Global mean (atmospheric) surface temperature

Global Mean Estimates based on Land and Ocean Data

- Annual Mean
- Lowess Smoothing

Temperature Anomaly (°C)

NASA GISS
The ocean as the climate’s reservoir
The ocean as the climate’s reservoir

Table 1. The Linear Trend (with 95% Confidence Level) for the Three Key Climate Indicators: Global Mean Surface Temperature (GMST), Ocean Heat Content (OHC), and Sea Level Rise (SLR)³

<table>
<thead>
<tr>
<th></th>
<th>Linear Trend</th>
<th>σ</th>
<th>S/N (1/years)</th>
<th>Time (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMST</td>
<td>0.016°C ± 0.005°C/yr</td>
<td>0.110°C/yr</td>
<td>0.14</td>
<td>27</td>
</tr>
<tr>
<td>OHC</td>
<td>0.79 ± 0.03 × 10^{22} J/yr</td>
<td>0.77 × 10^{22} J/yr</td>
<td>1.03</td>
<td>3.9</td>
</tr>
<tr>
<td>SLR</td>
<td>3.38 ± 0.10 mm/yr</td>
<td>3.90 mm/yr</td>
<td>0.87</td>
<td>4.6</td>
</tr>
</tbody>
</table>
Objectives

• Introduce some basics of the ocean system: emphasis will be on physical characteristics.

• Describe the primary mechanism by which the ocean responds to and contributes to changes in the climate system: the global overturning circulation.

• Two case studies of recent change:
  (i) the strength of the Atlantic meridional overturning circulation (AMOC);
  (ii) sea level rise.

Focus throughout on how we observe the ocean.
Oceanic motions are typically influenced by Earth’s rotation, which impacts the large-scale transport of heat.

The ocean is stably stratified with light (warm/fresh) water above heavy (cold/salty) water.

Both of these properties favor horizontal motion over vertical motion.
A layered ocean

Temperature (°C)

Depth [m]

Data: M. McCartney, WHOI; L. Talley and J. Swift, SIO
Jul/Aug 1988 (N)
Feb-Apr 1989 (S)

Ocean Data View
A layered ocean

Temperature (°C)

Depth [m]

Data: M. McCartney, WHOI; L. Talley and J. Swift, SIO

Jul/Aug 1988 (N)
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A layered ocean

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Ocean Data View

Jul/Aug 1988 (N)
Feb-Apr 1989 (S)
A layered ocean

Phosphate concentration (μmol/kg)
A layered ocean
Flat density surfaces in the basin interiors

Bowl-shaped density surfaces associated with gyre circulation.

Strongly-titled density surfaces associated with the Antarctic Circumpolar Current

Flat density surfaces in the basin interiors
The vertical structure of the ocean
The vertical structure of the ocean

- The mixed layer is the only part of the ocean that is in direct contact with the atmosphere.
The vertical structure of the ocean

• The **mixed layer** is the only part of the ocean that is in direct contact with the atmosphere.

• The *(ventilated)* **thermocline** is the region where surface properties are carried into the ocean interior in low and mid-latitudes.
The vertical structure of the ocean

- The **mixed layer** is the only part of the ocean that is in direct contact with the atmosphere.

- The **(ventilated) thermocline** is the region where surface properties are carried into the ocean interior in low and mid-latitudes.

- The **abyss** holds most of the ocean’s volume and is sourced from water masses formed at high latitudes.
Ocean currents movie from JPL
Oceanography in the age of satellites . . .

Sea surface temperature across the Gulf Stream
sets AR5 apart from its predecessor that the recent expansion of the ocean observing system clearly indicates the general lack of observations before 2000, as well the from the 1950–1955
diversity of observations for assessment of change in the oceans, which from Argo.

As the ocean south of 30°S and salinity observations from the Southern Ocean (de
acting the 100°S Ocean in one year than the total of all winter data collected dur
polar oceans; Argo delivers more winter pro
eliminated a major seasonal bias in sampling, particularly in the
Hemisphere and coastal regions are over-represented. Although
bias towards areas that are more easily sampled, so the Northern
by Argo compared with the previous century of measurements is
plan called for an array with global coverage of about 3,000
UC San Diego.

Figure courtesy of Megan Scanderbeg, Scripps Institution of Oceanography,
start another cycle. The typical duration of a complete cycle is 10

Argo or Iridium satellite systems. It then returns to the parking depth to

Descent to depth: 6 hours

1,000 m: drift approx. 9 days

Total cycle time: 10 days

Temperature and salinity profile recorded during ascent: 6 hours

Float descends to begin profile from a greater depth: 2,000 m

6–12 hours at surface to transmit data to satellite

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Figure 1 |

The typical cycle of an Argo float.

Increasing Temperature (°C) →

Increasing Depth (m)

0° 4° 8° 12° 16° 20° 24°

0 500 1000 1500 2000 2500 3000 3500 4000 4500

Thermocline

The resulting improvement in sampling of the ocean achieved
from satellites allows the construction of time series of the dynam
for ocean circulation with an unprecedented accuracy, varying with pressure and velocity, were measured (or for
refereed science literature have used Argo observations, attesting
widespread use of the data produced by the programme: since the
Perhaps the single most powerful metric of the value of Argo is the

DOI: 10.1038/NCLIMATE2872

www.nature.com/natureclimatechange

... and autonomy
Figure 2 | The sampling density of profiles reported by Argo floats.

a, ~1.5 million profiles collected between January 1999 and October 2015. Data from ref. 57.

b, The most complete assembly of all previous historical efforts (0.5 million largely shipboard observations collected over the past 100 years). Data from the World Ocean Data Base 2009. This sampling density is computed as the total number of samples in each 1° latitude × 1° longitude square and is colour coded according to the legend in each panel. The analysis only includes profiles that sample both temperature and salinity to a depth of 1,000 m or deeper.
The Argo archives to Oct. 2015
Density distribution of 1,451,650 profiles

World Ocean Database 2009
Density distribution of 534,905 profiles

Figure 2 | The sampling density of profiles reported by Argo floats.
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Ocean heat storage

0-2000 m Global Ocean Heat Content

- Red: 3-Month average through Apr-Jun 2016
- Black: Yearly average through 2015
- Blue: Pentadal average through 2011-2015

NOAA/NESDIS/NODC Ocean Climate Laboratory
Updated from Levitus et al. 2012
1276

52.5°S; 0.8 m averages 54.0°S (an average latitude of 45.0°S; 1.0 m averages 110 km in space. Dynamic heights of 1.2 m have computed from data points separated by less than 0.09° point represents the mean anomaly for a 0.1 averaged on the basis of dynamic height. Thus, each hydrography and ALACE and then were bin-averated this figure, differences between ALACE temperatures as a function of decade. To gener...

Fig. 2. Temperature trends computed from differences between ALACE temperatures as a function of decade. To gener-

files from shipboard observations and ALACE

Trends were computed from differences between

year as a function of dynamic height contour. 

ocean databases. (observations have not yet entered the world

the 1990s, because many 1990s hydrographic

board data were collected. Error bars are large in

averaged on the basis of the decade when ship-

peratures and shipboard observations were bin-

ations are included in

some XBT observa-

data, CTD data, and

in 1° by 1° squares. For this analysis, ALACE/

ALACE/hydrography differences bin-averaged

This implies that the

0.06°C

0.001°C/year between

18°C

1°C

-0.5°C

-1°C

Within error bars, data from the 1990s do not

decade in the latitude range from 35° to 65°S. 

19°C

1°C

-0.5°C

-1°C

Within error bars, data from the 1990s do not
The atmosphere-ocean heat budget

(a) net radiation at the top of the atmosphere

(b) northward heat transport by atmosphere and ocean
From Houghton et al. (1996), CUP

Net ocean heat flux across the equator!
Great ocean conveyor belt

Heat release to atmosphere

Atlantic Ocean

Indian Ocean

Pacific Ocean

Warm surface current

Cold saline deep current

+ brine rejection
The overturning circulation depends fundamentally on changing the density of a parcel of water from one density class to another, and then back again.
Overturning models: Push or pull

Munk’s Abyssal Recipes

(a) Case 1

\[ w \frac{\partial T}{\partial z} = \kappa \frac{\partial^2 T}{\partial z^2} \]

\[ \kappa \approx 10^{-4} \text{ m}^2 \text{ s}^{-1} \]

Southern Ocean upwelling

(b) Case 2
Overturning models: Push or pull

(a) Case 1

Munk’s Abyssal Recipes

(b) Case 2

Southern Ocean upwelling
Overturning models: Push and pull

Munk’s Abyssal Recipes

Southern Ocean upwelling
Glacial-interglacial cycles involve a rearrangement of density volumes and circulation strength.

Munk's Abyssal Recipes

Southern Ocean upwelling

Overturning models: Push and pull
The Atlantic Meridional Overturning Circulation (AMOC)
Changes in the AMOC

Bryden et al. (2005) indicated a slow down of the MOC based on multiple hydrographic sections across the Atlantic at 25°N.

Slowing of the Atlantic meridional overturning circulation at 25° N

Harry L. Bryden¹, Hannah R. Longworth¹ & Stuart A. Cunningham¹
Bryden et al. (2005) indicated a slow down of the MOC based on multiple hydrographic sections across the Atlantic at 25°N.
The RAPID array permits twice-daily estimates of the various components contribution to the AMOC.

http://www.rapid.ac.uk/
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Cunningham et al., Science (2007)

http://www.rapid.ac.uk/
The RAPID array now permits twice-daily estimates of the various components contribution to the AMOC.

Cunningham et al., Science (2007)

Measuring the AMOC
Observed fingerprint of a weakening Atlantic Ocean overturning circulation

L. Caesar1,2, S. Rahmstorf1,2, A. Robinson1,3,4,5, G. Feulner4 & V. Saba6

Anomalously weak Labrador Sea convection and Atlantic overturning during the past 150 years

David J. R. Thornalley1,2, Delia W. Oppo2, Pablo Ortega3, Jon I. Robson4, Chris M. Brierley5, Renee Davis4, Ian R. Hall4, Paola Moffa-Sanchez6, Neil L. Rose1, Peter T. Spooner1, Igor Yashayaev5 & Lloyd D. Keigwin2

Science & Environment

Climate change dials down Atlantic Ocean heating system

By Victoria Gill
Science correspondent, BBC News

The Atlantic meridional overturning circulation — the conveyor belt of the ocean — is slowing down. Scientists disagree about what’s behind it, but say it could mean bad news for the climate. Read the full story
NASA renews focus on Earth's frozen regions

In 2018, NASA will intensify its focus on one of the most critical but remote parts of our changing planet with the launch of two new satellite missions and an array of airborne campaigns.

› Full story

GLOBAL MEAN SEA LEVEL
↑ 3.2 ± 0.4 mm/yr

OCEAN MASS
↑ 1.8 ± 0.3 mm/yr

STERIC HEIGHT
↑ 0.8 ± 0.2 mm/yr

GREENLAND ICE MASS CHANGE
↓ 286 ± 21 Gt/yr

https://sealevel.nasa.gov/
Measuring sea level rise

Sea surface height from satellite altimetry

Gravity (mass) from GRACE

Ocean heat content from Argo floats
Sea level rise

Greenland & Antarctica:
- Greenland’s contribution to global sea-level rise is the largest, and increases every decade.
- Greenland melt: 0.09 mm/yr between 1992 and 2001; 0.59 mm/yr per year between 2002 and 2011.
- Antarctica melt: 0.08 mm/yr between 1992 and 2001; 0.40 mm/yr per year between 2002 and 2011.
- Greenland and Antarctica contribute about one third of present-day sea level rise.

Glaciers & Ice caps
- Account for a third of the present sea level rise; ~0.8 mm/yr over the past 20 years.
- Represent only 1% of Earth’s total ice; contribution to SLR is insignificant after 200 years.

Thermal expansion
- Thermosteric sea level rise, from 1971 to 2010 is 0.4 to 0.8 mm/yr.
- This corresponds to a warming of 0.015°C/decade in the upper 700 m between 1971 and 2010.
1 Introduction

The 2011 La Niña: So strong, the oceans fell

Carmen Boening,1 Josh K. Willis,1 Felix W. Landerer,1 R. Steven Nerem,2 and John Fasullo3

Antarctic ice streams and ice shelves

Fig. 2. Variability in the rate of Antarctic ice-shelf thickness change (meters per year). Maps for (columns from left to right) Filchner-Ronne, Amundsen, and Ross ice shelves (locations in the bottom right corner) showing average rate of thickness change for (rows) four consecutive 4.5-year intervals (1994–1998.5, 1998.5–2003, 2003–2007.5, and 2007.5–2012). Shorter-term rates can be higher than those from an 18-year interval. Ice-shelf perimeters are thin black lines, and the thick gray line demarcates the limit of satellite observations.

Fig. 1. Eighteen years of change in thickness and volume of Antarctic ice shelves. Rates of thickness change (meters per decade) are color-coded from −25 (thinning) to +10 (thickening). Circles represent percentage of thickness lost (red) or gained (blue) in 18 years. Only significant values at the 95% confidence level are plotted (table S1). (Bottom left) Time series and polynomial fit of average volume change (cubic kilometers) from 1994 to 2012 for the West (in red) and East (in blue) Antarctic ice shelves. The black curve is the polynomial fit for All Antarctic ice shelves. We divided Antarctica into eight regions (Fig. 3), which are labeled and delimited by line segments in black. Ice-shelf perimeters are shown as a thin black line. The central circle demarcates the area not surveyed by the satellites (south of 81.5°S). Original data were interpolated for mapping purposes (percentage area surveyed of each ice shelf is provided in table S1). Background is the Landsat Image Mosaic of Antarctica (LIMA).
The Antarctic margins

Regions of the Antarctic margins with “warm” water on the continental shelf are warming more rapidly.
West Antarctic Ice Sheet (WAIS)

Collapse of WAIS could lead to 15 m of sea level rise.
Collapse of WAIS could lead to 15 m of sea level rise.
Summary

• The ocean exchanges properties, e.g. heat, gases, with the atmosphere in a limited volume.

• More than 90% of the additional heat coming from greenhouse gases has been absorbed by the ocean.

• The residence time in the ocean is on the order of many hundreds to 1,000 years.

• Changes in the density classes that are exposed to the atmosphere and its storage capacity (volume, solubility) are needed to support glacial-interglacial cycles.