ATM 241, Spring 2020
Lecture 7
The Oceans

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Marshall & Plumb

Ch. 9

In this section…

Definitions

- Practical salinity units
- Density anomaly
- Surface zone
- Pycnocline
- Mixed layer
- Thermocline
- Abyss

Questions

- What are the properties of the Earth's oceans?
- What is the equation of state for seawater?
- In terms of salinity, temperature and density, what is the structure of the Earth's oceans?
- What are the layers of the Earth's oceans?
- What is the dynamical structure of the Earth's oceans?

Global Heat Transport (Four Mechanisms)

- **Large-scale circulation.** Bulk transport via the Hadley circulation. This is the primary mechanism for atmospheric heat transport near the equator.
- **Eddy flux of temperature.** Turbulent transport due to large-scale eddies (extratropical cyclones). This mechanism arises due to the rotation of the Earth.
- **Meridional latent heat transport.** Moisture transport from the subtropics to the midlatitudes (and farther north), largely due to atmospheric rivers.

About **80%** of the net equator-to-pole heat transport.

- **Ocean currents.** Transport and release of heat via, for example, the Gulf stream.

About **20%** of net heat transport.

Physical Character of Atmosphere and Ocean

How are the atmosphere and ocean different?

- The fluids are physically different: Water is (almost) **incompressible**, and so perturbations from the reference density are small (but not negligible). In fact, if the ocean were perfectly incompressible sea levels would be about 50m higher.

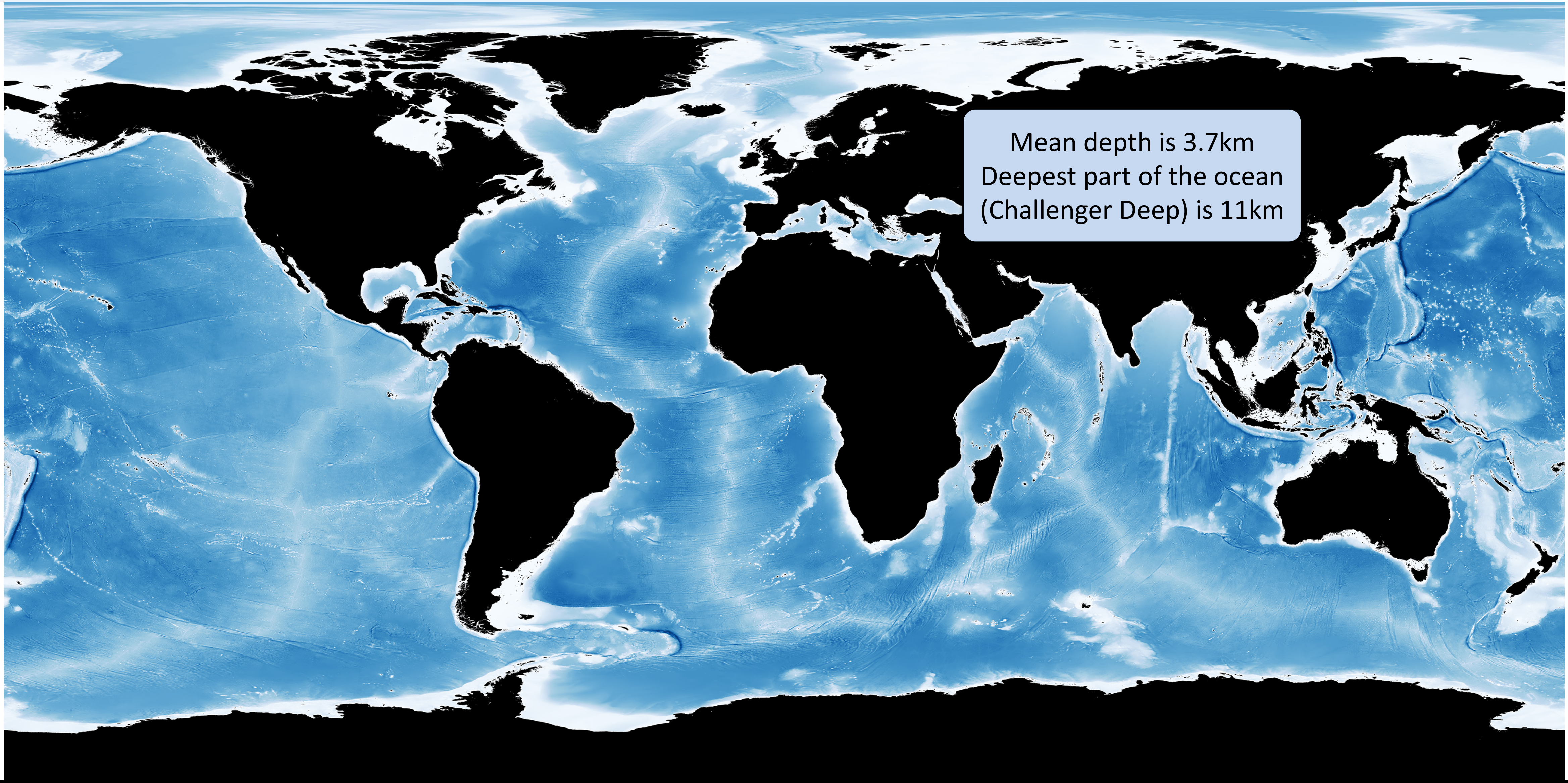
- Oceans do not have a thermodynamic analogue to atmospheric moisture (i.e. a species that condenses / evaporates).

- The major contributions to the equation of state for the ocean are **temperature** and **salinity**.

- Unlike the atmosphere, all oceans are **laterally bounded** by continents except in the Southern Ocean where fluid can pass through the Drake passage.

- Ocean circulation is almost exclusively forced from above. Solar forcing is essentially negligible beneath 200m. Turbulence in the upper ocean is driven by **wind stress** from the atmosphere.

Ocean Bathymetry

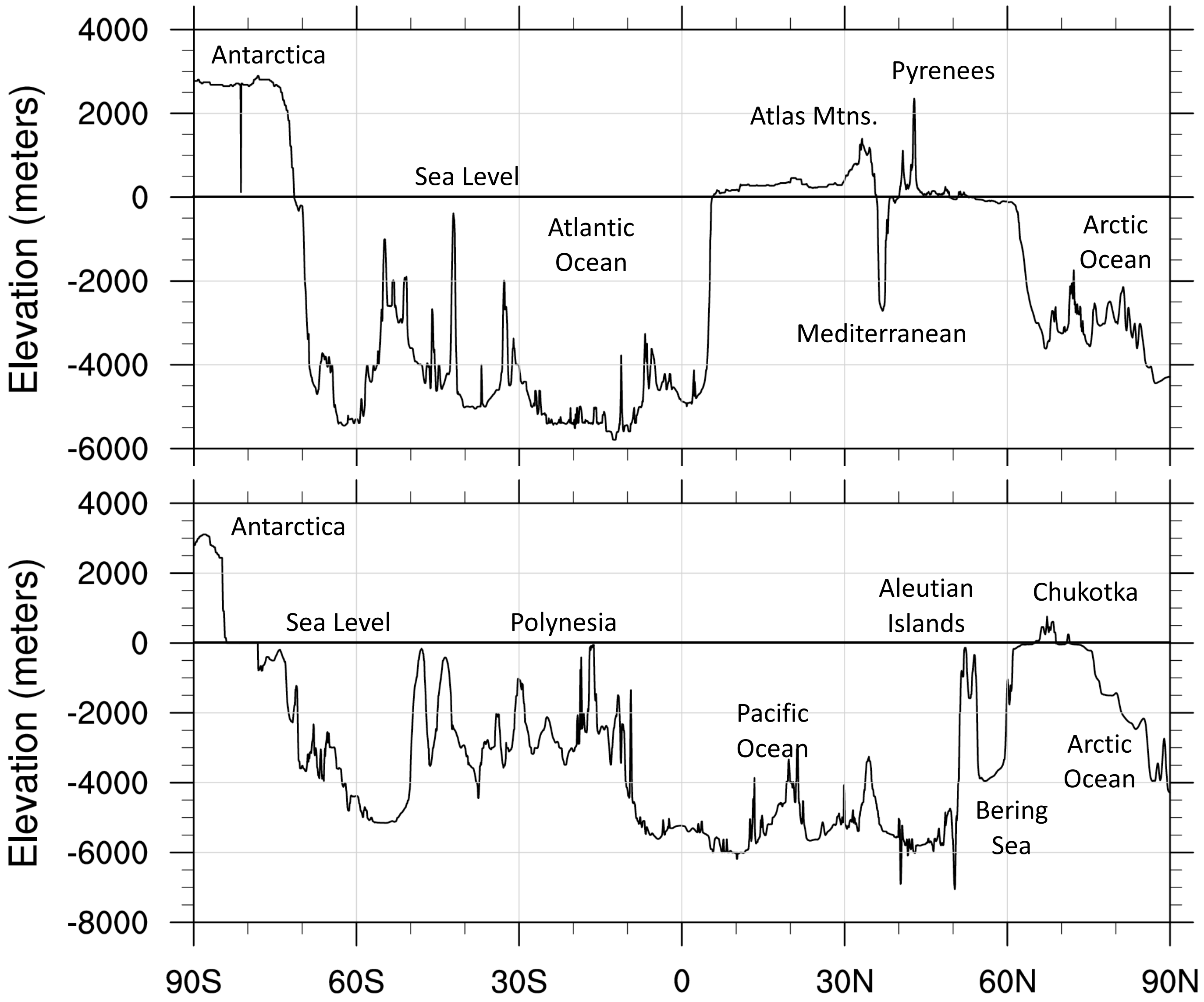


Mean depth is 3.7km
Deepest part of the ocean (Challenger Deep) is 11km

Ocean Bathymetry

Figure: North-south section through the Greenwich meridian, showing the bathymetry of the Atlantic Ocean, Mediterranean Sea and Arctic Ocean. Observe that ocean bottom topography is much more jagged than the land surface.

Figure: North-south section through 180E, showing the bathymetry of the Pacific and Arctic Oceans.



Ocean Geographical Parameters

Surface Area	3.61×10^{14} m^2
Mean Depth	3.7 km
Volume	3.2×10^{17} m^3
Mean Density	1.035×10^3 kg m^{-3}
Ocean Mass	1.3×10^{21} kg

Ocean Physical Parameters

Specific Heat	c_w	4.18×10^3 J kg^{-1} K^{-1}
Latent Heat of Fusion	L_f	3.33×10^5 J kg^{-1}
Latent Heat of Evaporation	L_e	2.25×10^6 J kg^{-1}
Density of Fresh Water	ρ_{fresh}	0.999×10^3 kg m^{-3}
Viscosity	μ_{water}	10^{-3} kg m^{-1} s^{-1}
Kinematic Viscosity	$\nu = \mu_{water} / \rho$	10^{-6} m^2 s^{-1}
Thermal Diffusivity	k	1.4×10^{-7} m^2 s^{-1}

Seawater Constituents

Salt	$^0/_{00}$ (g/kg)
Chloride	18.98
Sodium	10.56
Sulphate	2.65
Magnesium	1.27
Calcium	0.40

Salt	$^0/_{00}$ (g/kg)
Potassium	0.38
Bicarbonate	0.14
Others	0.11
Overall Salinity	34.48

The relative proportion of the dissolved salts tabulated here do not vary much from place to place, since salt in the ocean largely come from weathering of continents (which is a very slow input relative to the oceanic mixing rate).

Definition: Practical salinity units (psu) is the concentration of salinity in parts per thousand (by mass) or, equivalently, grams of salt per kilogram of total water.

Seawater Equation of State

Basic structure of the equation of state:

$$\rho = \rho(T, S, p)$$

T Temperature

S Salinity

p Pressure

Typical seawater has a salinity of **34.5 psu** (practical salinity units), which is defined as the number of parts per thousand (salt to seawater). This is approximately equal to the number of **grams of salt per kilogram of seawater**.

Seawater Equation of State

Definition: Density anomaly σ is the difference between actual density and a reference density, typically taken to be 1000 kg/m³.

$$\sigma = \rho - \rho_{ref} \qquad \rho_{ref} = 1000 \text{ kg m}^{-3}$$

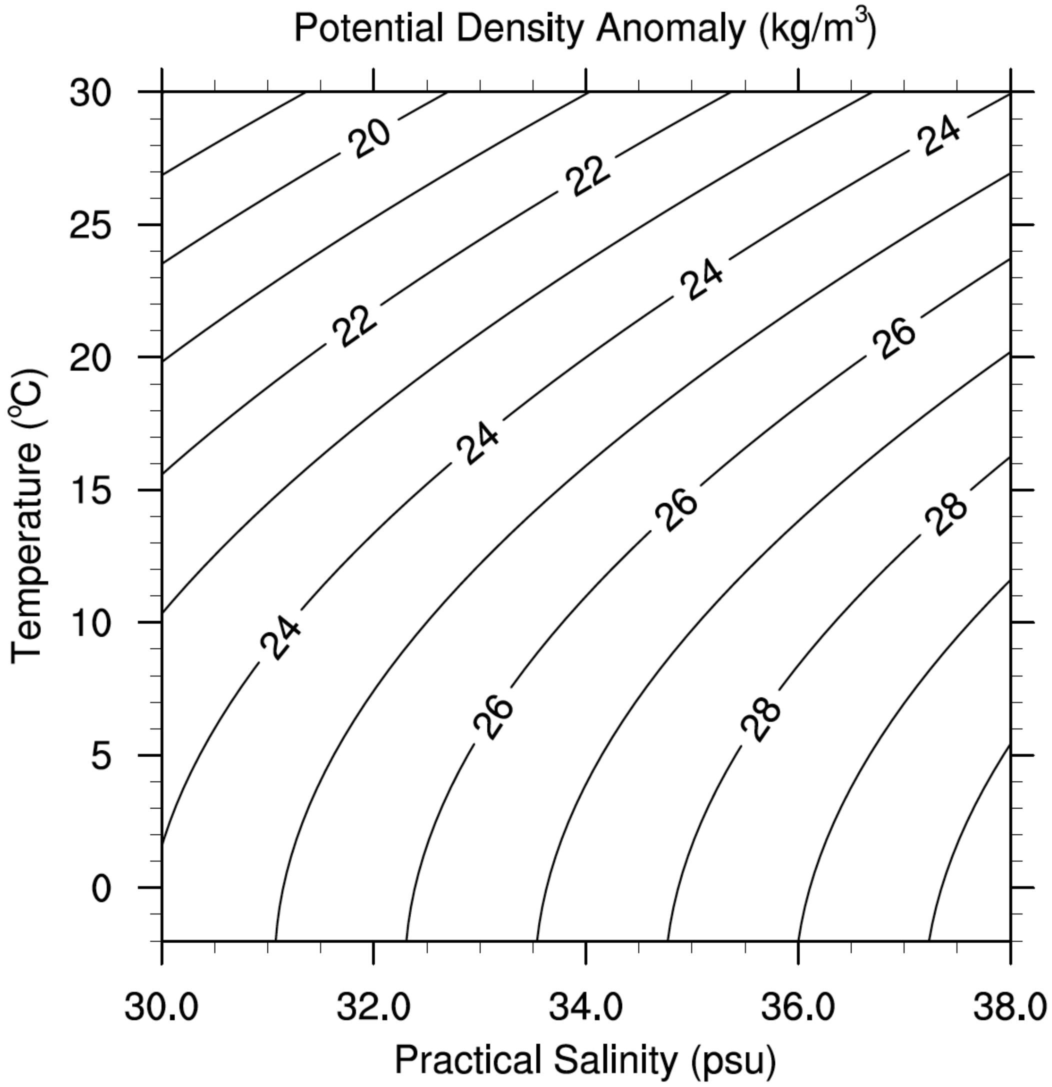
Seawater Equation of State

Recall that the equation of state for air is given by the ideal gas law, which relates density and temperature to pressure.

For sea water, the equation of state relates density to temperature, salinity and pressure.

When accuracy is needed the equation of state for seawater requires a complicated lookup table to find the density anomaly.

Figure: Density anomalies plotted against salinity and temperature.



Seawater Equation of State

Approximated equation of state by Taylor expansion

$$\sigma(T,S) \approx \sigma_0 + \rho_{\text{ref}}\Big(-\alpha_T\,[T - T_0] + \beta_S\,[S - S_0]\Big)$$

Thermal expansivity:

$$\alpha_T = -\frac{1}{\rho_{\text{ref}}}\left.\frac{\partial \rho}{\partial T}\right|_{T=T_0,S=S_0}$$

Varies between 0.3 and 2 (x 10^{-4} K^{-1})

Effect of salinity on density:

$$\beta_S = \frac{1}{\rho_{\text{ref}}}\left.\frac{\partial \rho}{\partial S}\right|_{T=T_0,S=S_0}$$

Typically near 7.6 x 10^{-4} psu^{-1}

These parameters have some dependence on pressure, temperature and salinity.

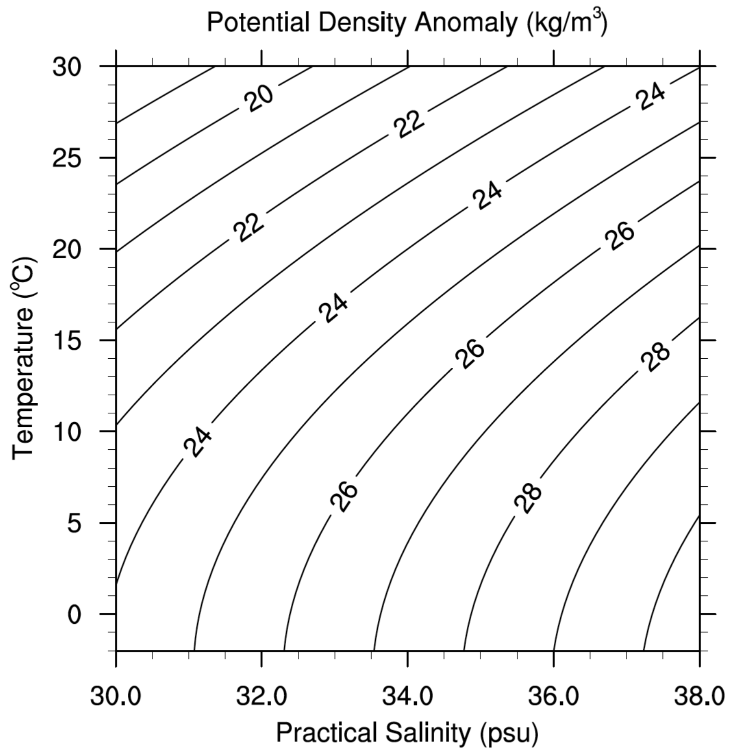


Figure: Density anomalies plotted against salinity and temperature.

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	Surface			1km Depth		
T_0	-1.5°C	5°C	15°C	-1.5°C	3°C	13°C
α (x 10^{-4} K^{-1})	0.3	1	2	0.65	1.1	2.2
S_0 (psu)	34	36	38	34	35	38
β_S (x 10^{-4} psu^{-1})	7.8	7.8	7.6	7.1	7.7	7.4
σ_0 (kg m^{-3})	28	29	28	-3	0.6	6.9

Source: Marshall and Plumb Table 9.4

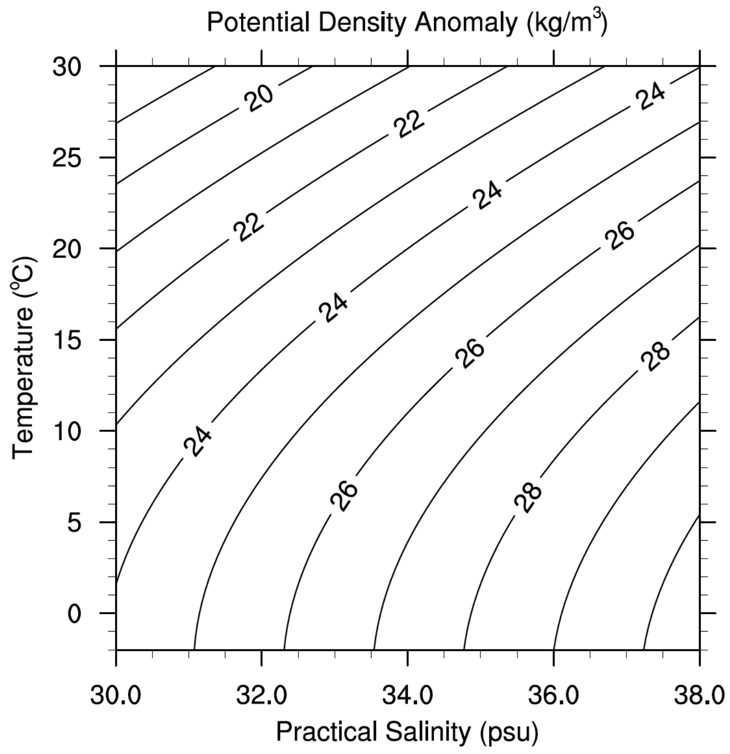


Figure: Density anomalies plotted against salinity and temperature.

Ocean Character and Structure

SODA3 Data

In this lecture, plots have been produced using Simple Ocean Data Assimilation ocean/sea ice reanalysis version 3 (SODA3) data

Carton, J. A., G. A. Chepurin, L. Chen, S. Grodsky, E. Kalnay, and S. G. Penny. 2019. *SODA Project: SODA3 Ensemble Means and Standard Deviations*. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. https://doi.org/10.5065/HBTB-R521. Accessed 18 04 2020.

Surface Salinity

Figure: Surface practical salinity from SODA3.

Over long time periods, ocean salinity originates from weathering of rocks.

Latitudinal variations in salinity are primarily driven by precipitation and evaporation.

Evaporation increases salinity by removing fresh water. Precipitation decreases salinity by adding fresh water.

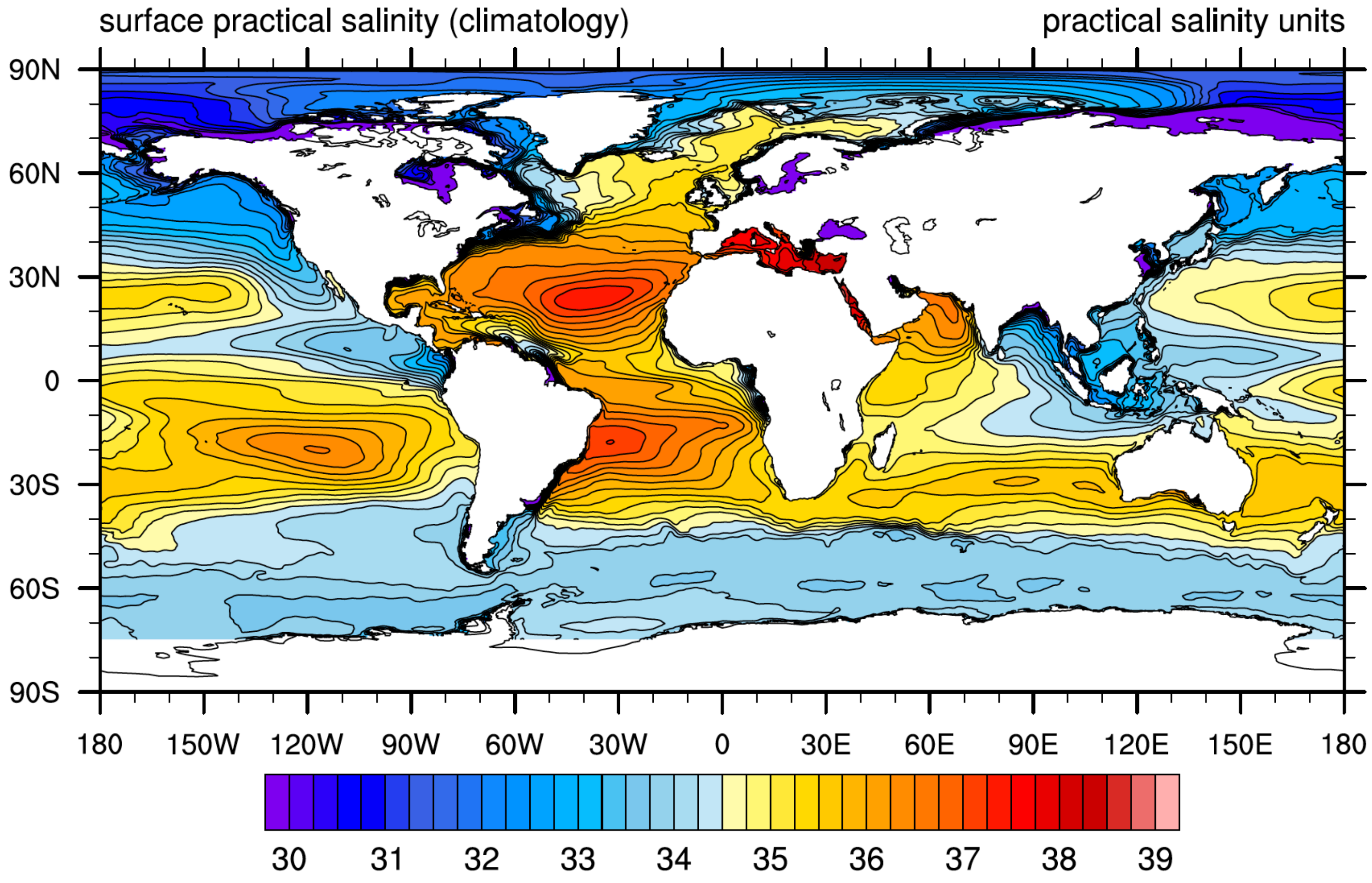


Figure: Annual mean salinity distribution at the surface of the ocean (in PSU).

Sea Surface Temperature (°C)

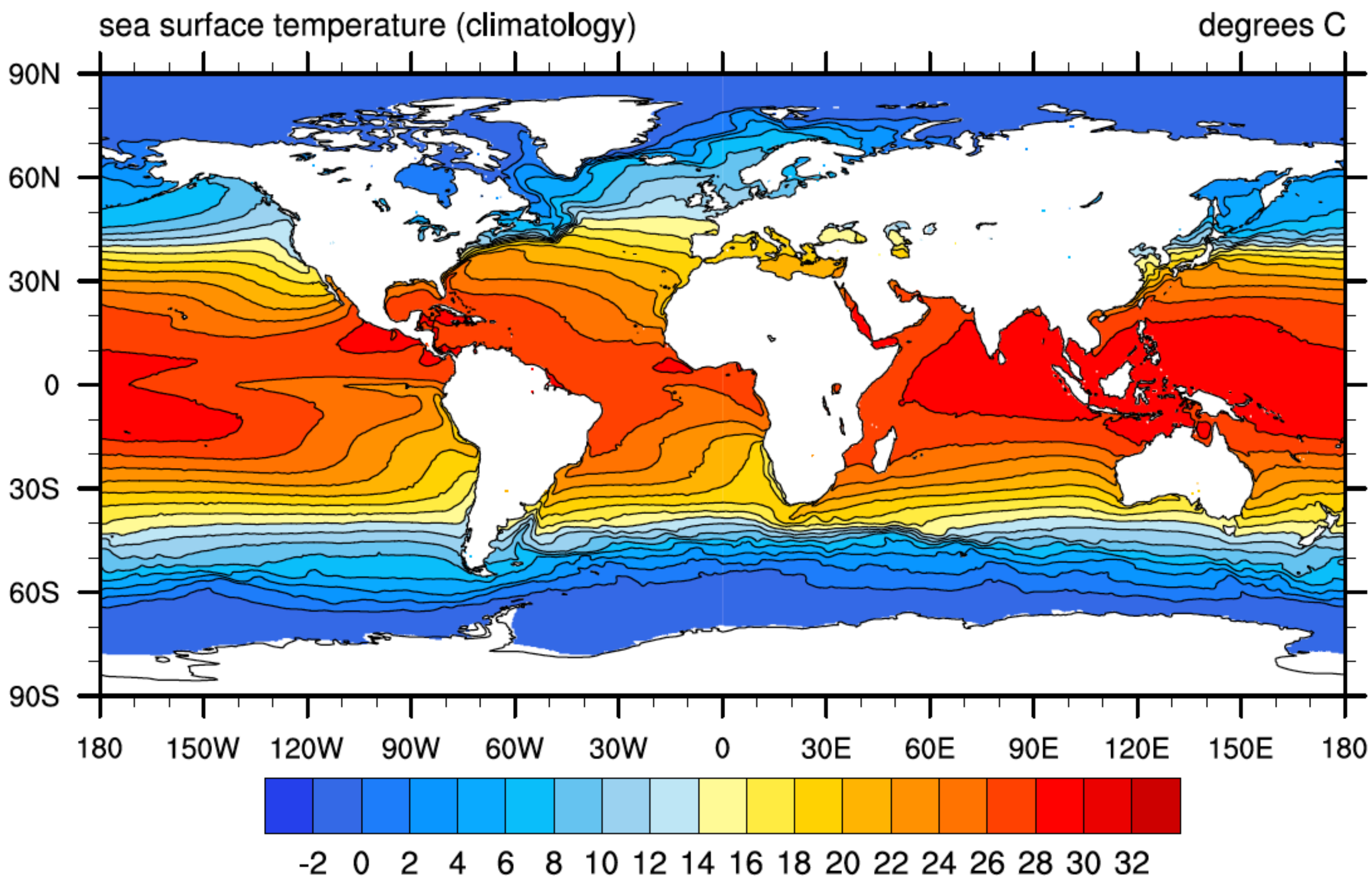
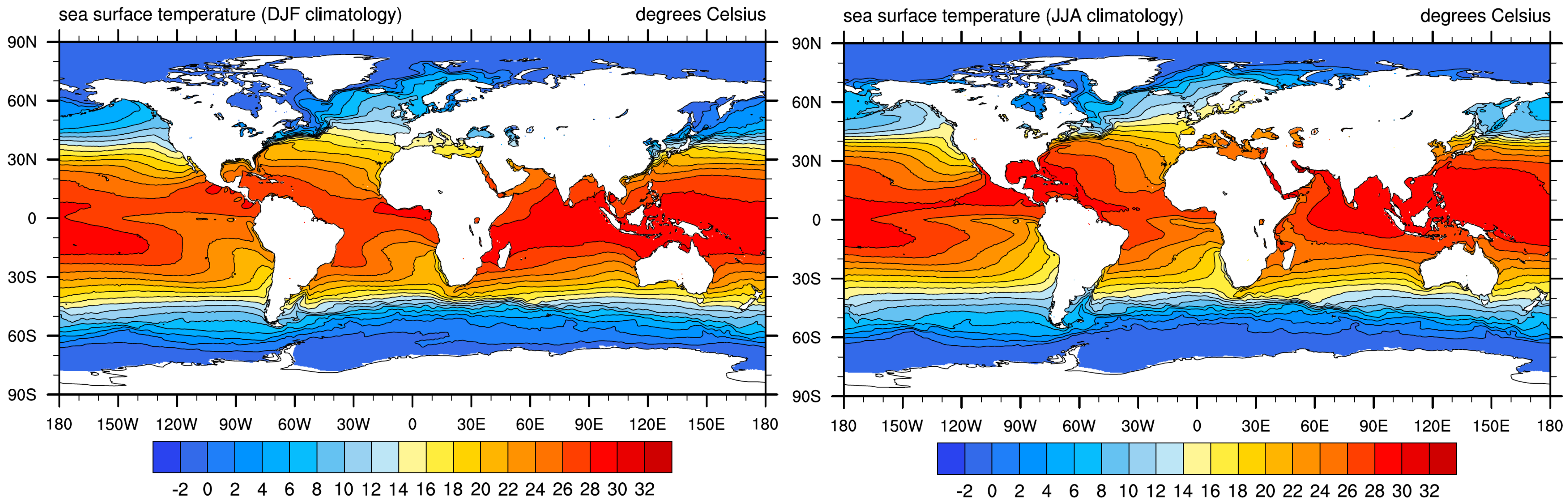


Figure: Average annual-mean sea-surface temperatures from ECMWF ERA5.

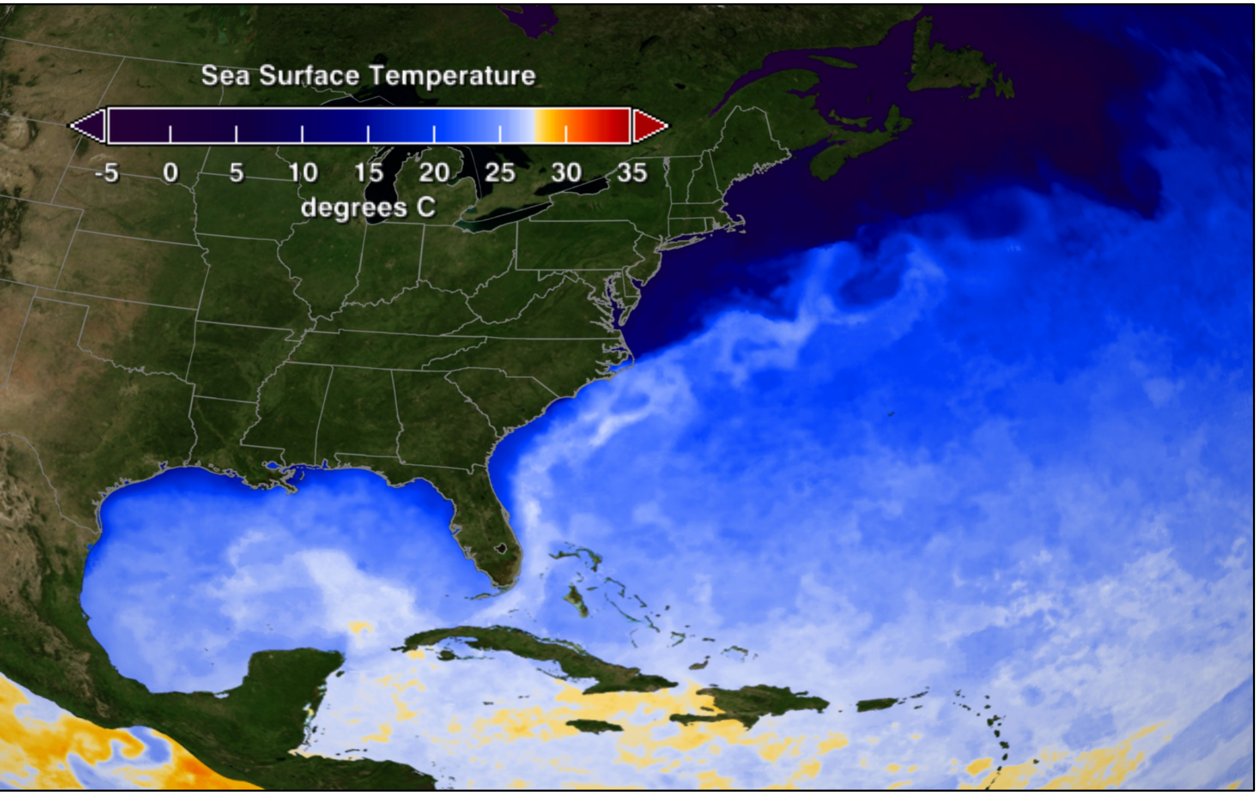
Sea Surface Temperature (^oC)

Figure: DJF and JJA sea-surface temperatures (neglecting ice extent).

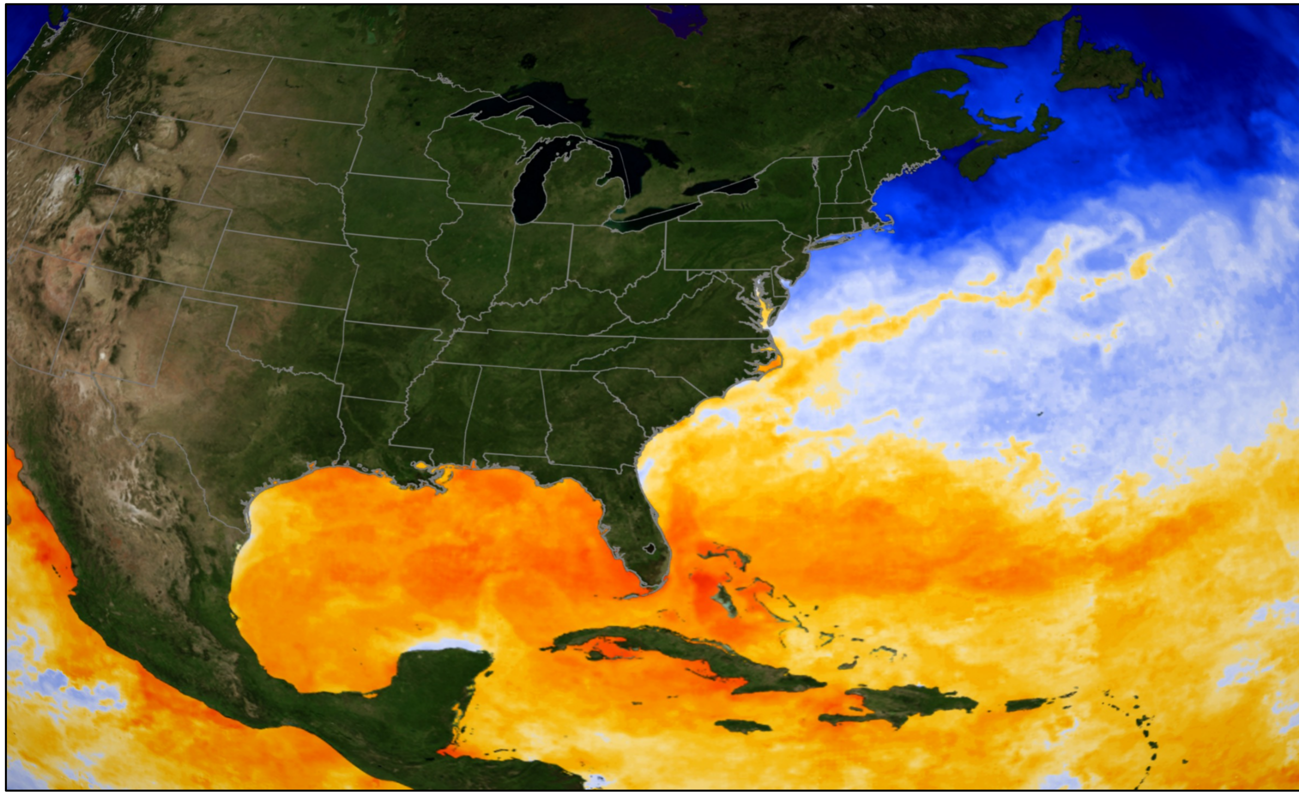


Sea Surface Temperatures

January 1st, 2008



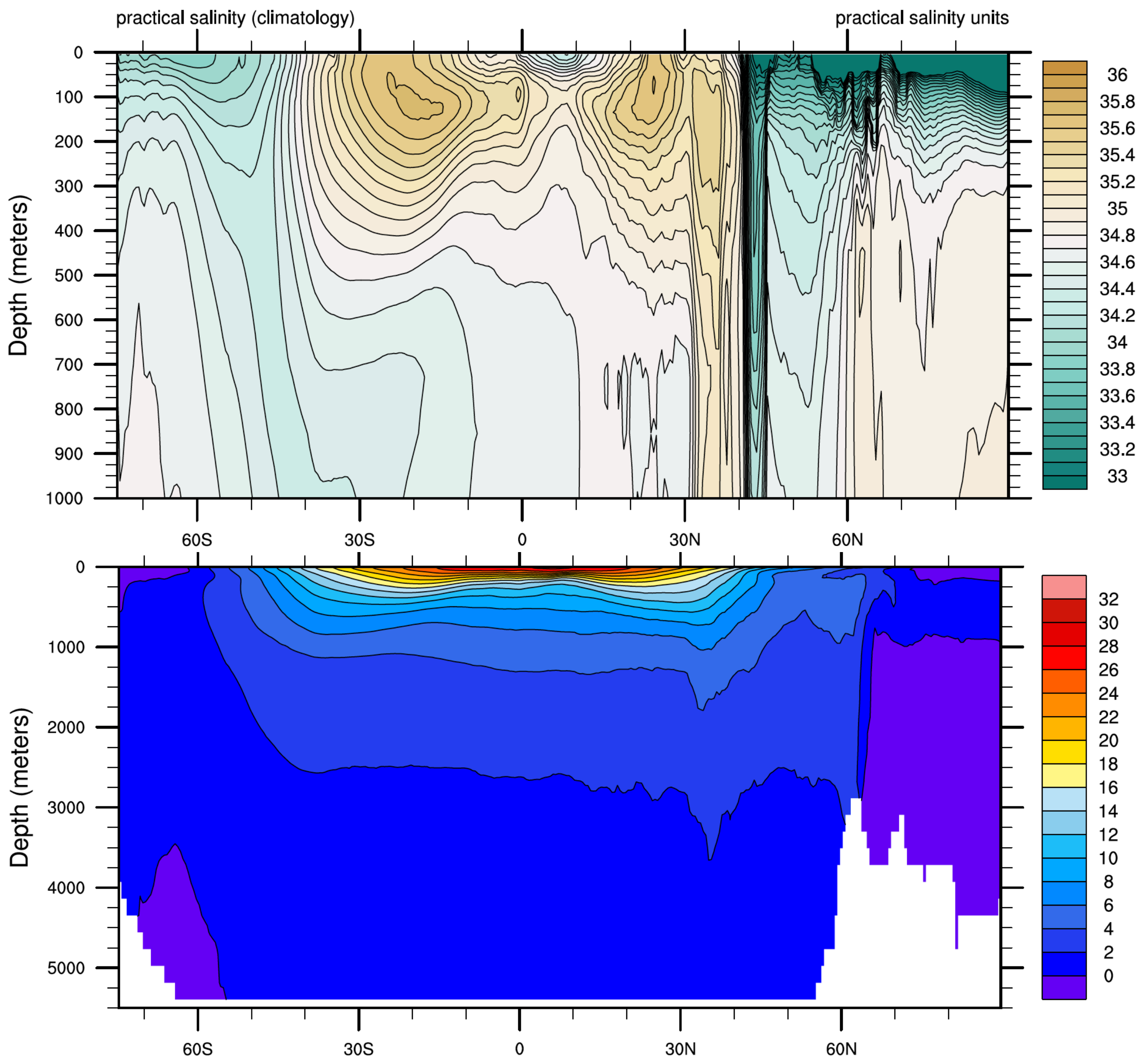
August 1st, 2008



Temperature

Figure: Zonal average annual-mean potential temperature in the world oceans.

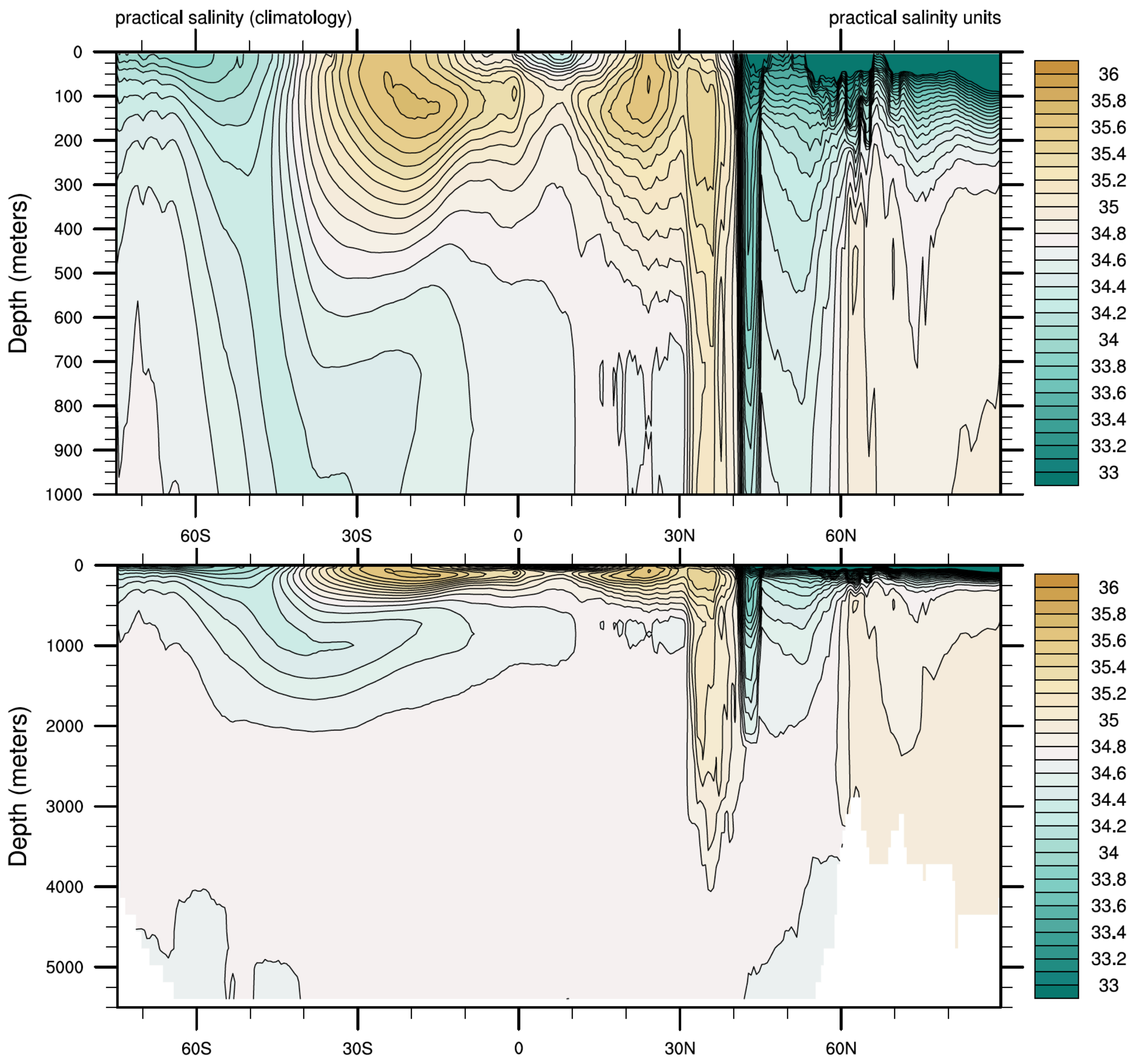
Temperatures follow atmospheric temperatures at the near-surface, but are largely uniform at depths below 1000 meters.



Salinity

Figure: Zonal average annual-mean salinity in the world oceans.

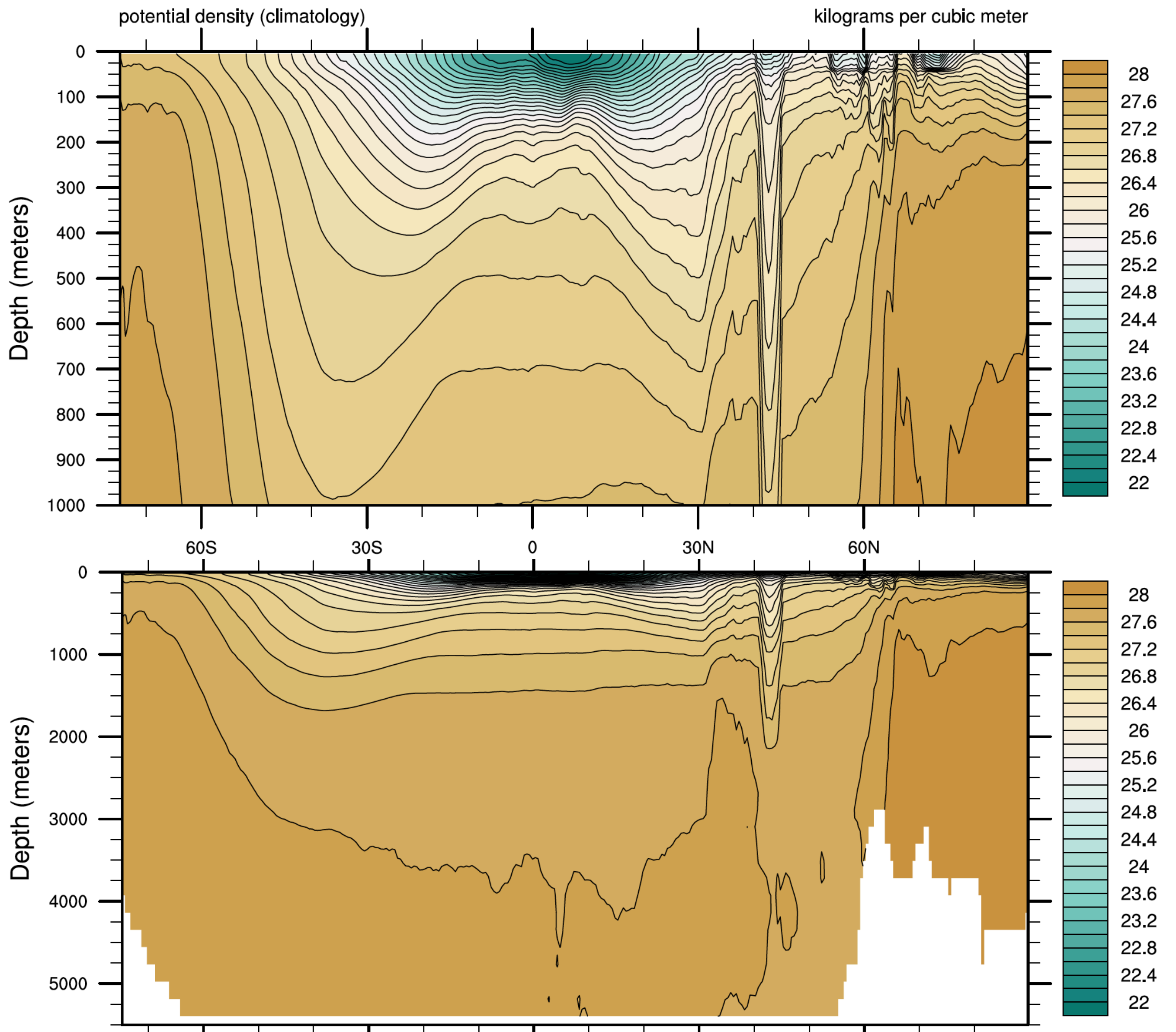
The spike in salinity with depth driven by averaging over the Mediterranean.



Potential Density

Figure: Zonal average annual-mean potential density anomaly in the world oceans. Note that darker colors indicate less dense fluid. Compare with zonal average annual-mean temperature.

$$\sigma = \rho - \rho_{ref}$$



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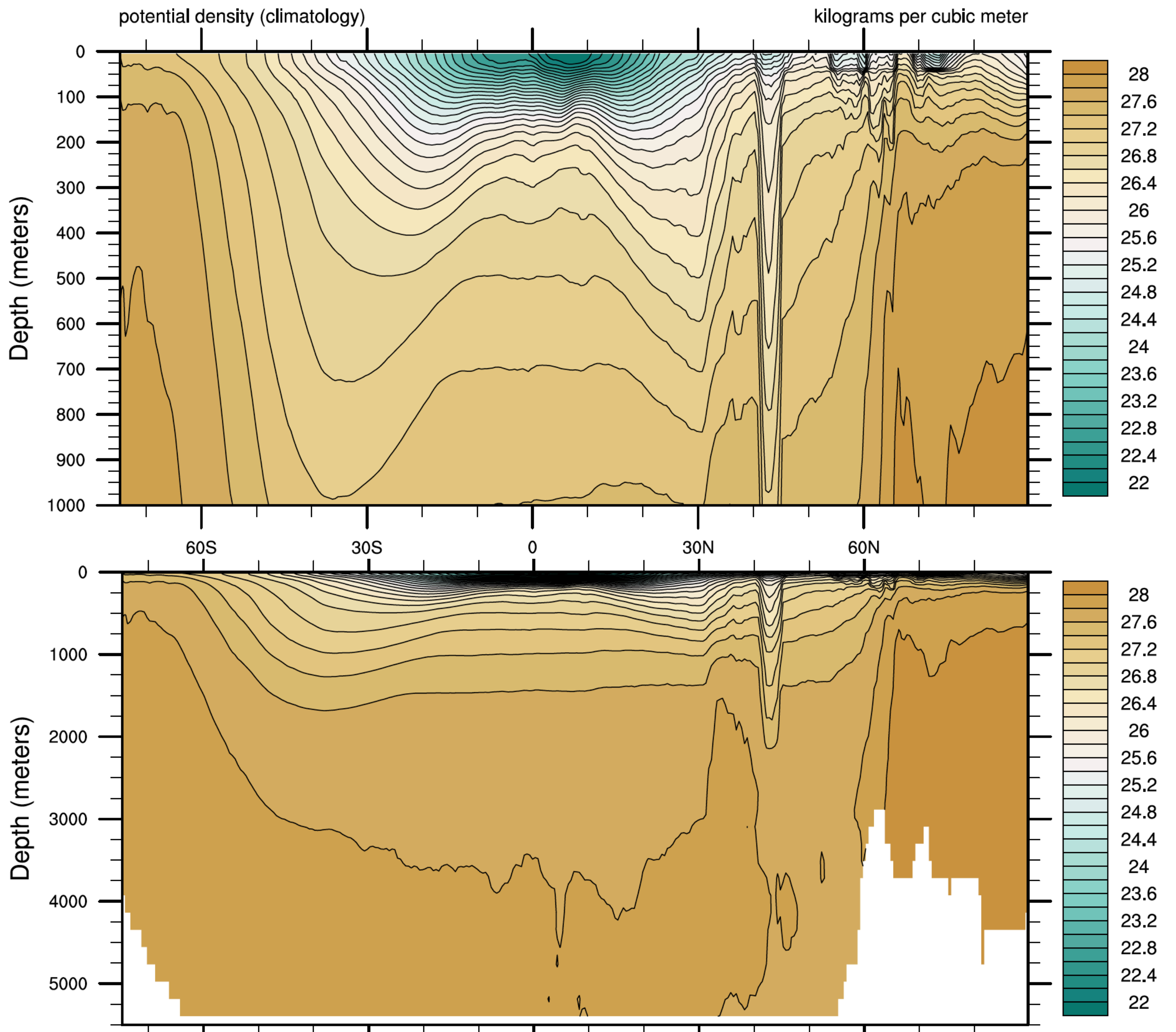
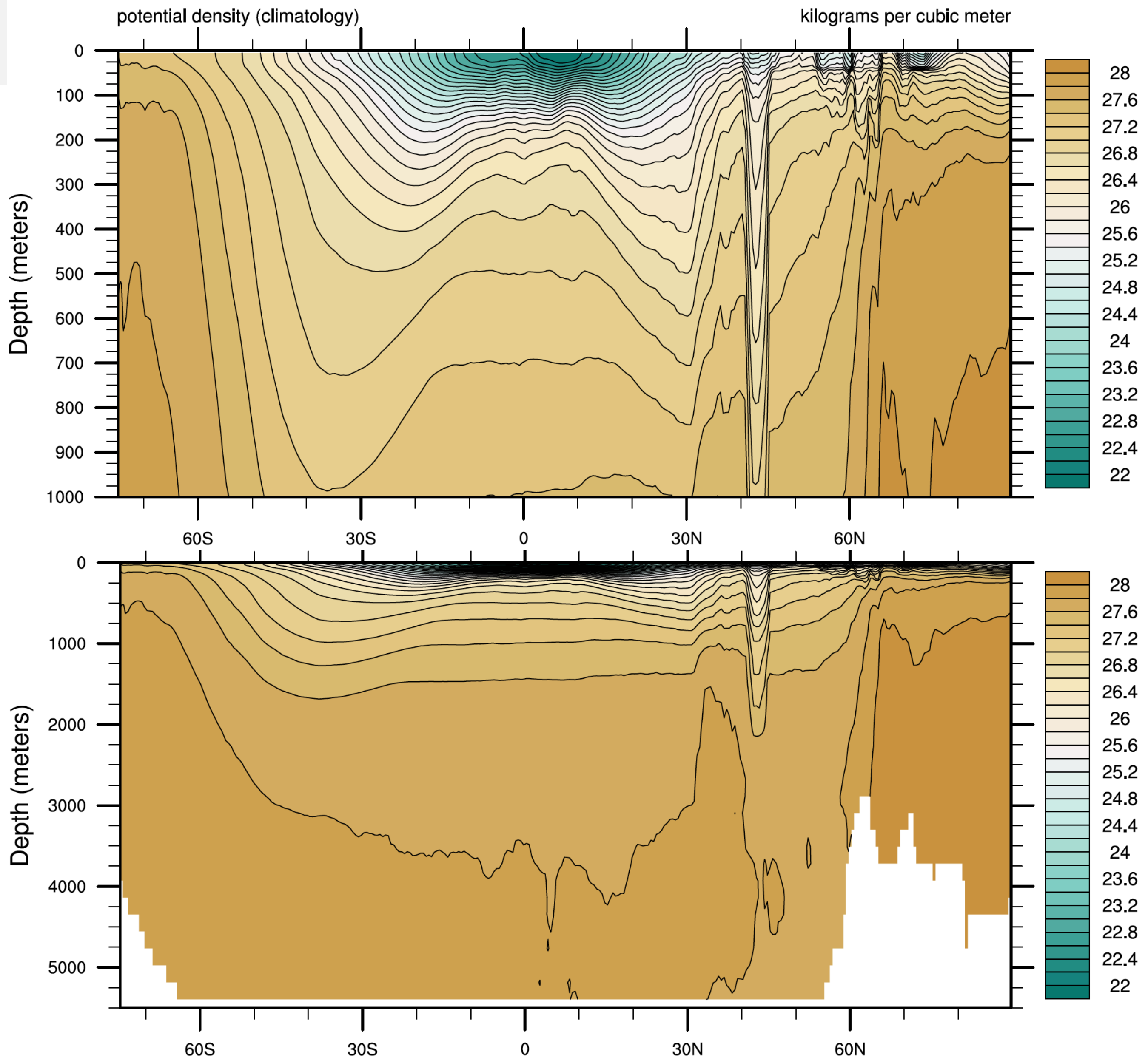


Ocean Density Structure

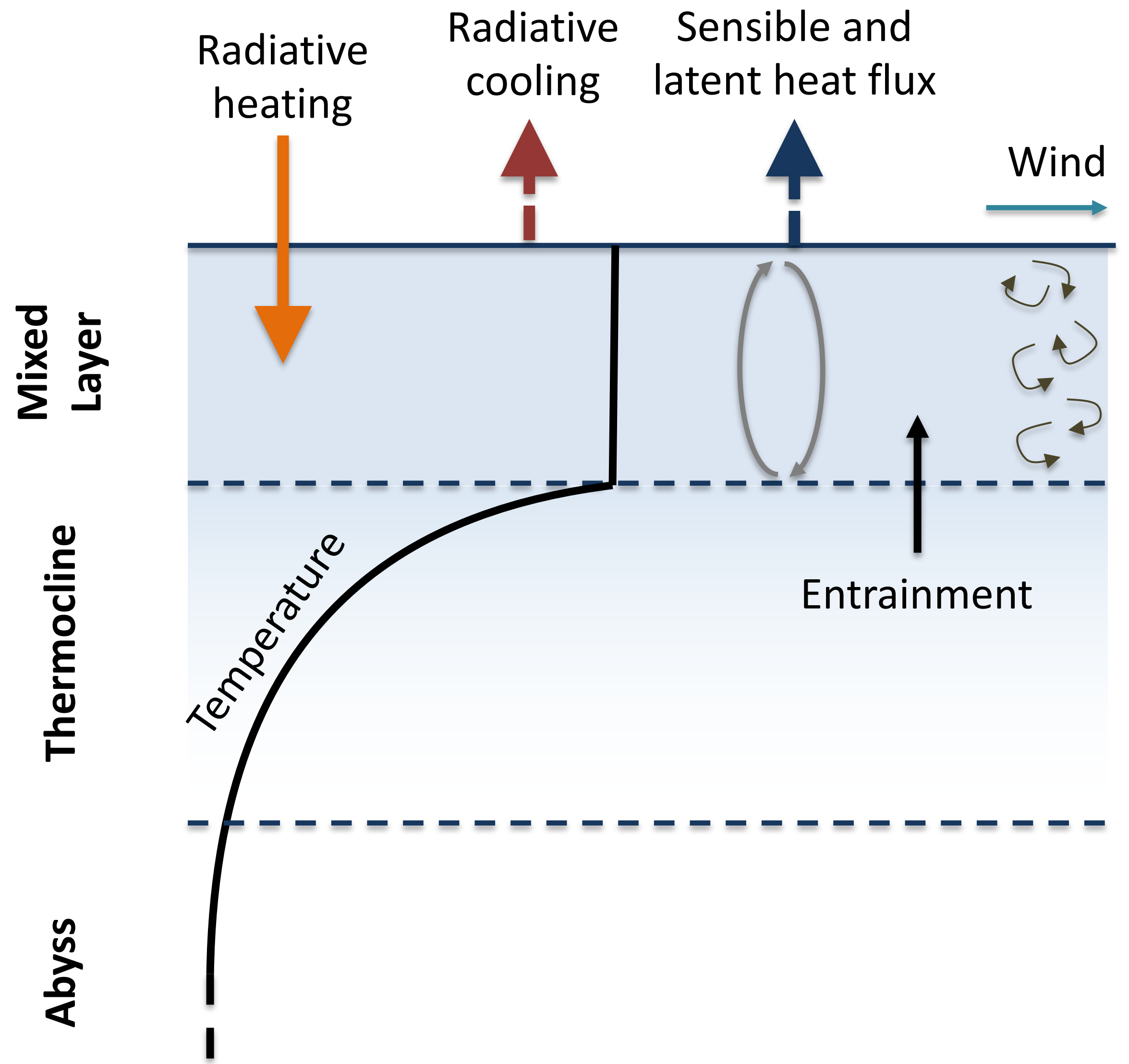
Definition: The **Surface Zone** is the upper layer of the ocean containing the least dense water (about 2% of ocean volume).

Definition: The **Pycnocline** is a zone in which density increases rapidly with depth (about 18% of ocean volume).

Deep ocean waters make up about 80% of all ocean water and refer to regions where there is little change in density. Much of this water originates at the surface in the high latitudes where it cools and sinks.



Ocean Temperature Structure



Definition: The **Mixed Layer** is a layer in which active turbulence has homogenized some range of depths.

Definition: The **Thermocline** is a layer of fluid where the temperature changes more rapidly than in layers above or below.

Definition: The **Abyss** is the deepest part of the open ocean, below 4000m depth. This region is in complete darkness and (largely) thermodynamically homogeneous.

Ocean Structure

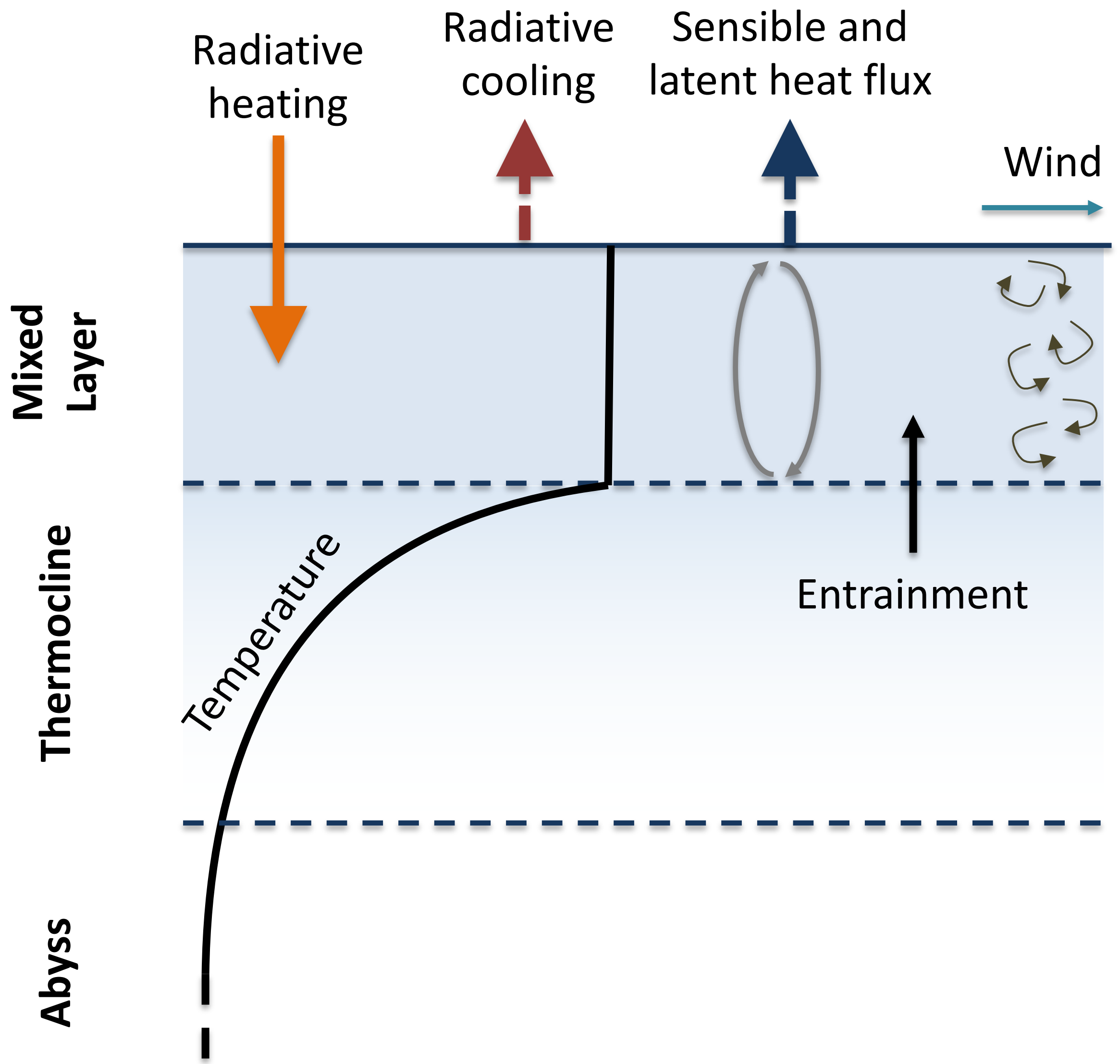
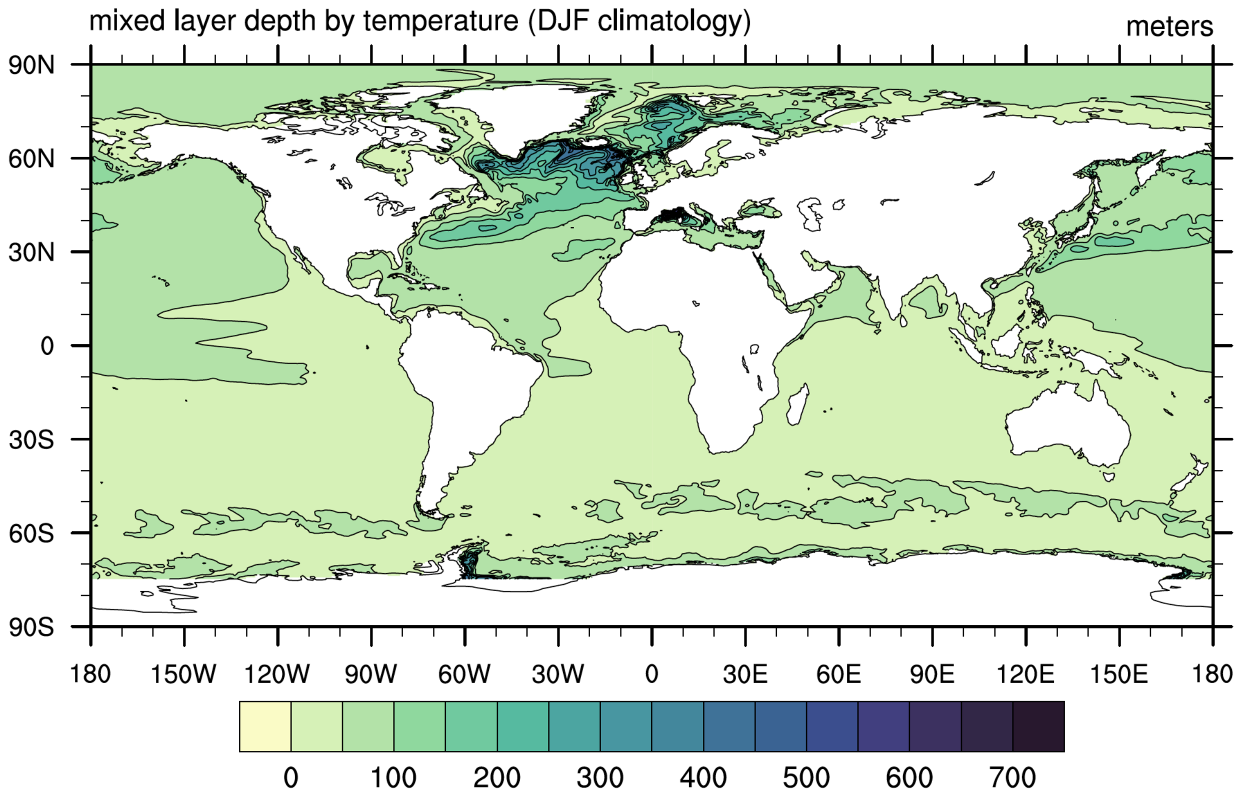


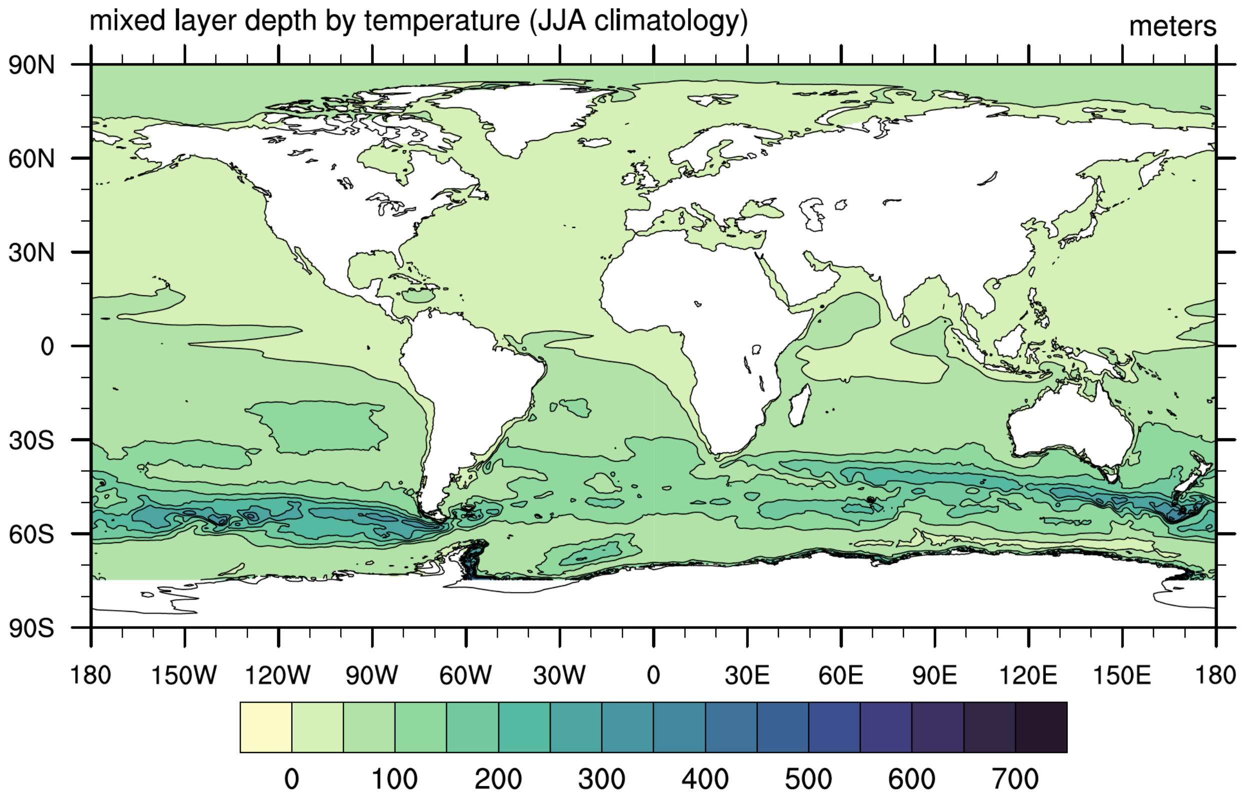
Figure: Schematic diagram showing processes at work in the mixed layer of the ocean. Note that the vertical scale is exaggerated.

Mixed Layer Depth

Figure: Mixed layer depth (in meters) for DJF (left) and JJA (right).

The mixed layer is deepest in the wintertime of each hemisphere, when strong winds and surface friction drive turbulence to depth.





Temperature and Salinity at Depth

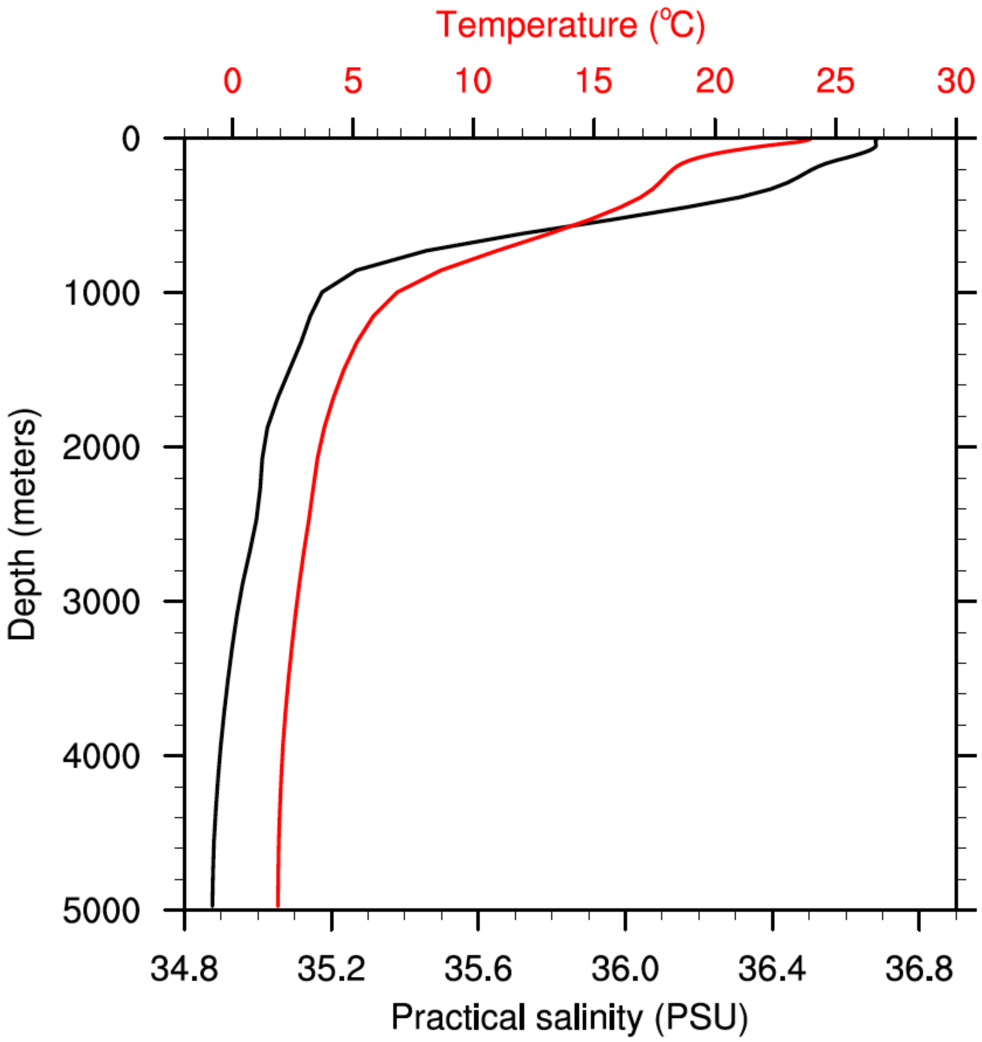


Figure: Annual mean T and S profile at 50W, 30N in the Atlantic Ocean. The thermocline is clearly evident near the surface. The relative homogeneity of the ocean below depths of 2000m is apparent.

Temperature and Salinity at Depth

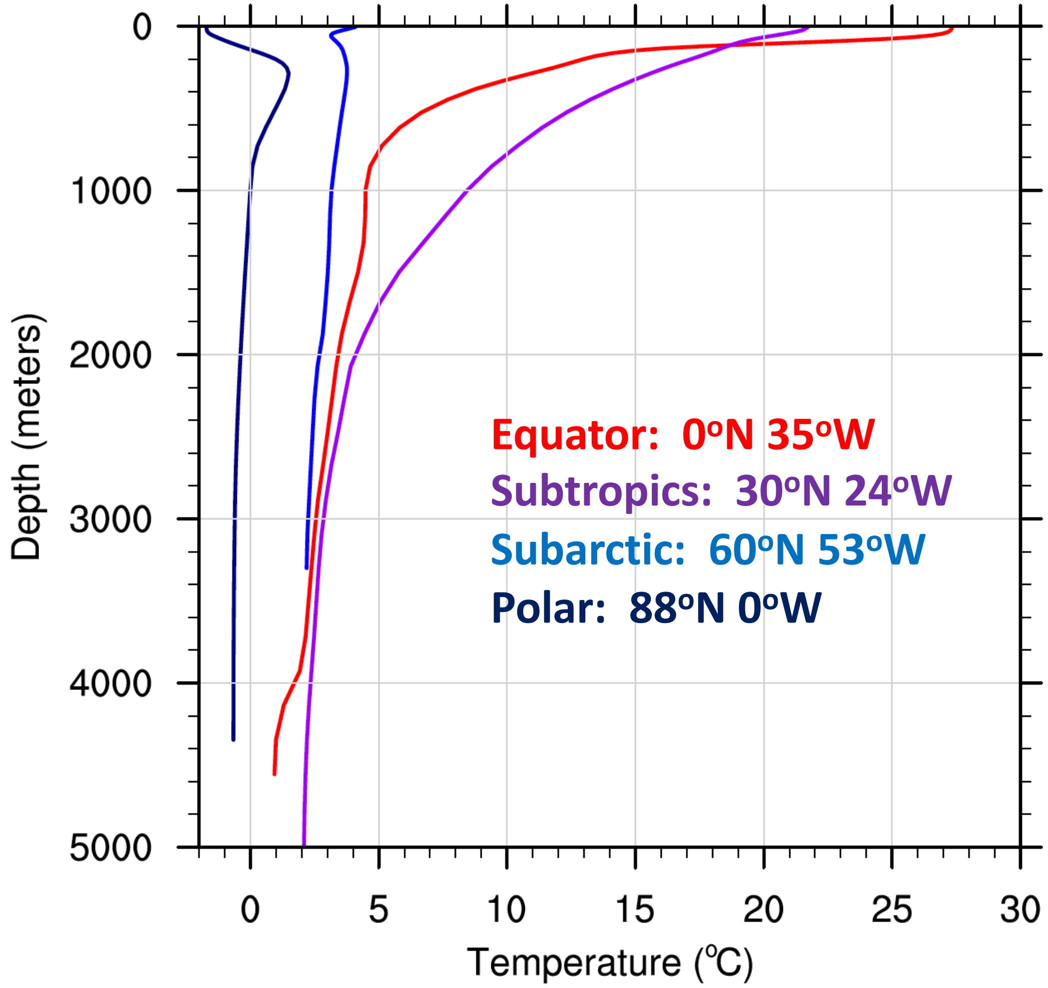


Figure: Annual mean T profile at various points in the Atlantic and Arctic Oceans.

The thermocline is clearly evident near the surface in the subtropics and equatorial region, but disappears at higher latitudes.

The relative homogeneity of Atlantic ocean temperatures below depths of 2000m is apparent.

Temperature Seasonality

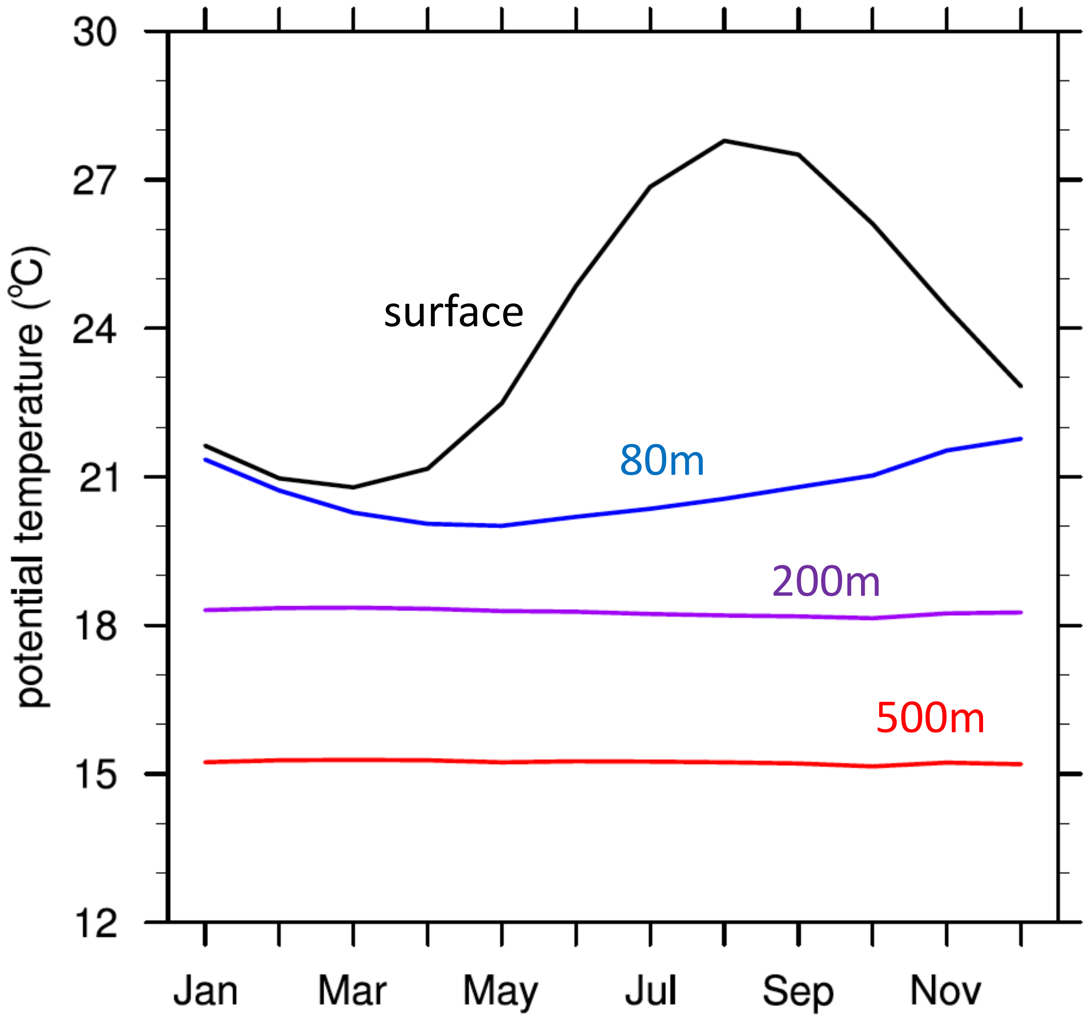


Figure: T profile at 50W 30N in the Atlantic Ocean at various depths. A strong seasonal cycle is apparent in temperature at the surface which disappears rapidly at depth.

The Observed Mean Circulation

Observed Mean Circulation

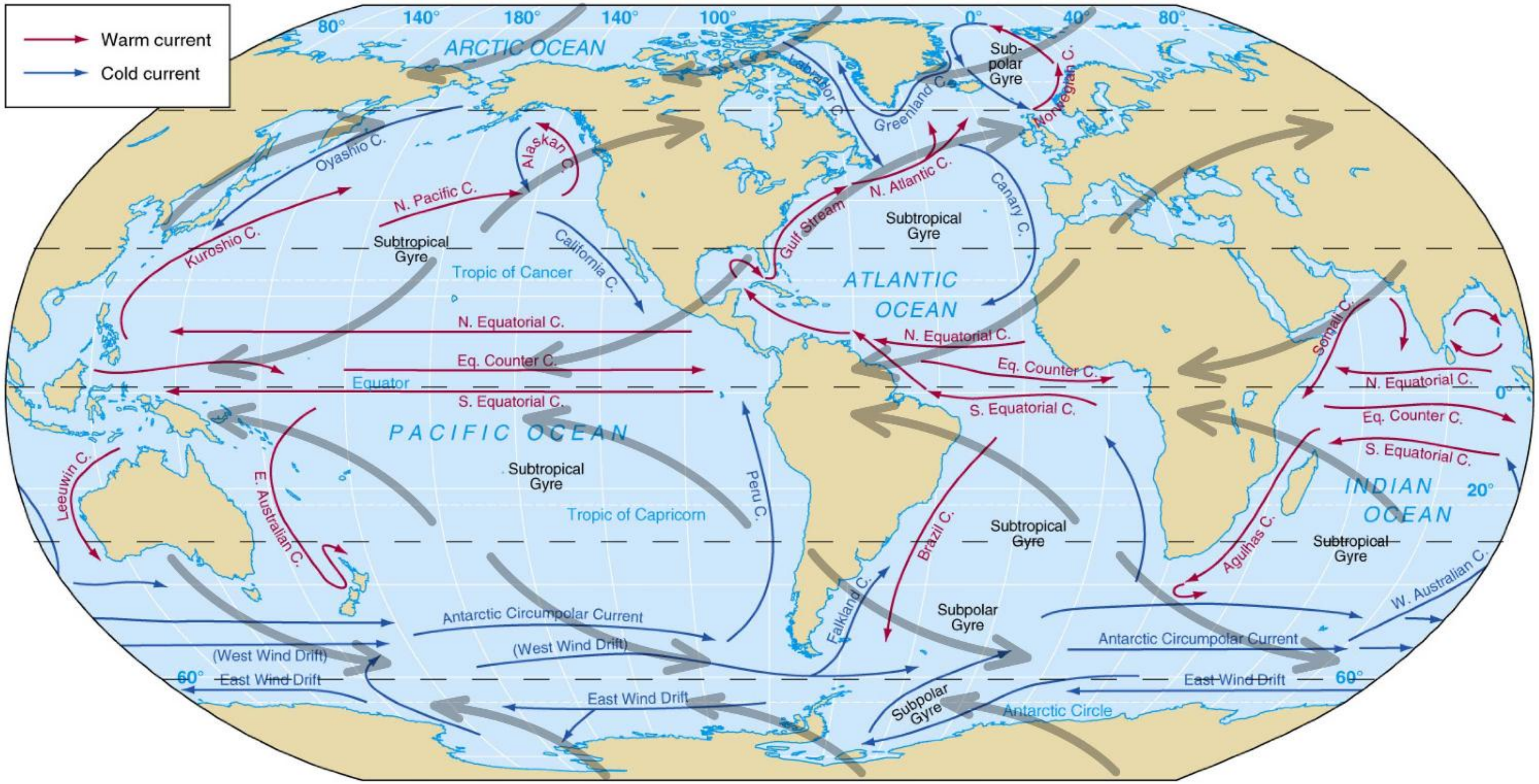
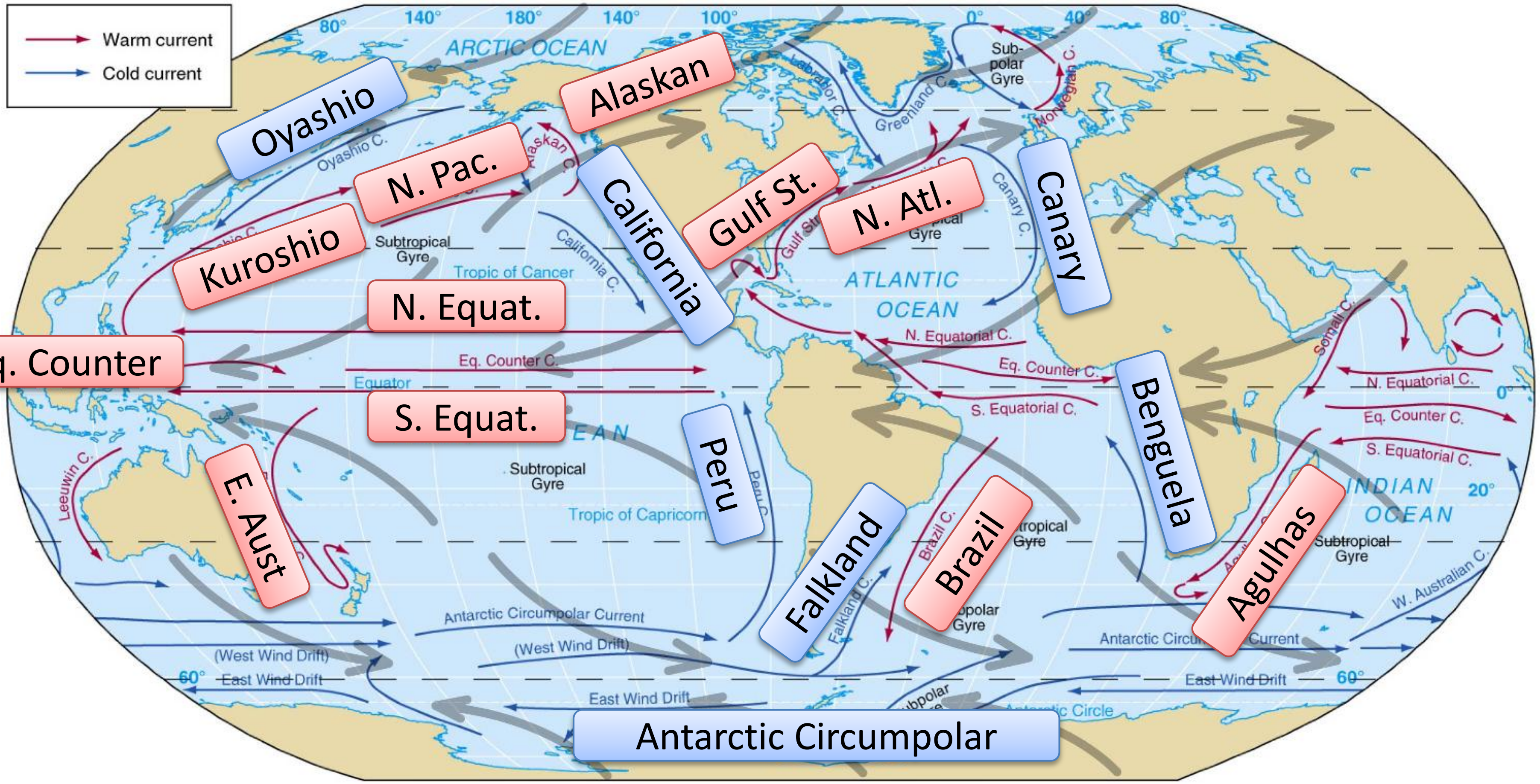


Figure: Major surface currents (with overlaid atmospheric circulation). Warm surface currents are indicated in red; cold surface currents are indicated in blue.

Observed Mean Circulation



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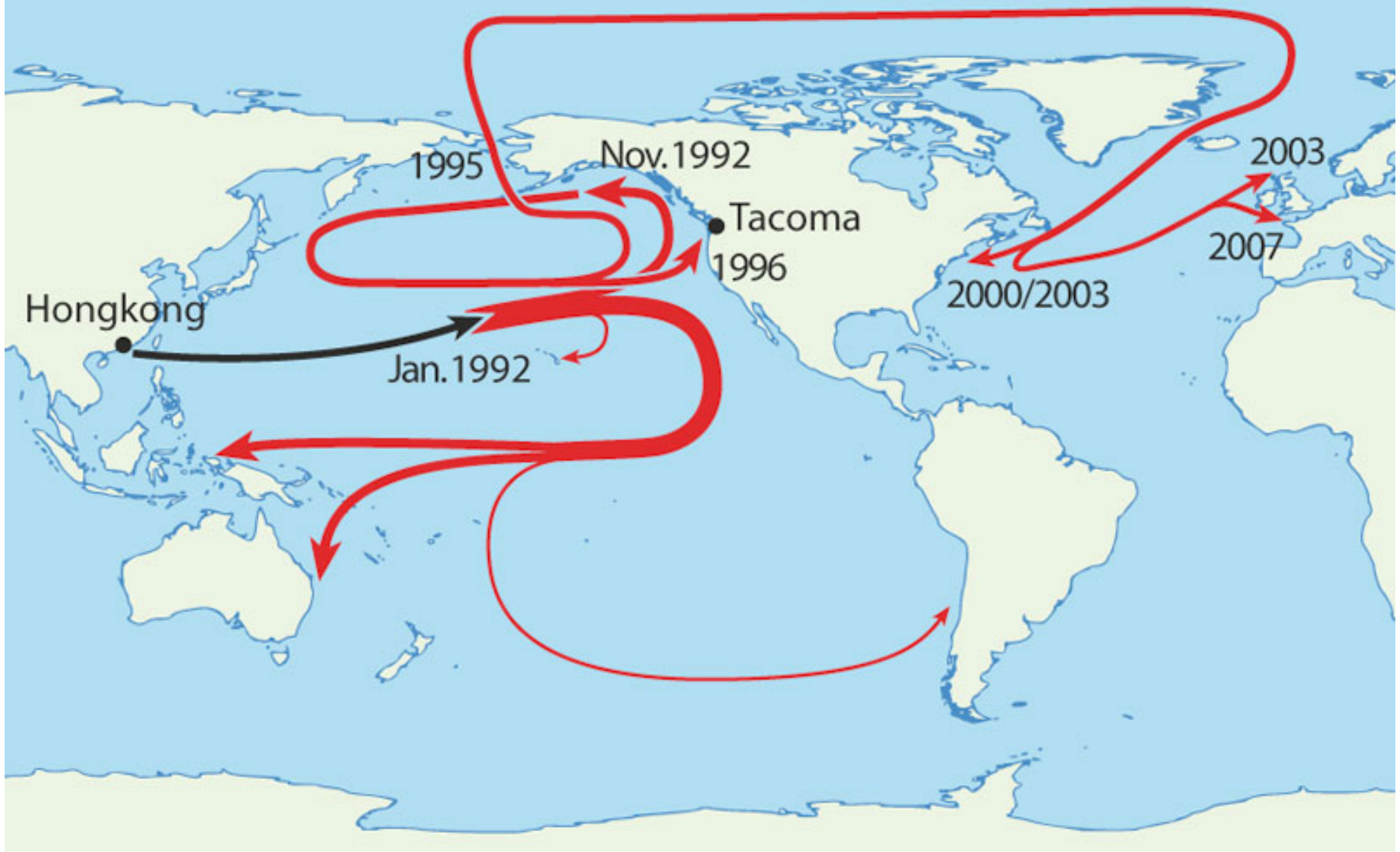
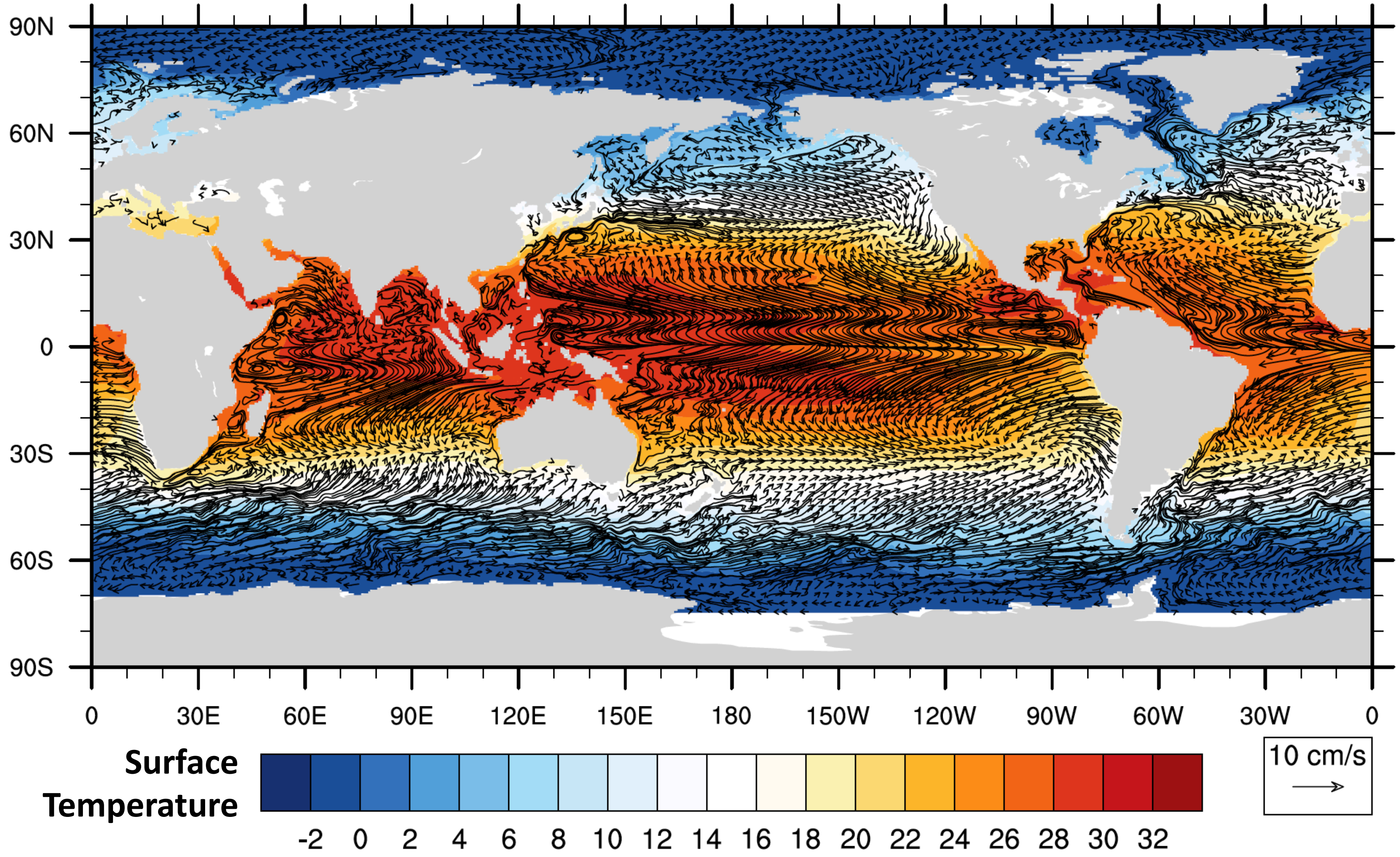


Figure: In 1992, approximately 29000 rubber duckies fell off a cargo ship in the middle of the Pacific. They have been making landfall all over the world ever since. https://en.wikipedia.org/wiki/Friendly_Floatees

Current Observations

- Ocean currents are typically **100 times weaker than atmospheric winds**. Observations of ocean currents are typically obtained using surface drifters.
- Flow is dominated by closed-circulation patterns known as **gyres**, driven by the oceanic boundaries.
- The **mid-latitudes** are dominated by **anti-cyclonic gyres** (clockwise in northern hemisphere, counter-clockwise in southern hemisphere).
- Typical current speeds in the interior of gyres are < 10 cm/s. At the western edge of these subtropical gyres are strong poleward currents reaching speeds > 100 cm/s. No strong equatorward currents are observed.
- The north polar regions also have cyclonic gyres (counter-clockwise in the northern hemisphere), known as the sub-polar gyres.

Global Ocean Surface Currents

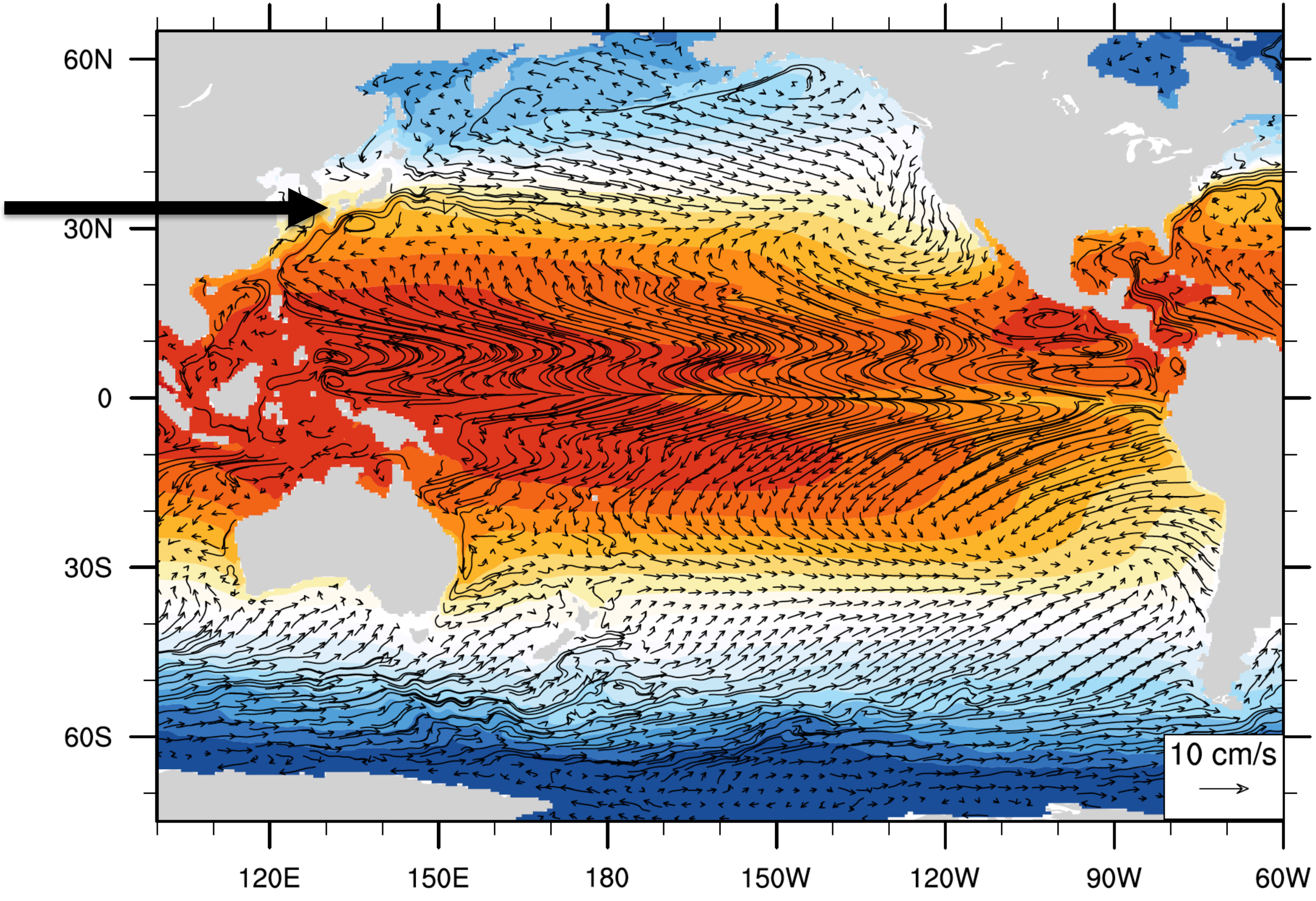


Pacific Ocean Surface Currents

Figure: Major surface currents in the Pacific Ocean from SODA3.

The Kuroshio Current is an example of a strong western boundary current, transporting warm subtropical waters into the North Pacific.

On the eastern flank of the North Pacific the flow is northerly, leading to cold ocean temperatures along the US West Coast.

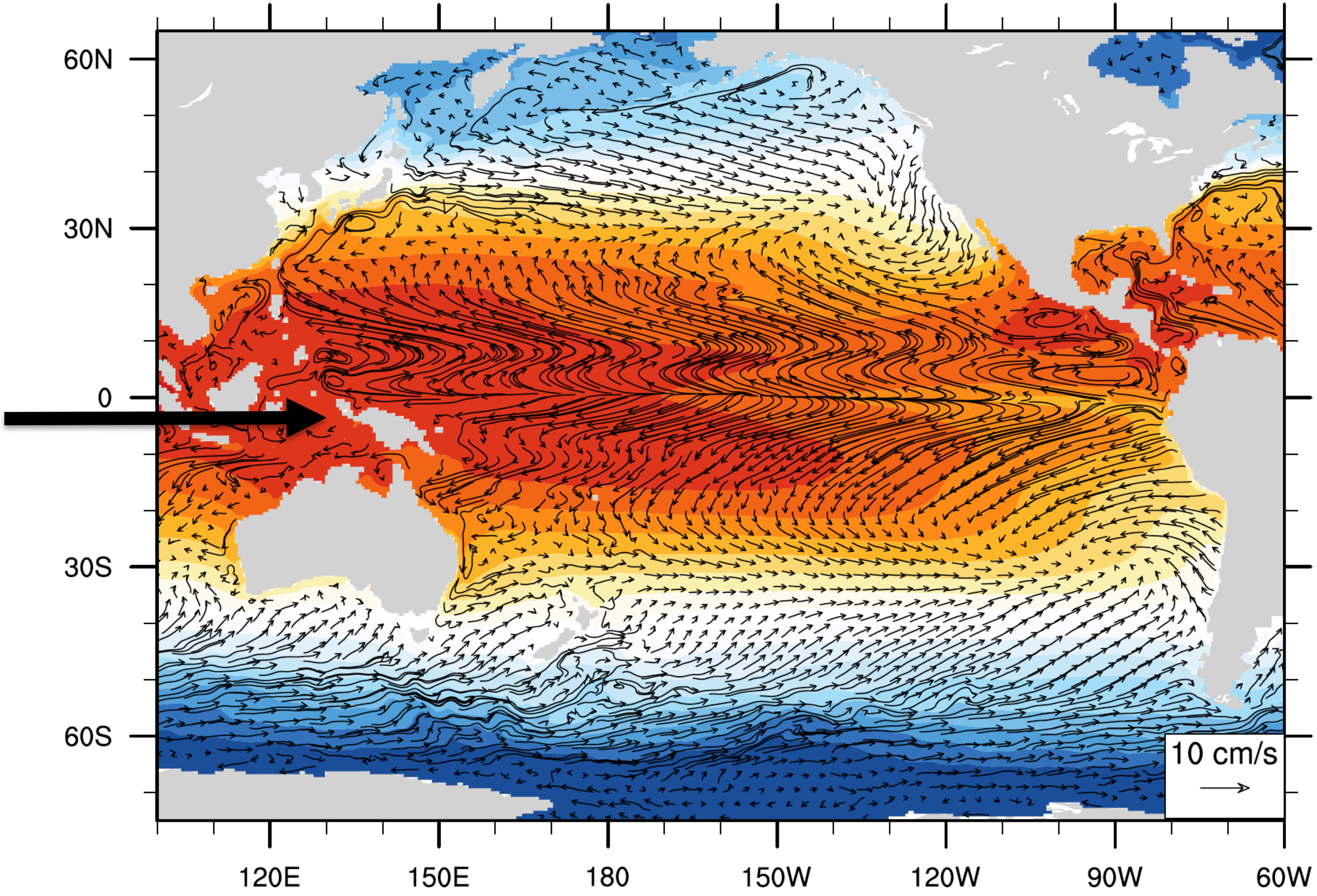


Pacific Ocean Surface Currents

Figure: Major surface currents in the Pacific Ocean from SODA3.

Observe equatorial current and midlatitudinal currents driven by prevailing winds. Also observe equatorial counter-current (against prevailing winds).

The counter-current driven by zonal temperature gradients in the tropics (see El Niño-Southern Oscillation, ENSO).

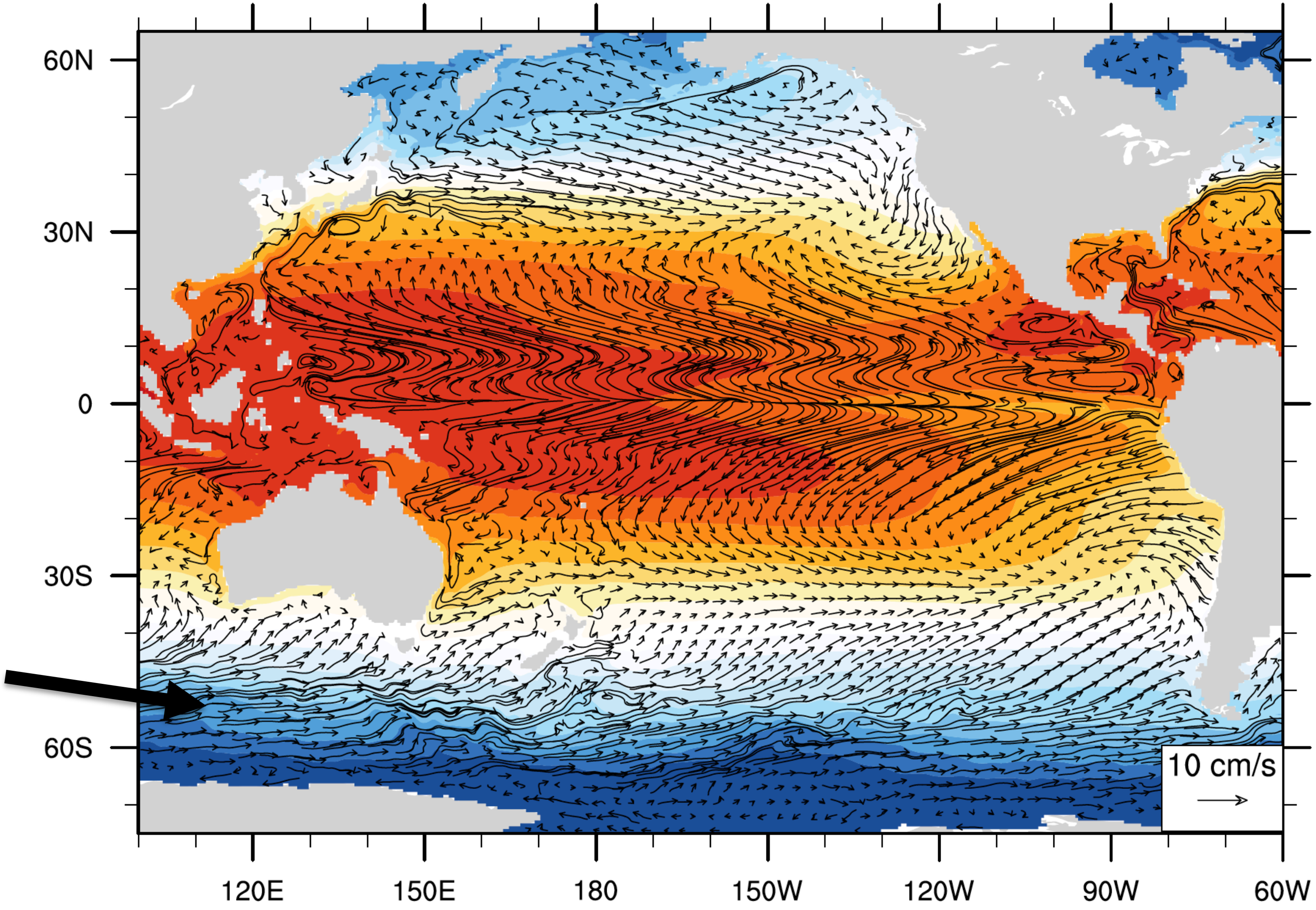


Pacific Ocean Surface Currents

Figure: Major surface currents in the Pacific Ocean from SODA3.

Observe strong eastward circulation in the Southern hemisphere around Antarctica (Antarctic Circumpolar Current, ACC).

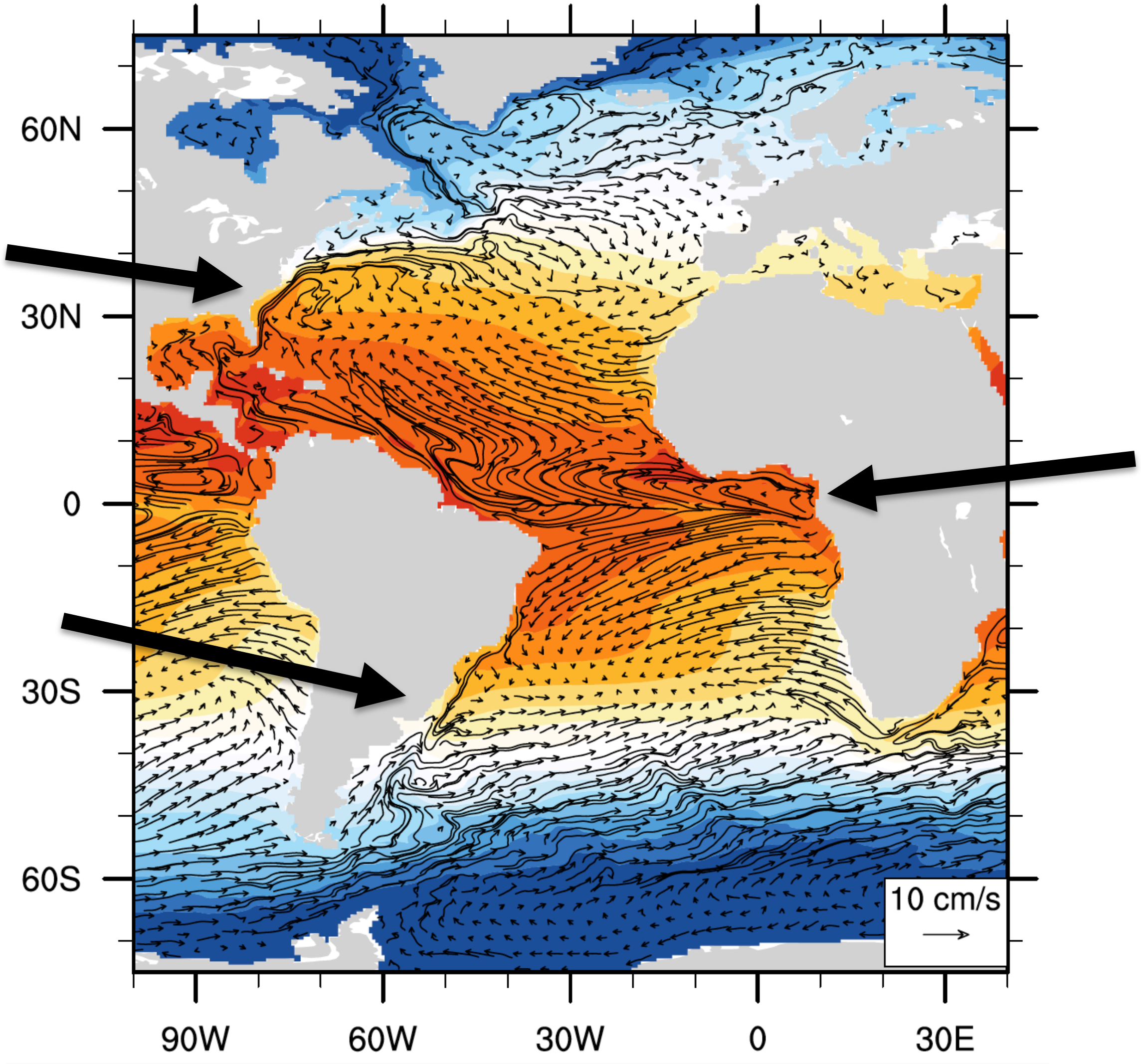
This current is most closely analogous to the atmospheric jet stream. Typical currents are about 30 cm/s, and so circumnavigate the globe in ~ 2 years.



Atlatnic Ocean Surface Currents

Figure: Major surface currents in the Atlantic Ocean from SODA3.

Note the strong equatorial currents and equatorial counter currents, weak eastern boundary currents, and strong western boundary currents (including the Gulf Stream).



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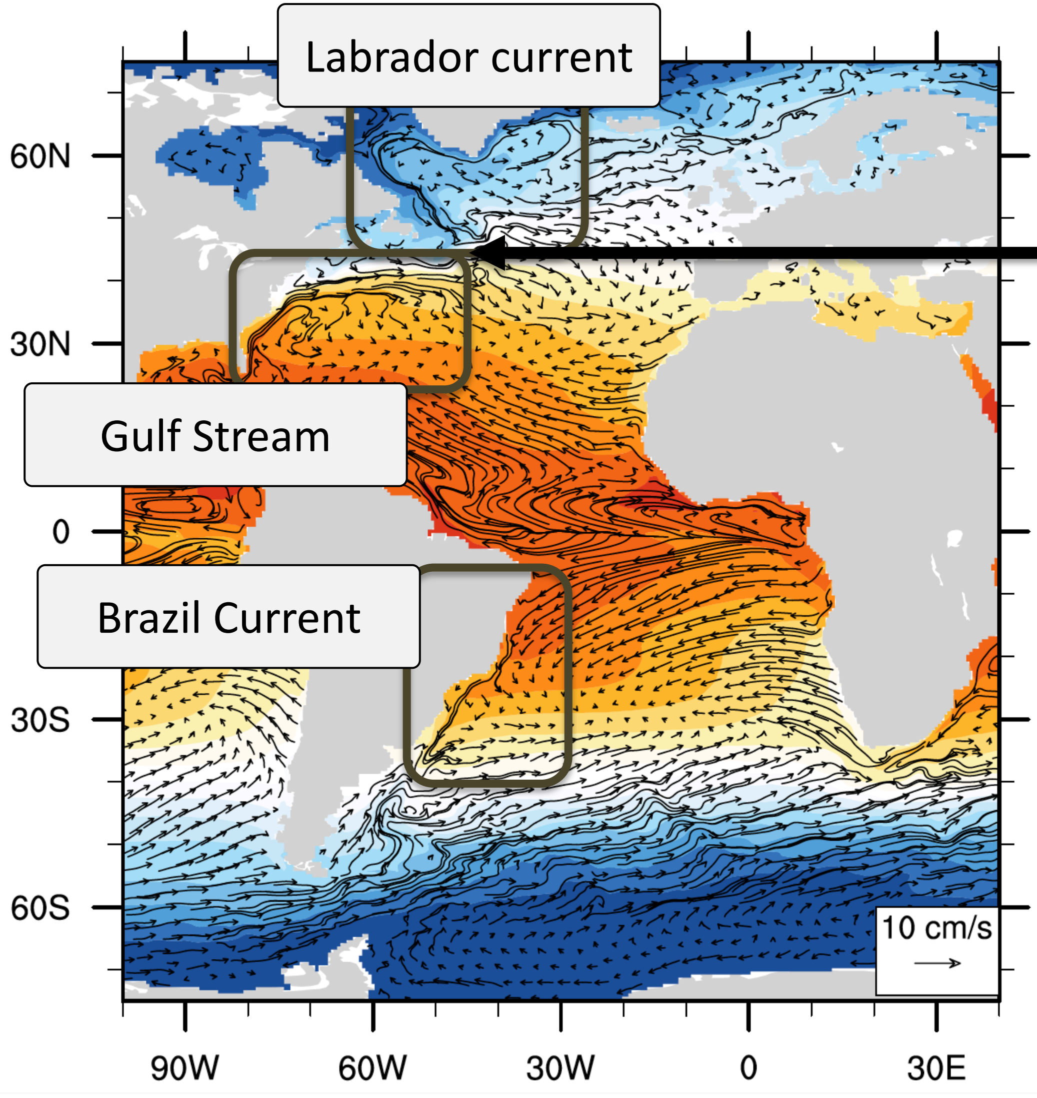
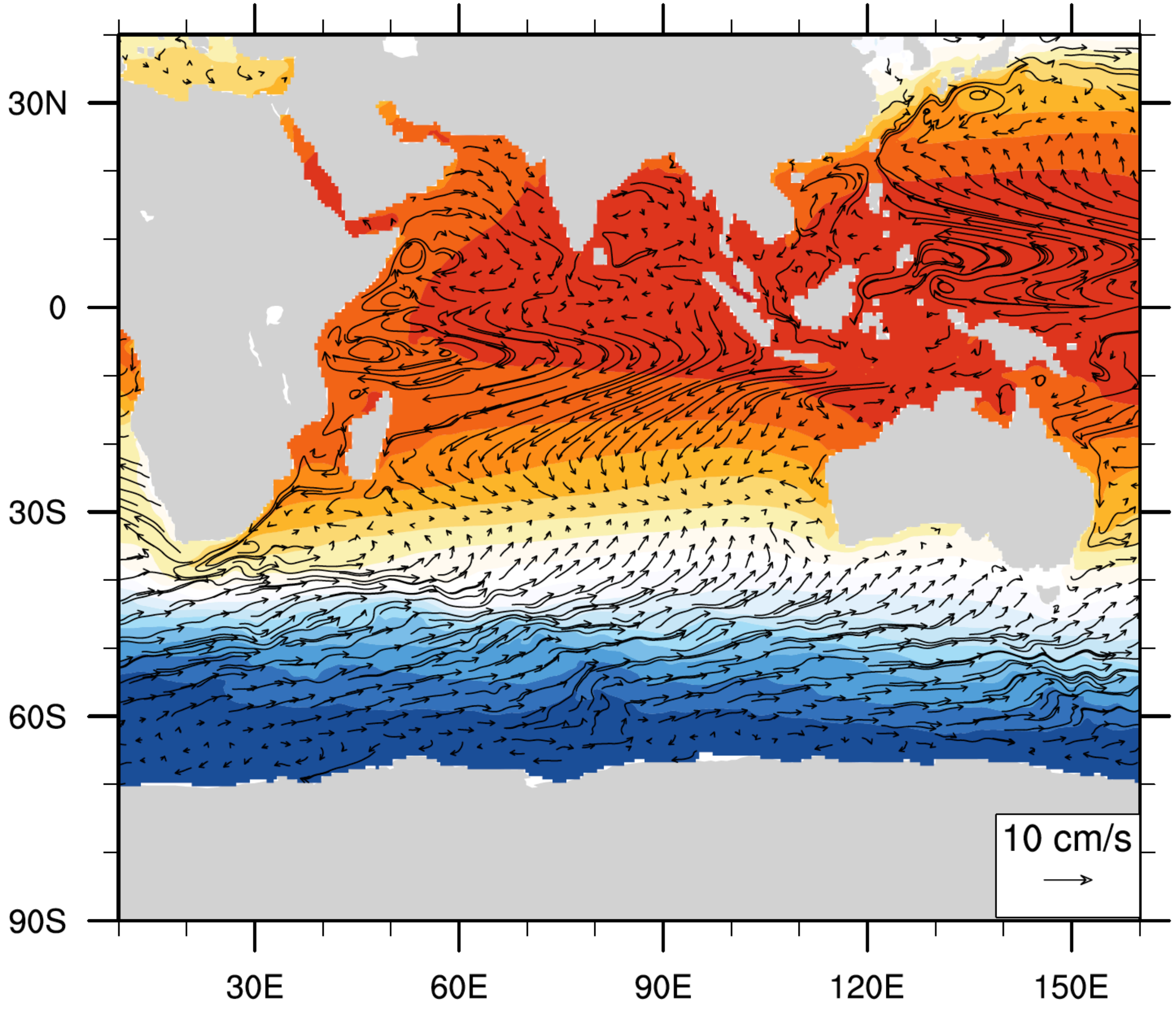


The Grand Banks where the Labrador current and Gulf Stream meet are some of the richest fishing grounds in the world.

Indian Ocean Surface Currents

Figure: Major surface currents in the Indian Ocean from SODA3.

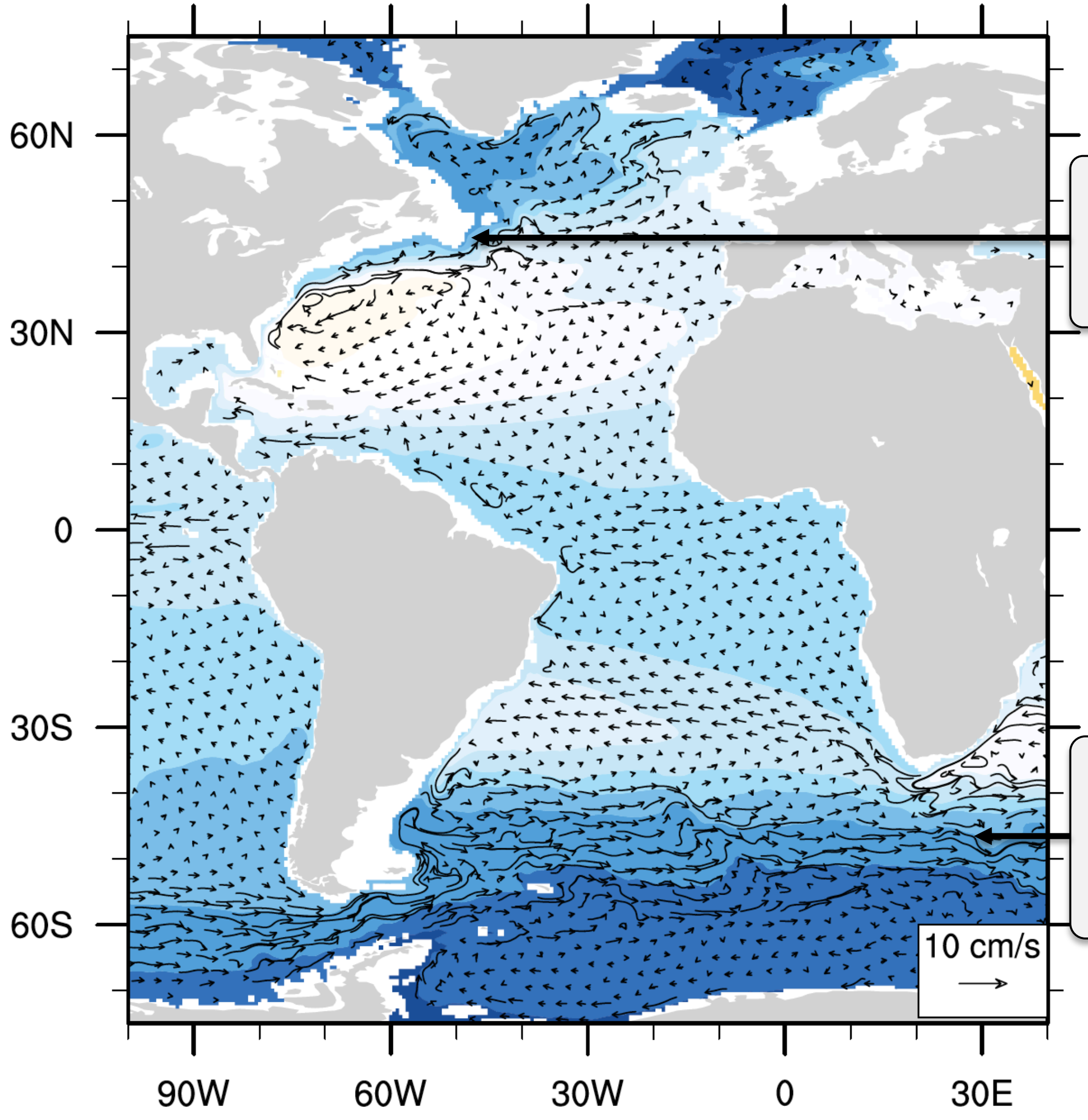
Note the convergence of warm equatorial and cold Antarctic waters in the Southern Indian Ocean.



Atlatnic Ocean Currents at Depth

The mean circulation of the ocean decays rapidly with depth, however ocean gyres (which will be discussed later) decay less rapidly with depth.

Figure: Currents at a depth of 500m in the Atlantic from SODA3, with temperatures overset.



Gulf stream remains strong at depth.

Antarctic Circumpolar Current remains strong at depth

ATM 241 Climate Dynamics
Lecture 7
The Oceans

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Thank You!