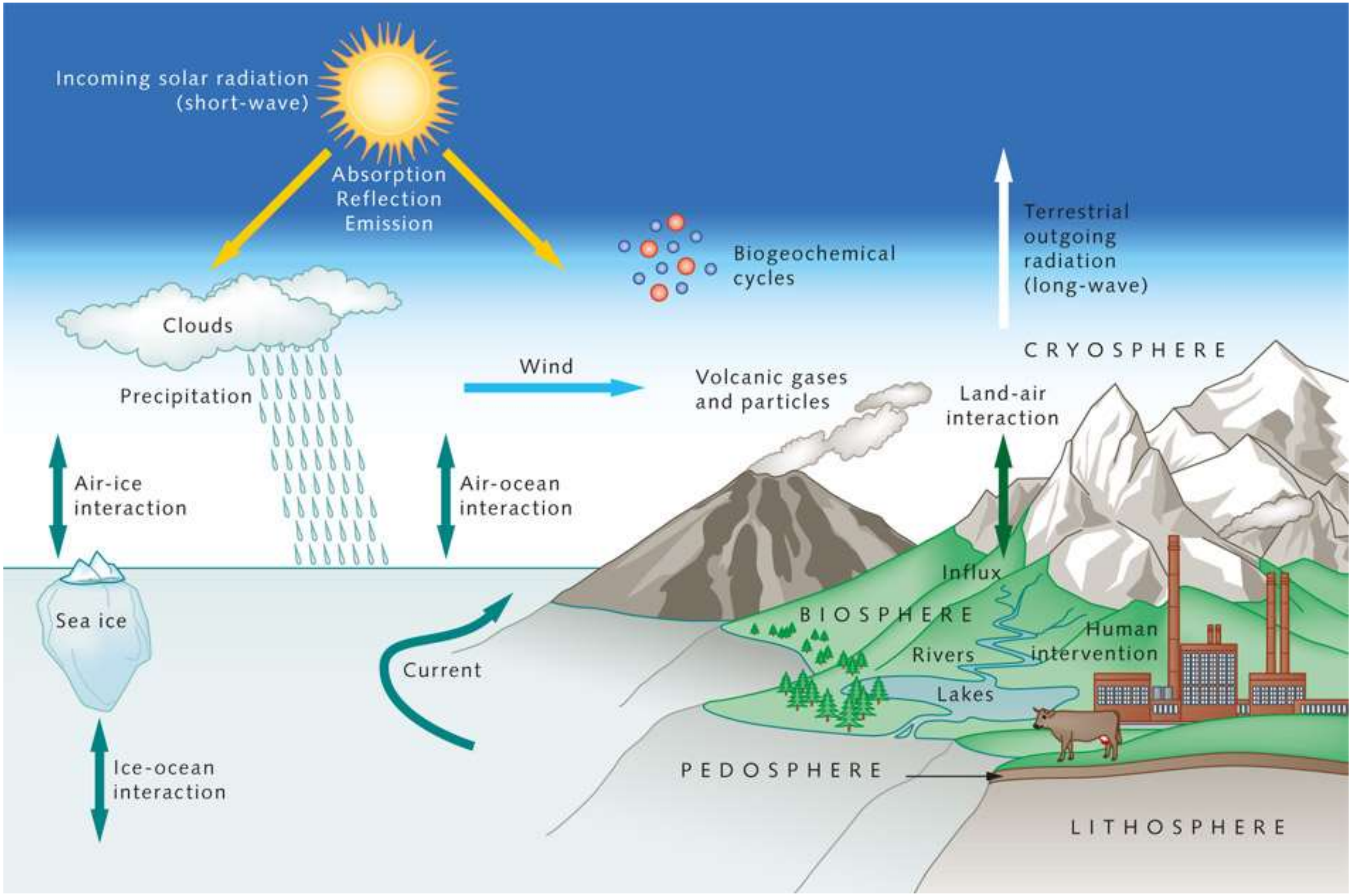
Ocean-atmosphere interactions



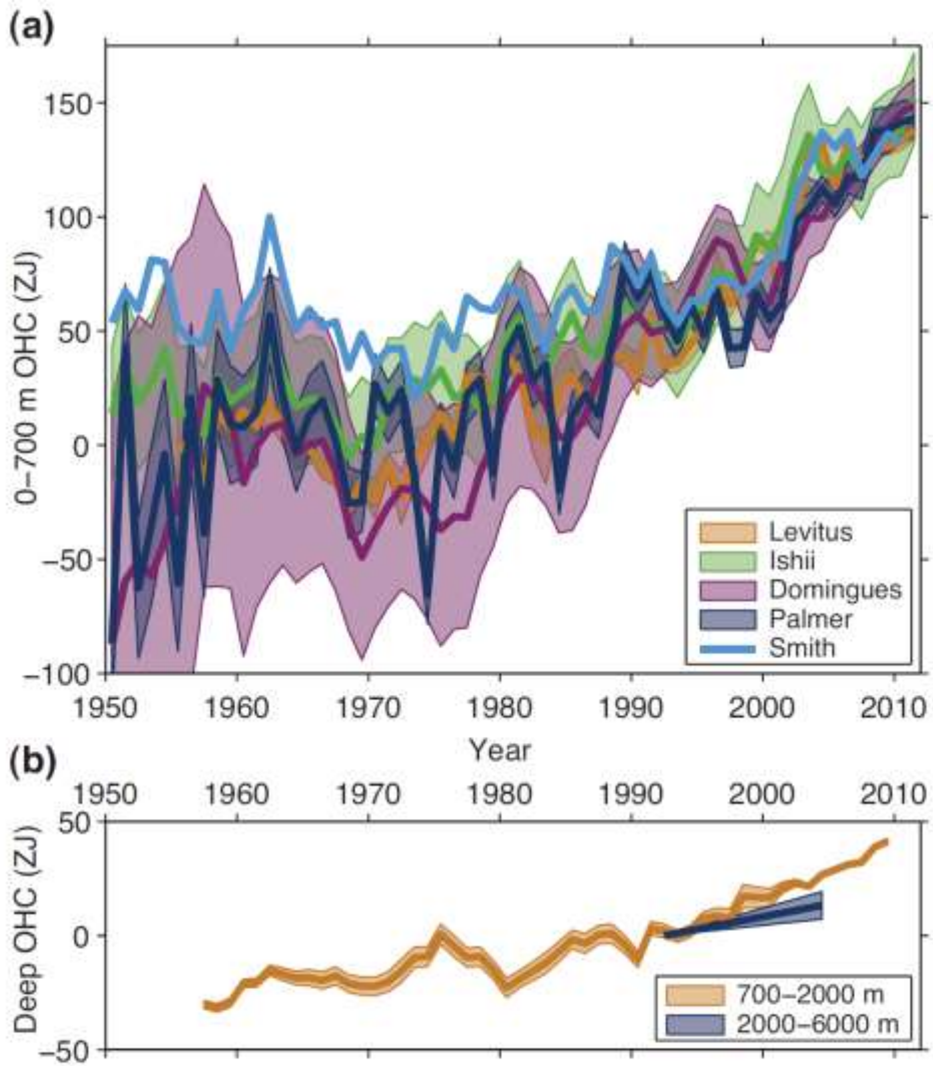
World Ocean Review (2010)

Recap

Ocean heat content (OHC)

0-700 m depth
(1σ std dev.)

700-2000 m
2000-6000 m



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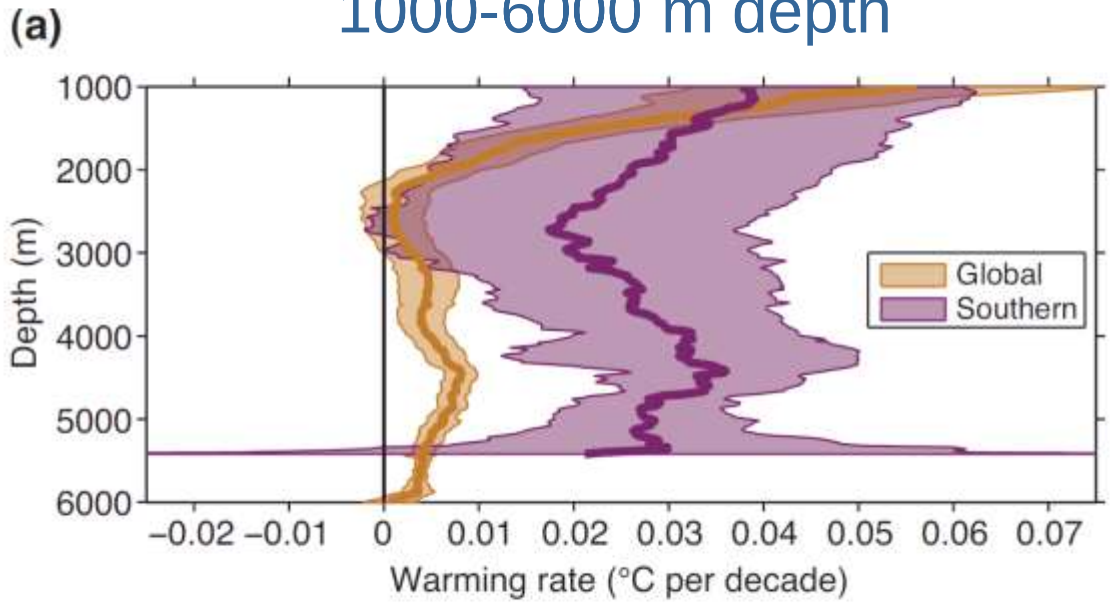
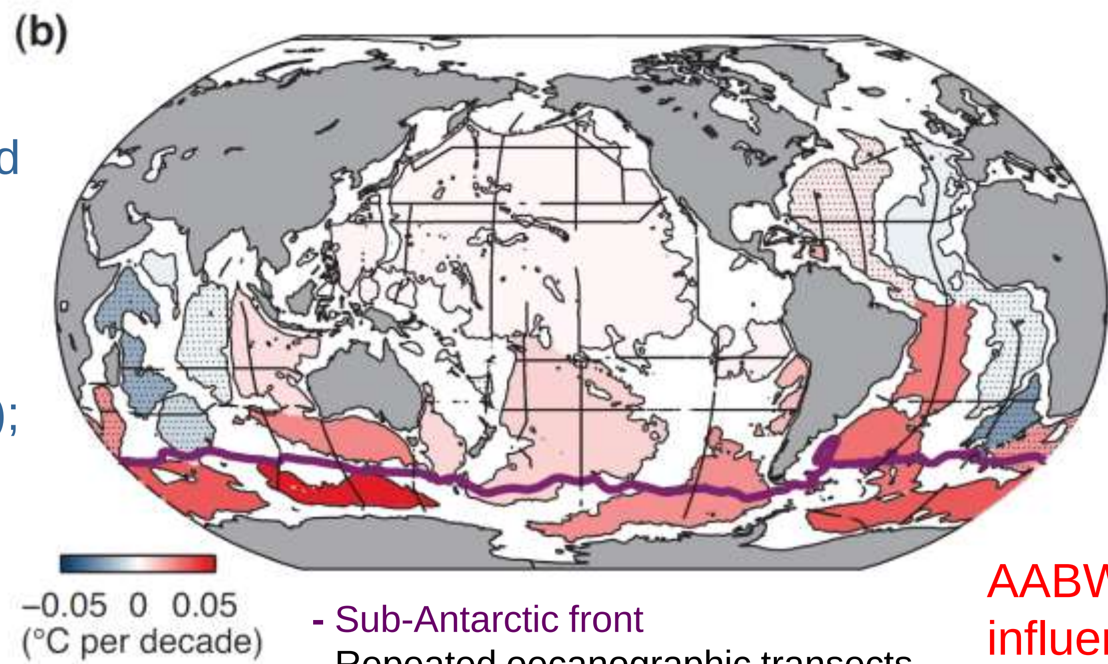
Warming rates for 1992-2005
(deg C/decade)

1000-6000 m depth



<4000 m depth



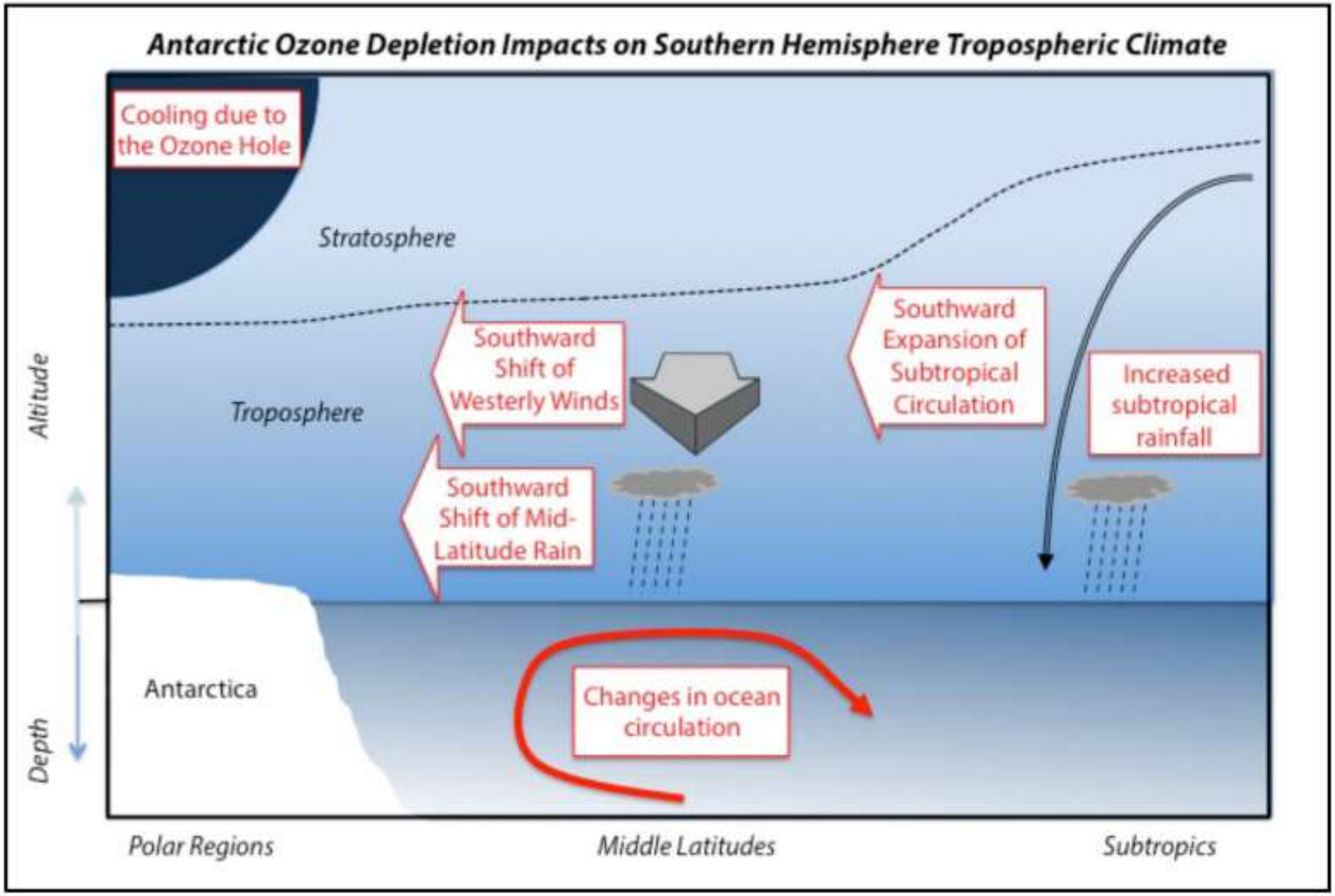
- Sub-Antarctic front
- Repeated oecanographic transects

AABW influence

- 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.

Why is the AABW warming?

- Discuss together…
- …
- …

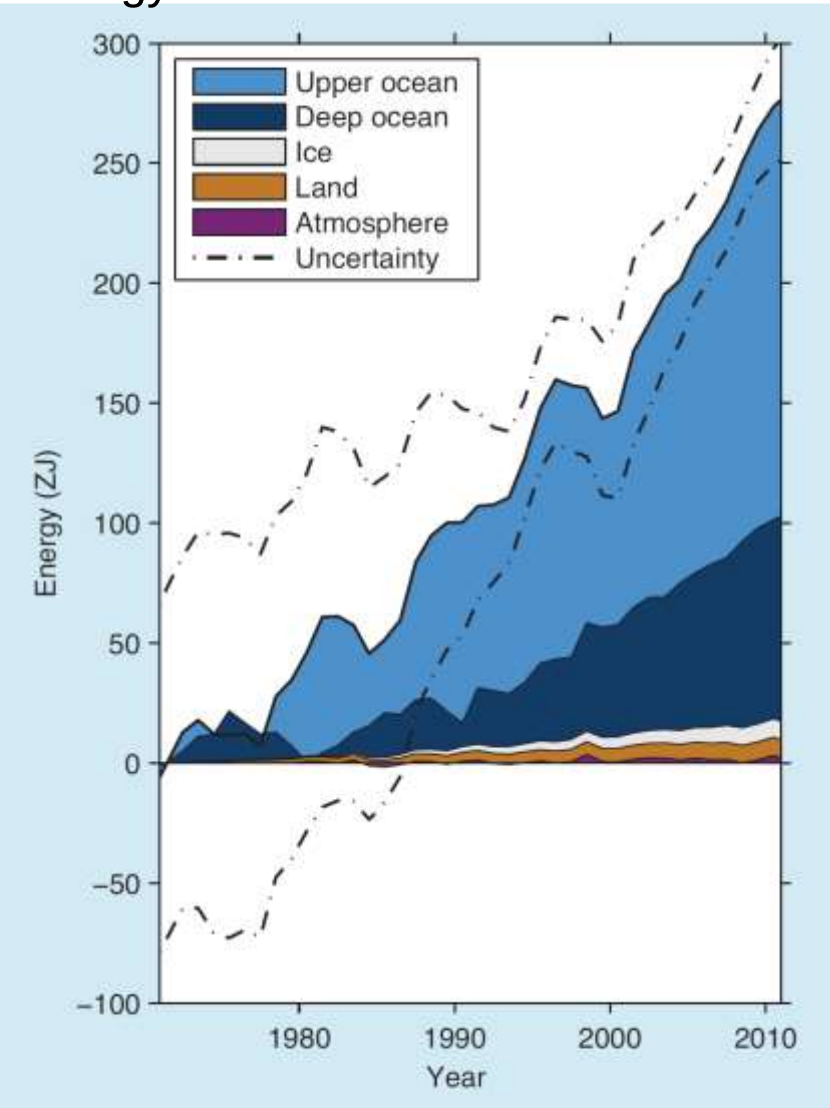


Stratospheric O_3 depletion > strengthening westerly winds (positive Southern Annular Mode) > increased surface wind stress > strengthening overturning circulation of the Southern Ocean

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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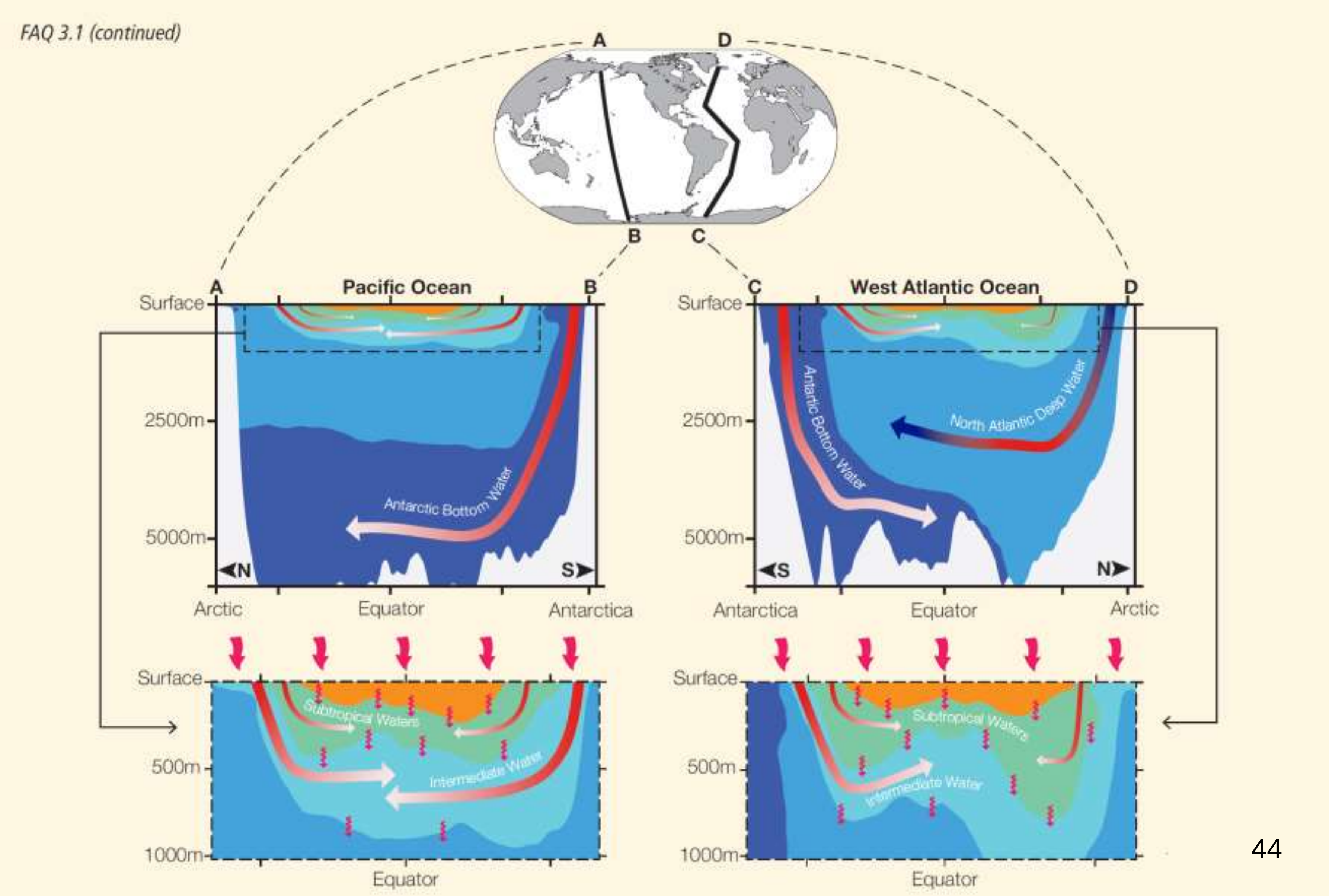
FAQ 3.1: Is the ocean warming?

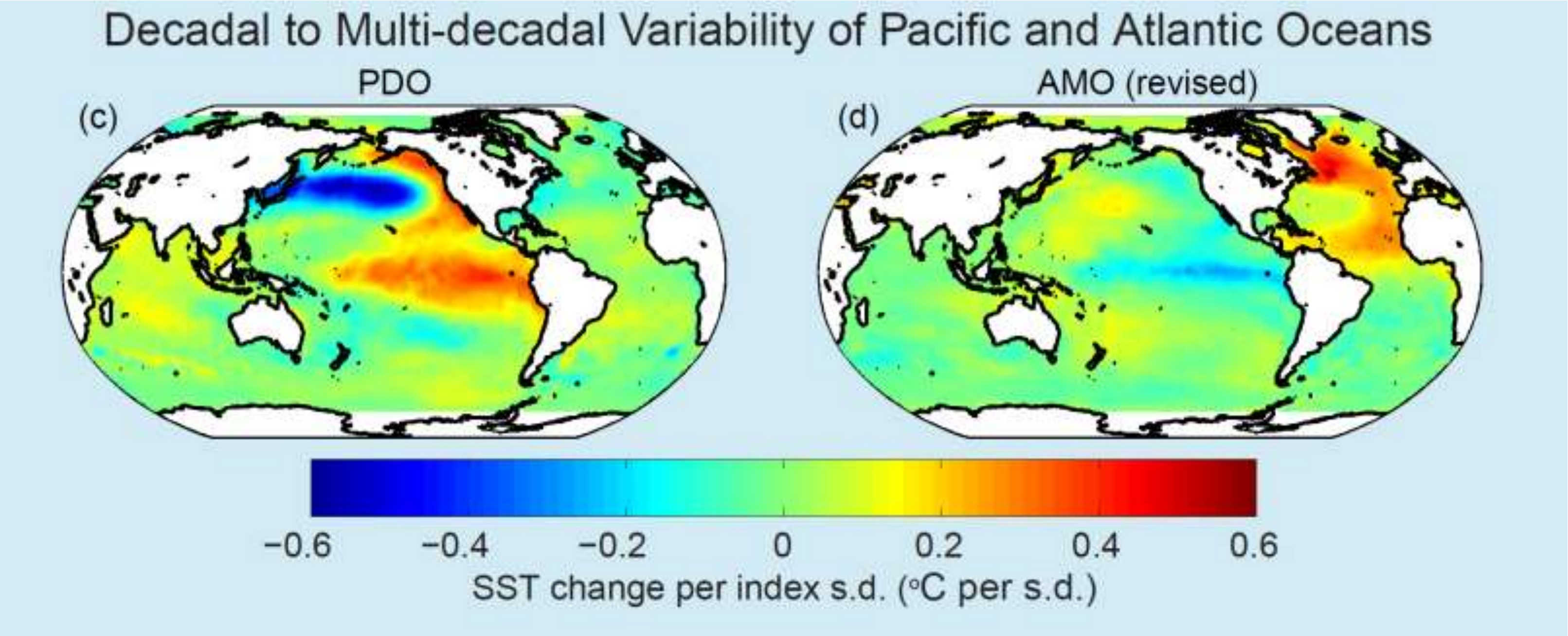
First, let's discuss in groups pro's and con's.

- **"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?

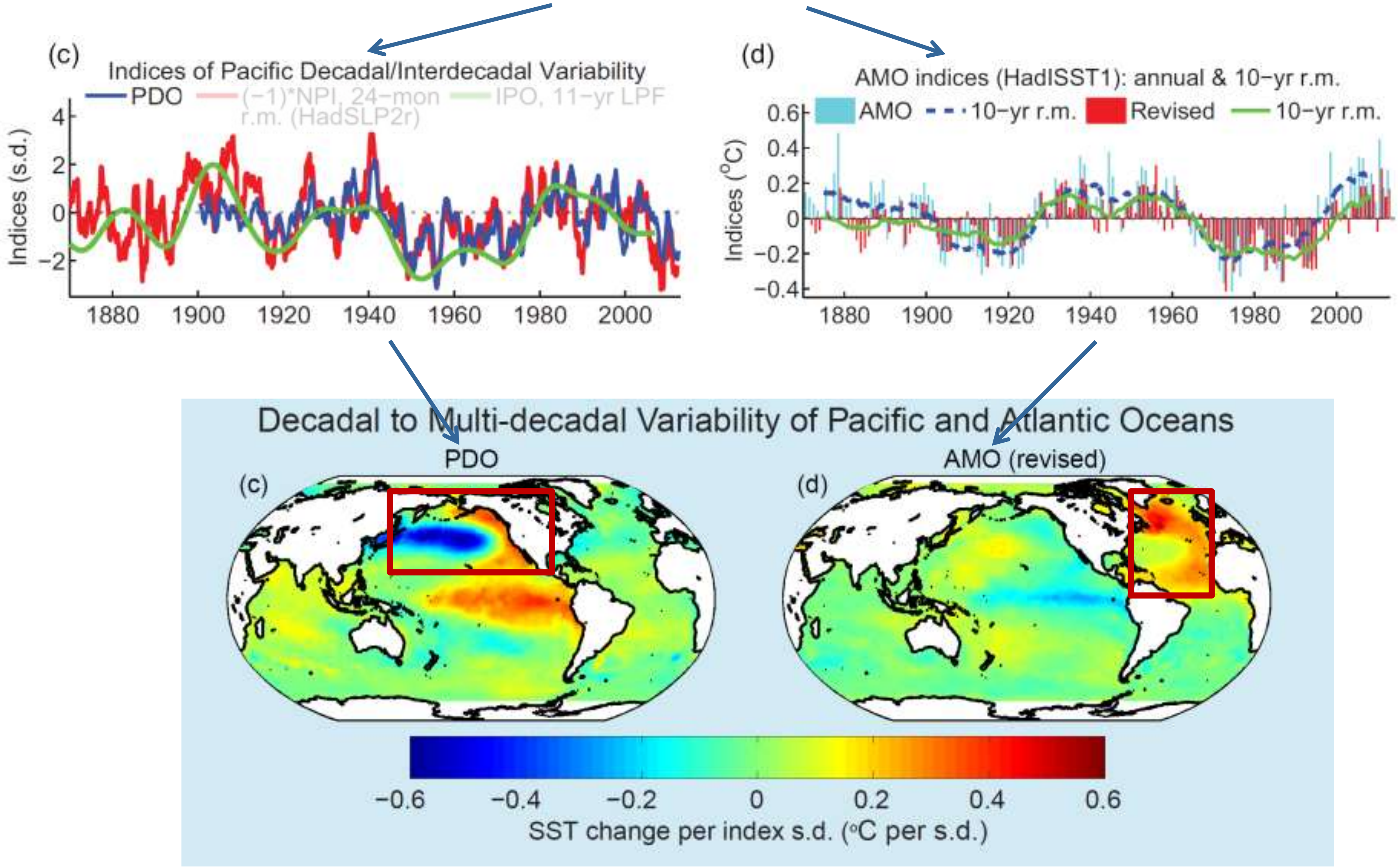


Box 2.5 - Patterns and Indices of Climate Variability – PDV (PDO) and AMV (AMO)



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.”

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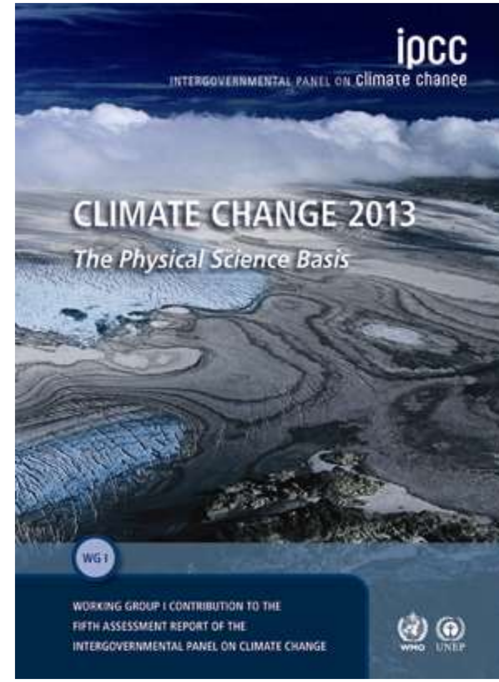

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3.3 Salinity and fresh water content

The ocean plays a pivotal role in the **global water cycle**: **~85%** of **evaporation** and **77%** of **precipitation** occurs **over** the **ocean**.

- **No robust trends** in regional **precipitation** and **evaporation over** the **ocean** are available yet →**surface ocean salinity**; ocean acts as a rain gauge.
- **Upper ocean salinity** distribution largely **reflects exchange** of **freshwater** (with high surface salinity generally found in regions where evaporation exceeds precipitation, and low salinity found in regions of excess precipitation and runoff).
- **Ocean circulation** also **affects** the regional distribution of **surface salinity**.
- The **subduction** of **surface waters transfers** the surface **salinity signal into** the **ocean** interior…
- Melting and freezing of ice (both **sea ice** and **glacial ice**) also **influence ocean salinity**.

→**Diagnosis and understanding of salinity changes, which affect ocean circulation and stratification**.

Salinity

- "'Salinity' refers to the weight of dissolved salts in a kilogram of seawater. Because the total amount of salt in the ocean does not change, the salinity of **seawater can be changed only by addition or removal of fresh water**. All salinity values quoted in the chapter are expressed on the Practical Salinity Scale 1978 (PSS78*) (Lewis and Fofonoff, 1979)."

*PSS-78: Practical Salinity Scale 1978 is based on an equation relating salinity to the ratio of the electrical conductivity of seawater at 15°C to that of a standard potassium chloride solution (KCl).

Salinity observations improvements since AR4

- In AR4, surface and subsurface salinity changes consistent with a warmer climate were highlighted…
- In the early few decades the **salinity data distribution was good in the NH**, but the **coverage was poor** in some regions such as the central **South Pacific, central Indian and polar oceans**.
- **Argo provides much more even spatial and temporal coverage in the 2000s**.

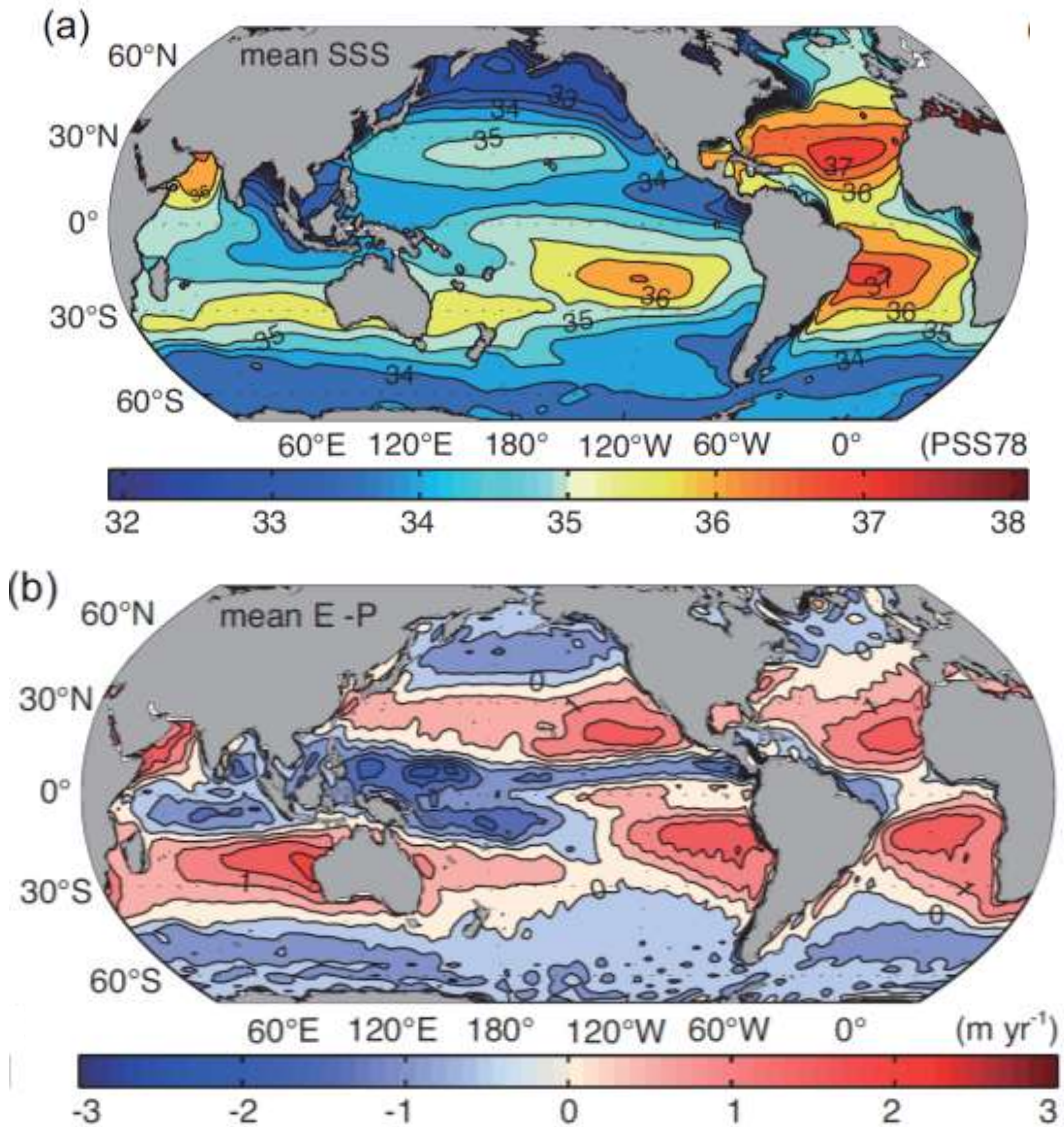
→**Additional observations**, **improvements** in the **availability** and **quality** of historical data and **new analysis approaches** now allow a **more complete AR5 assessment of changes in salinity**.

AR4/5: IPCC assessment report No. 4/5 published in 2007/2013.

Salinity and E-P Climatologies

Sea surface salinity (SSS) mean 1955-2005

Evaporation-Precipitation (E-P) 1950-2000



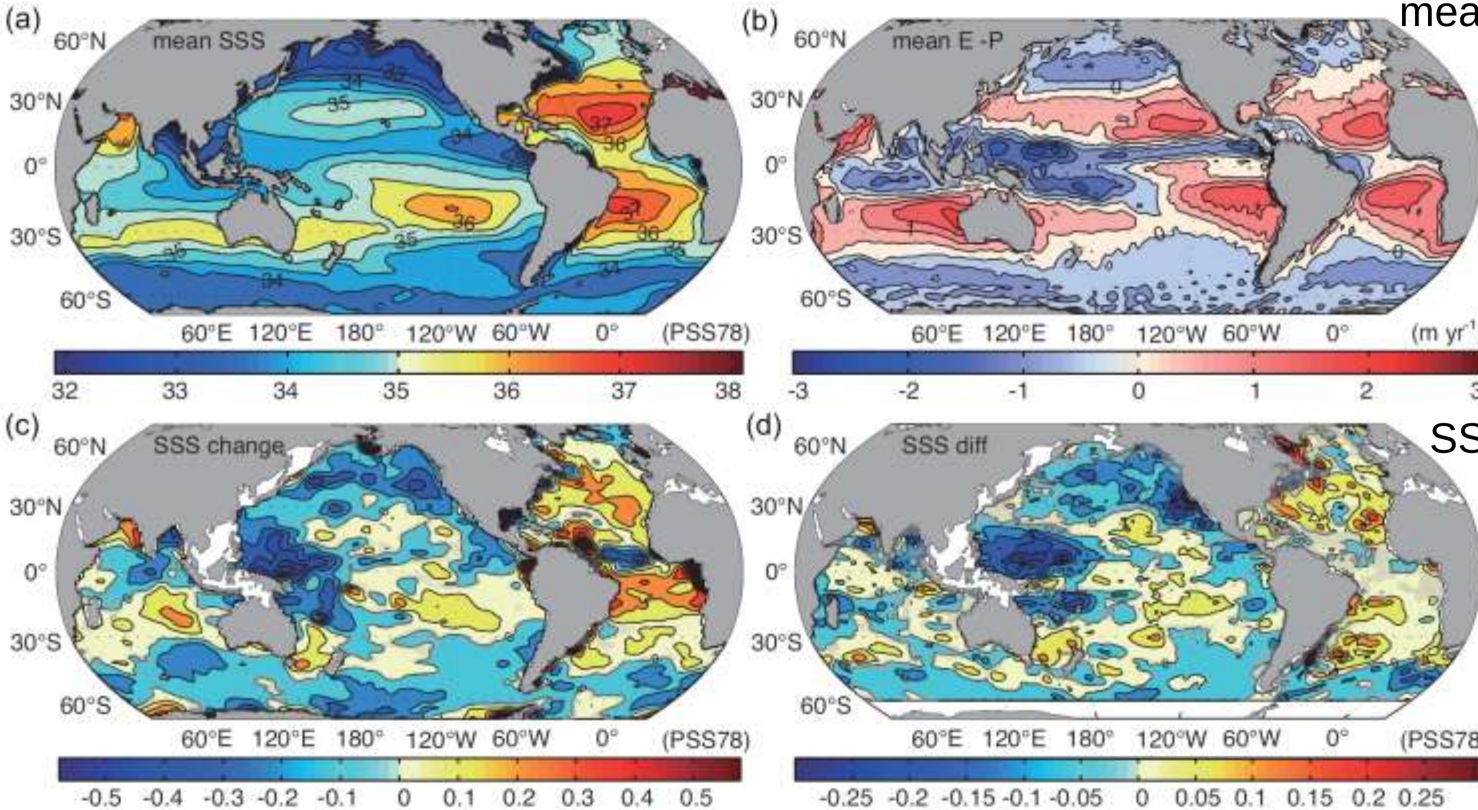
- Maxima in evaporation-dominated subtropical gyres.
- Minima at subpolar lat and ITCZ.
- Interbasin differences: Atlantic more saline, Pacific more fresh.

SSS: World Ocean Atlas (WOA) 1955-2005 data

Salinity and E-P Climatologies

SSS 1955-2005 mean

E-P 1950-2000 mean



SSS 58yr change: 2008-1950

SSS 30yr diff: 2005mean-1975mean

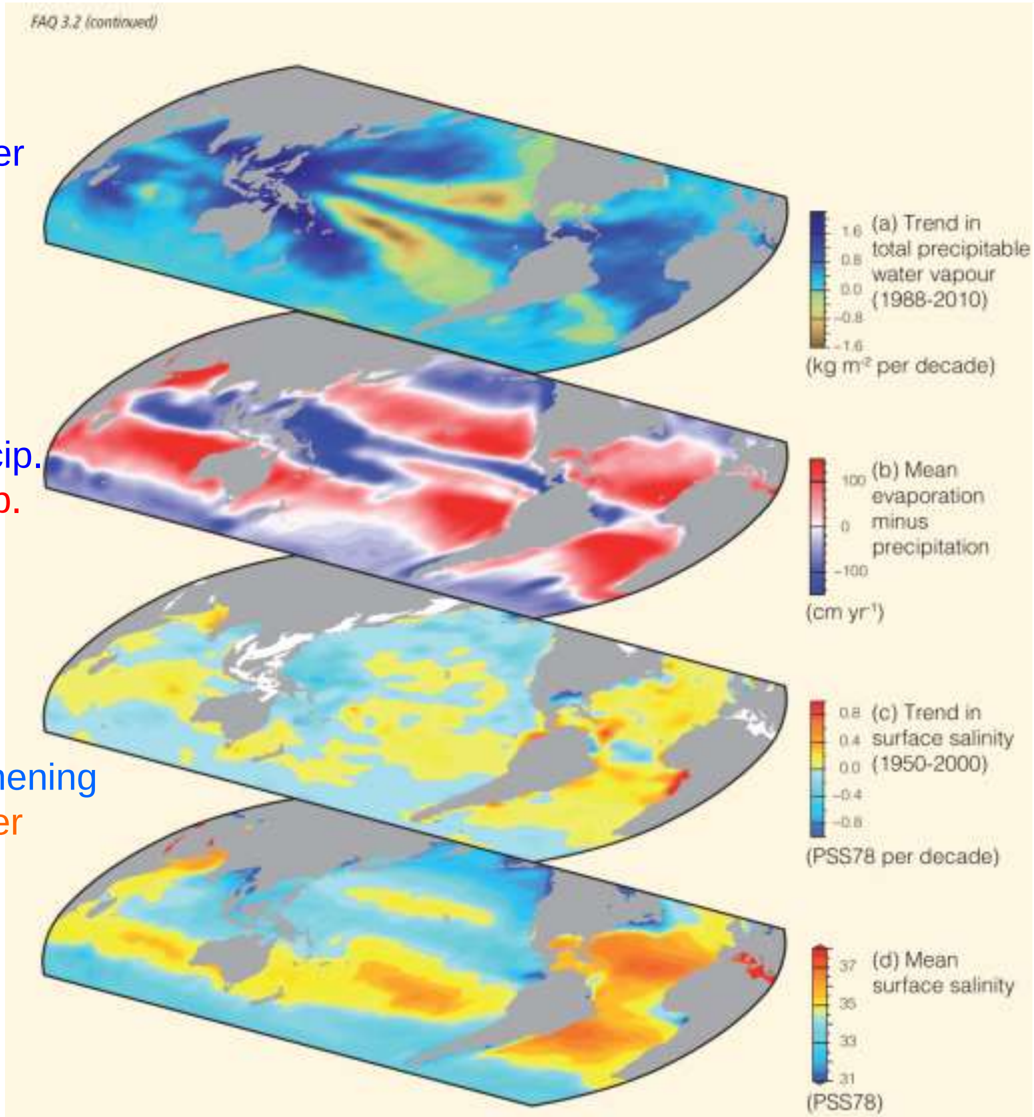
- Salinity tends to increase in regions of high mean salinity, where evaporation exceeds precipitation.
- Salinity tends to decrease in regions of low mean salinity, where precipitation dominates.

FAQ 3.2: Is There Evidence for Changes in the Earth's Water Cycle?

wetter
drier

Net
-precip.
-evap.

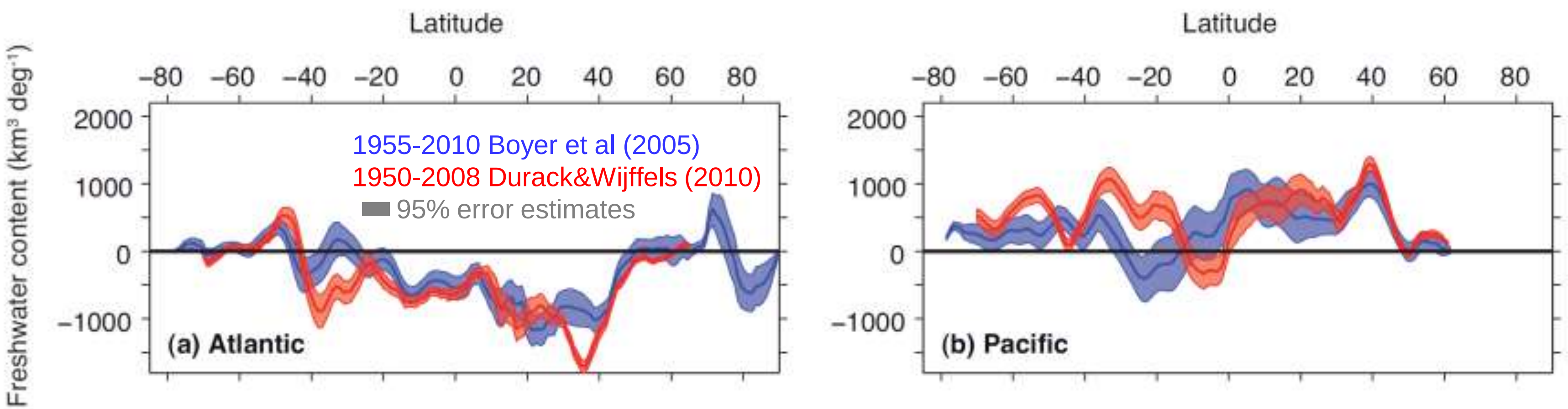
freshening
saltier



- Changes in the atmosphere's water vapour content provide **strong evidence that the water cycle is already responding to a warming climate**.
- Further evidence comes from **changes in** the distribution of **ocean salinity**,
- **Observations since** the **1970s** show **increases** in surface and lower atmospheric **water vapour** at a rate consistent with observed warming **(~7% H_2O increase /1 deg C**).
- Moreover, **evaporation and precipitation are projected to intensify in a warmer climate**.

Fresh water content changes (km^3/deg lat) and trend (PSS78/decade)

upper 500m, 1955-2010

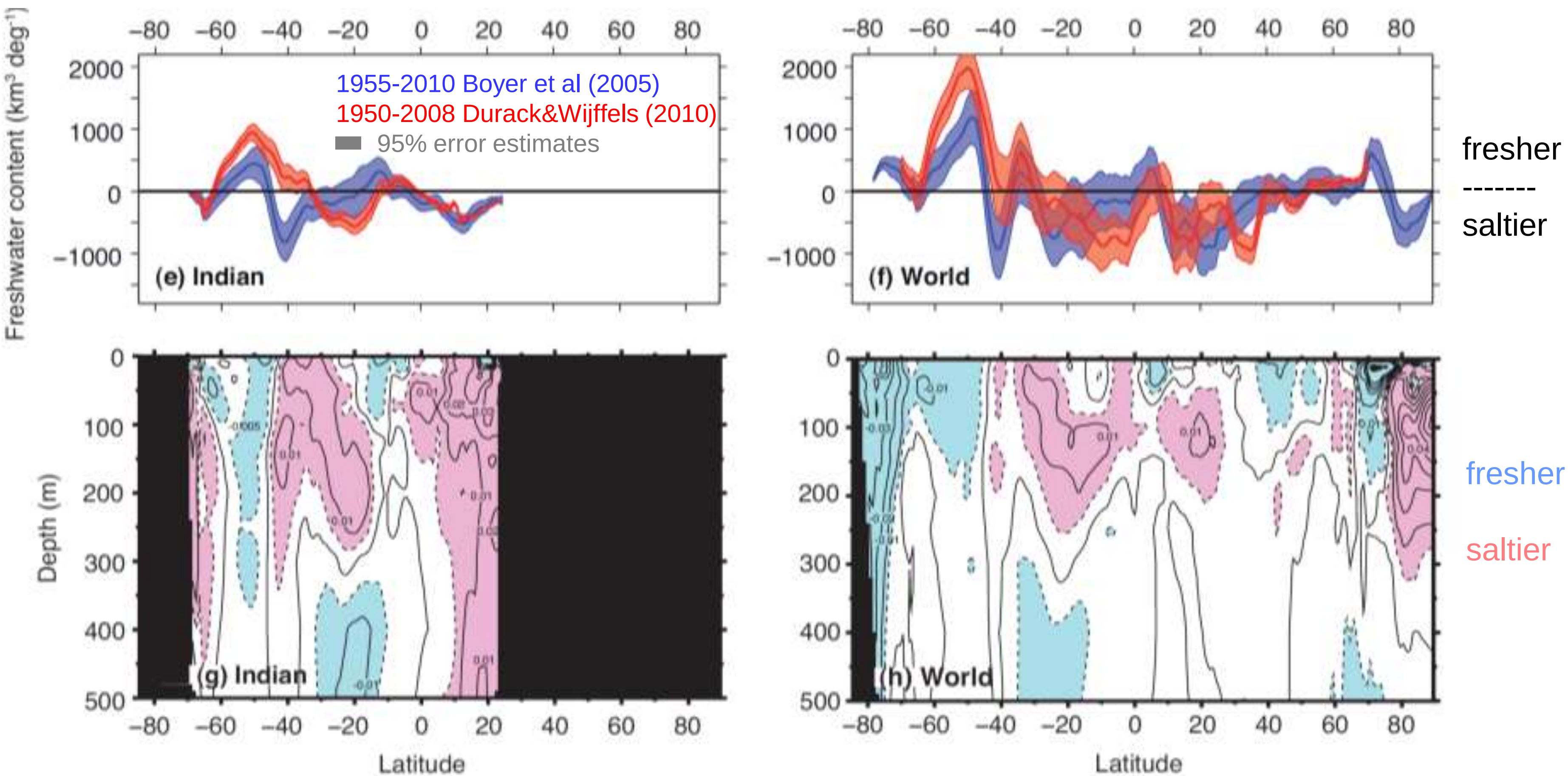


fresher
----
saltier

On average, the Pacific freshened, and the Atlantic became more saline since 1955, significant at 95% confidence interval.

Fresh water content changes (km^3/deg lat) and trend (PSS78/decade)

upper 500m, 1955-2010



Significant Southern Ocean freshening, which exceeds other regional trends and is present in each basin (Indian, Atlantic and Pacific).

3.3 Conlusions - Salinity and Freshwater Content Changes

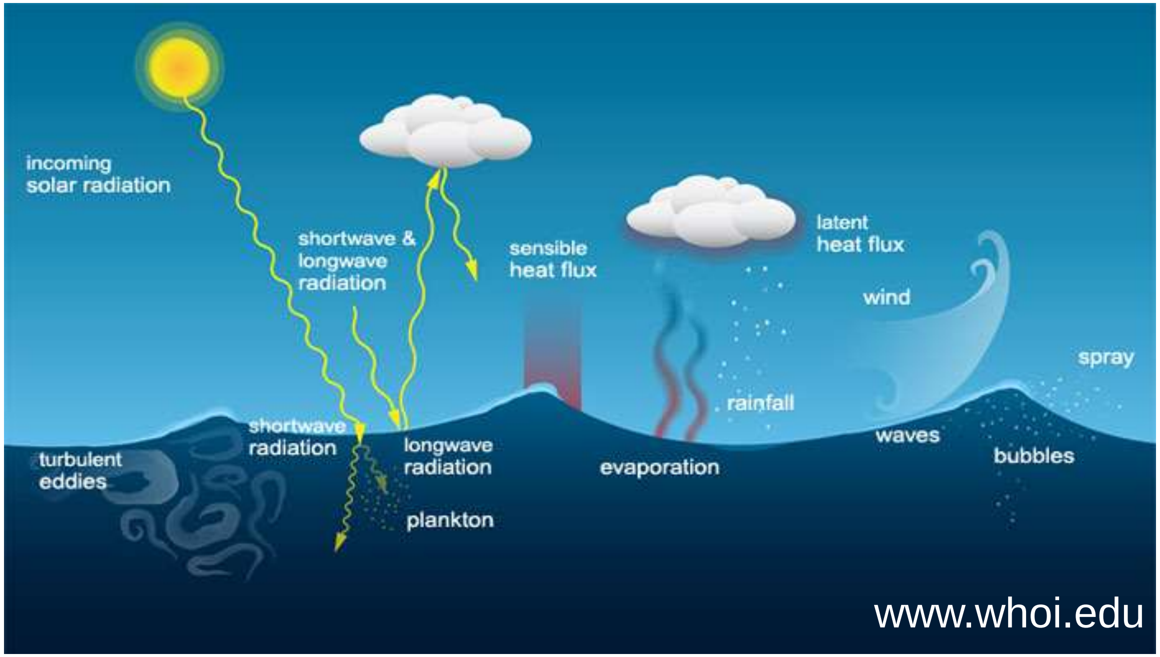
- “Both **positive** and **negative trends** in **ocean salinity** and **freshwater content** have been **observed** throughout much of the ocean …
- …**high confidence** in the assessment of trends in **ocean salinity**…
- It is **very likely** that **regional trends have enhanced** the mean geographical contrasts in sea surface salinity **since** the **1950s**: **saline surface waters** in the **evaporation-dominated *mid-latitudes*** have become **more saline**, while relatively **fresh surface waters** in **rainfall-dominated tropical** and **polar regions** have become **fresher**.

Here, I would rather call this «subtropics» than mid-latitudes.

- It is **very likely** that large-scale trends in **salinity** have also occurred in the **ocean interior**.
- The spatial patterns of the salinity trends, mean salinity and the mean distribution of E – P are all similar.”

3.4 Ocean surface fluxes

Relevance of ocean surface fluxes:



- **“Exchanges of heat, water and momentum (wind stress) at the sea surface are important factors for driving the ocean circulation.**
- Changes in the air–sea fluxes may result from variations in the driving surface meteorological state variables (air temperature and humidity, SST, wind speed, cloud cover, precipitation) and can impact both water-mass formation rates and ocean circulation.
- Air–sea fluxes also influence temperature and humidity in the atmosphere and, therefore, the hydrological cycle and atmospheric circulation.
- The **net air–sea heat flux** is the **sum** of two turbulent (**latent and sensible**) and two radiative (**shortwave and longwave**) components.”

Ocean surface fluxes - improvements since AR4

- “AR4 concluded that, at the global scale, the accuracy of the observations is **insufficient** to permit a direct **assessment** of **changes** in **heat flux**...

- …although **substantial progress** has been made since AR4, that **conclusion still holds** for this assessment.”

How to derive?

- “The **latent and sensible heat fluxes are computed** from the state variables using bulk parameterizations; they depend primarily on the products of wind speed and the vertical near-sea-surface gradients of humidity and temperature respectively.
- The **air–sea freshwater flux is the difference of precipitation (P) and evaporation (E)**. It is linked to heat flux through the relationship between evaporation and latent heat flux.
- **Ocean surface shortwave and longwave radiative fluxes** can be **inferred from satellite** measurements using radiative transfer models, or **computed using empirical formulae**, involving astronomical parameters, atmospheric humidity, cloud cover and SST.
- The **wind stress** is given by the product of the wind speed squared, and the drag coefficient.”

Box 2.3 – Global Atmospheric Reanalyses

Institution	Reanalysis	Period	Approximate Resolution at Equator	Reference
Cooperative Institute for Research in Environmental Sciences (CIRES), National Oceanic and Atmospheric Administration (NOAA), USA	20th Century Reanalysis, Vers. 2 (20CR)	1871–2010	320 km	Compo et al. (2011)
National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR), USA	NCEP/NCAR R1 (NNR)	1948–	320 km	Kistler et al. (2001)
European Centre for Medium-Range Weather Forecasts (ECMWF)	ERA-40	1957–2002	125 km	Uppala et al. (2005)
Japan Meteorological Agency (JMA)	JRA-55	1958–	60 km	Ebita et al. (2011)
National Centers for Environmental Prediction (NCEP), US Department of Energy, USA	NCEP/DOE R2	1979–	320 km	Kanamitsu et al. (2002)
Japan Meteorological Agency (JMA)	JRA-25	1979–	190 km	Onogi et al. (2007)
National Aeronautics and Space Administration (NASA), USA	MERRA	1979–	75 km	Rienecker et al. (2011)
European Centre for Medium-Range Weather Forecasts (ECMWF)	ERA-Interim	1979–	80 km	Dee et al. (2011b)
National Centers for Environmental Prediction (NCEP), USA	CFSR	1979–	50 km	Saha et al. (2010)

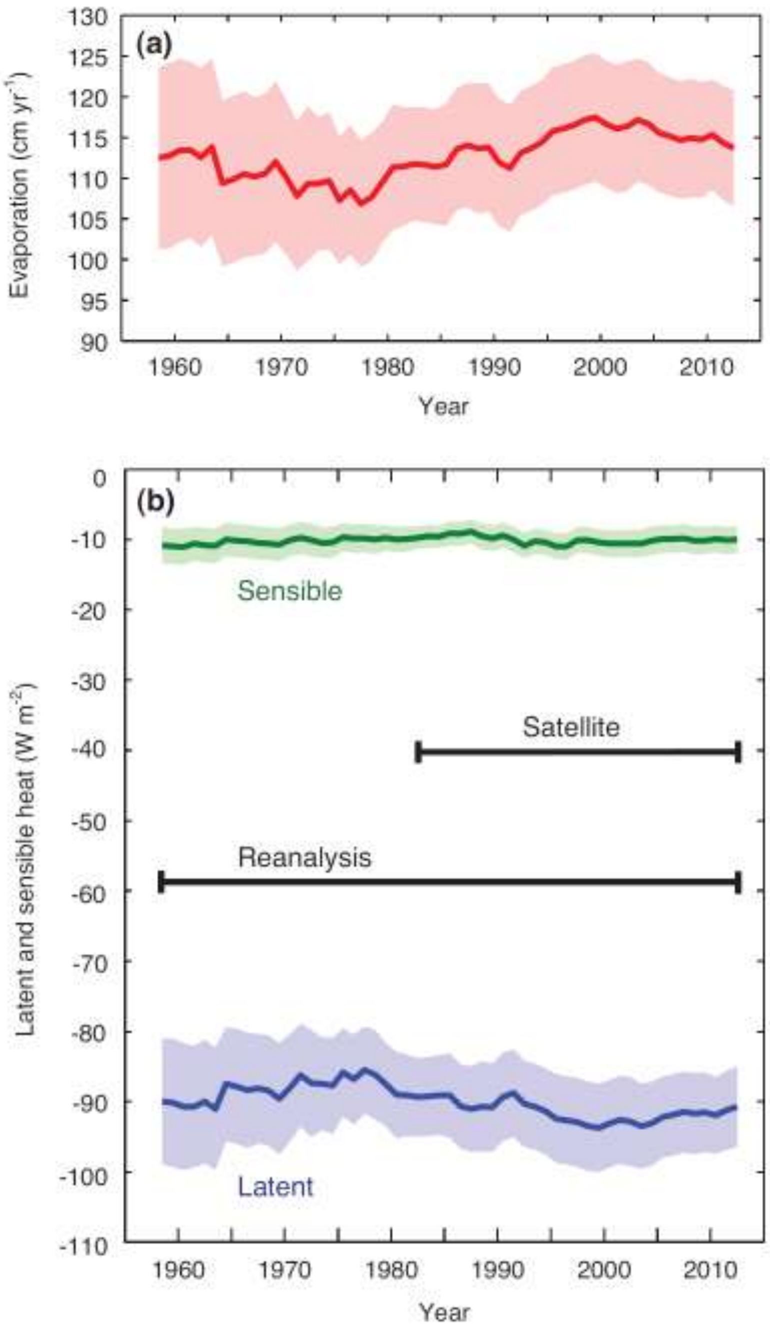
- MERRA and ERA-Interim reanalyses show improved tropical precipitation and hence better represent the global hydrological cycle (Dee et al., 2011b).
- The NCEP/CFSR reanalysis uses a coupled ocean–atmosphere–land-sea–ice model (Saha et al., 2010).
- 20CR (Compo et al., 2011) is a 56-member ensemble and covers 140 years by assimilating only surface and sea level pressure (SLP) information.

Atmospheric Reanalyses - Abbreviations

- **ERA40**: ECMWF 40-year Reanalysis (Uppala et al., 2005)
- **ERAI**: ECMWF Interim Reanalysis (Dee et al., 2011)

NCEP/NCAR: National Centers for Environmental Prediction/ National Center for Atmospheric Research:

- **NCEP1** (or NNR): NCEP/NCAR Reanalysis 1 (Kalnay et al., 1996)
- **NCEP2**: NCEP/DOE Reanalysis 2 (Kanamitsu et al., 2002)
- **CFSR**: NCEP Climate Forecast System Reanalysis (Saha et al., 2010)
- **MERRA**: Modern Era Reanalysis for Research and Applications from NASA(Rienecker et al., 2011)
- **20CRv2**: 20th Century Reanalysis, version 2 from NOAA-CIRES (Compo et al., 2011).

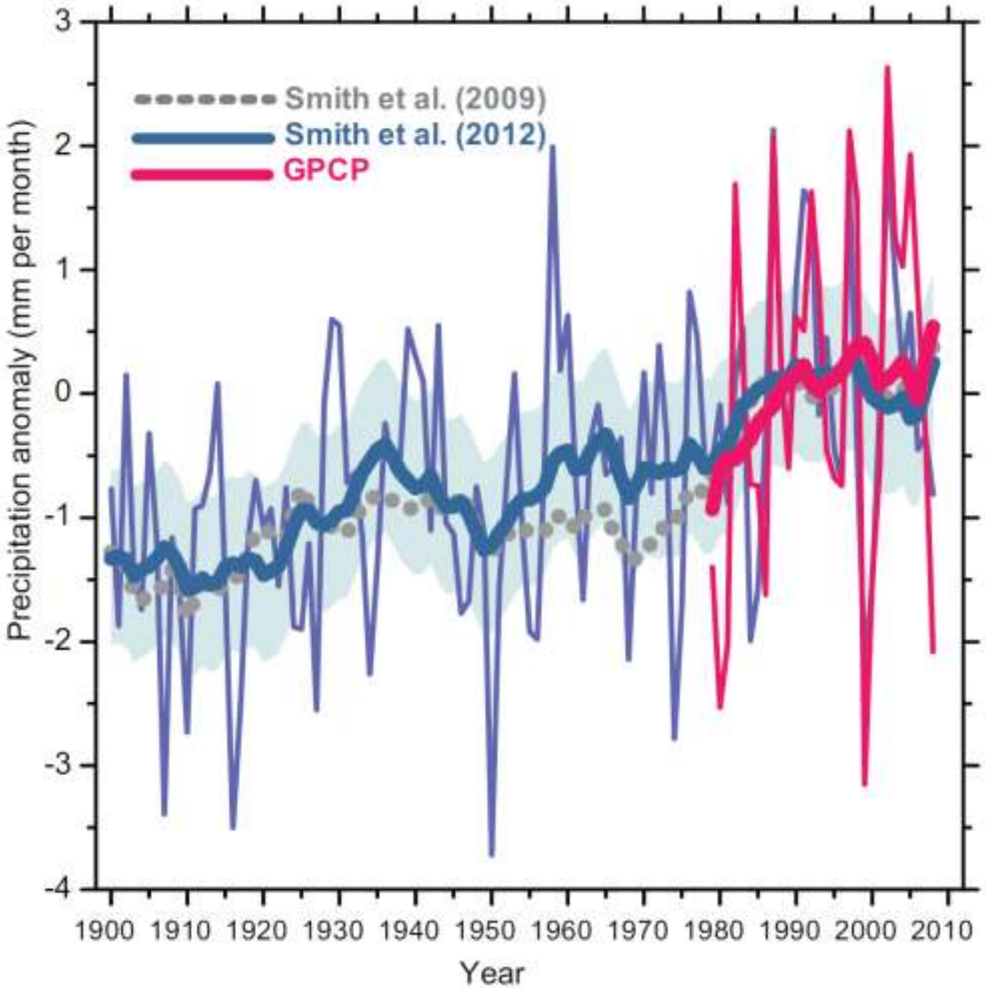


Ocean evaporation and surface fluxes

- “Analysis of OAFlux suggests that global mean evaporation may vary at inter-decadal time scales, with the variability being relatively small compared to the mean (Fig. a).
- Changing data sources …may contribute to this variability …
- The latent heat flux variations (Fig. b) closely follow those in evaporation (negative values of latent heat flux corresponding to positive values of evaporation).”

OAFlux: Objectively Analysed Air–Sea heat flux data

Precipitation anomaly wrt 1979-2008



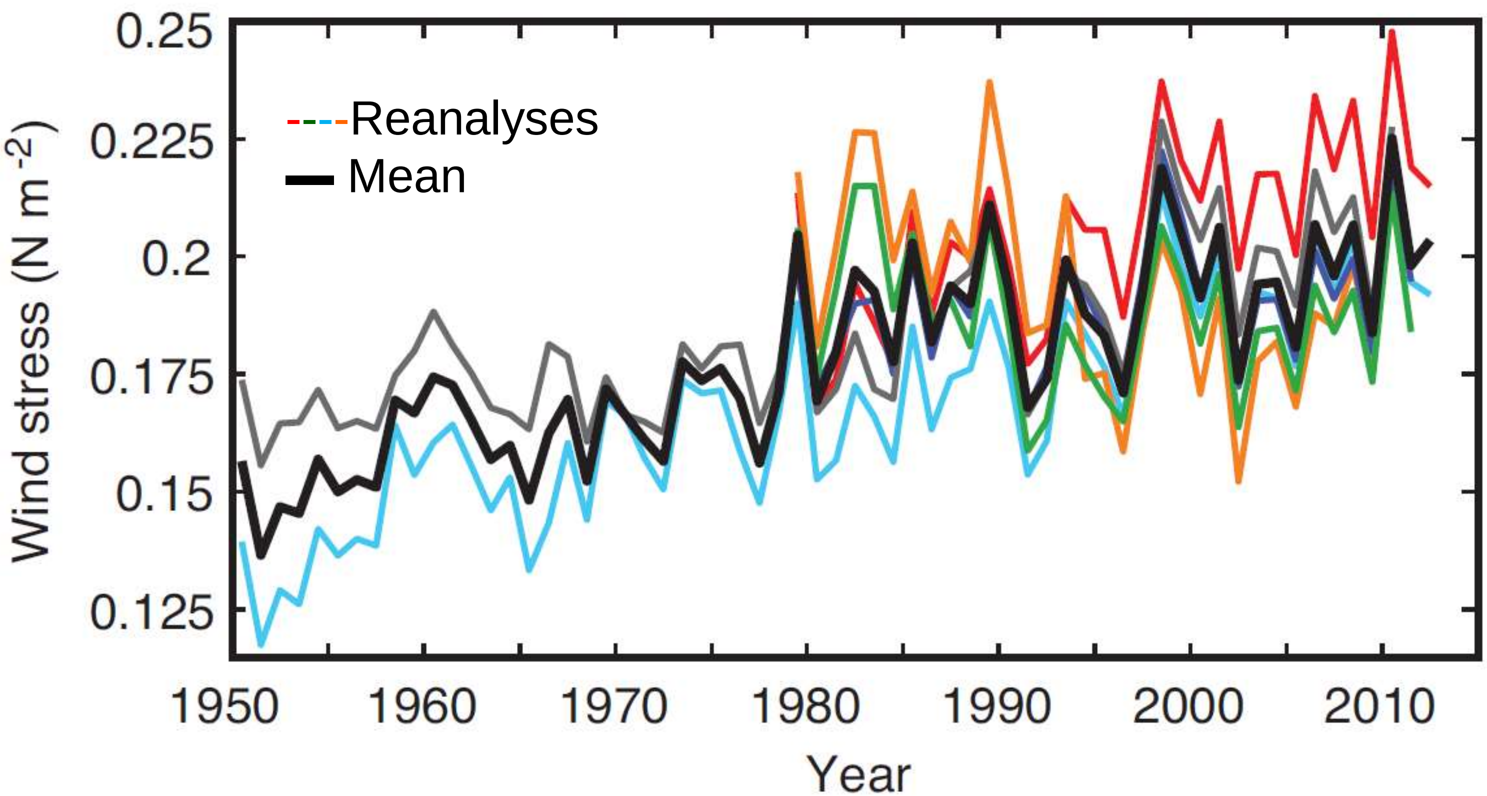
- Centennial and decadal variability in global ocean mean precipitation.
- Trend from 1900 to 2008 is 1.5 mm/month/century.
- Reconstructed global ocean mean precipitation time series show consistent variability with GPCP as is to be expected.
- Tropical Ocean (25°S to 25°N) 1979–2005 have a precipitation trend of 0.06 mm/day/decade (GPCP data; Gu et al., 2007).

→**Confidence in ocean precip. trend results is low**.

GPCP: Global Precipitation Climatology Project, Remote sensing based precipitation observations
Smith et al (2009/ 2012): used GPCP (1979-2003) to reconstruct precipitation for 1900–2008 (75°S to 75°N) by employing statistical techniques using correlation between precipitation and both SST and SLP.

$\tau_{wind} = \rho_{air} C_D U_h^2,$

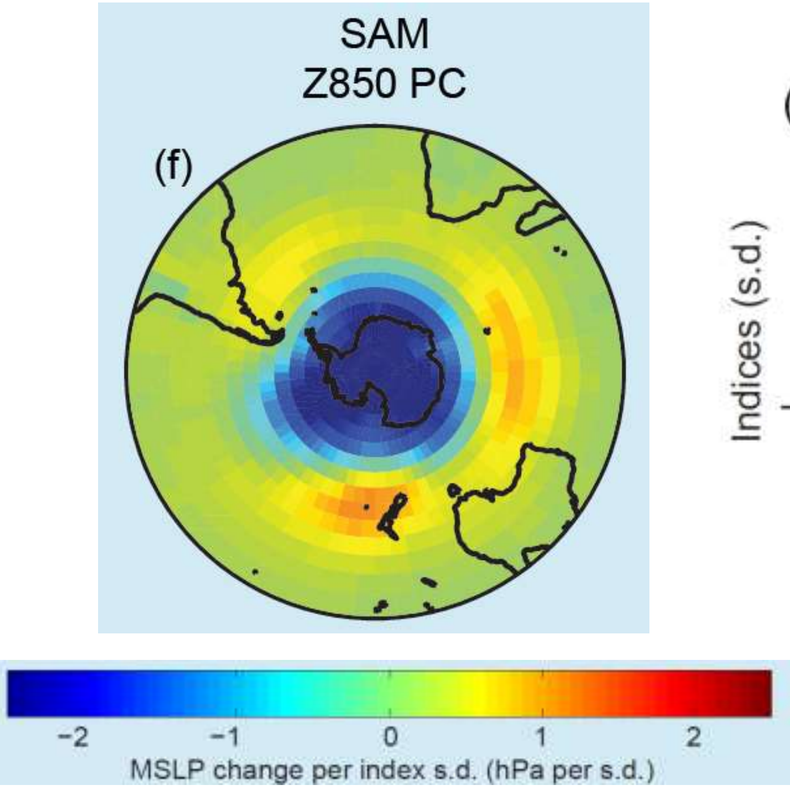
Zonal wind stress: Southern Ocean (SO)

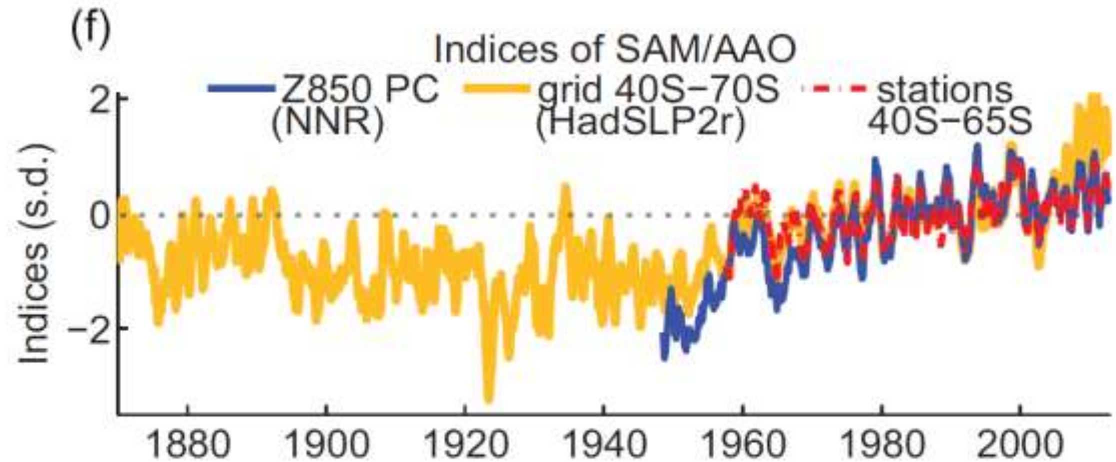


- Increase in the annual mean zonal wind stress;
- Upward trend from 0.15 N m^{-2} in early 1950s to 0.20 N m^{-2} in early 2010s.
- Wind stress strengthening has a seasonal dependence, with strongest trends in January, linked to changes (upward trend) in the Southern Annular Mode (SAM).

→**Medium confidence that SO wind stress has strengthened since 1980s.**

Box 2.5 - Southern Annular Mode (SAM)





Southern Annular Mode (SAM)	PC-based SAM or Antarctic Oscillation (AAO) index	1st PC of $Z850_a$ or $Z700_a$ south of 20°S	Thompson and Wallace (2000)
	Grid-based SAM index: 40°S–70°S difference	Difference between standardized zonally averaged SLP_a at 40°S and 70°S, using gridded SLP fields	Nan and Li (2003)
	Station-based SAM index: 40°S–65°S	Difference in standardized zonal mean SLP_a at 40°S and 65°S, using station data	Marshall (2003)

HadSLP2r: data interpolated gridded products based on data historical observations
PC: Principle Component analyses; Sub-script “a” stands for anomalies

3.4 Conclusions - Air–Sea Flux

- “**Uncertainties in air–sea heat flux data** sets are **too large to allow detection** of the change in global mean net air-sea heat flux, of the order of 0.5 W m^{-2} since 1971, required for consistency with the observed ocean heat content increase.

- Basin-scale **wind stress trends** at **decadal to centennial** time scales have been observed in the North Atlantic, Tropical Pacific and Southern Ocean with **low to medium confidence**.”

3.6 Changes in Ocean circulation

Present-day global ocean observations of velocity:

- **sea surface** by **Global Drifter Program** (Dohan et al., 2010)
- **at 1000 m depth** by **Argo** Program (Freeland et al., 2010). In addition, Argo observes the geostrophic shear between 2000 m and the sea surface.
- **Historic**ally, global measurements of ocean circulation are much **sparse**r, so estimates of decadal and longer-term changes in circulation are very limited.
- Since 1992, **high-precision satellite altimetry** has measured the time variations in sea surface height (SSH), whose horizontal gradients are proportional to the surface geostrophic velocity.
- In addition, a single **global top-to-bottom hydrographic survey** was carried out by the World Ocean Circulation Experiment (WOCE, ~1991–1997), measuring geostrophic shear as well as velocity from mid-depth floats and from lowered acoustic Doppler current profilers. A subset of WOCE and pre-WOCE transects is being repeated at 5- to 10-year intervals (Hood et al., 2010).

Changes in Ocean Circulations in AR5

“**An assessment is now possible of the recent mean and the changes in global geostrophic circulation** over the previous decade.

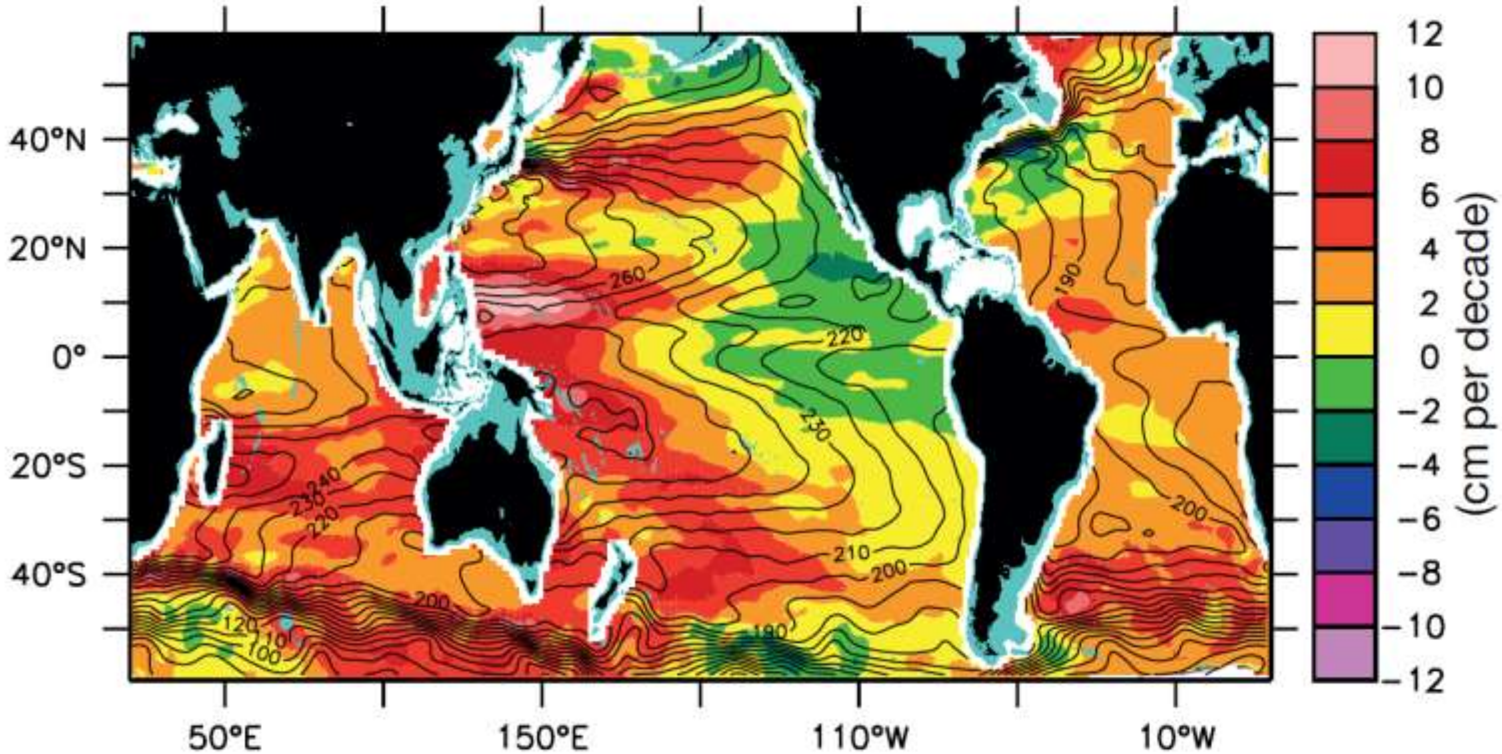
In general, **changes in the slope of Sea Surface Height** (SSH) across ocean basins indicate changes in the major gyres and the interior component of MOCs.

Changes occurring in high gradient regions such as the Antarctic Circumpolar Current (ACC) may indicate shifts in the location of those currents.

In the following, the **best-studied a**nd **most significant aspects** of **circulation variability** and **change** are assessed including wind-driven circulation in the Pacific, the Atlantic and Antarctic MOCs, and selected interbasin exchanges.”

Geostrophic flow: mean and changes

Sea surface height trend: 1993-2011, AVISO altimetry

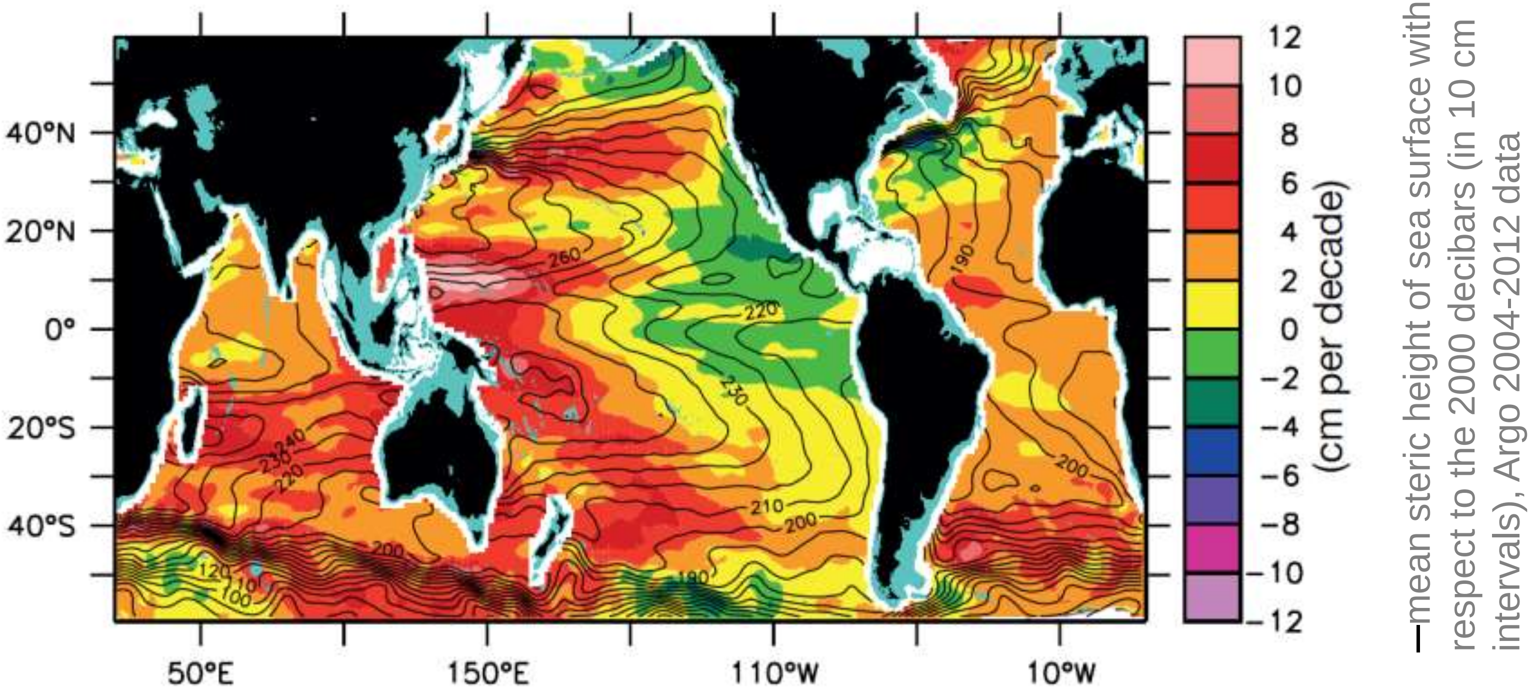


—mean steric height of sea surface with respect to the 2000 decibars (in 10 cm intervals), Argo 2004-2012 data

- Pattern of geostrophic flow (horizontal gradients of SSH proportional to surface geostrophic velocity);
- changes in surface geostrophic velocity proportional to spatial gradients in SSH trend divided by *f.*
- The term "steric" refers to global changes in sea level due to thermal expansion and salinity variations.

Geostrophic flow: mean and changes

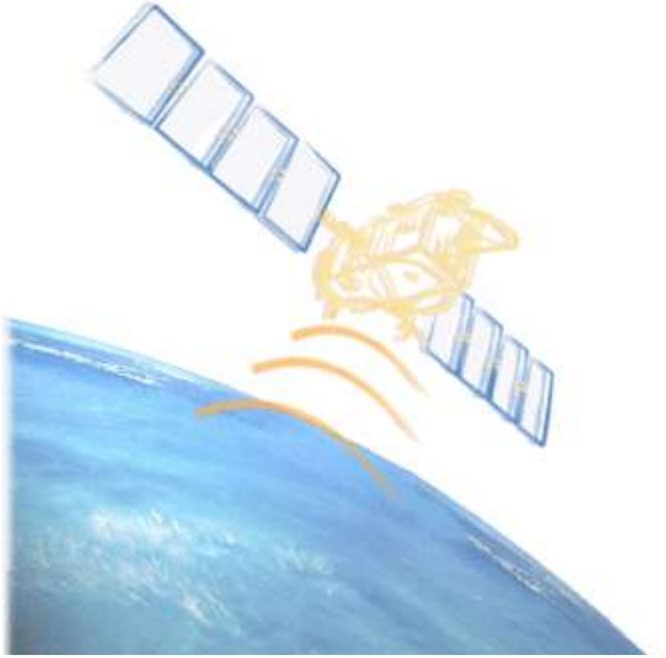
Sea surface height trend: 1993-2011, AVISO altimetry



"Changes in Pacific Ocean circulation since 1993 (medium to high confidence):

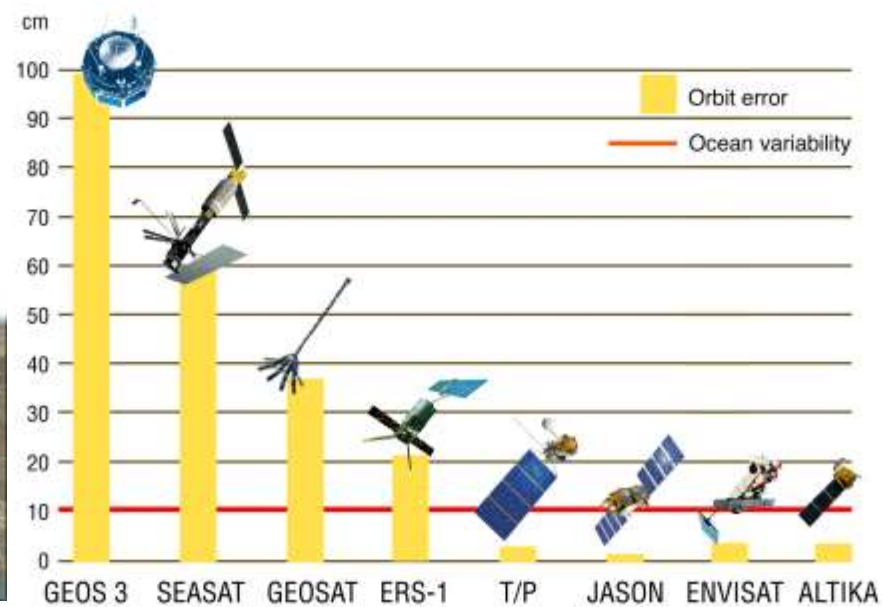
- intensification of North Pacific subpolar gyre, South Pacific subtropical gyre,…
- expansion of North Pacific sub-tropical gyre,
- southward shift of the ACC.

It is likely that these wind-driven changes are predominantly due to interannual-to-decadal variability…"



AVISO data:

Altimetry is a technique for measuring height. **Satellite altimetry measures the time taken by a radar pulse to travel from the satellite antenna to the surface and back to the satellite receiver.** Combined with precise satellite location data, altimetry measurements yield sea-surface heights.

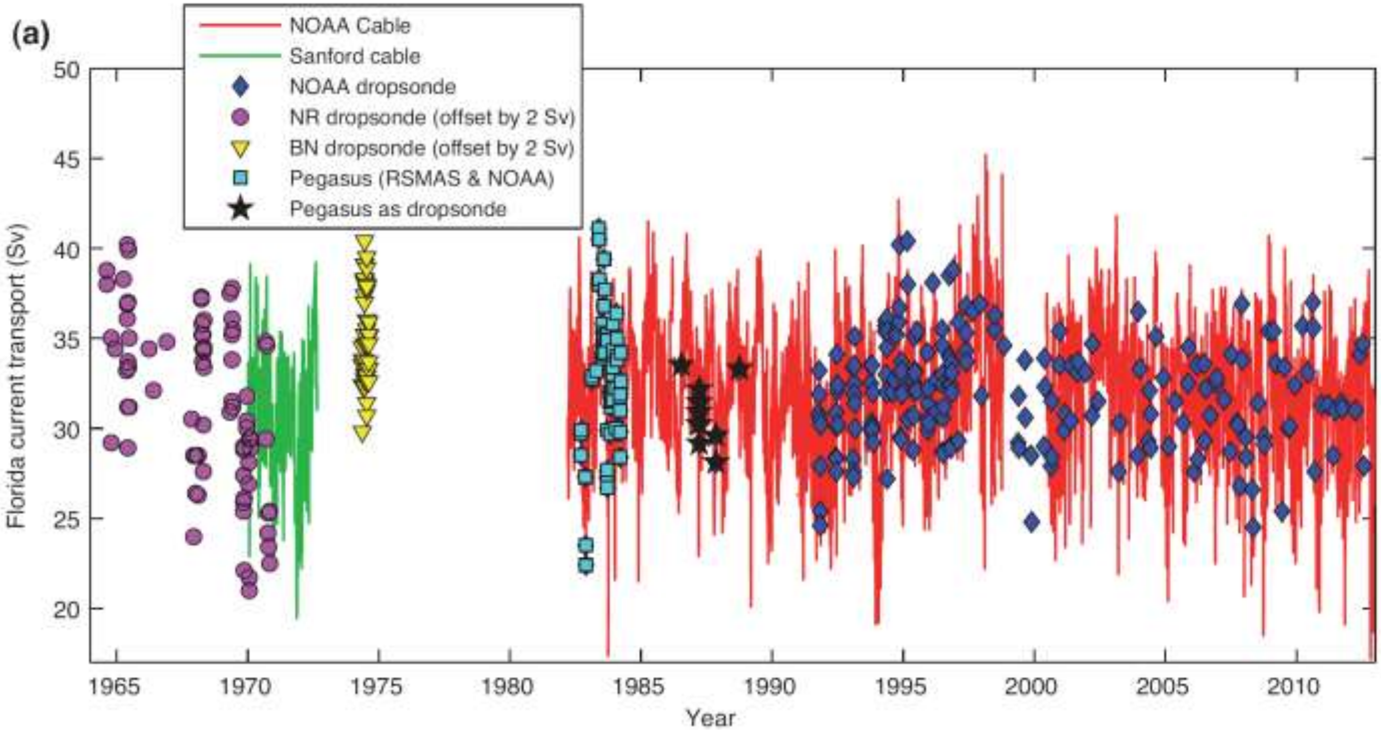


www.aviso.altimetry.fr

AVISO: Archiving, Validation and Interpretation of Satellite Oceanographic *data*

Improvements in measurement accuracy since the first *satellite altimetry* missions has enabled us to observe ocean variations at close quarters since 1992.

Ocean current: Florida current transport (SV)

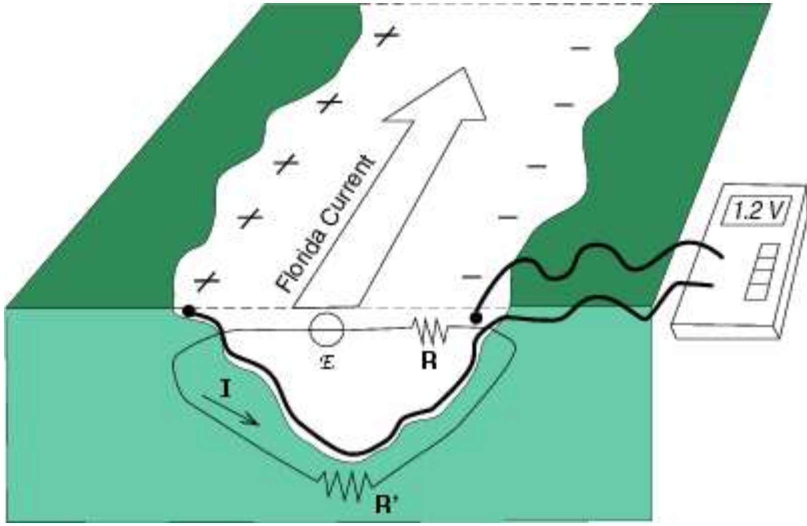


The longest time series of observations of ocean transport in the world (dropsonde and cable voltage measurements in the Florida Straits) from mid-1960s present (Meinen et al., 2010):

- small decadal variability of about 1 Sv,
- no evidence of a multi-decadal trend.

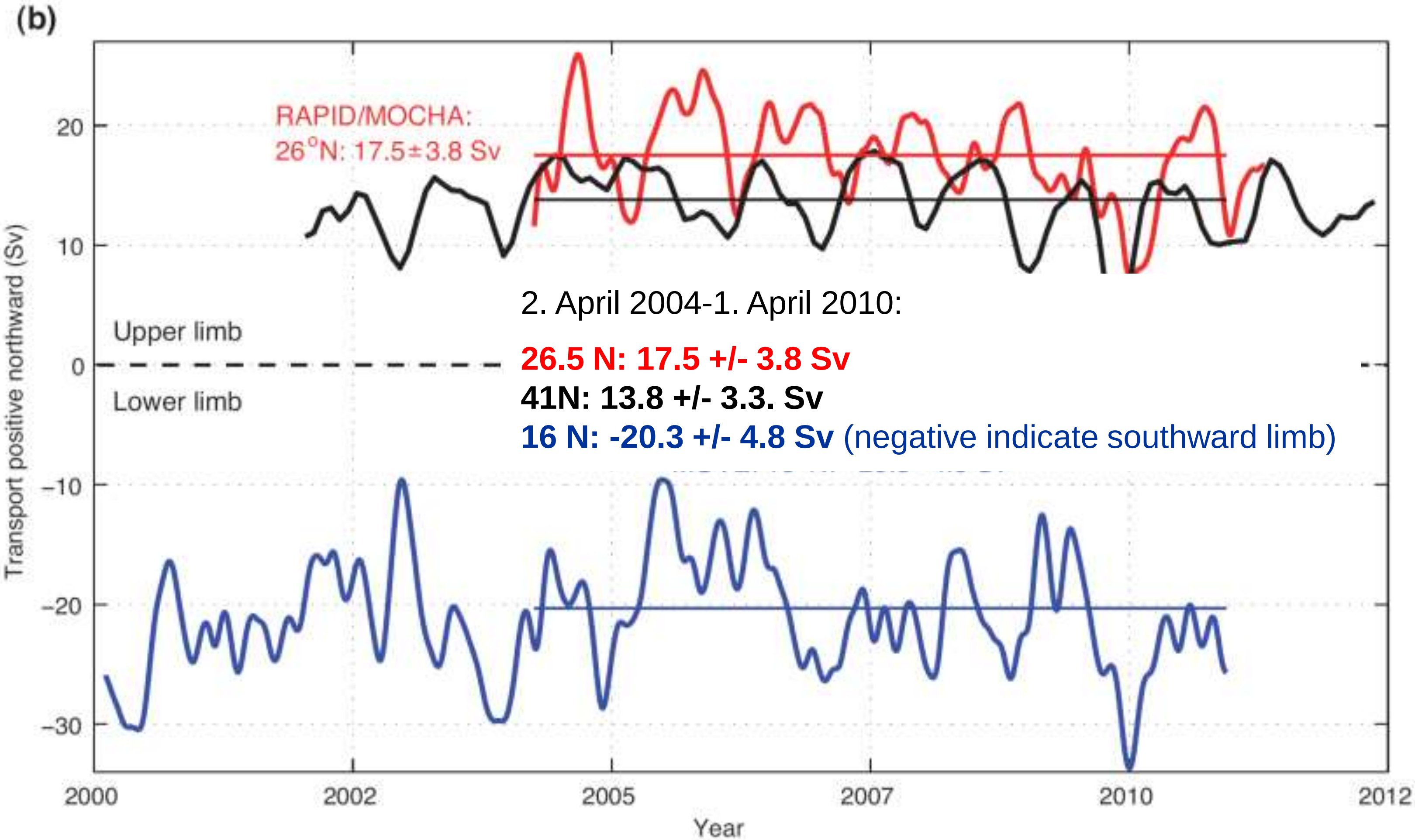
Sverdrup (Sv): unit of measure of volume transport; 1 Sv = 10^6 m^3/s.

Basics of cable physics



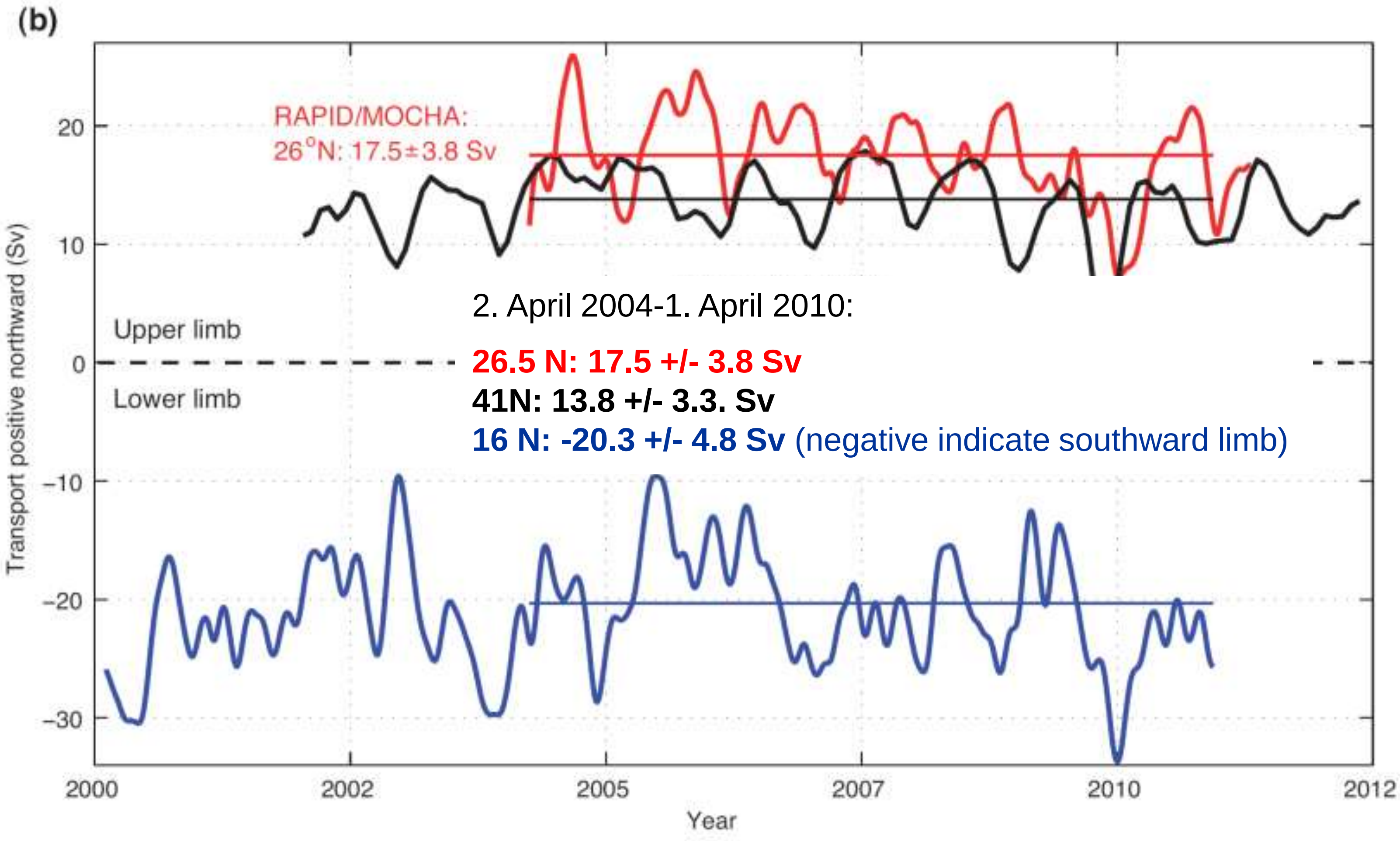
- When electrically charged particles move through a magnetic field an electrical field is developed that is perpendicular to the movement of the particles. This has been known since the pioneering experiments of James Maxwell in the mid-1800s. The same physics dictate that when **ions in seawater are advected by ocean currents through the magnetic field of the Earth**, an electric field is produced perpendicular to the direction of the water motion. Because seawater is a conductive media, these electric fields "short-out" in the vertical, yielding a single electric field corresponding to the vertically averaged horizontal flow (with a minor vertical weighting effect due to small conductivity changes at different depths). Submarine cables provide a means for measuring these "motionally-induced" voltages in the ocean. Using the voltages induced on the cables, the full-water-column transports across the cable can be estimated.

Atlantic Meridional Overturning Circulation: AMOC transport estimates



RAPID/MOCHA: Rapid Climate Change programme/ Meridional Ocean Circulation and Heatfllux Array
MOVE: Meridional Overturning Variability Experiment at 16 N between Caribbean and mid-Atlantic Ridge

Atlantic Meridional Overturning Circulation: AMOC transport estimates



- AMOC weakening in 2009/2010 was large; subsequently rebounded,
- large year-to-year changes,
- no trend is detected.

3.6 Conclusions: Changes in Ocean Circulation

- Recent observations have **strengthened evidence** for **variability** in major ocean circulation systems on time scales from **years** to **decades.**
- It is **very likely** that the **subtropical gyres** in the **North Pacific and South Pacific** have **expanded** and **strengthened since 1993**. It is about as likely as not that this is linked to decadal variability in wind forcing rather than being part of a longer-term trend.
- Based on measurements of the full **Atlantic Meridional Overturning Circulation** and its individual components at various latitudes and different time periods, there is **no evidence of a long-term trend.**
- There is also **no evidence for trends** in the **transports of** the Indonesian Throughflow, the Antarctic Circumpolar Current (ACC), or between the Atlantic Ocean and Nordic Seas.
- However, there is **medium confidence** that the **ACC shifted south between 1950** and **2010**, at a rate equivalent to about **1°** of **latitude** in **40 years**.

GEF4400 “The Earth System”

Prof. Dr. Jon Egill Kristjansson,

Prof. Dr. Kirstin Krüger (UiO)

- **Lecture/ interactive seminar/ field excursion**
  Teaching language: English
  Time and location: see next slide,
  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 course.

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 -

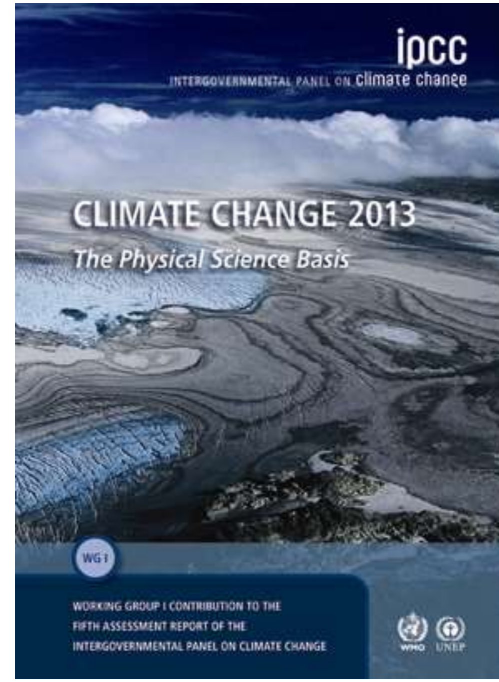
Mo. 02.11.15: 10:00-12:30, Wed 04.11.15 10:15-12:00

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

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.

3.7 Sea level change

Sea level varies:

- as **ocean warms** or **cools**
- as **water** is **transferred** between the **ocean** and **continents**, between the **ocean** and **ice sheets**,
- as **water** is **redistributed** within the ocean due to **tides** and **changes** in **oceanic** and **atmospheric circulation**,
- on **time scales** from **hours** to **centuries,**
- **spatial scales** from **<1 km** to **global**,
- **height changes** from **mm** to **m** or more (**due** to **tides**).

Measurements of sea level are the **longest-running ocean observation** system.

3.7 assesses interannual and longer **variations in non-tidal sea level** from the instrumented period (late 18th century to the present).

Sea level measurements

Tide gauges measurements since 1700s:

- Amsterdam from 1700 and 3 sites in Northern Europe after 1770,
- are limited to coastlines and islands.

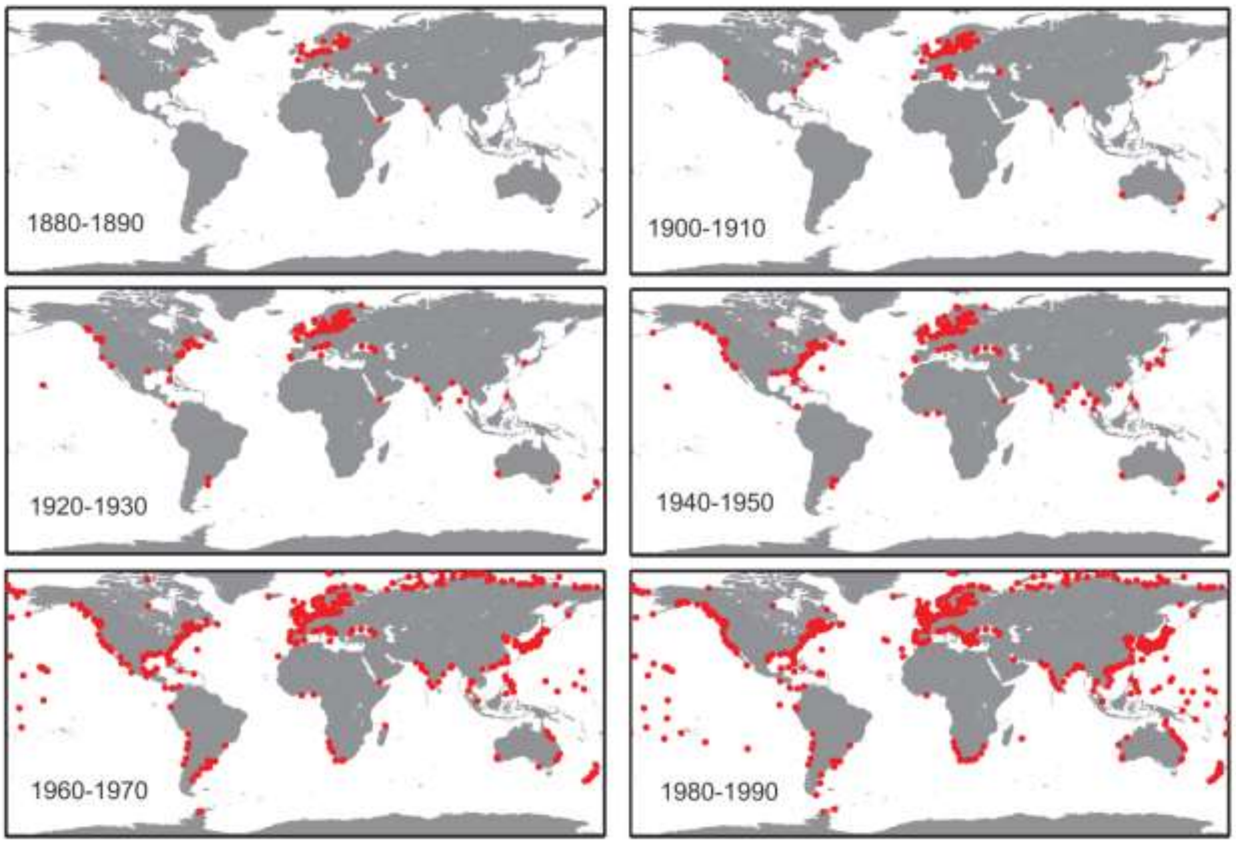
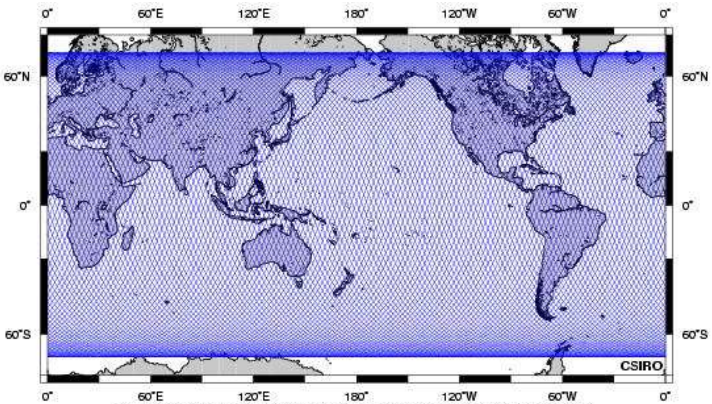


Figure 3.A.4 | Location of tide gauges (red dots) that had at least 1 year of observations within the decade indicated.

Sea level measurements

Tide gauges measurements since 1700s:
- Amsterdam from 1700 and 3 sites in Northern Europe after 1770,
- are limited to coastlines and islands.

Satellite altimeter measurements since 1992:
- high-precision, continuous, near-global measurements of sea level from space,
- measurements are made along the satellite's ground track (~7 km).
- limited by the inclination of the orbital plane by ±66° (TOPEX/Poseidon, Jason),
- horizontal resolution (track spacing) is between 100 and 200 km,
- temporal sampling is limited to satellite orbit: days at the equator and hours at high radius.

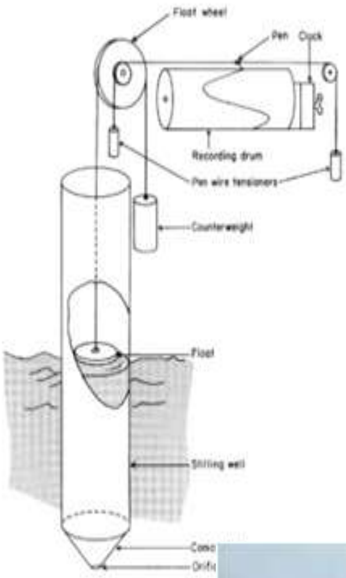


The ground track of one complete 10-day cycle of TOPEX/Poseidon

www.cmar.csiro.au

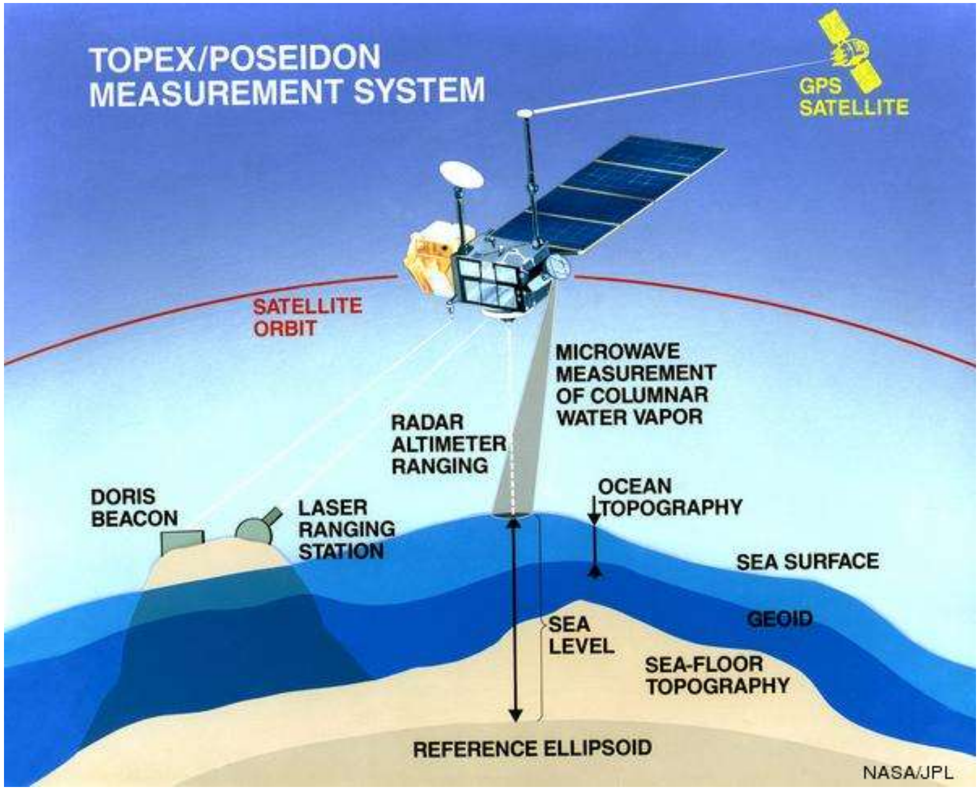
Sea level measurements

Tide gauges



www.noc.ac.uk

Satellite altimeter



www.cmar.csiro.au

Tide gauge records **measure** the **combined effect** of **ocean volume change** and **vertical land motion** (VLM), …**VLM signal must be removed**.

One component that can be accounted for to a certain extent is the VLM associated with **glacial isostatic adjustment** (GIA).

More recently, **Global Positioning System** (GPS) receivers have been installed at tide gauge sites to **measure VLM as directly** as possible.
However, these measurements of VLM are only available since the late 1990s at the earliest, and either have to be extrapolated into the past to apply to older records, or used to identify sites without extensive VLM.

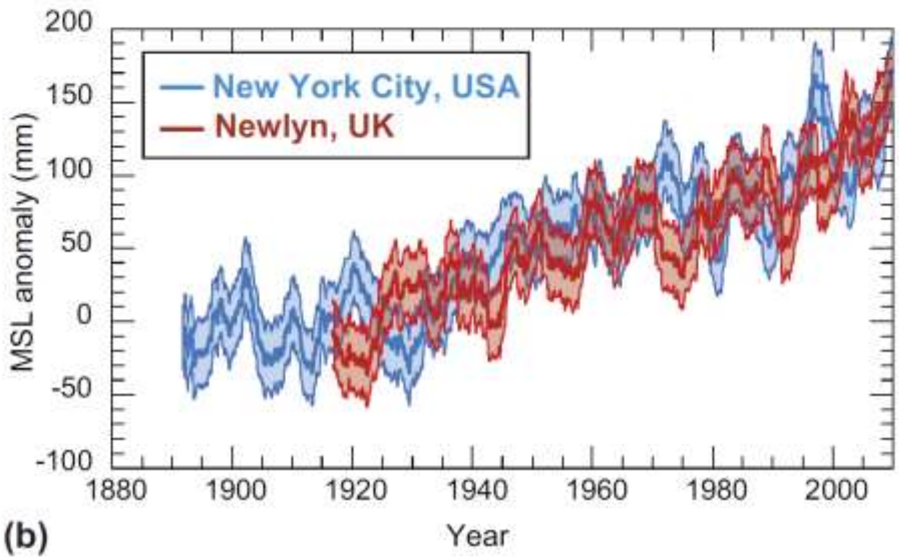
Satellite radar altimeters in the 1970s and 1980s made the first **nearly global observations of sea level**, but these early measurements were highly uncertain and of short duration.

The **first precise record began** with the launch of **TOPEX/Poseidon satellite and successors in 1992** and have provided continuous measurements of sea level variability at 10-day intervals between approximately ±66° latitude.

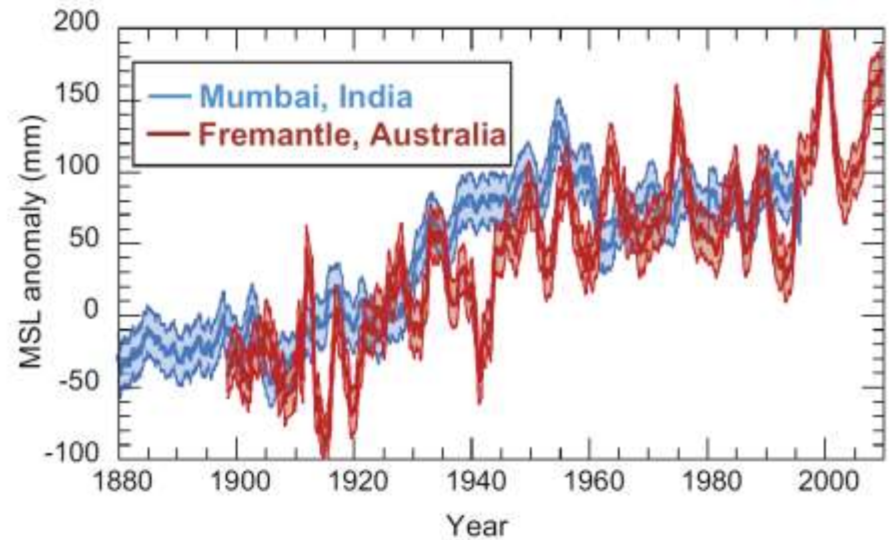
Additional altimeters in different orbits (ERS-1, ERS-2, Envisat, Geosat Follow-on) have allowed for measurements up to ±82° latitude and at different temporal sampling (3 to 35 days), although these measurements are not as accurate as those from the T/P and Jason satellites.

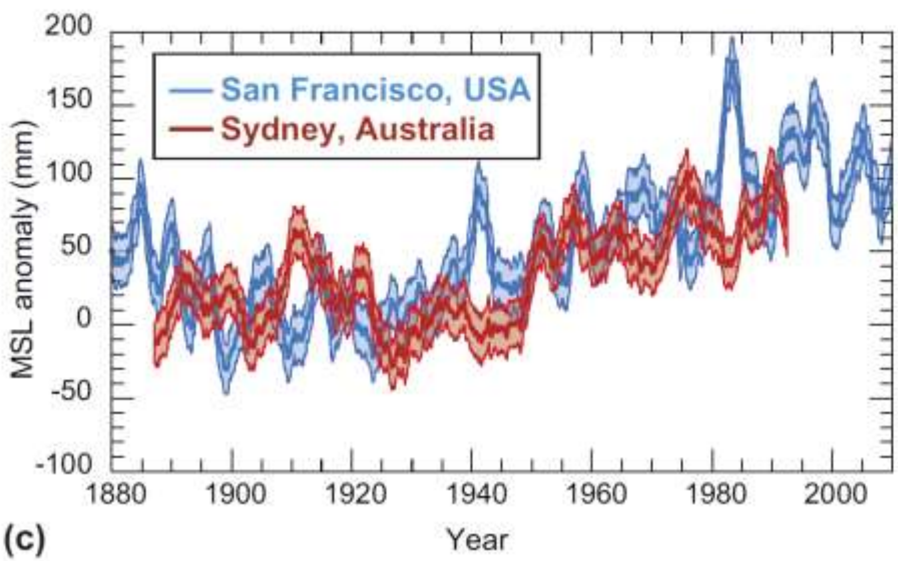
Mean sea level anomalies (mm)
rel to 1900-1905

(a)



(b)





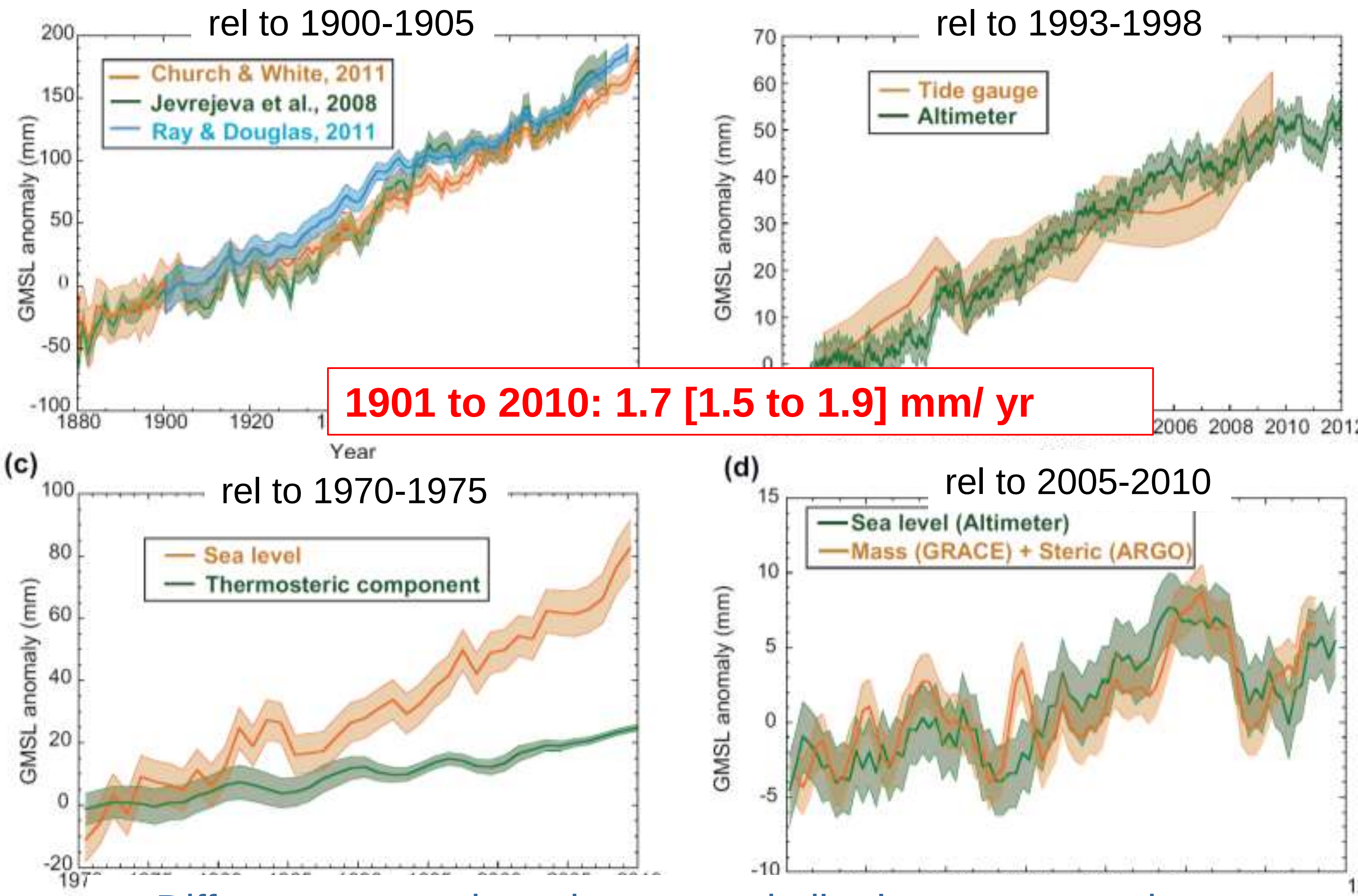
(c)

Tide gauges with the longest nearly continuous records of sea level show **increasing sea level** over 20th century.

Significant interannual and **decadal-**scale **fluctuations** about the average rate of sea level rise in all records.

Data were corrected for Glacial Isostatic Adjustment (GIA).

Global mean sea level (GMSL) anomalies [mm] – different measuring systems



- Different approaches show very similar long-term trends,
- but noticeably different interannual and decadal-scale variability.

Estimated trends in GMSL

Quantity	Period	Trend (mm yr^{-1})	Source	Resolution
GMSL	1901–2010	1.7 [1.5 to 1.9]	Tide Gauge Reconstruction (Church and White, 2011)	Yearly
	1901–1990	1.5 [1.3 to 1.7]	Tide Gauge Reconstruction (Church and White, 2011)	Yearly
	1971–2010	2.0 [1.7 to 2.3]	Tide Gauge Reconstruction (Church and White, 2011)	Yearly
	1993–2010	2.8 [2.3 to 3.3]	Tide Gauge Reconstruction (Church and White, 2011)	Yearly
	1993–2010	3.2 [2.8 to 3.6][a]	Altimetry (Nerem et al., 2010) time-series	10-Day
Thermosteric Component (upper 700 m)	1971–2010	0.6 [0.4 to 0.8]	XBT Reconstruction (updated from Domingues et al., 2008)	3-Year running means
	1993–2010	0.8 [0.5 to 1.1]	XBT Reconstruction (updated from Domingues et al., 2008)	3-Year running means
Thermosteric Component (700 to 2000 m)	1971–2010	0.1 [0 to 0.2]	Objective mapping of historical temperature data (Levitus et al., 2012)	5-Year averages
	1993–2010	0.2 [0.1 to 0.3]	Objective mapping of historical temperature data (Levitus et al., 2012)	5-Year averages
Thermosteric Component (below 2000 m)	1992–2005	0.11 [0.01 to 0.21][b]	Deep hydrographic sections (Purkey and Johnson, 2010)	Trend only
Thermosteric Component (whole depth)	1971–2010	0.8 [0.5 to 1.1][c]	Combination of estimates from 0 to 700 m, 700 to 2000 m, and below 2000 m[c]	Trend only
	1993–2010	1.1 [0.8 to 1.4][c]	Combination of estimates from 0–700 m, 700 to 2000 m, and below 2000 m[c]	Trend only

Table 3.1 | Estimated trends in GMSL and components over different periods from representative time-series. Trends and uncertainty have been estimated from a time series provided by the authors using ordinary least squares with the uncertainty representing the 90% confidence interval. The model fit for yearly averaged time series was a bias + trend; the model fit for monthly and 10-day averaged data was a bias + trend + seasonal sinusoids. Uncertainty accounts for correlations in the residuals.

Global mean sea level rise (mm/yr)

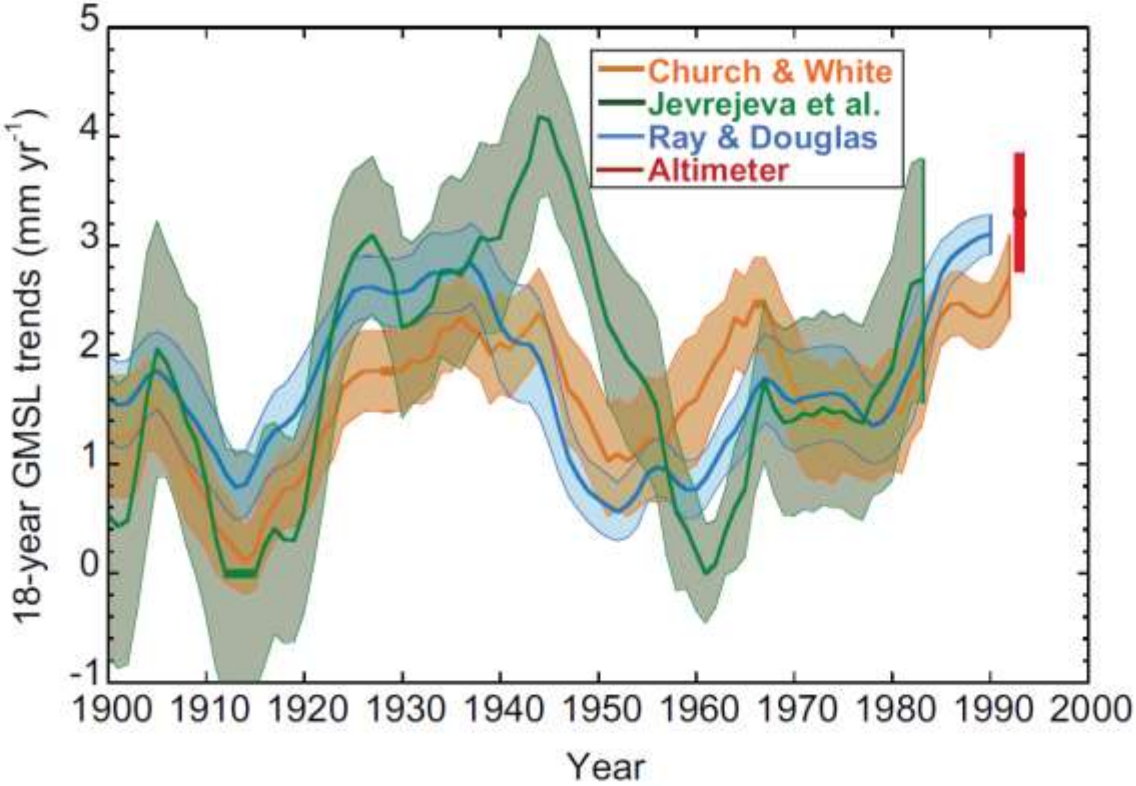


Figure 3.14 | 18-year trends of GMSL rise estimated at 1-year intervals. The time is the start date of the 18-year period, and the shading represents the 90% confidence. The estimate from satellite altimetry is also given, with the 90% confidence given as an error bar. Uncertainty is estimated by the variance of the residuals about the fit, and accounts for serial correlation in the residuals as quantified by the lag-1 autocorrelation.

-A **long time scale** is needed because **significant multi-decadal variability** appears in numerous tide gauge records during 20th century.

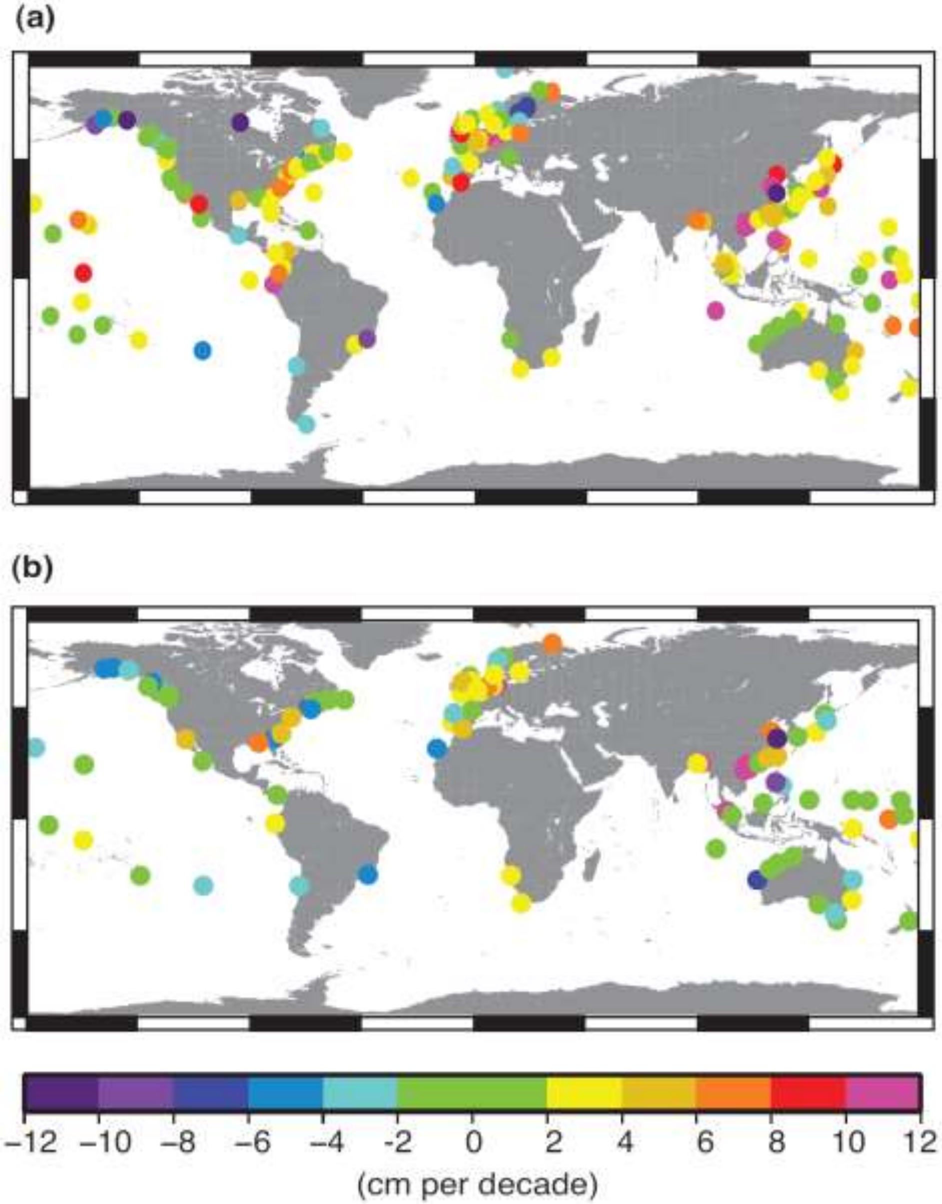
-All do indicate 18-year trends that were significantly **higher than** the 20th century average at certain times (**1920–1950, 1990–present**) and **lower at** other periods (**1910–1920, 1955–1980**), likely related to multi-decadal variability.

-Linking these to climate fluctuations like AMO and/or PDO are not conclusive.

Interannual fluctuations - real or artefact?

- “**Satellite altimetry** can **resolve interannual fluctuations** in GMSL better than tide gauge records because less temporal smoothing is required.
- **Deviations** from long-term trend can **exist for periods of several years**, especially during **El Niño** (1997–1998) and **La Niña** (2011).
- There is high confidence that the **higher GMSL rise from 1993–2010 is 3.2 [2.8 to 3.6] mm/yr** is **real** and not an artefact of the different sampling or change in instrumentation, as the trends estimated over the same period from tide gauges and altimetry are consistent.
- Although the rate of **GMSL rise has a slightly lower trend between 2005 and 2010**, this variation is consistent with earlier interannual fluctuations in the record (e.g., 1993–1997), mostly attributable to El Niño/La Niña cycles.”

Extreme sea level events: estimated trends (cm/decade)



Top figure: The **height** of a **50-year flood event** has **increased anywhere** from **2** to more than **10 cm/decade** since 1970 (<0: vertical land motion).

Bottom figure: **annual median height** at each gauge is **removed** to reduce effect of local mean sea level rise:

- rate of extreme sea level change drops in 49% below significance,
- 45% it fell to less than 5 mm/yr.
- **6% of tide gauge records** had a **change** of more than **5 mm/yr** (US, western Pacific, Southeast Asia, Northern Europe.

3.7 Conclusions: Sea Level Change

- "It is virtually certain that globally averaged sea level has risen over the 20th century, with a very likely mean rate between 1900 and 2010 of 1.7 [1.5 to 1.9] mm/yr and 3.2 [2.8 and 3.6] mm/yr between 1993 and 2010.
- It is virtually certain that interannual and decadal changes in the large-scale winds and ocean circulation can cause significantly higher or lower rates over shorter periods at individual locations, as this has been observed in tide gauge records around the world.
- It is very likely that the rate of mean sea level rise along Northern European coastlines has accelerated since the early 1800s and that this has continued through the 20th century, as the increased rate since 1875 has been observed in multiple long tide gauge records and by different groups using different analysis techniques.
- It is likely that sea level rise throughout the NH has also accelerated since 1850…
- Finally, it is likely that extreme sea levels have increased since 1970, largely as a result of the rise in mean sea level."

3.8 Ocean Biogeochemical Changes

- **Oceans** can **store large amounts** of **CO_2**.

- Reservoir of inorganic carbon in the ocean is **~50 times** that **of** the **atmosphere** (Sabine et al., 2004).

- **Ocean** also provides an **important sink for** carbon dioxide released by human activities, the **anthropogenic CO_2** (C_{ant}).

- Currently, an amount of CO_2 equivalent to **~30% of the total human emissions of CO_2** to the atmosphere **is accumulating** in the **ocean** (Mikaloff-Fletcher et al., 2006; Le Quéré et al., 2010).

- Section 3.8: "Observations of change in the ocean uptake of carbon, the inventory of C_{ant}, and ocean acidification are assessed…"

→Chapter 6 synthesis of the overall carbon cycle for past trends and future projections.

→ "Causes and relevance of oxygen minimum zones" GEF9400 presentation by Hans Brenna on 09.11.2015.

Ocean Uptake of Carbon

- Air–sea flux of CO_2 is computed from the observed difference in the partial pressure of CO_2 (pCO_2) across the air–water interface:

$\Delta pCO_2 = pCO_{2,sw} - pCO_{2,air}$ the solubility of CO_2 in seawater, and the gas transfer velocity (Wanninkhof et al., 2009).

- Large uncertainties ±50% in derived CO_2 (Wanninkhof et al., 2013) due to limited geographic and temporal coverage of ΔpCO_2 measurements, as well as uncertainties in wind forcing and transfer velocity parameterizations.

- Estimating global uptake rates ranges between:
    - 1.9 [1.2 to 2.5] PgC yr^{-1} for the time period 1995–2000 (Gruber et al., 2009),
    - 2.0 [1.0 to 3.0] PgC yr^{-1} normalized for 2000 (Takahashi et al., 2009).

- Uncertainties in fluxes calculated from ΔpCO_2 are currently too large to detect trends in global ocean carbon uptake.

1 Petagram: 1Pg= 10^{12} kg= 10^{15} g

Ocean Carbon Climatology - Global Ocean Data Analysis Project (GLODAP)

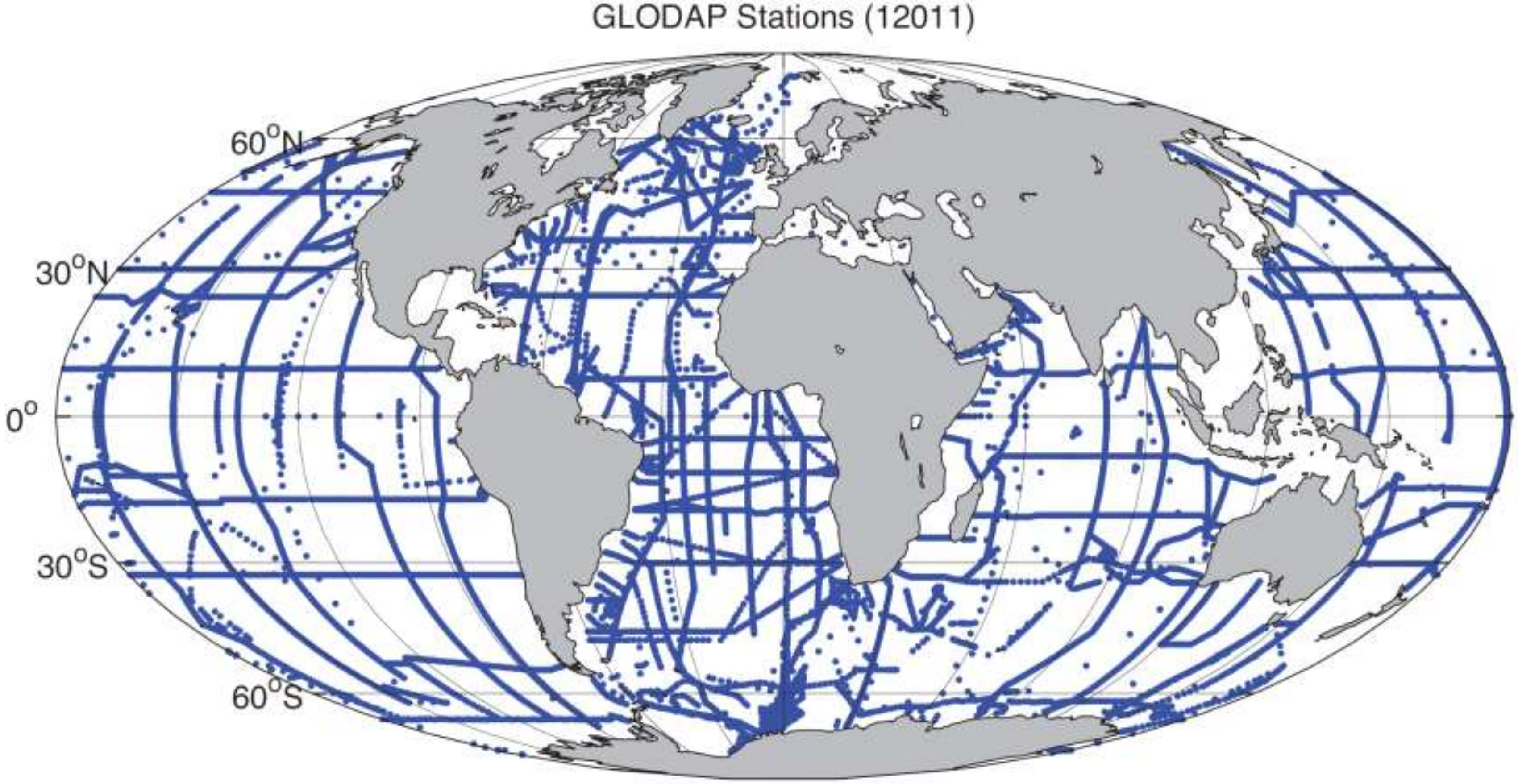


Figure 3.A.5 | Location of profiles used to construct the Global Ocean Data Analysis Project (GLODAP) ocean carbon climatology.

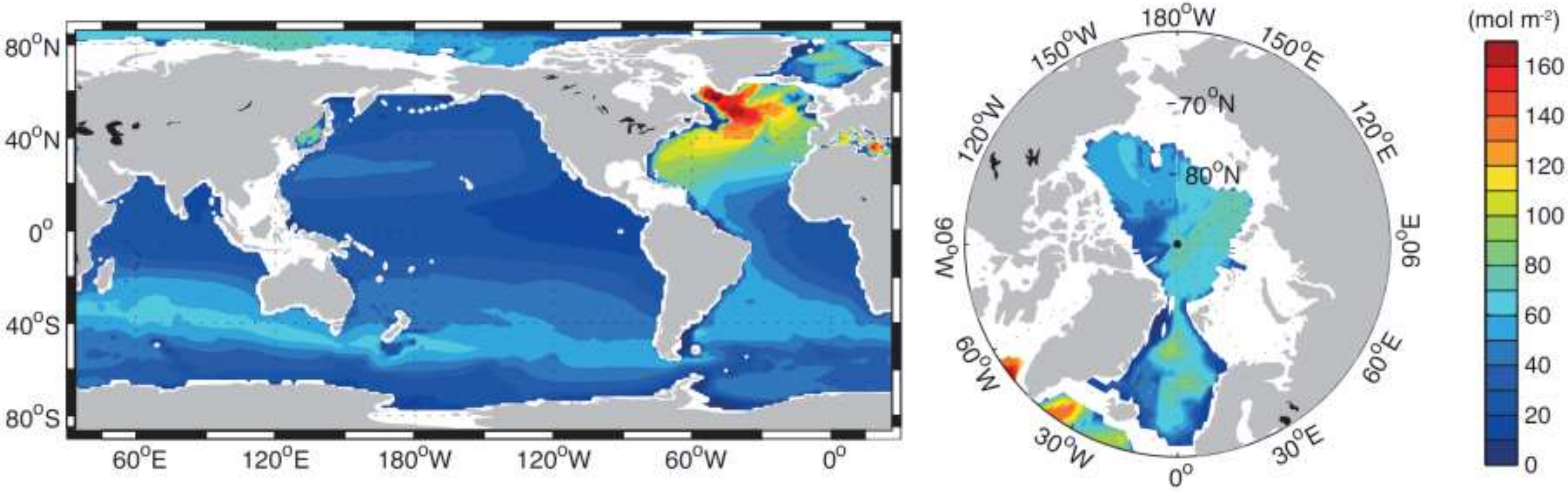
Oceanic Inventory of anthropogenic CO_2

- **Ocean carbon uptake** and **storage** is **inferred** from **changes in** the **inventory** of **anthropogenic carbon** (C_{ant}).
- **C_{ant} cannot be measured directly** but is calculated from observations of ocean properties (see 3.A).
- Two independent data-based methods to calculate anthropogenic carbon inventories exist:

- the **ΔC* method** (back-calculations; Sabine et al., 2004),

- transit time distribution (**TTD**) **method** (Waugh et al., 2006) (→Green's function approach uses different tracer data mostly chlorofluorocarbon measurements).

Anthropogenic CO_2 inventory in 2010



Combining measurement methods with model studies, results in a “**best” estimate** of global ocean inventory (including marginal seas) **of anthropogenic carbon uptake** from **1750 to 2010** of **155 PgC** with an uncertainty of ±20% (Khatiwala et al., 2013).

1 Petagram: 1Pg= 10^{12} kg= 10^{15} g

Anthropogenic carbon storage: 1980-2005

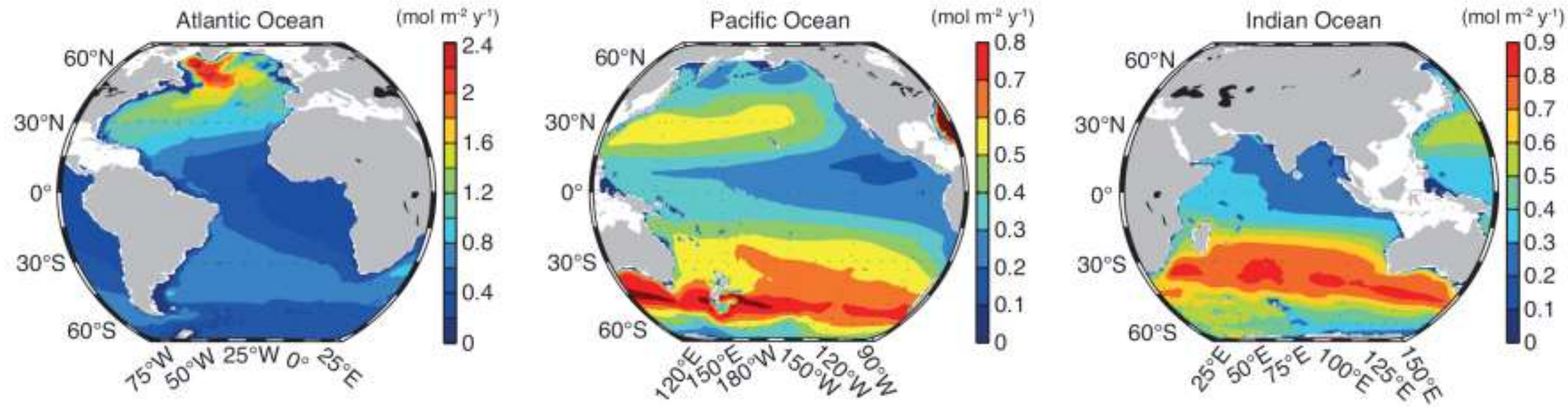


Figure 3.17 | Maps of storage rate distribution of anthropogenic carbon (mol m^{-2} yr^{-1}) for the three ocean basins (left to right: Atlantic, Pacific and Indian Ocean) averaged over 1980–2005 estimated by the Green's function approach (Khatiwala et al., 2009). Note that a different colour scale is used in each basin.

The North Atlantic and the Southern Ocean are estimated to be key regions for anthropogenic carbon storage.

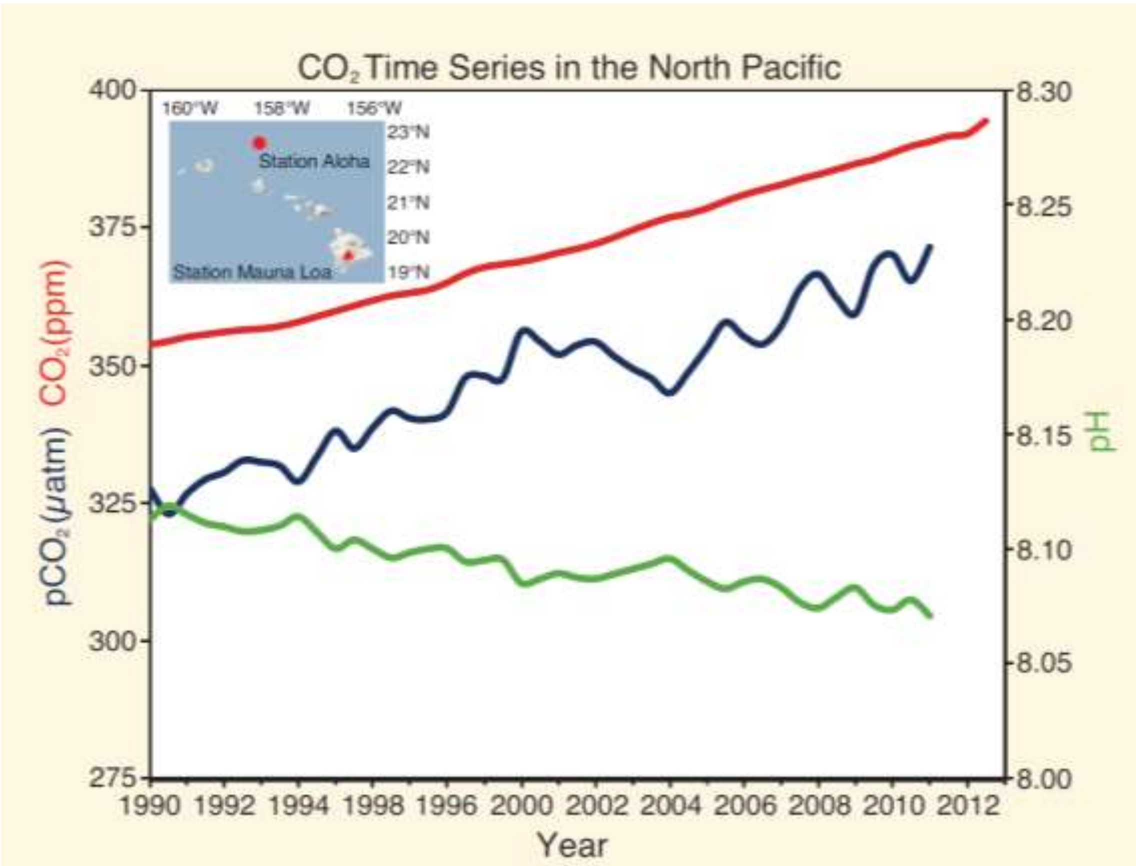
Why does the North Atlantic show maximum anthropogenic carbon storage?

The North Atlantic has **high variability** in **circulation** and **deep water formation**, influencing the C_{ant} inventory.

Dependence of the C_{ant} **storage rate in the North Atlantic on the NAO** with high/low C_{ant} storage rate during phases of high/low NAO (i.e., high/low Labrador Sea Water formation rates) (Perez et al., 2010).

Wanninkhof et al. (2010) found a smaller inventory increase in the North Atlantic compared to the South Atlantic between 1989 and 2005.

FAQ 3.3 How Does Anthropogenic Ocean Acidification Relate to Climate Change?



$$CO_{2(atmos)} \rightleftarrows CO_{2(aq)}$$
$$CO_{2(aq)} + H_2O \rightleftarrows H_2CO_3$$
$$H_2CO_3 \rightleftarrows H^+ + HCO_3^-$$
$$HCO_3^- \rightleftarrows H^+ + CO_3^{2-}$$

Dissolved carbon dioxide: $CO_{2(aq)}$
Carbonic acid: H_2CO_3
Bicarbonate HCO_3^-
Hydrogen ions: H^+
Carbonate ion: CO_3^{2-}

Increase in oceanic hydrogen ion concentrations leads to a reduction in pH or an increase in acidity.

FAQ 3.3 How Does Anthropogenic Ocean Acidification Relate to Climate Change?

When atmospheric CO_2 exchanges across the air–sea interface it reacts with seawater through a series of four chemical reactions that increase the concentrations of the carbon species: dissolved carbon dioxide ($CO_{2(aq)}$), carbonic acid (H_2CO_3) and bicarbonate (HCO_3^-):

$$CO_{2(atmos)} \rightleftarrows CO_{2(aq)} \quad (1)$$

$$CO_{2(aq)} + H_2O \rightleftarrows H_2CO_3 \quad (2)$$

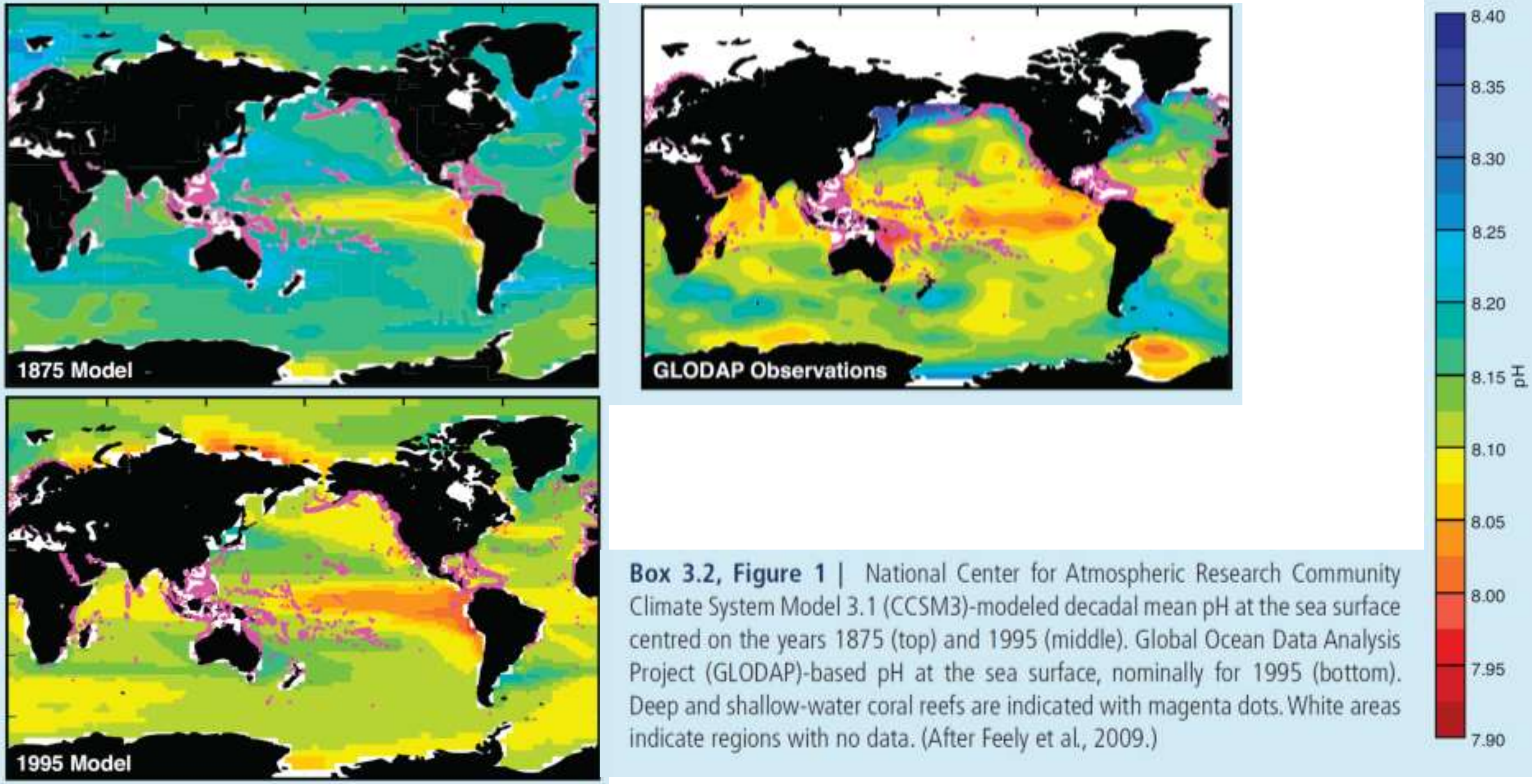
$$H_2CO_3 \rightleftarrows H^+ + HCO_3^- \quad (3)$$

$$HCO_3^- \rightleftarrows H^+ + CO_3^{2-} \quad (4)$$

Hydrogen ions (H^+) are produced by these reactions. This increase in the ocean's hydrogen ion concentration corresponds to a reduction in pH, or an increase in acidity. Under normal seawater conditions, more than 99.99% of the hydrogen ions that are produced will combine with carbonate ion (CO_3^{2-}) to produce additional HCO_3^-. Thus, the addition of anthropogenic CO_2 into the oceans lowers the pH and consumes carbonate ion. These reactions are fully reversible and the basic thermodynamics of these reactions in seawater are well known, such that at a pH of approximately 8.1 approximately 90% the carbon is in the form of bicarbonate ion, 9% in the form of carbonate ion, and only about 1% of the carbon is in the form of dissolved CO_2. Results from laboratory, field, and modeling studies, as well as evidence from the geological record, clearly indicate that marine ecosystems are highly susceptible to the increases in oceanic CO_2 and the corresponding decreases in pH and carbonate ion.

Box 3.2 | Ocean Acidification

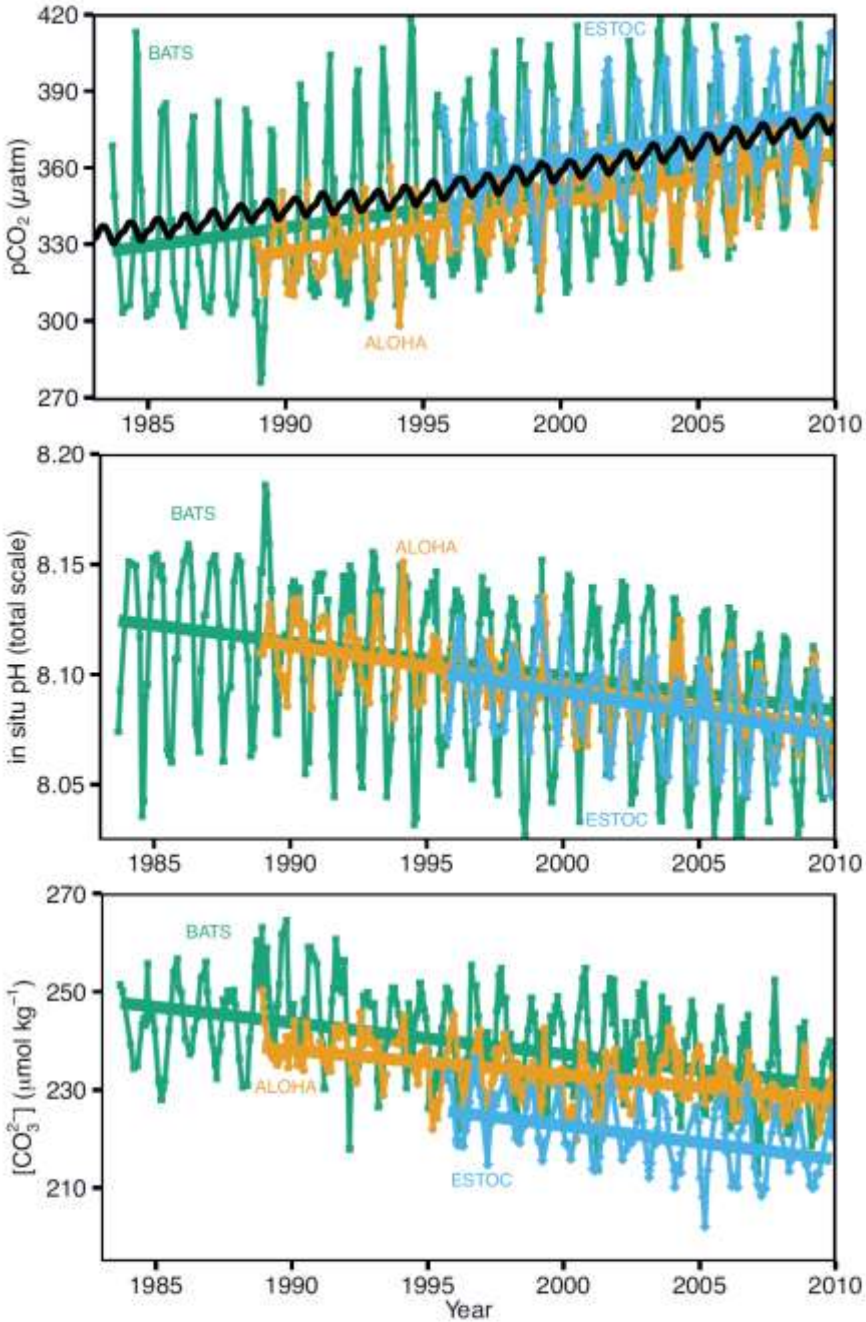
Ocean acidification refers to a reduction in pH of the ocean over an extended period, typically decades or longer, caused primarily by the uptake of carbon dioxide (CO_2) from the atmosphere. Ocean acidification can also be caused by other chemical additions or subtractions from the oceans that are natural (e.g., increased volcanic activity, methane hydrate releases, long-term changes in net respiration) or human-induced (e.g., release of nitrogen and sulphur compounds into the atmosphere). Anthropogenic ocean acidification refers to the component of pH reduction that is caused by human activity (IPCC, 2011).



Box 3.2, Figure 1 | National Center for Atmospheric Research Community Climate System Model 3.1 (CCSM3)-modeled decadal mean pH at the sea surface centred on the years 1875 (top) and 1995 (middle). Global Ocean Data Analysis Project (GLODAP)-based pH at the sea surface, nominally for 1995 (bottom). Deep and shallow-water coral reefs are indicated with magenta dots. White areas indicate regions with no data. (After Feely et al., 2009.)

GLODAP: GLobal Ocean Data Analysis Project

Surface seawater pCO_2, pH, carbonate ion in northern subtropics



BATS: Bermuda Atlantic Time Series (31N, 64W)

HOT-ALOHA: Hawaii Ocean Time Series (22N, 158W)

ESTOC: European Station for Time Series in the Ocean (29N, 15W)

Atmospheric pCO_2 (µatm=ppm)

Summary: Changes in Ocean Biogeochemistry

- "Based on high agreement between independent estimates using different methods and data sets …it is **very likely** that the global ocean inventory of **anthropogenic carbon (C_{ant}) increased** from **1994** to **2010**.
- The oceanic **C_{ant} inventory in 2010** is estimated to be **155 PgC** with an **uncertainty** of **±20%.**
- The **annual global oceanic uptake** rates calculated from independent data sets and for different time periods agree with each other within their uncertainties and **very likely** are in the range of **1.0 to 3.2 PgC yr^{-1}**.
- **Uptake** of **anthropogenic CO_2** results in gradual **acidification** of **the ocean**.
- The **pH** of **surface seawater** has **decreased by 0.1 since** the beginning of the **industrial era**, corresponding to a 26% increase in hydrogen ion concentration.

GEF4400 “The Earth System”

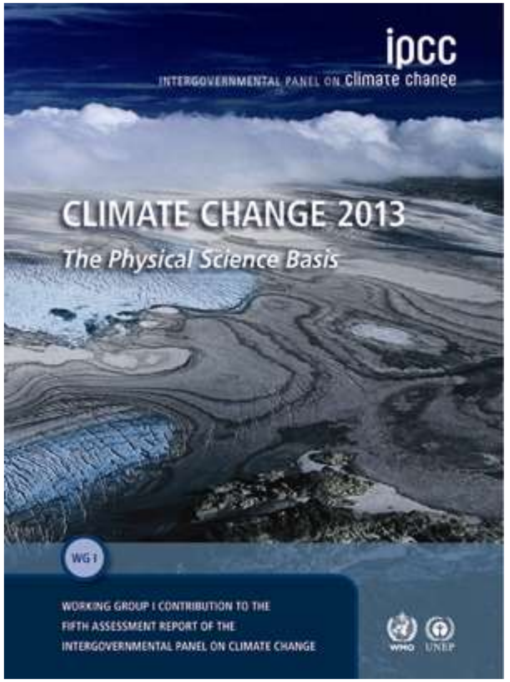
Prof. Dr. Jon Egill Kristjansson,

Prof. Dr. Kirstin Krüger (UiO)

- **Lecture/ interactive seminar/ field excursion**
  Teaching language: English
  Time and location: see next slide,
  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 course.

3.9 Synthesis

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)*
- Synthesis *(Section 3.9)*

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.

Ocean changes since 1950s – Summary

Increase of anthropogenic CO_2, global mean sea level, upper ocean heat content, and high-low salinity regions.

→high confidence.

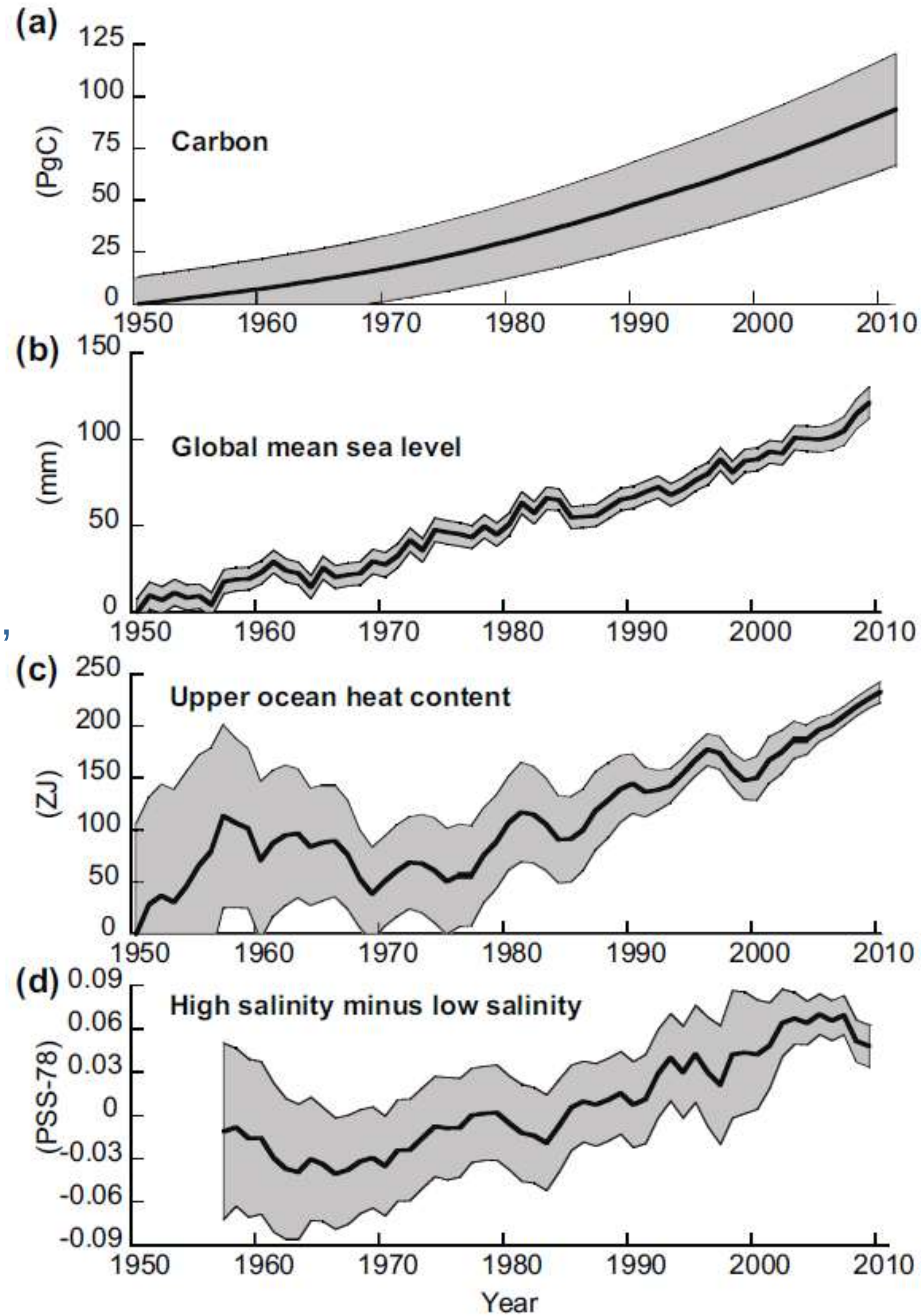
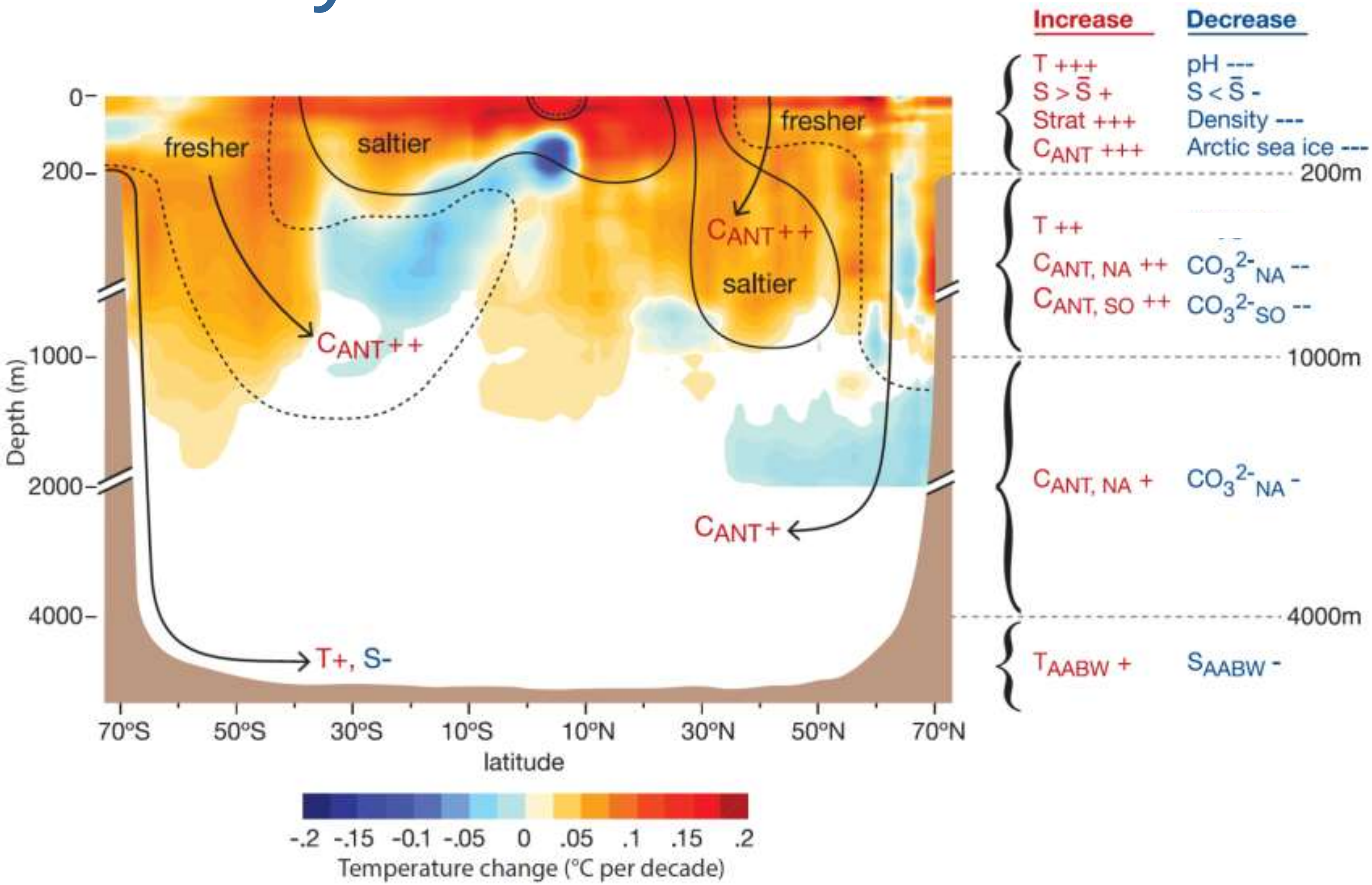


Figure 3.21 | Time series of changes in large-scale ocean climate properties. From top to bottom: global ocean inventory of anthropogenic carbon dioxide, updated from Khatiwala et al. (2009); global mean sea level (GMSL), from Church and White (2011); global upper ocean heat content anomaly, updated from Domingues et al. (2008); the difference between salinity averaged over regions where the sea surface salinity is greater than the global mean sea surface salinity ("High Salinity") and salinity averaged over regions values below the global mean ("Low Salinity"), from Boyer et al. (2009).

Summary



+++: *high confidence*; ++: *medium confidence*; +: *low confidence*

C_{ANT}: Anthropogenic Carbon, NA: North Atlantic, SO: Southern Ocean AABW: Antarctic Bottom Water

Carbonate ion: CO_3^{2-}

3.9 Synthesis

Overall Summary:

- "The observations summarized in this chapter provide strong evidence that **ocean** properties of relevance to climate **have changed during the past 40 years,** including **temperature, salinity, sea level, carbon, pH…**

- The **observed patterns of change in the subsurface ocean are consistent** with changes in the surface ocean in response **to climate change and natural variability** and with known physical and biogeochemical processes in the ocean, providing **high confidence** in this assessment."

Check also Executive Summary (PP. 257-259)