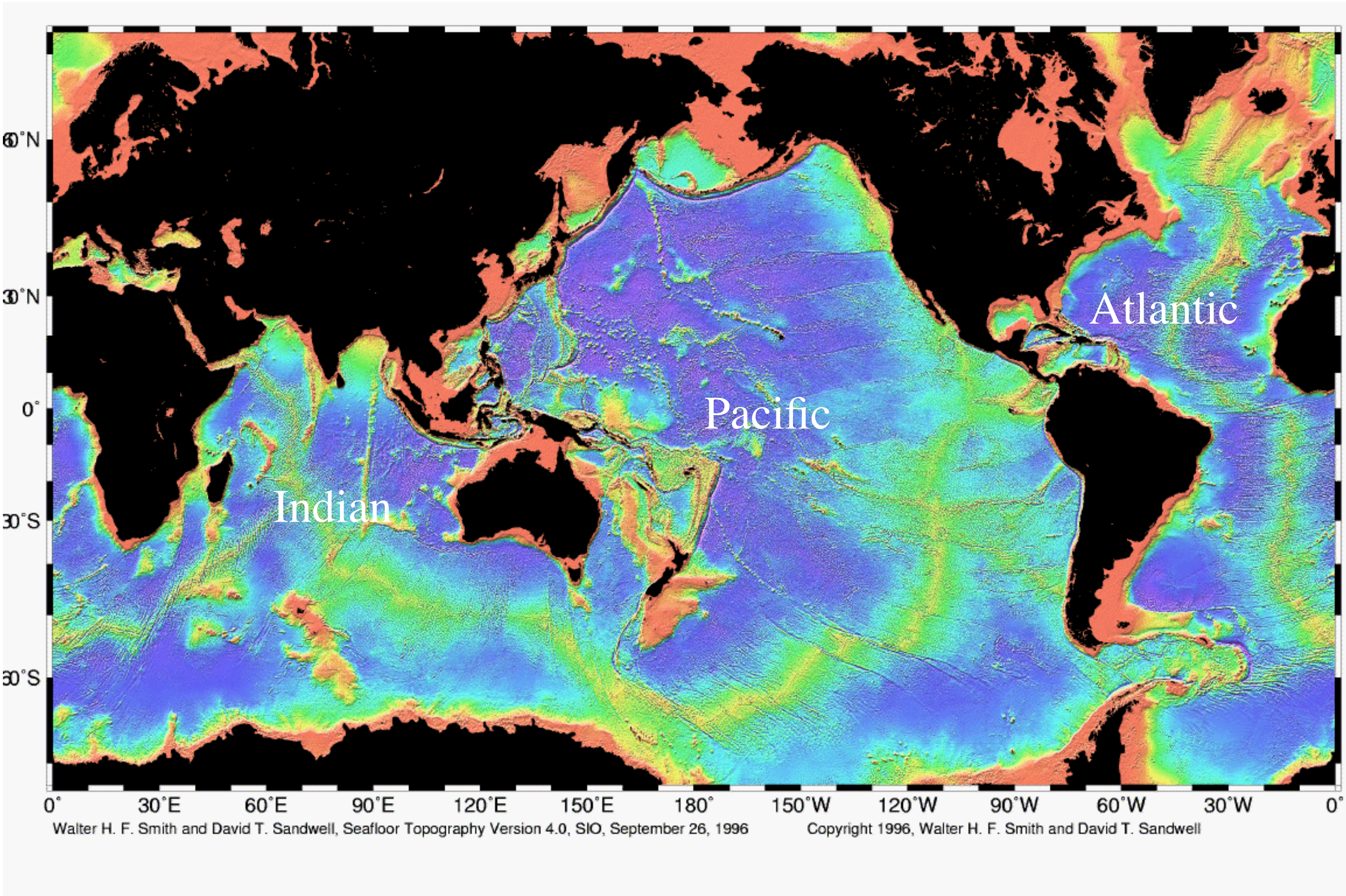
Descriptive Physical Oceanography

AOS660, Fall 2013, Prof. McKinley

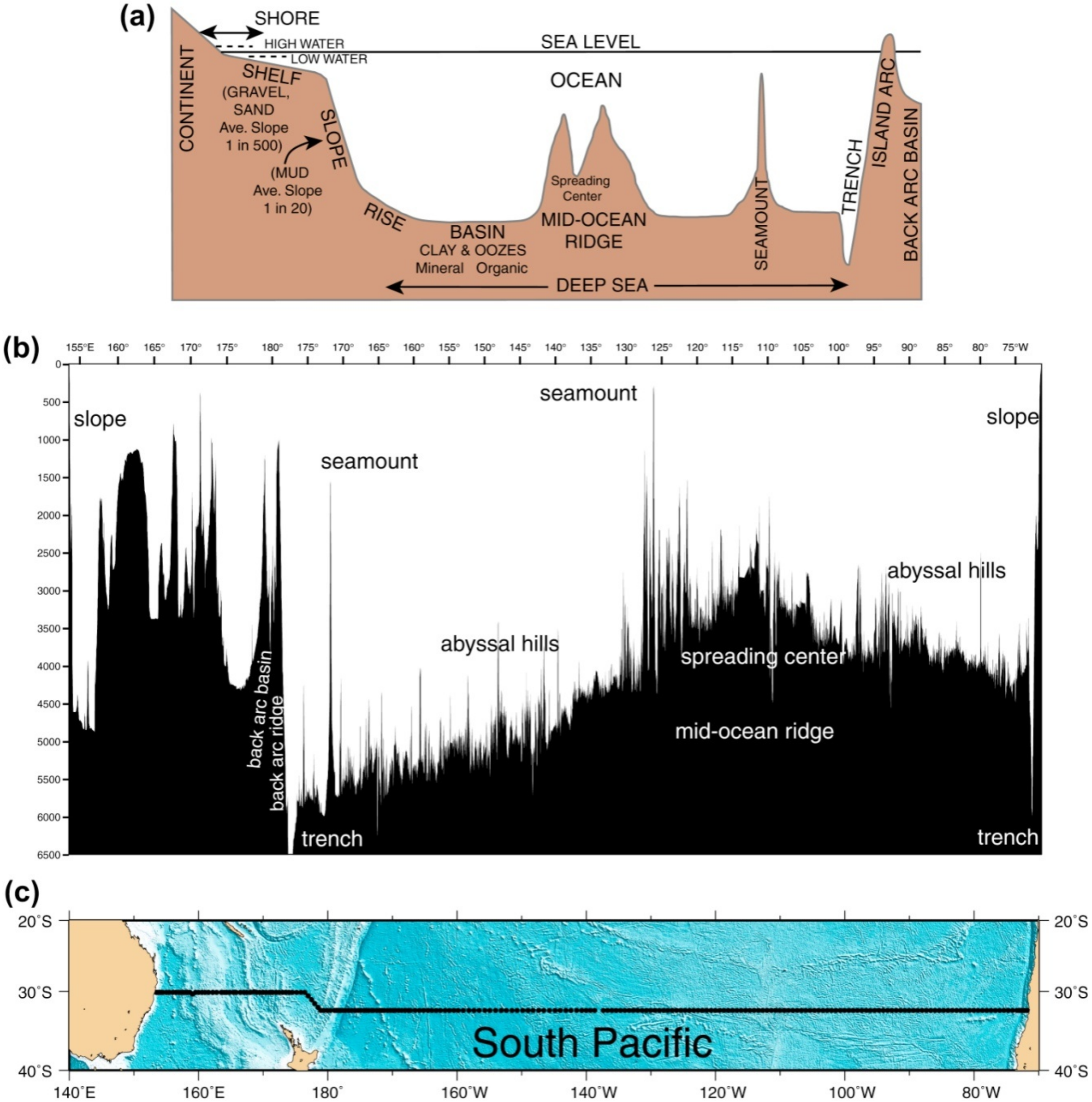
- Bathymetry
- Salinity, Temperature, Density
- Buoyancy and Buoyancy Forcing
- Brunt-Vaisala / Buoyancy frequency (N)
- Seasonal Mixed Layer

- Observing the ocean

Physical structure



Atlantic
Pacific
Indian
60°N
30°N
0°
30°S
60°S
0°
30°E
60°E
90°E
120°E
150°E
180°
150°W
120°W
90°W
60°W
30°W
0°
Walter H. F. Smith and David T. Sandwell, Seafloor Topography Version 4.0, SIO, September 26, 1996
Copyright 1996, Walter H. F. Smith and David T. Sandwell

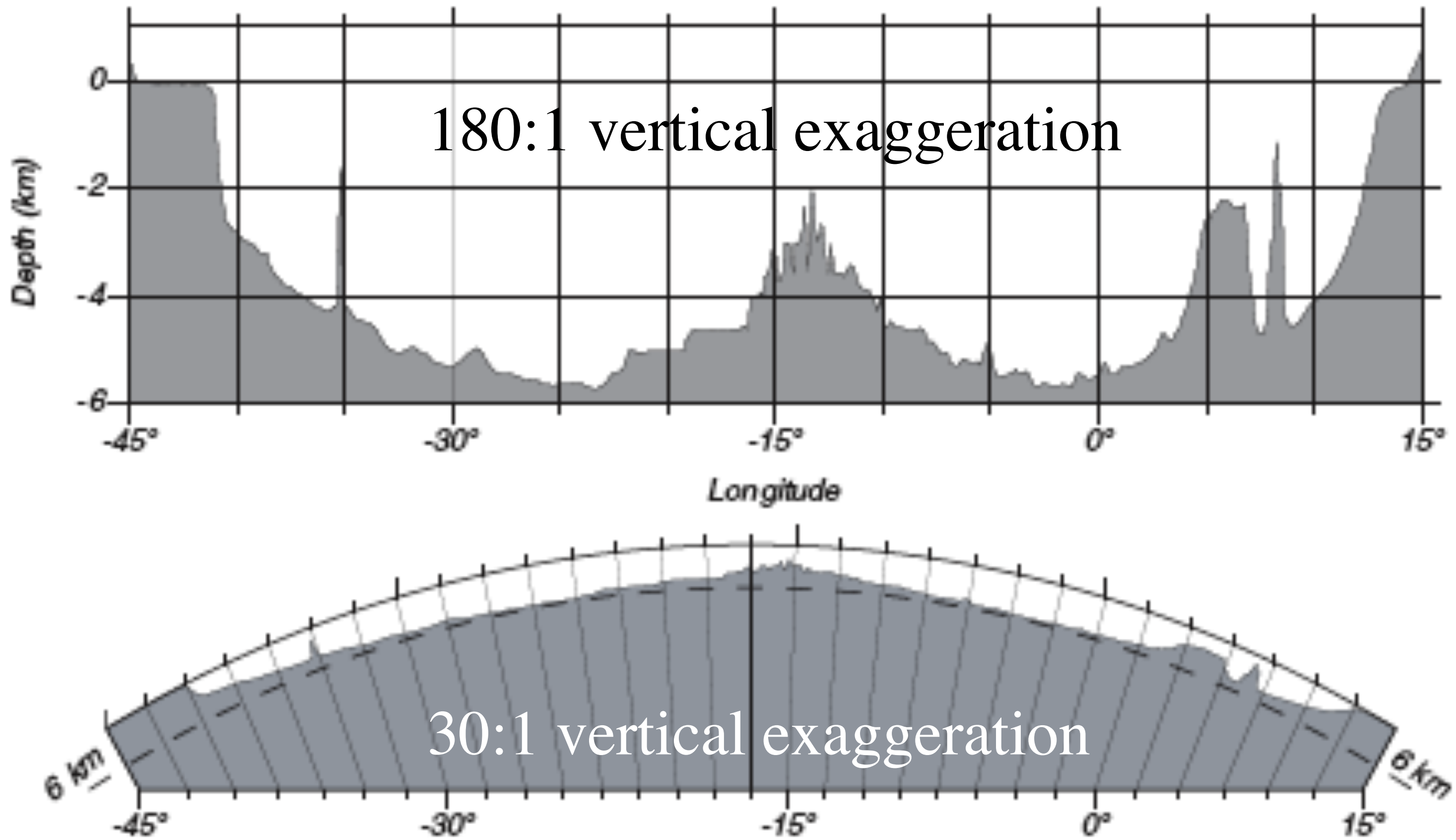


(a) Schematic section through ocean floor to show principal features. (b) Sample of bathymetry, measured along the South Pacific ship track shown in (c).

FIGURE 2.5

TALLEY

Width / Depth Ratio



Thus, a 2D approximation is often reasonable

Horizontal velocities (u,v) >> Vertical velocities (w)

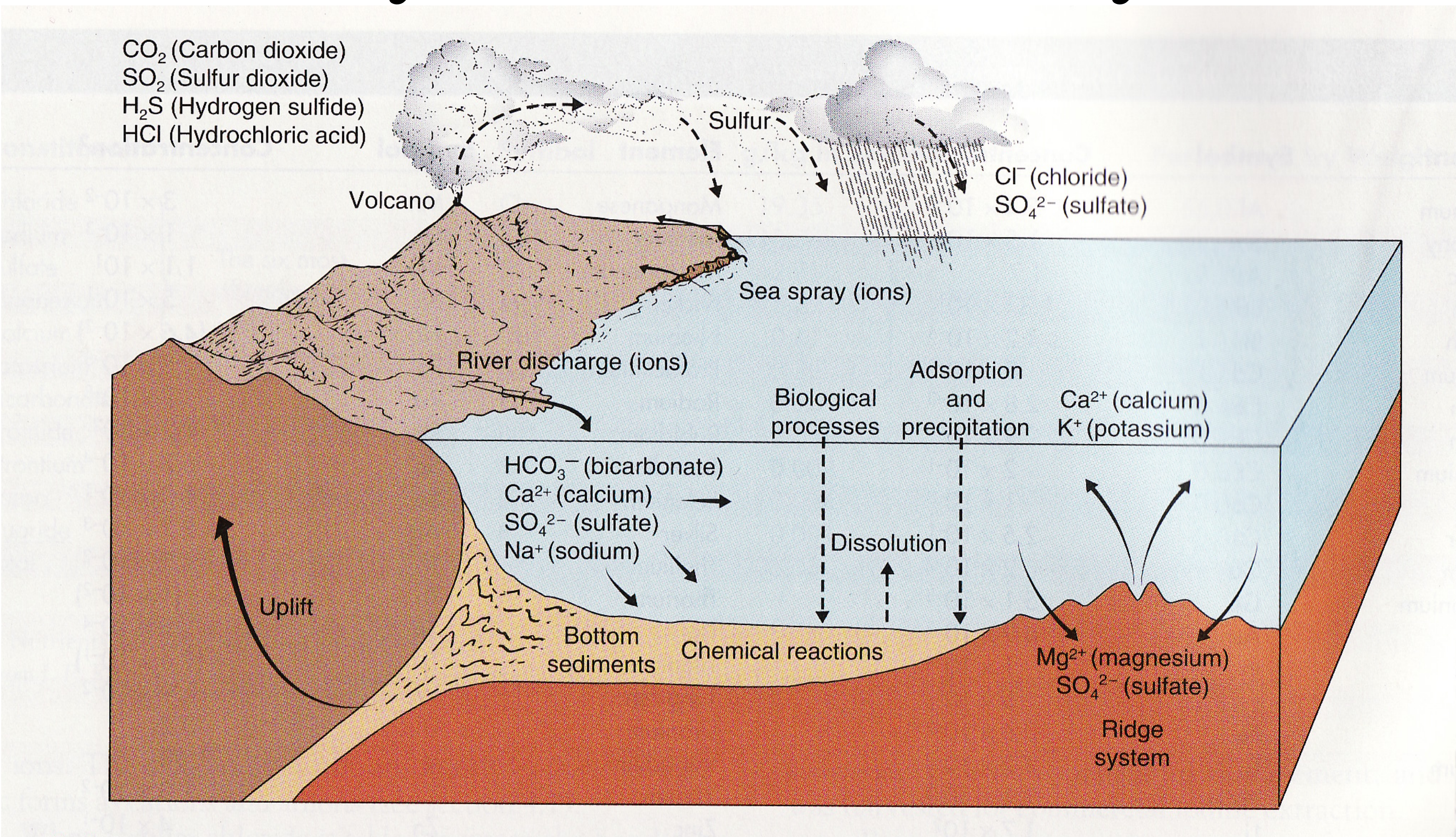
Properties of Seawater

Salinity, Temperature, Density

What makes the ocean salty?

Ion	*% weight*	*Residence time (yrs)*
Chloride	55.07	100 million +
Sodium	30.62	210 million
Magnesium	3.68	22 million
Potassium	1.10	11 million
Sulfate	7.72	11 million
Calcium	1.17	1 million

Why is the ocean salty?



Sverdrup, Duxbury and Duxbury, 2000

Salinity observed

- All mass dissolved in the a parcel of water (1800's) -- hard to measure
- Proportionality to chlorinity (early to mid-1900's)
  - S= 1.80655Cl
  - A very accurate relationship (to +-0.005 in salinity)
- Conductivity
  - Precise, easy to use
  - Eventually breaking the link to a chlorinity standard with the Practical Salinity Scale of 1979 (JPOTS 1981)

Practical Salinity Scale of 1978

$$S = 0.0080 - 0.1692\,K_{15}^{1/2} + 25.3851\,K_{15} + 14.0941\,K_{15}^{3/2} - 7.0261\,K_{15}^{2} + 2.7081\,K_{15}^{5/2} \quad (6.4a)$$

$$K_{15} = C(S,15,0)/C(KCl,15,0) \quad (6.4b)$$

$$2 \le S \le 42$$

- C(S,15,0) = conductivity of seawater sample at T=15 C and standard atmospheric pressure (1 atm)
- C(KCl,15,0) = conductivity of standard KCl sample at same conditions

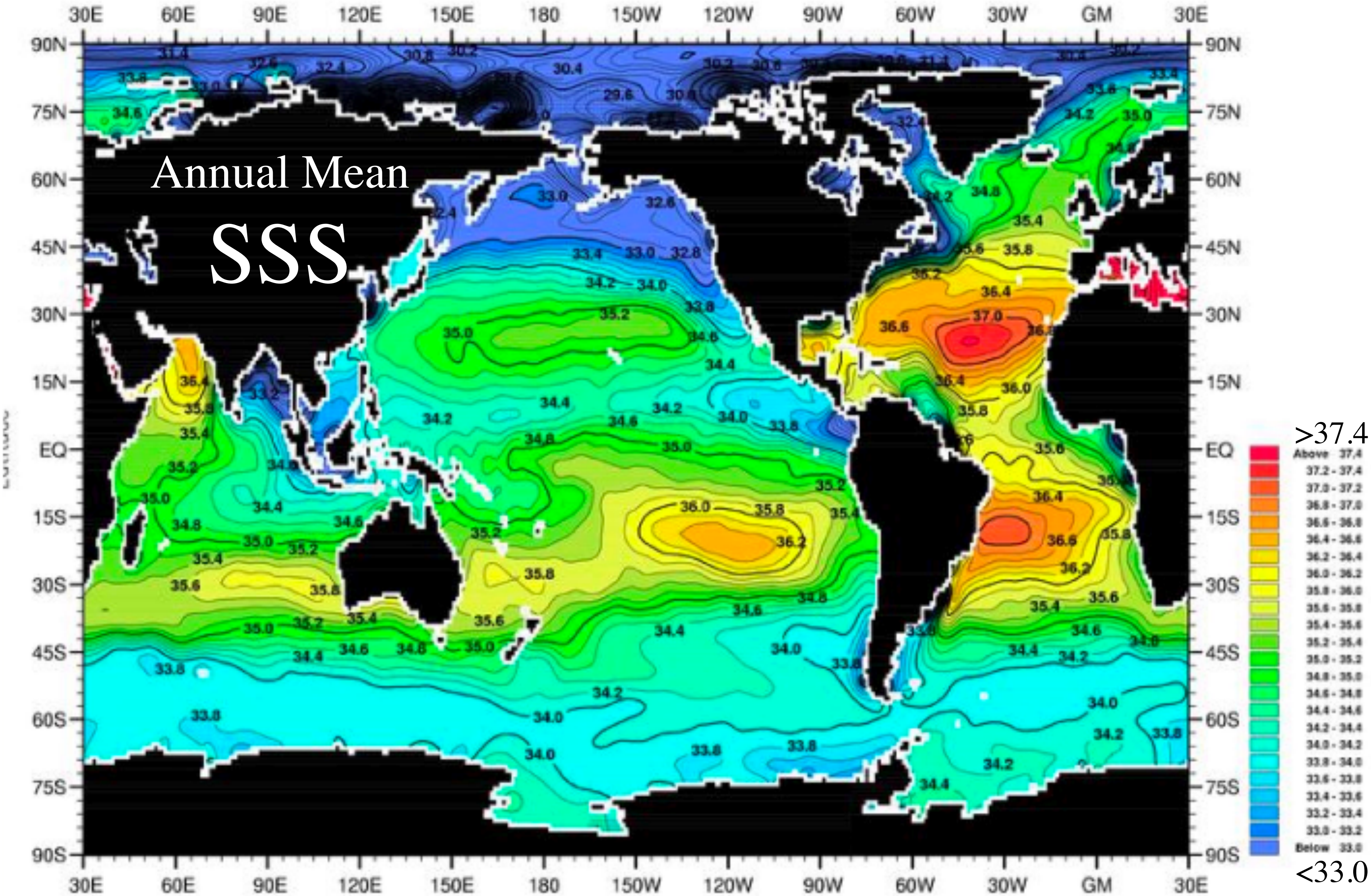
Extension to other temperatures

$$S = 0.0080 - 0.1692\,R_t^{1/2} + 25.3851\,R_t + 14.0941\,R_t^{3/2} - 7.0261\,R_t^2 + 2.7081\,R_t^{5/2} + \Delta S$$

$$R_t = C(S,t,0)/C(KCl,t,0)$$

$$\Delta S = \left[\frac{(t-15)}{1+0.0162\,(t-15)}\right]\left(0.0005 - 0.0056\,R_t^{1/2} - 0.0066\,R_t - 0.0375\,R_t^{3/2} + 0.636\,R_t^2 - 0.0144\,R_t^{5/2}\right)$$

$$2^\circ C \;\le t \le 35^\circ C$$



SSS = Sea Surface Salinity

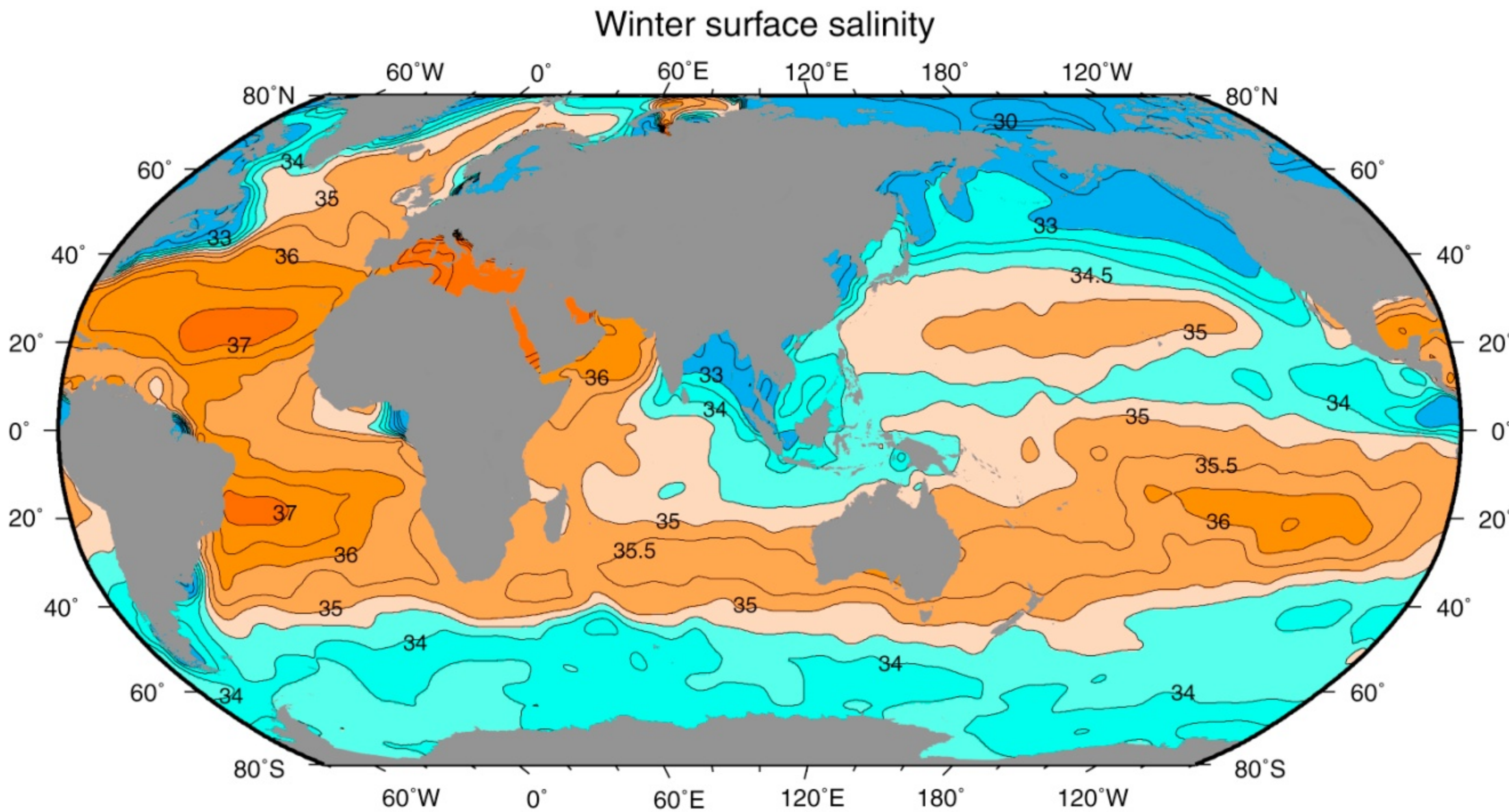


FIGURE 4.15

Surface salinity (psu) in winter (January, February, and March north of the equator; July, August, and September south of the equator) based on averaged (climatological) *data from Levitus et al. (1994b)*.

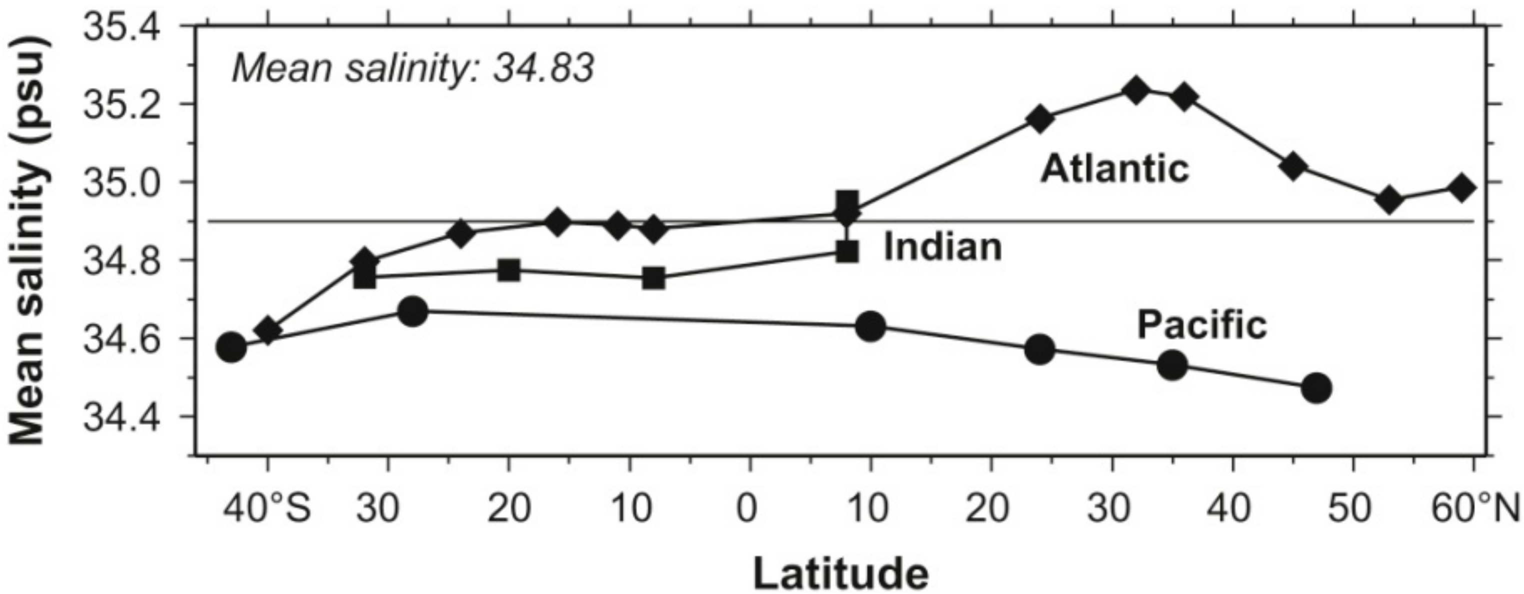
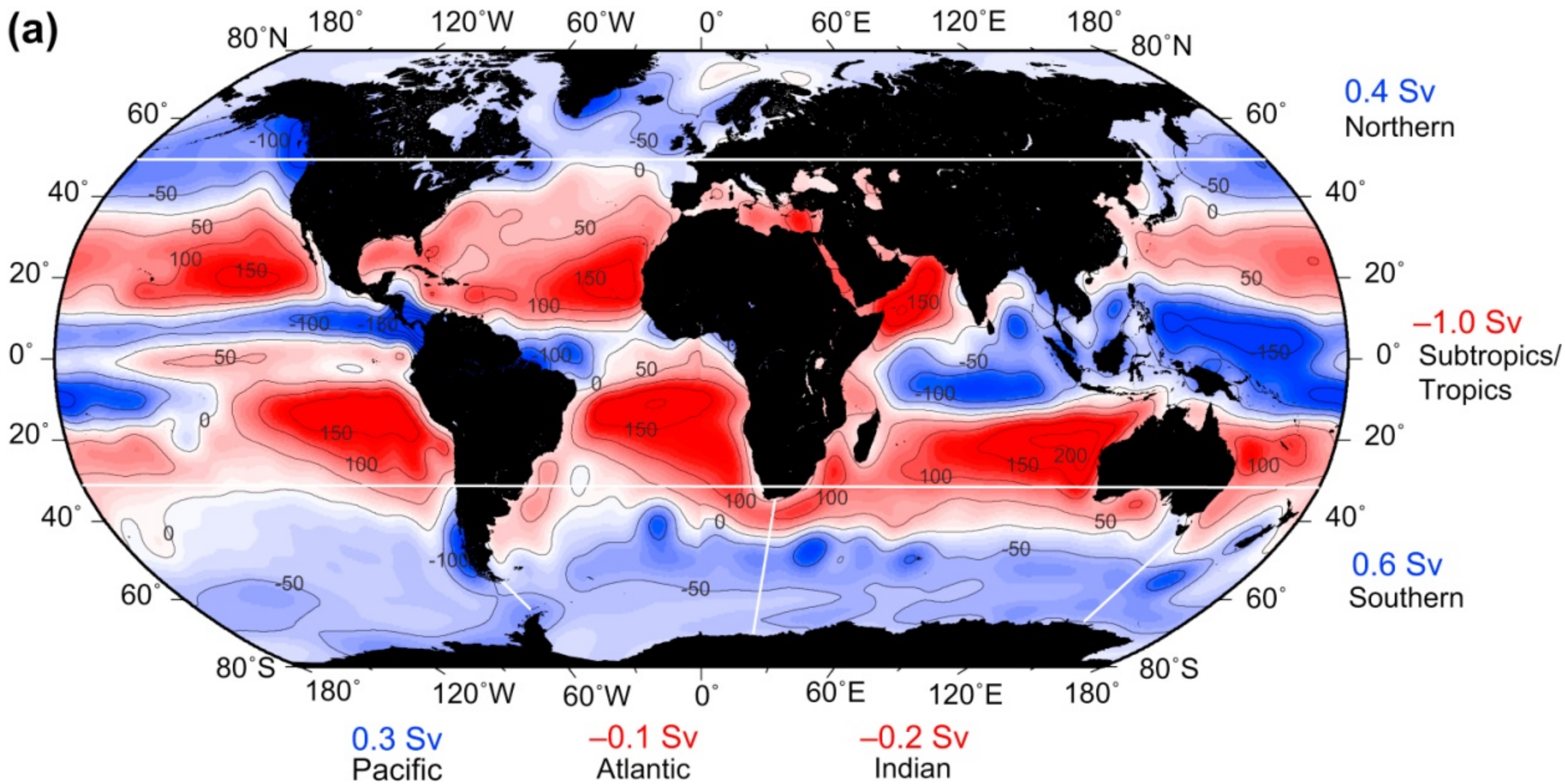


FIGURE 4.14

Mean salinity, zonally averaged and from top to bottom, based on hydrographic section data. The overall mean salinity is for just these sections and does not include the Arctic, Southern Ocean, or marginal seas. *Source: From Talley (2008).*

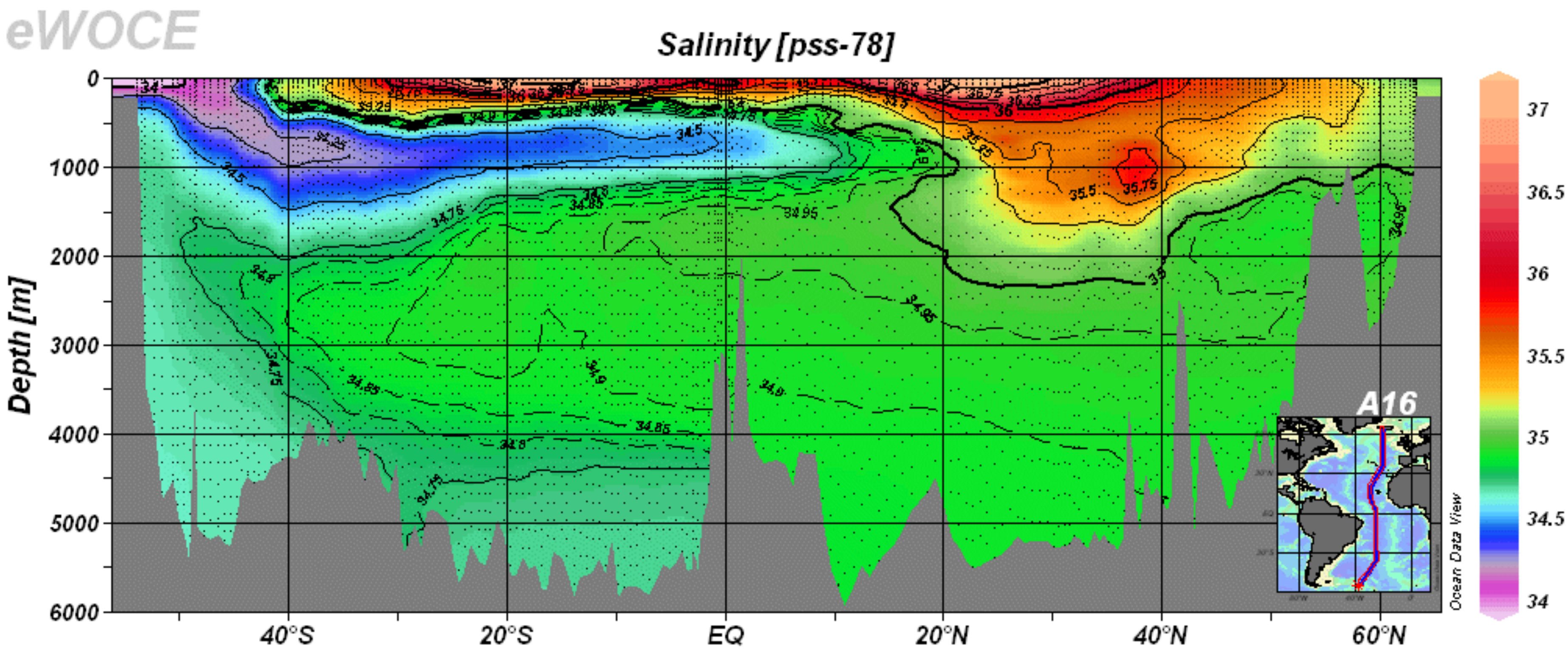
SSS forcing is Evaporation - Precipitation

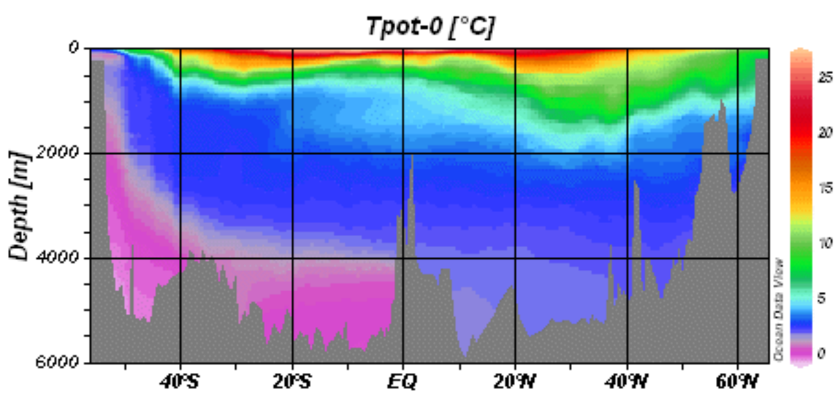


(a) Net evaporation and precipitation (E–P) (cm/yr) based on climatological annual mean data(1979–2005) from the National Center for Environmental Prediction. Net precipitation is negative (blue), net evaporation is positive (red). Overlain: freshwater transport divergences (Sverdrups or 1×10^9 kg/sec) based on ocean velocity and salinity observations.

FIGURE 5.4

Atlantic Section





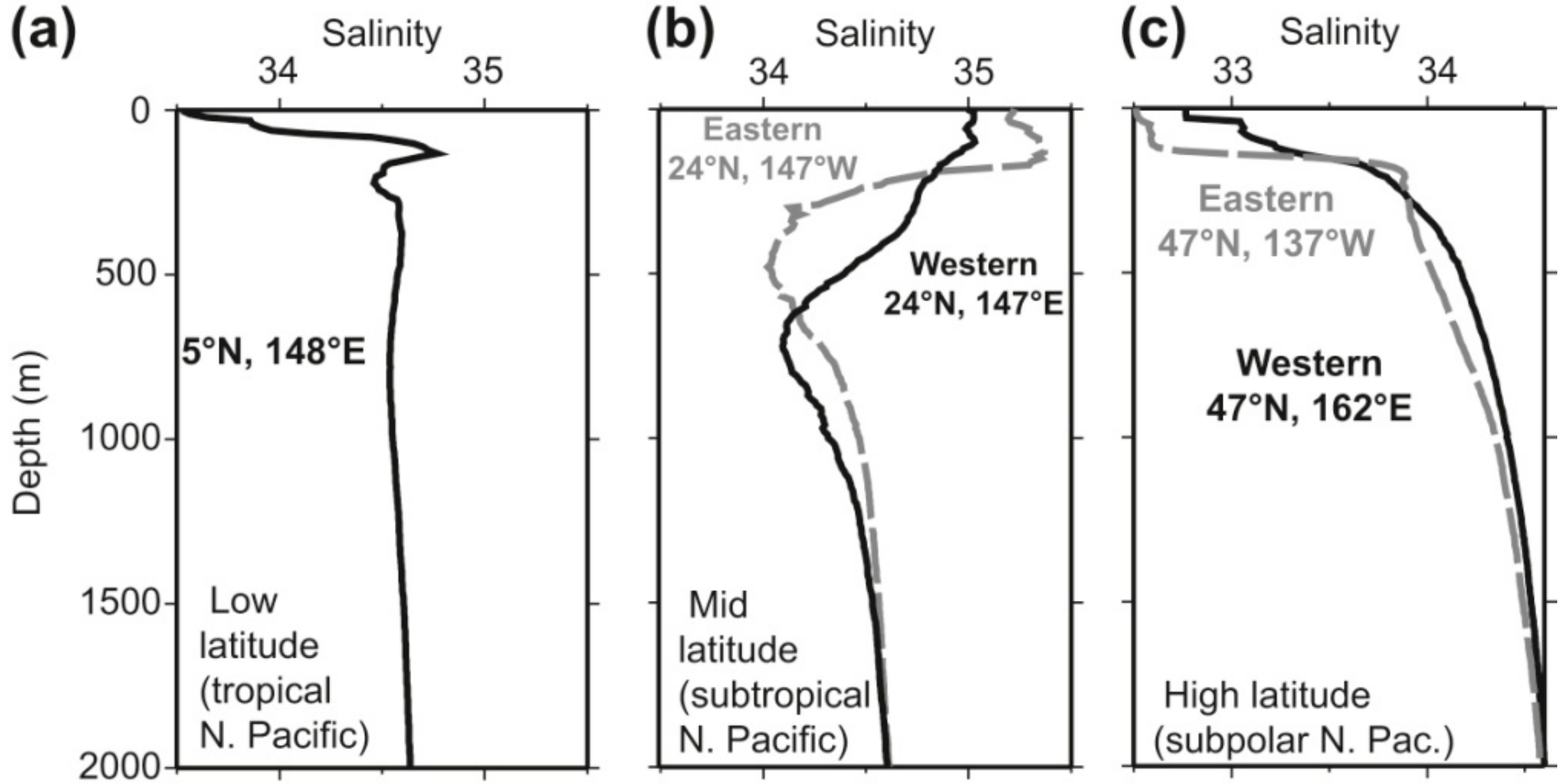


FIGURE 4.16

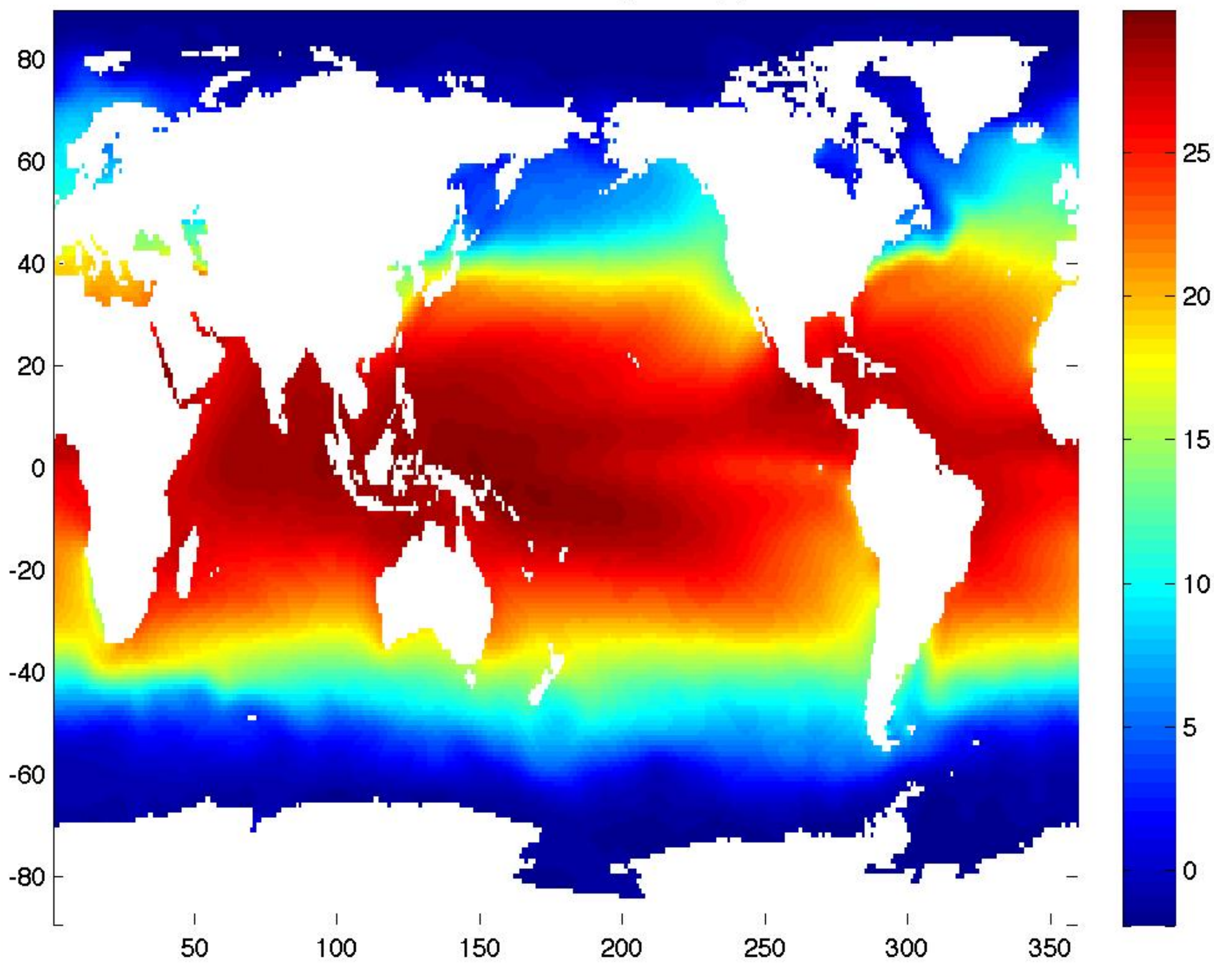
Typical salinity (psu) profiles for the tropical, subtropical, and subpolar regions of the North Pacific. Corresponding temperature profiles are shown in Figure 4.2.

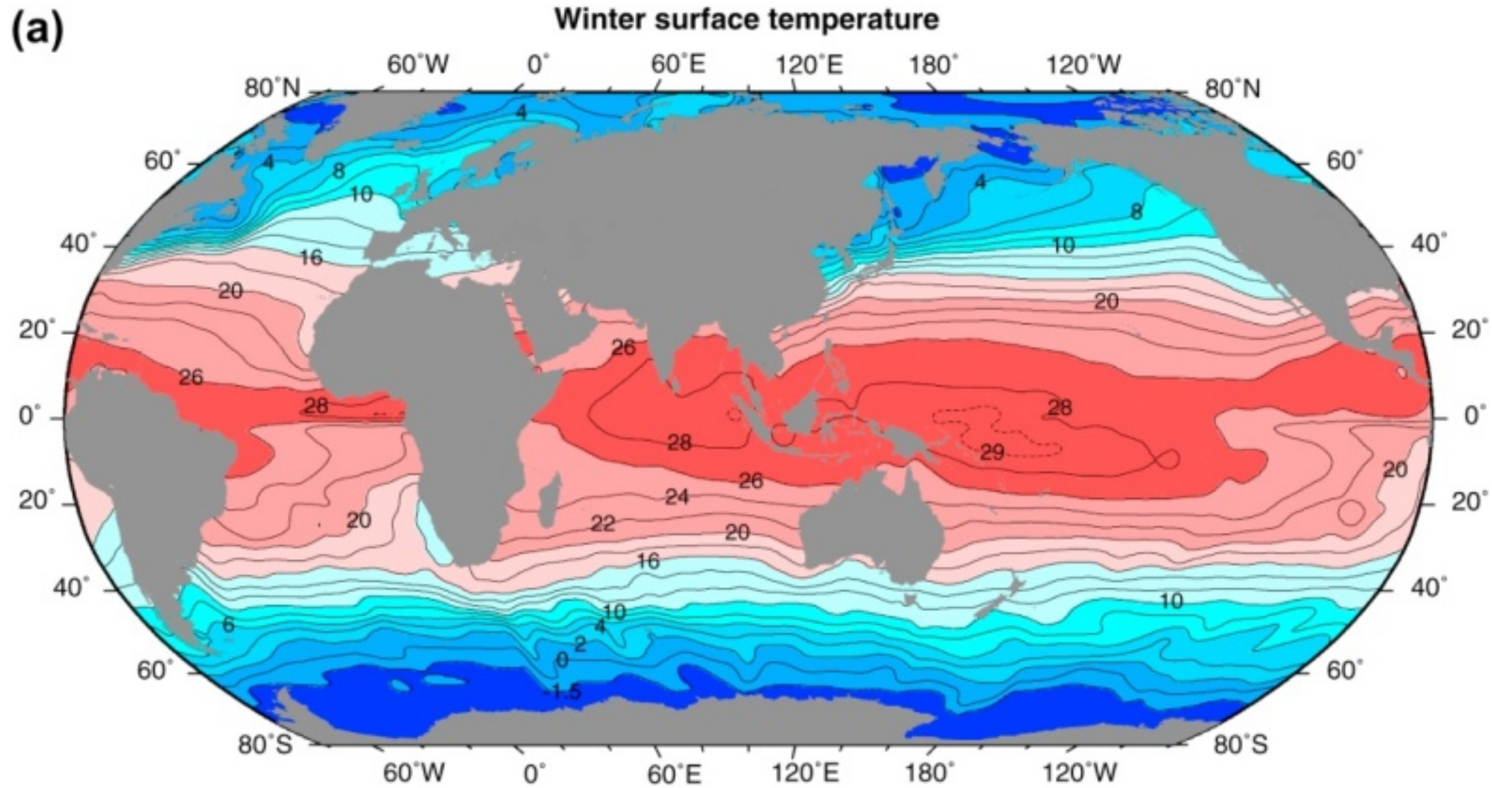
Temperature and Potential Temperature

Observing temperature

- Absolute temperature
  - Hard to measure, used to define calibration points
  - Standard is now: International temperature scale of 1990 (ITS-90)
- Platnium resistance thermometer used for calibration of other instruments
- Thermistors for actual observations (now)
  - Semiconductor with resistance that varies with temperature
  - High resolution, Accuracy +- 0.001C

Annual average sea surface temperature (SST)





(a) Surface temperature (°C) of the oceans in winter (January, February, March north of the equator; July, August, September south of the equator) based on averaged (climatological) *data from Levitus and Boyer (1994)*.

FIGURE 4.1

Satellite SST, week of 1/3/08

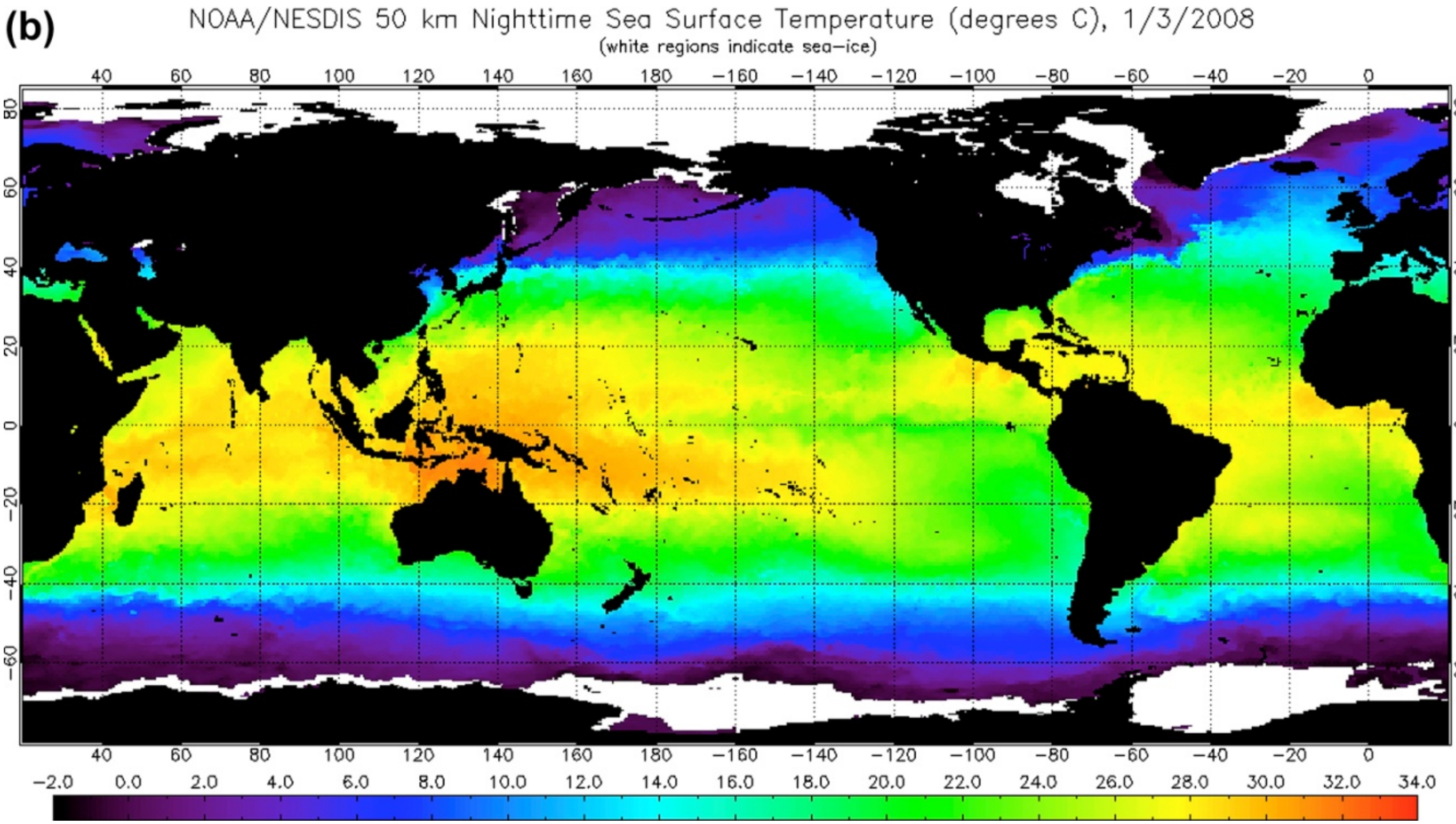
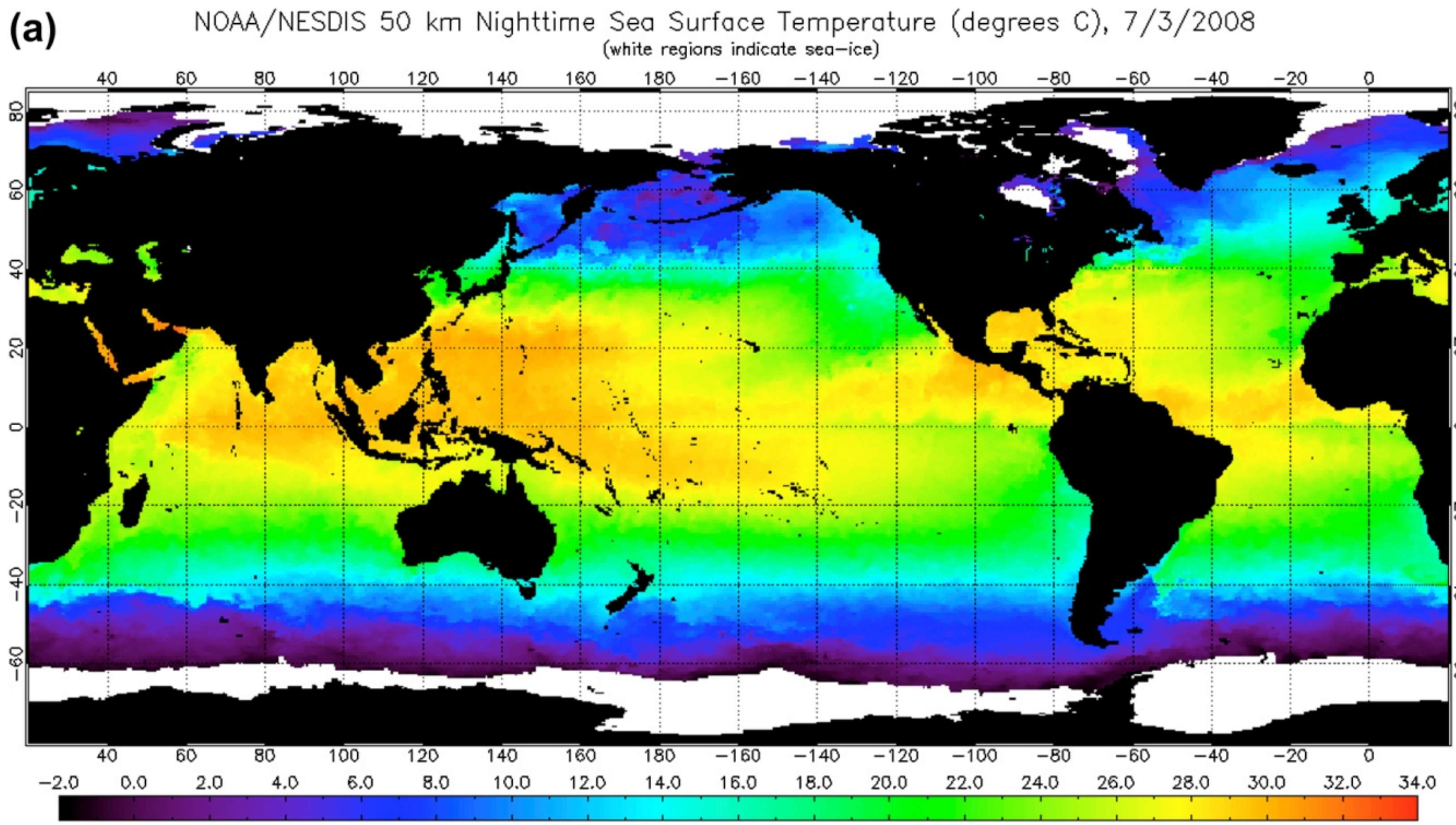


FIGURE S4.1(Continued)

Satellite SST, week of 7/3/08



Satellite infrared sea-surface temperature (ºC; nighttime only), averaged to 50 km and 1 week, for (a) July 3, 2008 (austral winter) (b) January 3, 2008 (also Figure 4.1b in the textbook, where it appears in gray scale only). White is sea ice. *Source: From NOAA NESDIS, (2009b).*

FIGURE S4.1

Potential Temperature (Θ)

- Compression does work on fluid parcel
- First law of thermodynamics

$$dQ = dU - dW$$

- Internal energy must increase, i.e. temperature must go up
- Up to 0.9^{o}C at deepest points in ocean (8km)

Potential Temperature

- Potential temperature is defined to remove the effect of compression
- Defined as the temperature of a parcel of seawater at the surface after if has been raised adiabatically from depth
- Calculated based on in situ temperature and depth

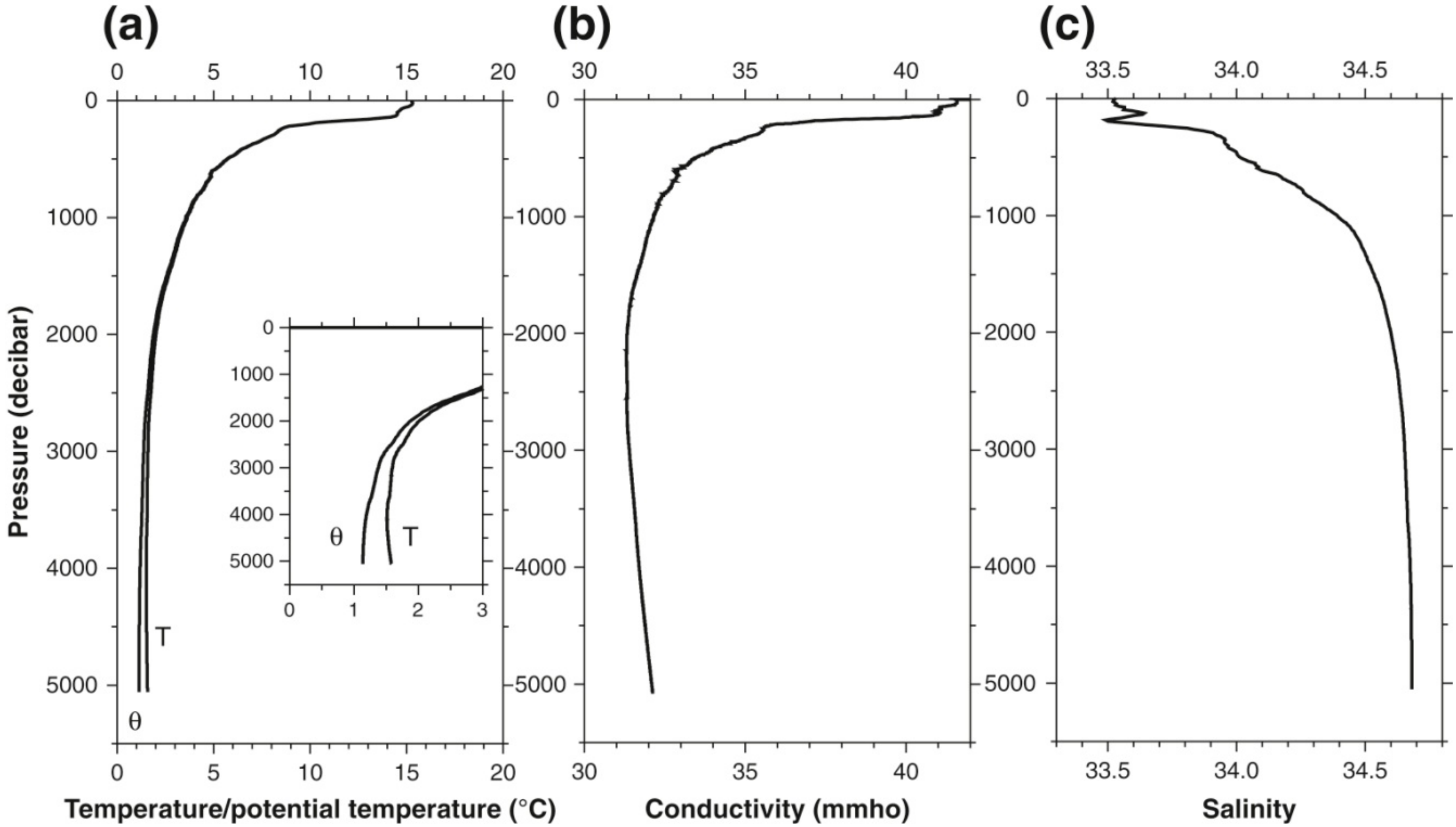
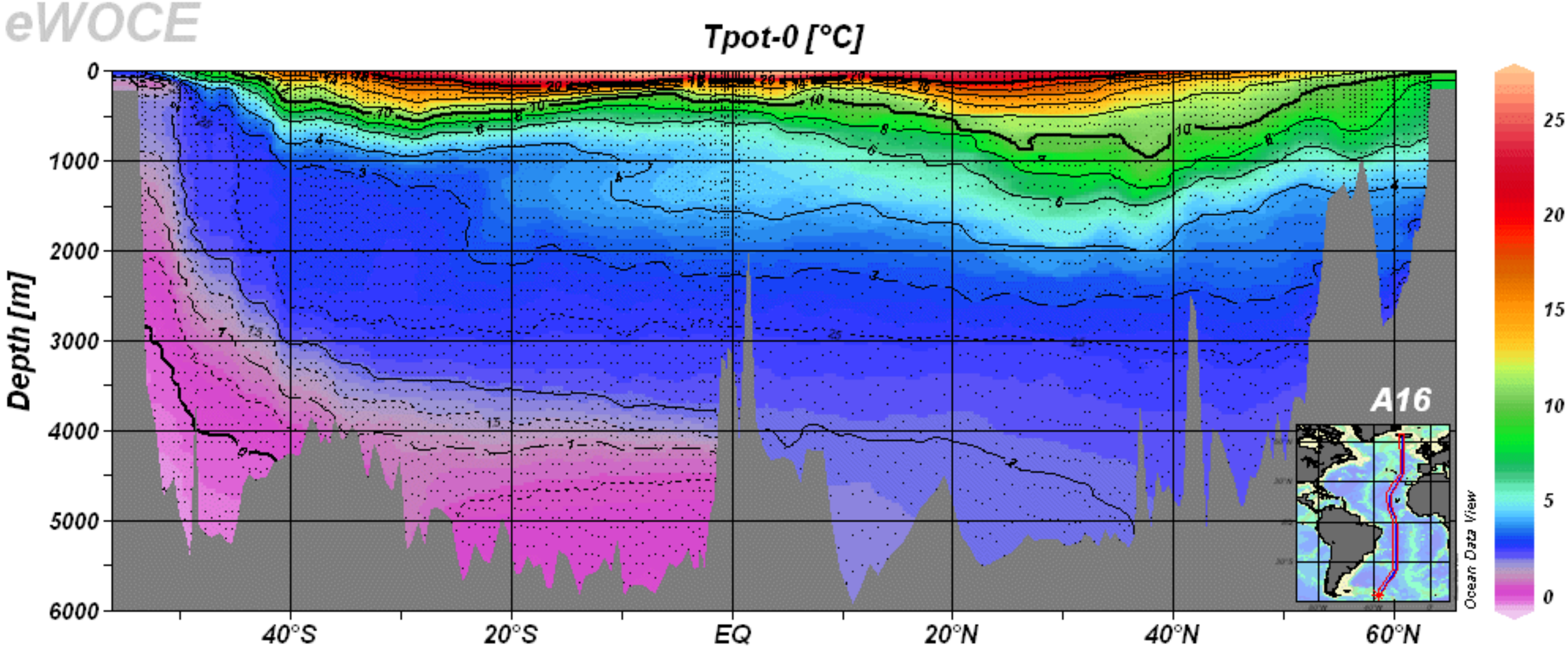
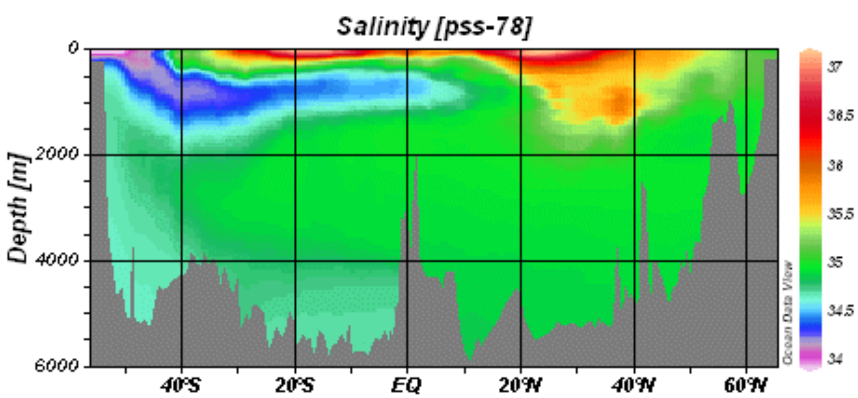


FIGURE 3.3

(a) Potential temperature (θ) and temperature (T) (°C), (b) conductivity (mmho), and (c) salinity in the northeastern North Pacific (36° 30' N, 135°W).

TALLEY


Tpot-0 [°C]
Depth [m]
0
1000
2000
3000
4000
5000
6000
40°S
20°S
EQ
20°N
40°N
60°N
A16
25
20
15
10
5
0
Ocean Data View


Salinity [pss-78]
Depth [m]
0
2000
4000
6000
40°S
20°S
EQ
20°N
40°N
60°N
37
36.5
36
35.5
35
34.5
34
Ocean Data View

Density

Density

- Density is difficult to measure directly
- Calculated from T, S, pressure with Equation of State of Seawater
  - Most common: EOS80 (JPOTS, 1981)
    - 3 polynomials, 41 constants!
  - New: TEOS-10 (IOC, SCOR and IAPSO, 2010)
  - Given limited sampling, and the direct dependence of flow on density field, it is critical to have international coordination.

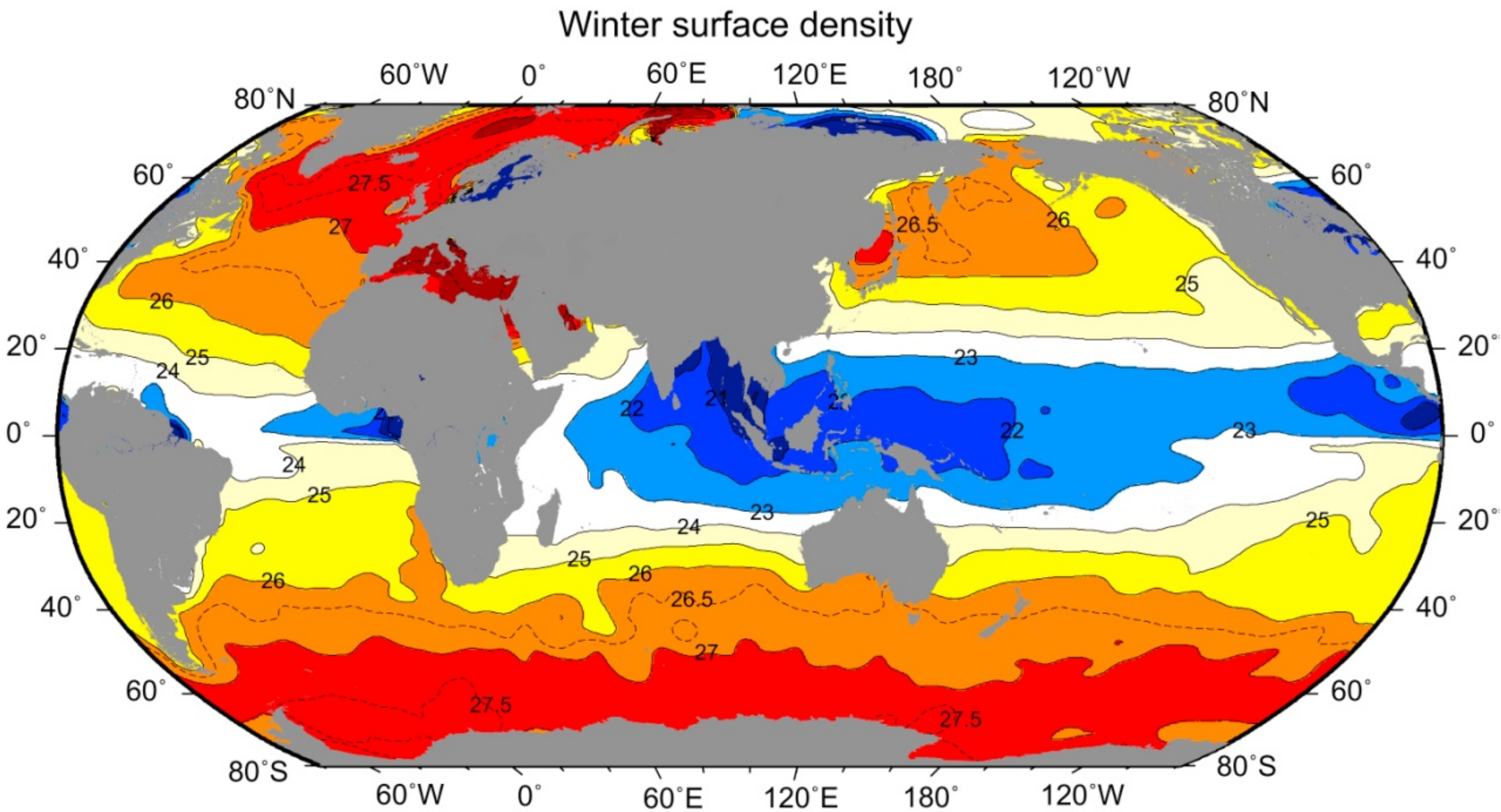


FIGURE 4.19

Surface density σ_θ (kg m^{-3}) in winter (January, February, and March north of the equator; July, August, and September south of the equator) based on averaged (climatological) *data from Levitus and Boyer (1994) and Levitus et al. (1994b)*.

Density and sigma-T (σ_T)

- Surface density in ocean range:

  $$1027 \pm 4 \text{ kg/m}^3$$

- For convenience, drop the "10"

  $$\sigma_T(S,T,p) = \rho(S,T,p) - 1000 \text{ kg/m}^3$$

- Also known as the "density anomaly"

Pressure important as go down

- 1 dbar = 10^4 Pa (N/m^2)

- <u>Pressure in dbar ~ depth in meters</u>

sigma-Θ (σ_Θ): A conserved thermodynamic property

- σ_Θ is σ_T (= $\rho - 1000$) calculated with Θ instead of T
- $\sigma_\Theta = \sigma(S,\Theta,0)$
  - Referenced to surface
- $\sigma_4 = \sigma(S,\Theta,4000)$
  - As above, but referenced to 4000m
  - Accounts for effect of pressure on the coefficients for thermal expansion and saline contraction
  - Cleanest comparison is for water masses at similar depths

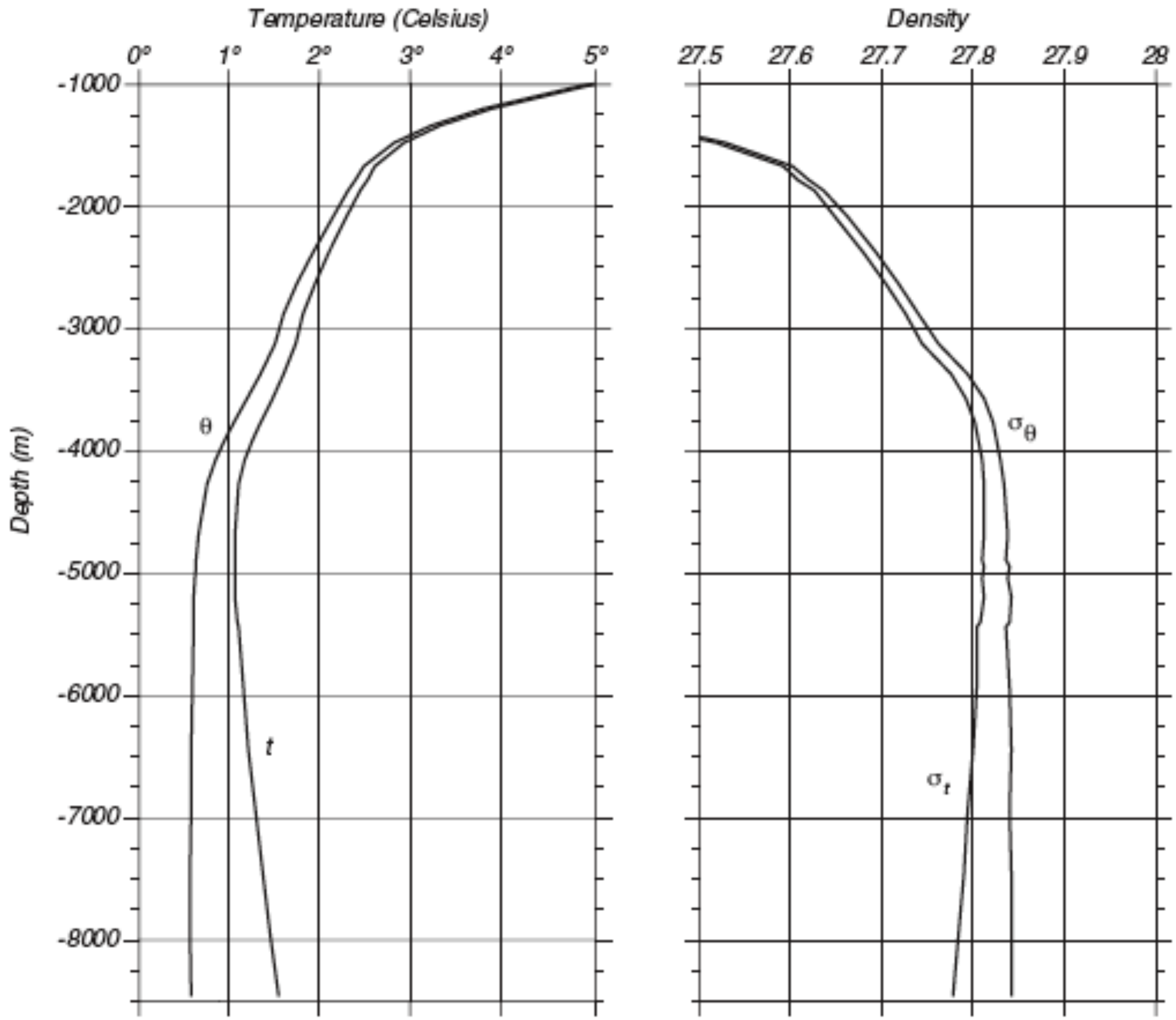
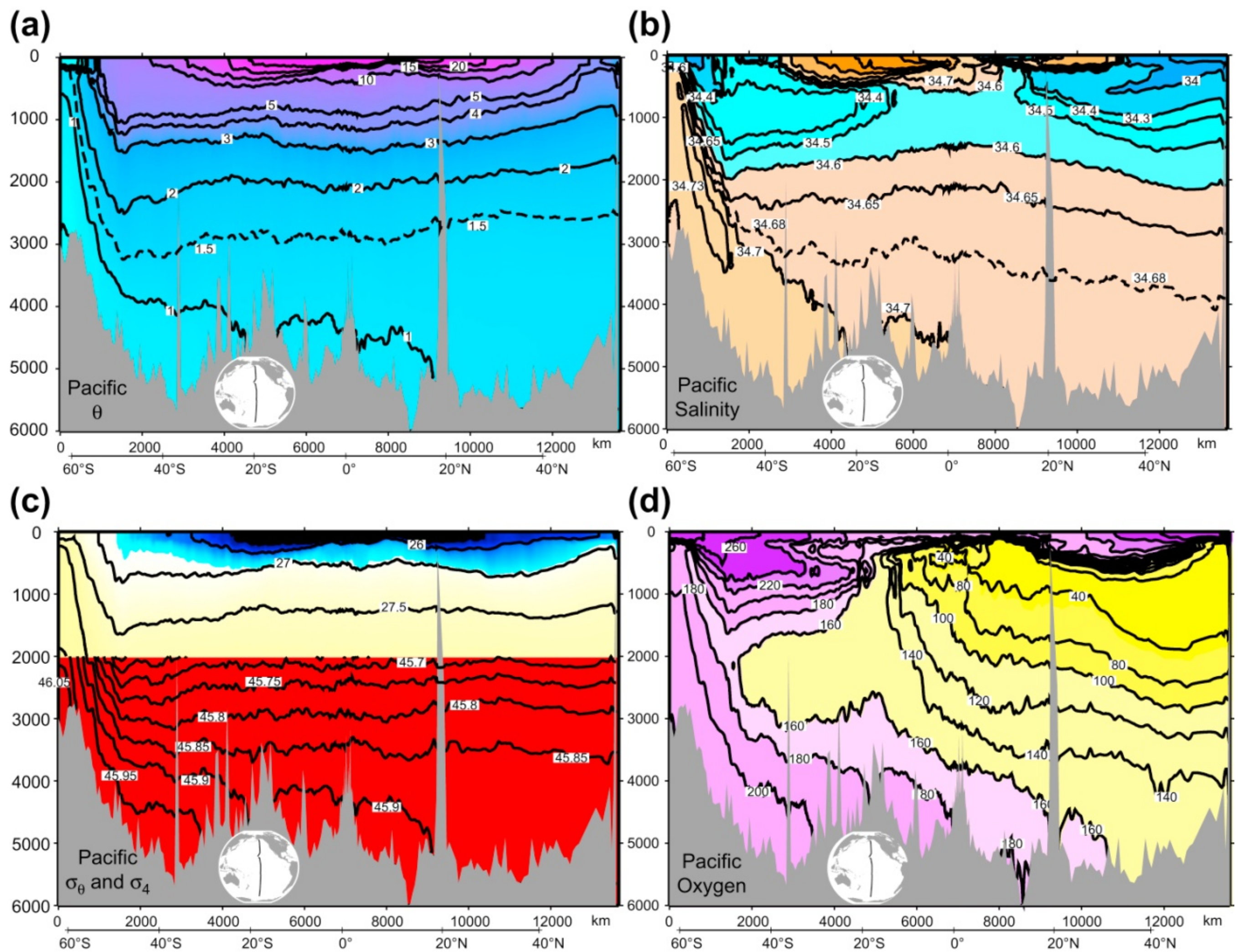
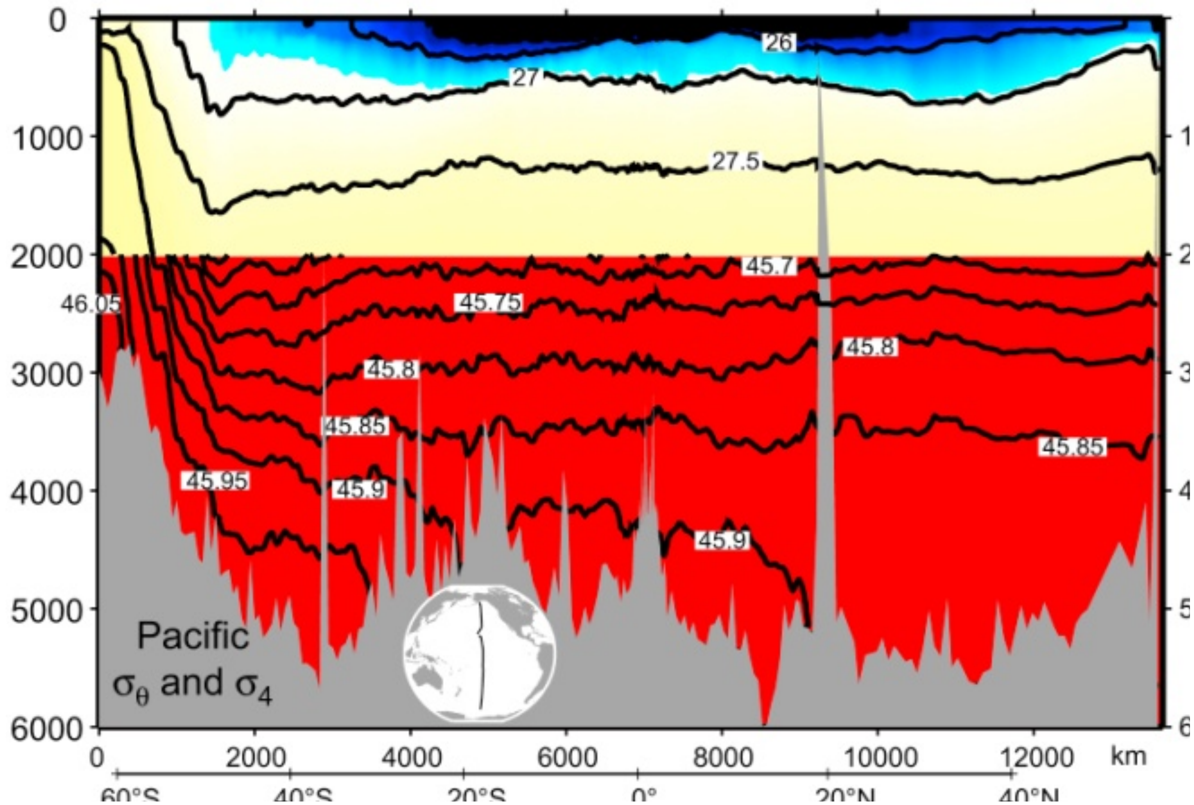


Figure 6.9 Profiles of **Left** *in situ* t and potential θ temperature and **Right** sigma-t and sigma-theta in the Kermadec Trench in the Pacific measured by the R/V Eltanin during the Scorpio Expedition on 13 July 1967 at 175.825° E and 28.258° S. Data from Warren (1973).



(a) Potential temperature (°C), (b) salinity (psu), (c) potential density σ_θ (top) and potential density σ_4 (bottom; kg m^{-3}), and (d) oxygen (μmol/kg) in the Pacific Ocean at longitude 150°W. Data from the World Ocean Circulation Experiment.

FIGURE 4.12



(a) Potential temperature (°C), (b) salinity (psu), (c) potential density σ_θ (top) and potential density σ_4 (bottom; kg m^{-3}), and (d) oxygen (μmol/kg) in the Pacific Ocean at longitude 150°W. Data from the World Ocean Circulation Experiment.

FIGURE 4.12c

Neutral Density γ^N

Jackett and McDougal 1997

- Estimate of quasi-isentropic surfaces in the modern ocean
- Calculation based on observed climatology of temperature and salinity
  - Dependent on latitude, longitude, pressure
- Removes need to vary the reference pressure along surfaces with depth variation
- Widely-used, but still debated because the approximation to isentropic is imperfect

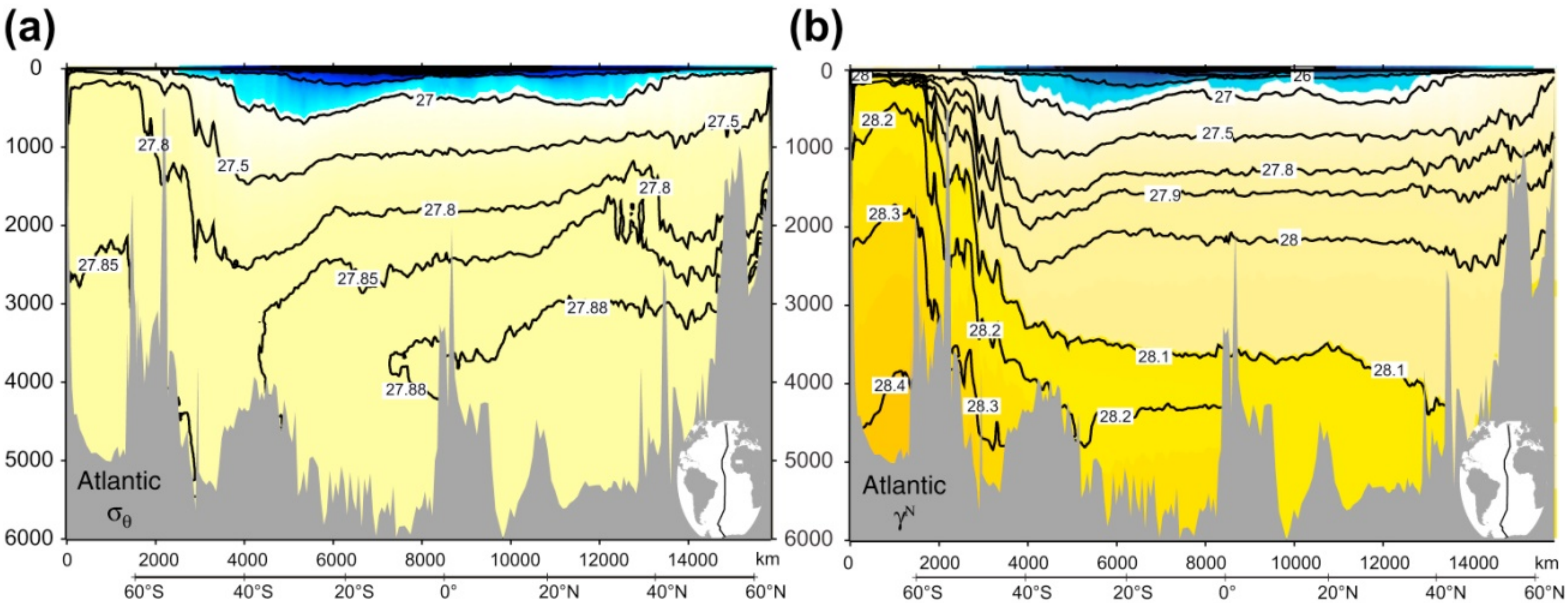


FIGURE 4.18

(a) Potential density σ_θ (kg m^{-3}) and (b) neutral density γ^N in the Atlantic Ocean at longitude 20° to 25°W. Compare with Figure 4.12c. *Data from the World Ocean Circulation Experiment*.

Optical properties

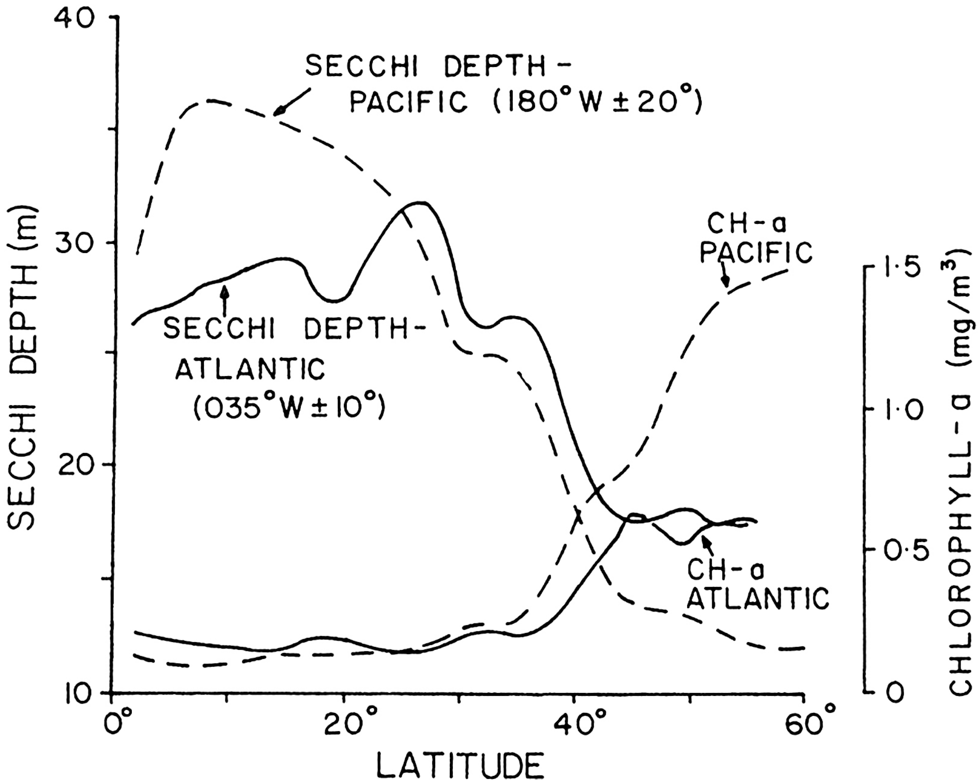


FIGURE 4.26

Mean Secchi disk depths as functions of latitude in the Pacific and Atlantic Oceans. *Source: From Lewis et al. (1988).*

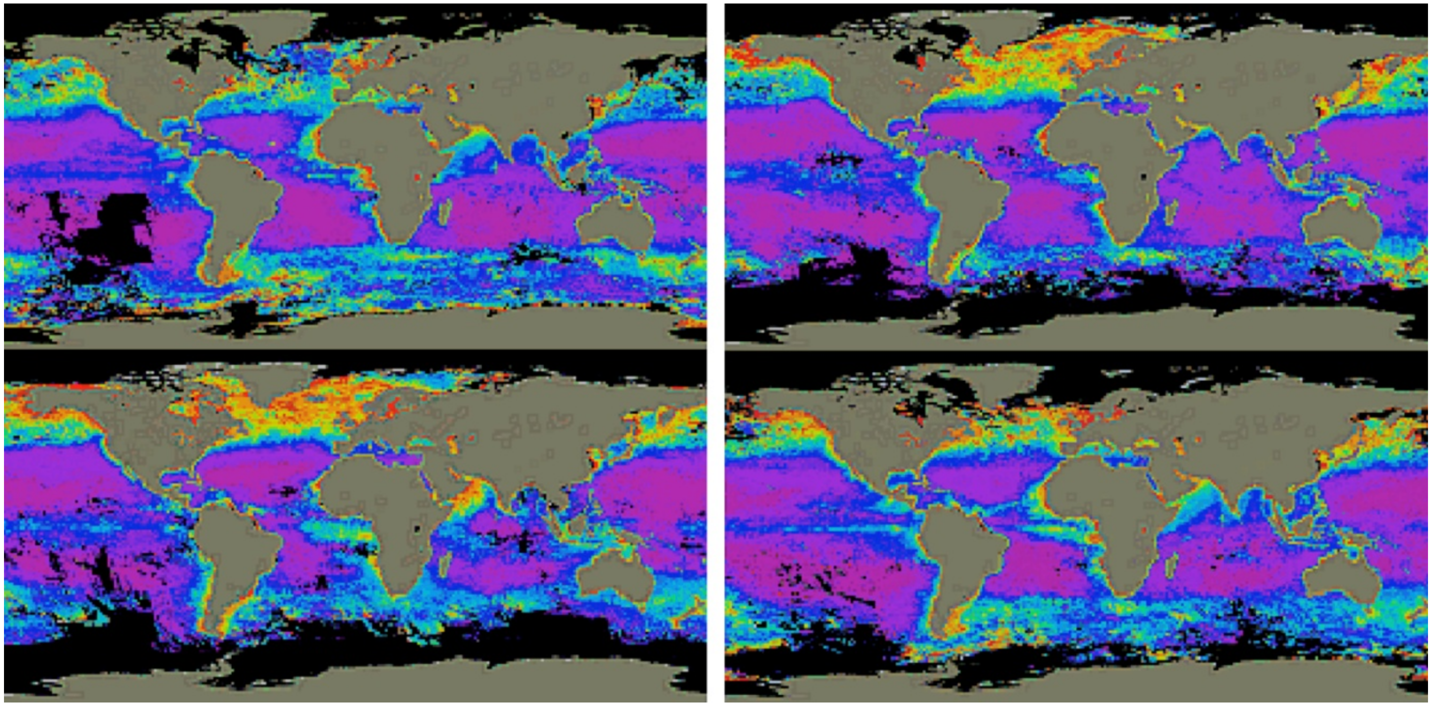
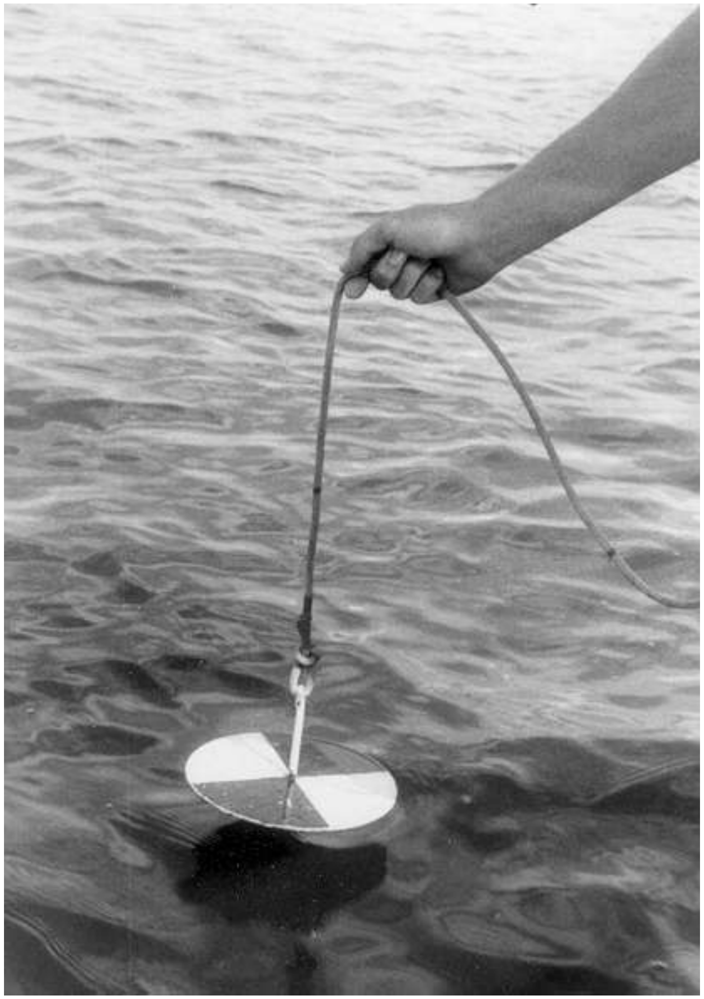


FIGURE 4.28

Global images of chlorophyll derived from the Coastal Zone Color Scanner (CZCS). Global phytoplankton concentrations change seasonally, as revealed by these three-month “climatological” composites for all months between November 1978–June 1986 during which the CZCS collected data: January–March (upper left), April–June (upper right), July–September (lower left), and October–December (lower right). Note the “blooming” of phytoplankton over the entire North Atlantic with the advent of Northern Hemisphere spring, and seasonal increases in equatorial phytoplankton concentrations in both Atlantic and Pacific Oceans and off the western coasts of Africa and Peru. Figure 4.28 will also be found in the color insert. See Figure S4.2 from the online supplementary material for maps showing the similarity between particulate organic carbon (POC) and chlorophyll. *Source: From NASA (2009a).*

Secchi Depth



Modern Radiometer

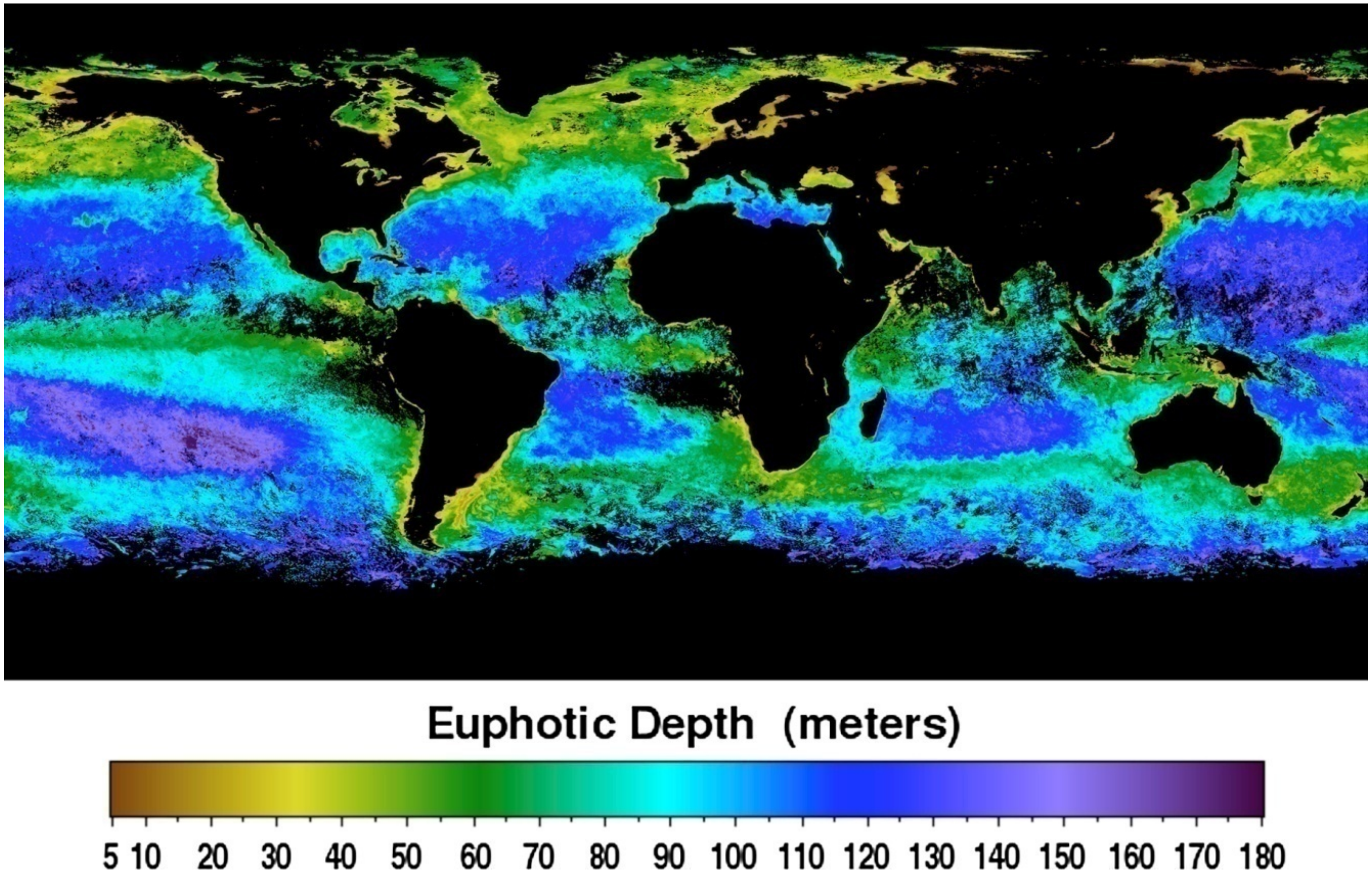


FIGURE 4.29

Euphotic zone depth (m) from the Aqua MODIS satellite, 9 km resolution, monthly composite for September 2007. (Black over oceans is cloud cover that could not be removed in the monthly composite.) See Figure S4.3 from the online supplementary material for the related map of photosynthetically available radiation (PAR). This figure can also be seen in the color insert. *Source: From NASA (2009b).*

Buoyancy and Mixing

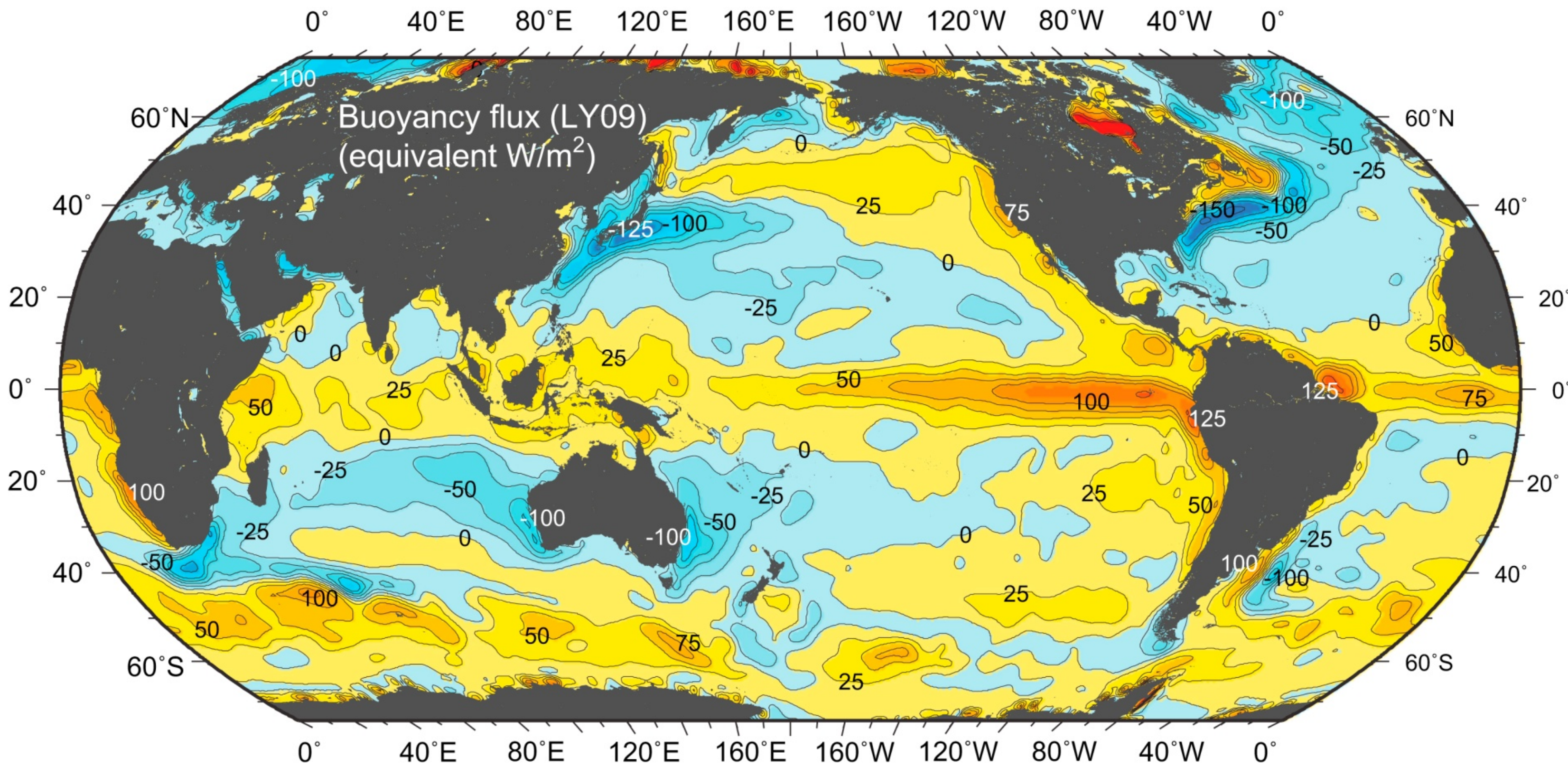
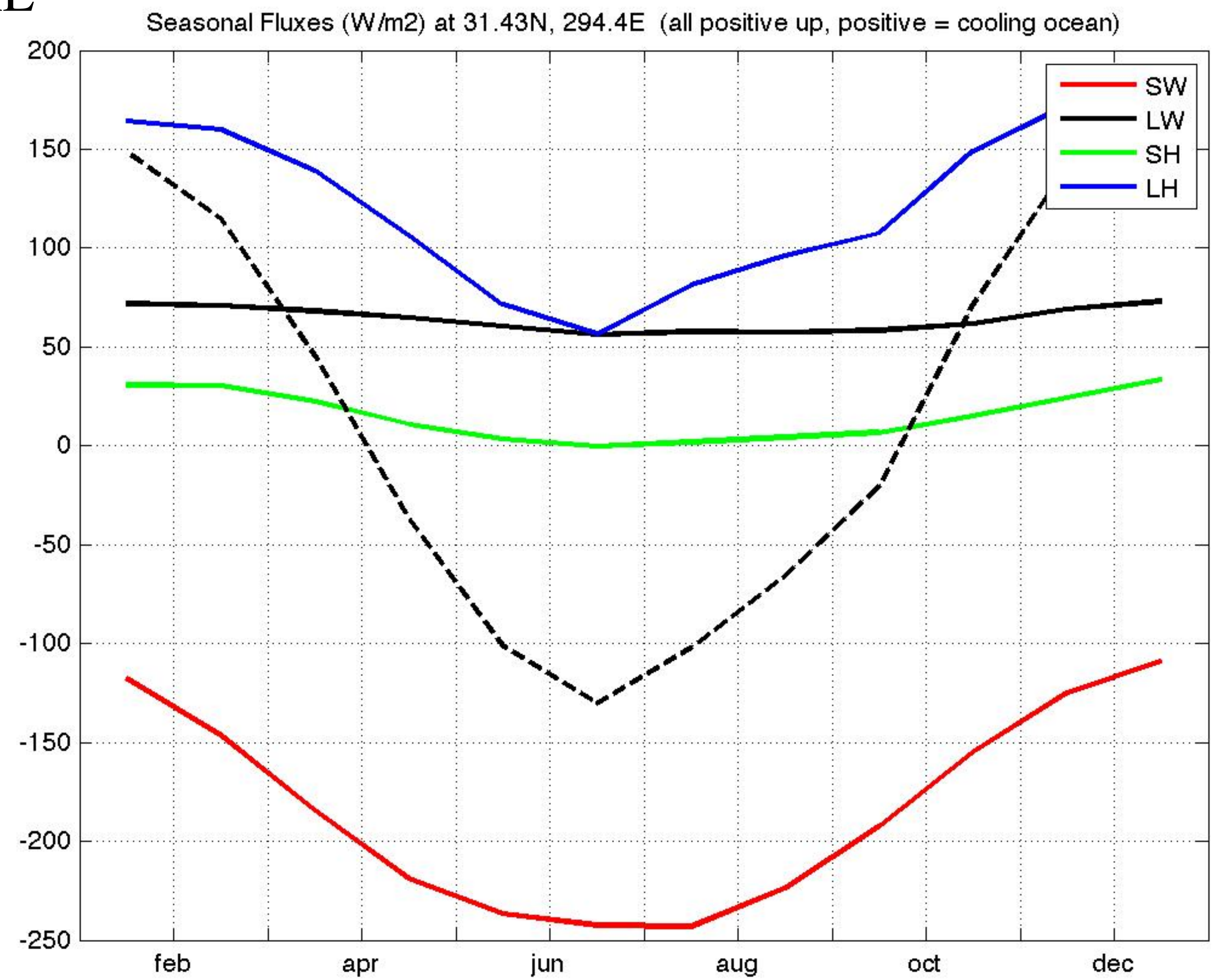


FIGURE 5.15

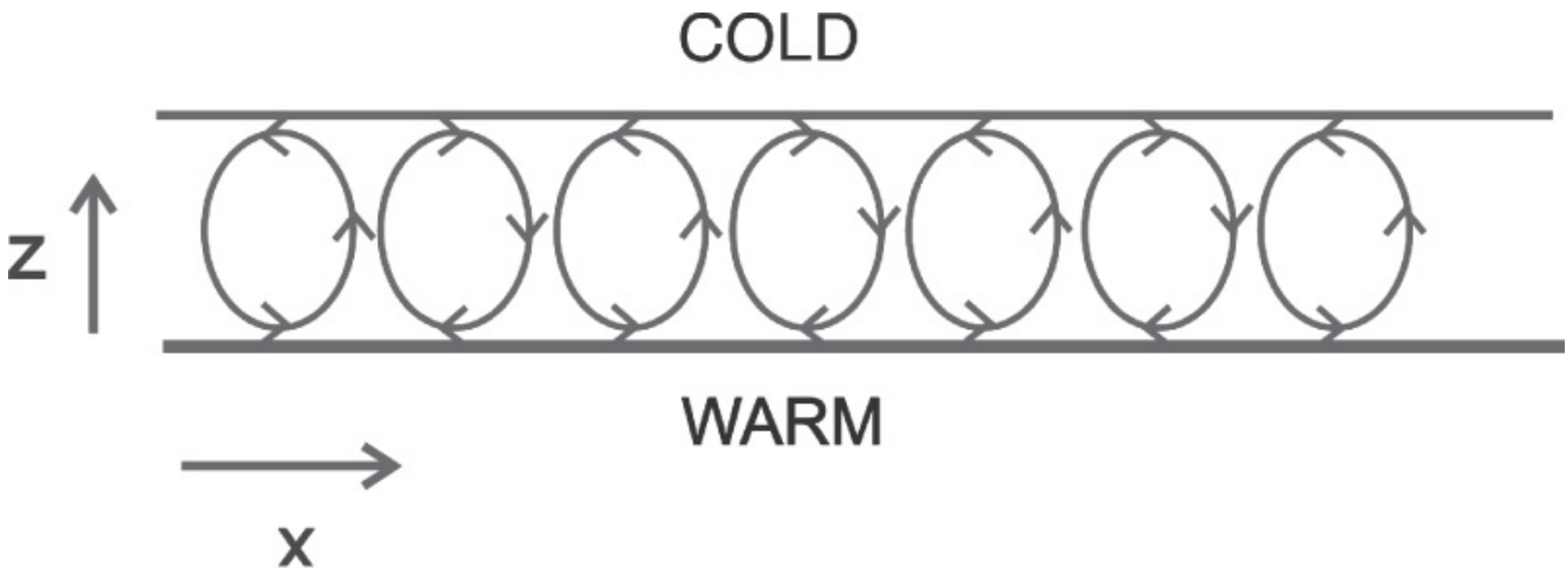
Annual mean air–sea buoyancy flux converted to equivalent heat fluxes (W/m^2), *based on Large and Yeager (2009)* air–sea fluxes. Positive values indicate that the ocean is becoming less dense. Contour interval is 25 W/m^2. The heat and freshwater flux maps used to construct this map are in the online supplement to Chapter 5 (Figure S5.8).

What happens when buoyancy is lost from the surface ocean?

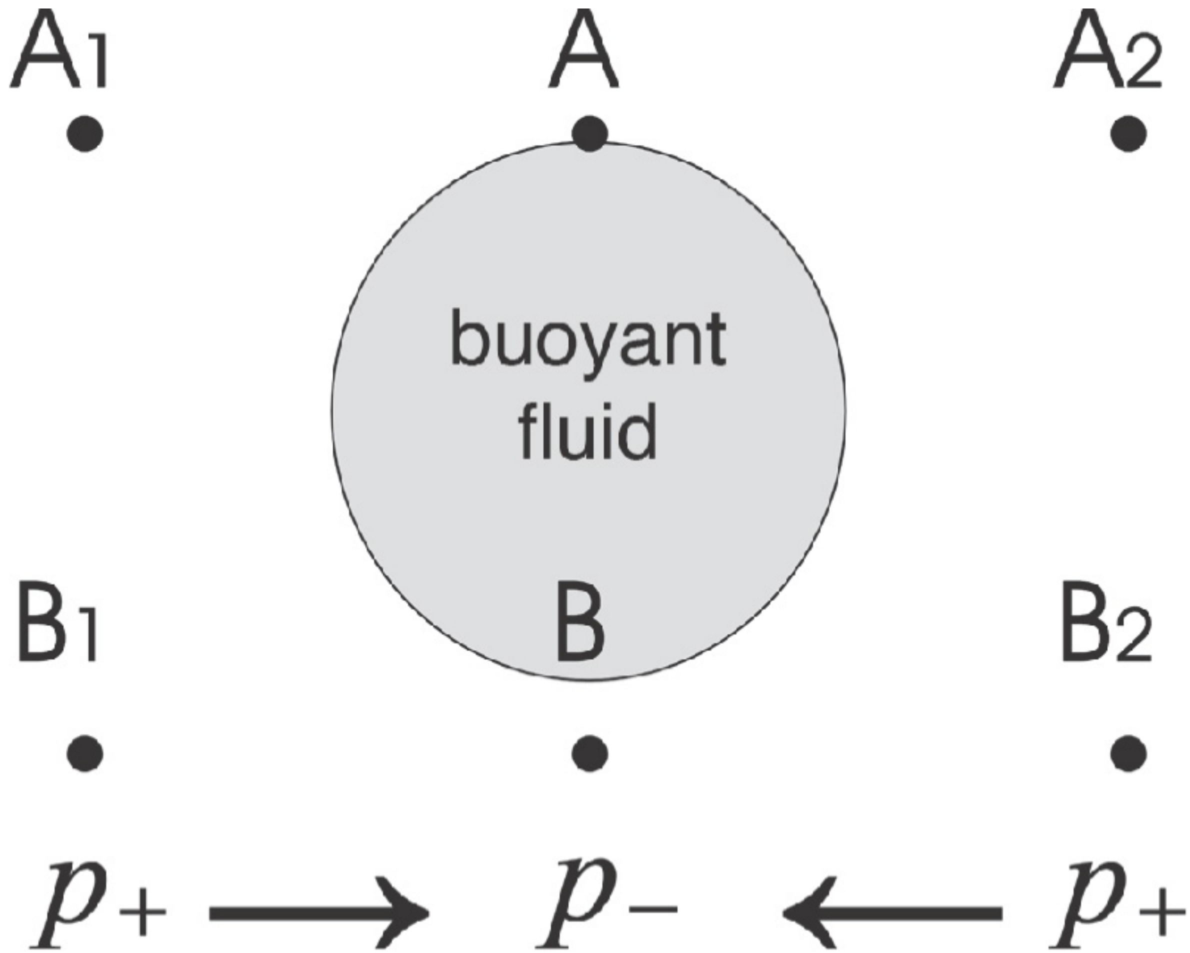
BERMUDA SEASONAL FLUXES



Convection



Buoyancy



Buoyancy

$$b = -g\left(\frac{\rho - \rho_e}{\rho}\right)$$

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

Stability

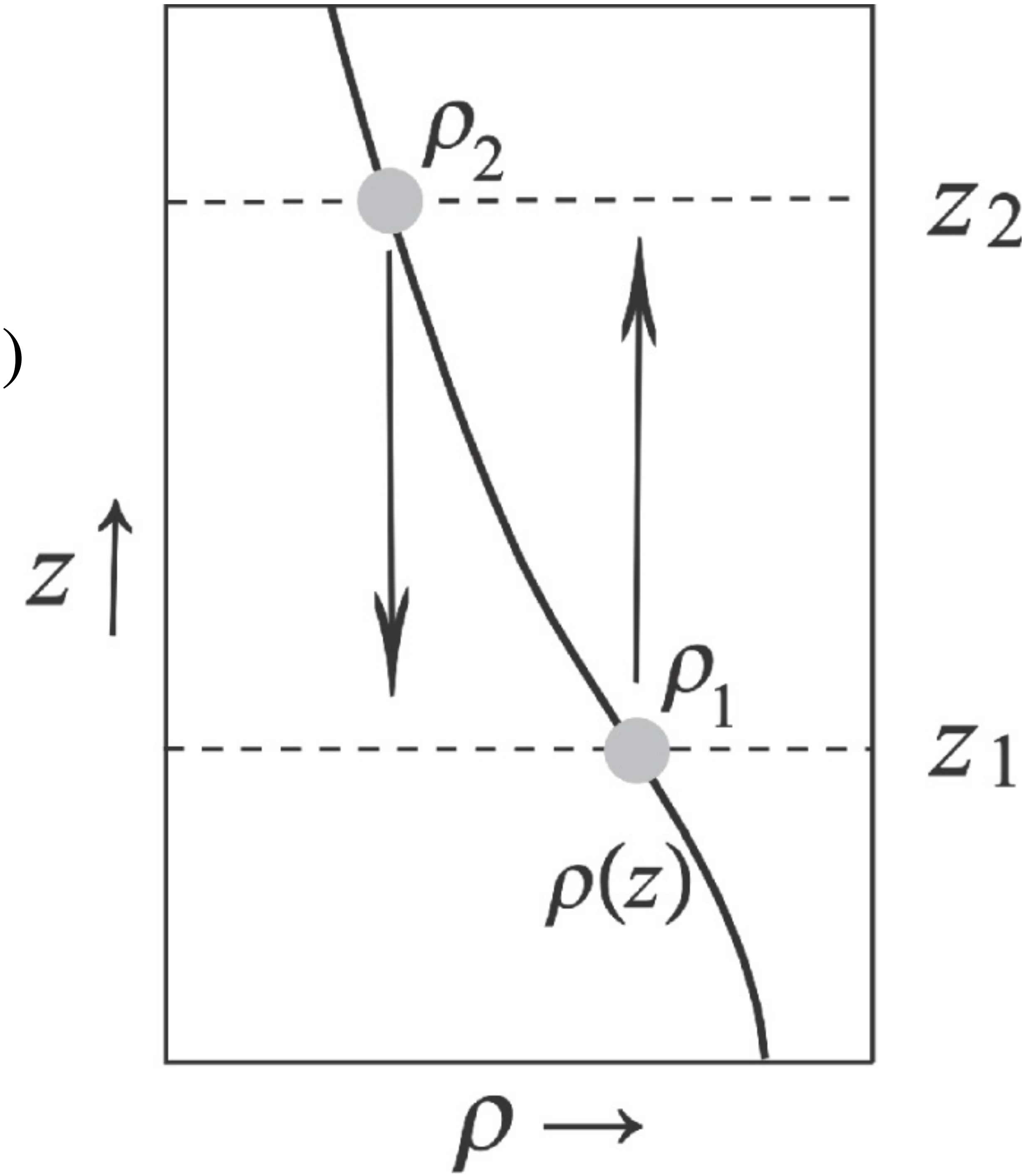
Light fluid over heavy fluid ($\Delta\rho/\Delta z < 0$)

vs.

Heavy fluid over light fluid ($\Delta\rho/\Delta z > 0$)

Stable

($\Delta\rho/\Delta z < 0$)



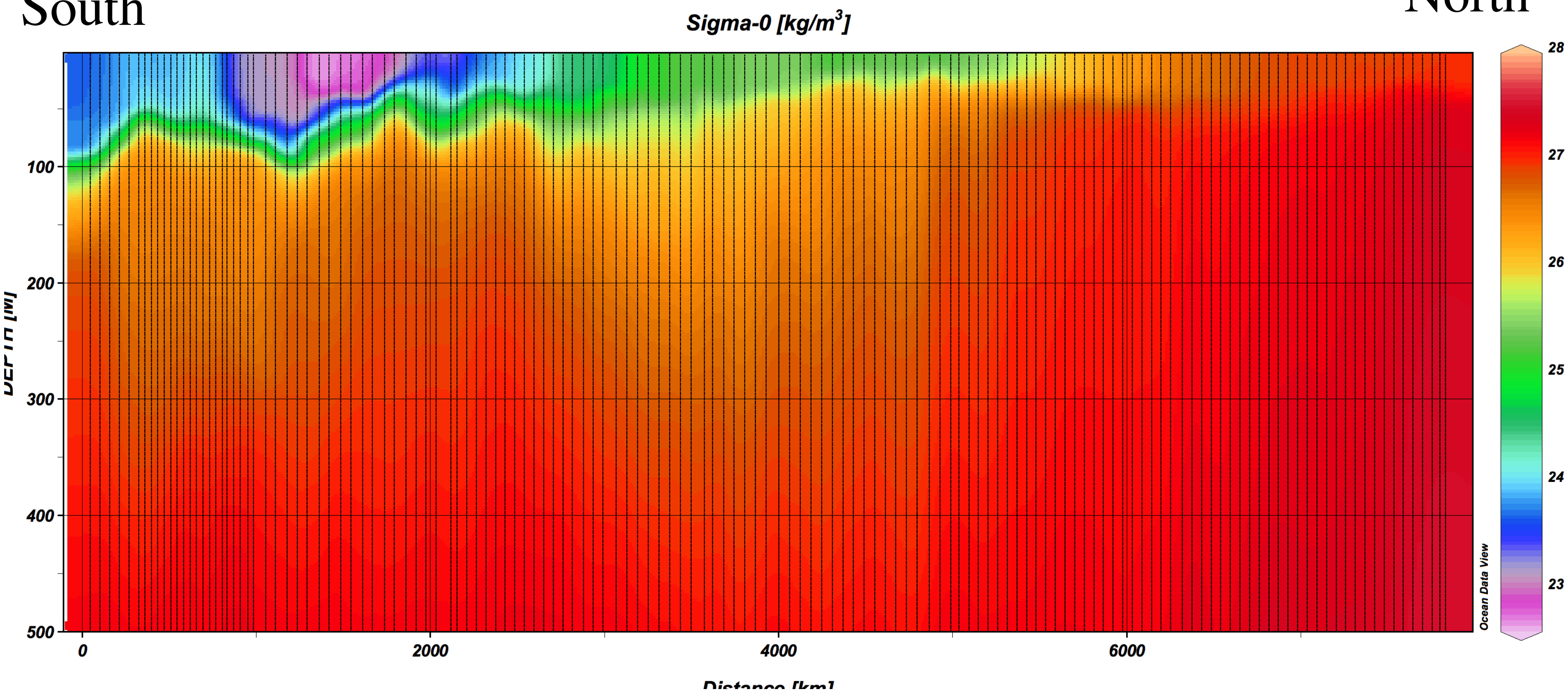
Stratification

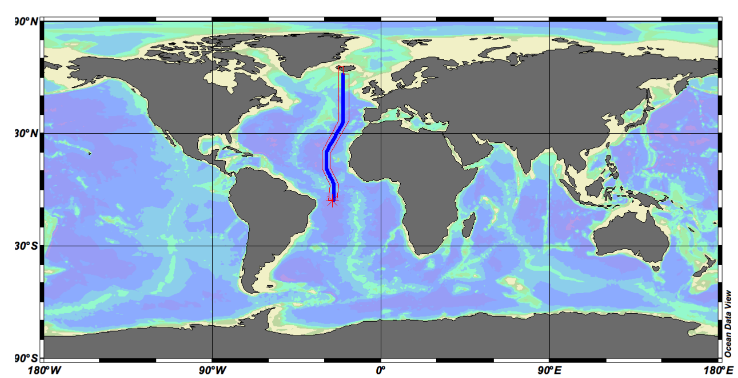
- The continuous change of density with depth, i.e. $\delta\rho/\delta z$ (= $\delta\sigma/\delta z$)

Stratification

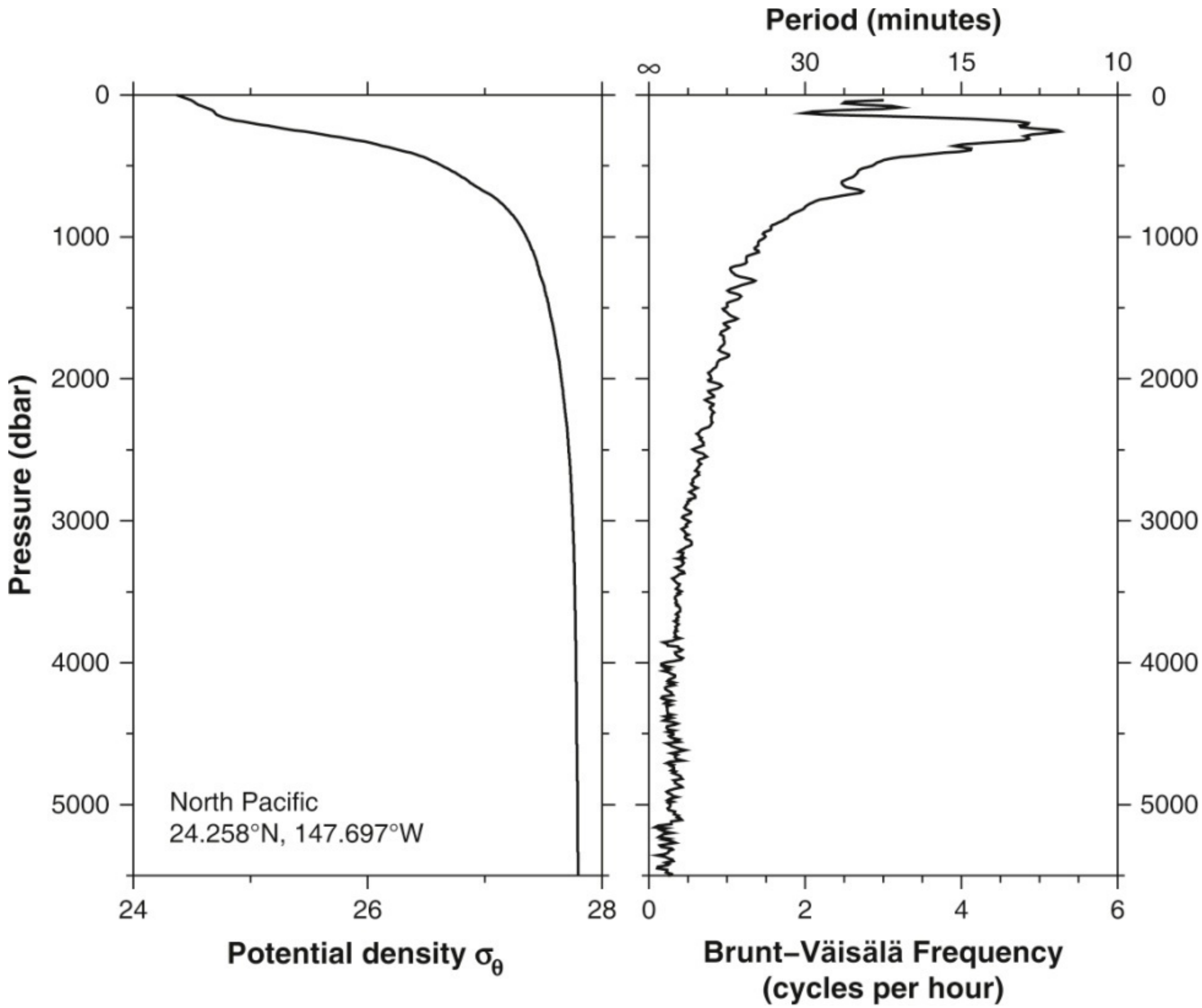
- The continuous change of density with depth, i.e. $\delta\rho/\delta z$ $(= \delta\sigma/\delta z)$
- What does it mean to be
  - "More stratified"?
  - "Less stratified"?
- How to quantify?
- Critical for response of water column to forcing

South North


Sigma-0 [kg/m3]
100
200
300
400
500
0
2000
4000
6000
Distance [km]
28
27
26
25
24
23
Ocean Data View


90°N
30°N
30°S
90°S
180°W
90°W
0°
90°E
180°E
Ocean Data View

Brunt-Vaisala / Buoyancy frequency (N)



(a) Potential density and (b) Brunt-Väisälä frequency (cycles/h) and period (minutes) for a profile in the western North Pacific.

FIGURE 3.6

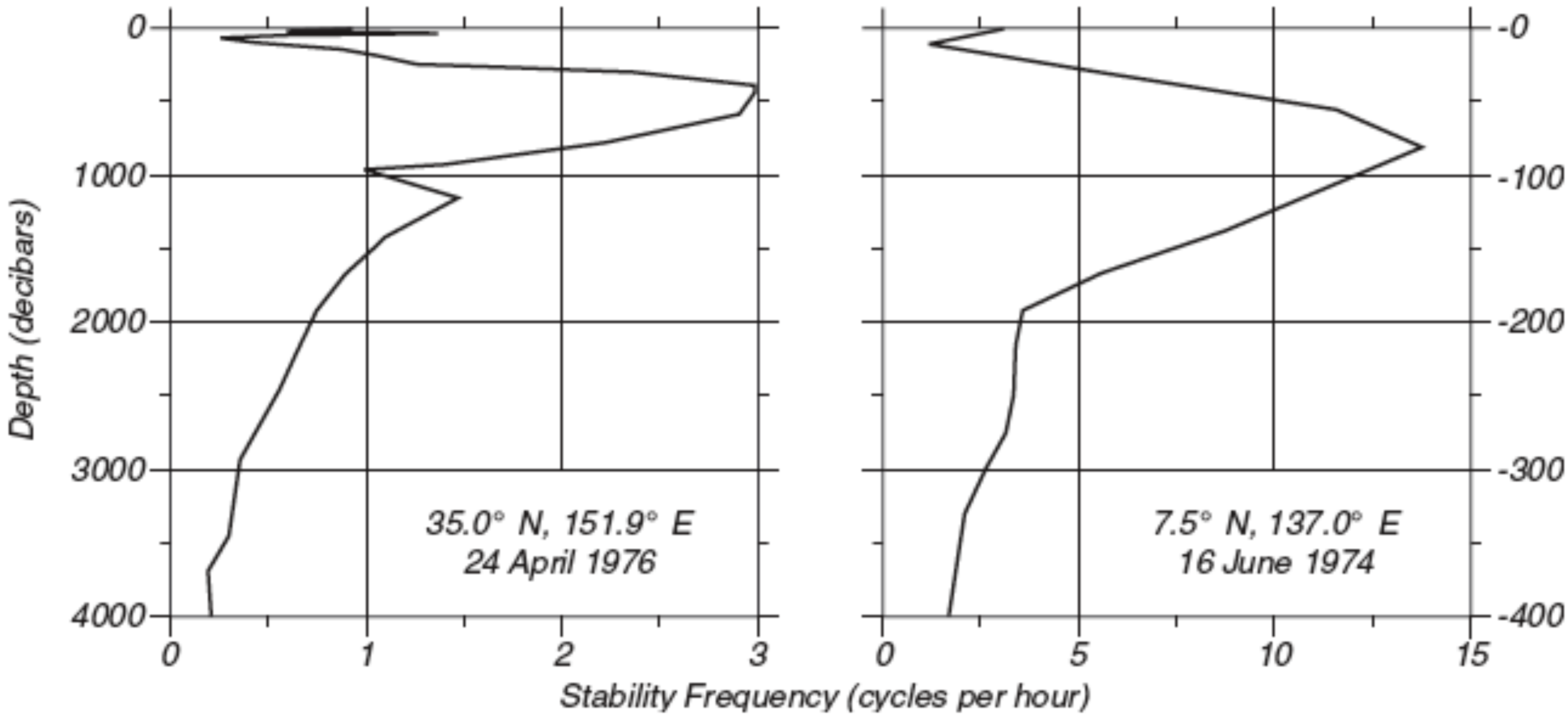
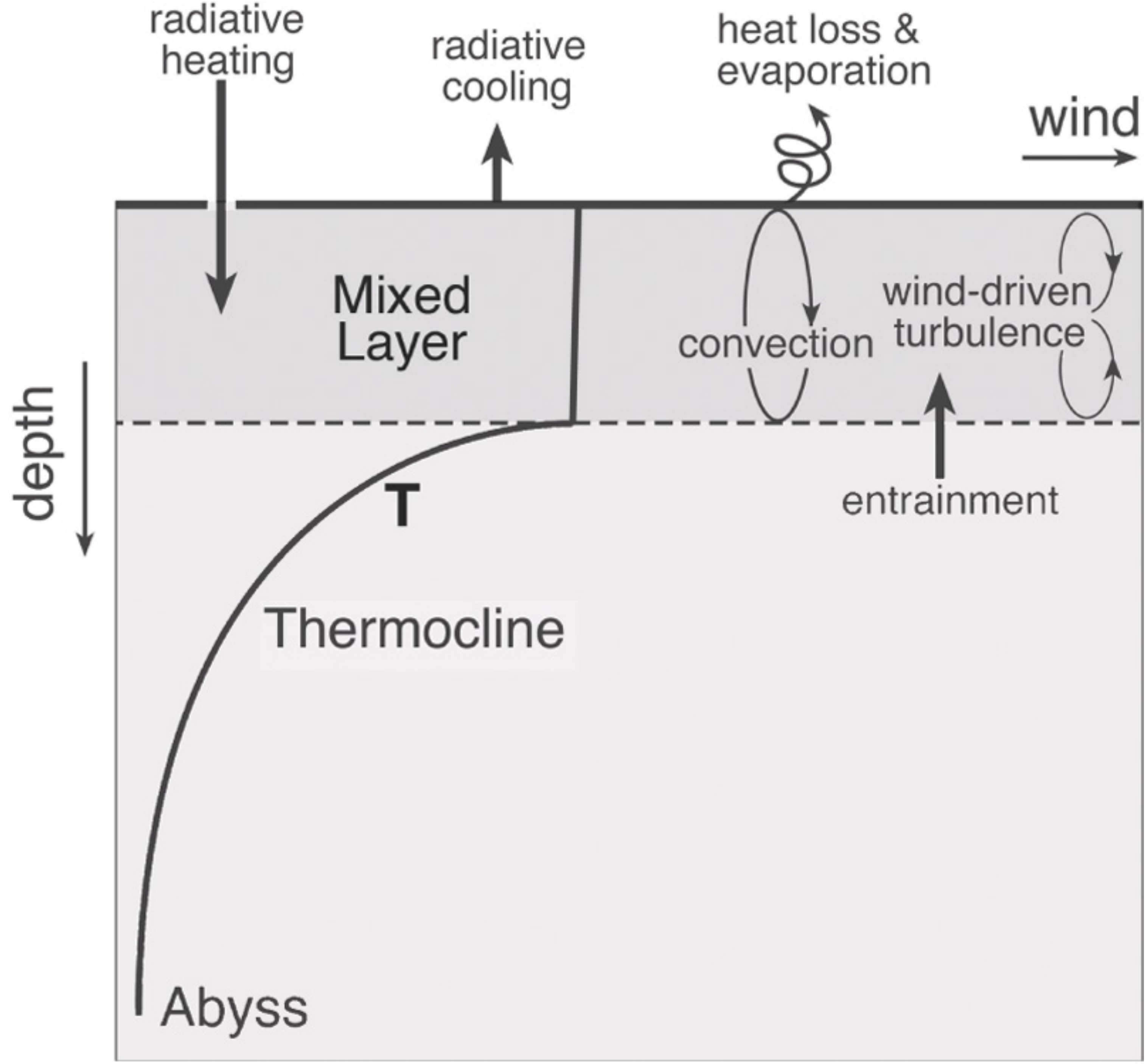
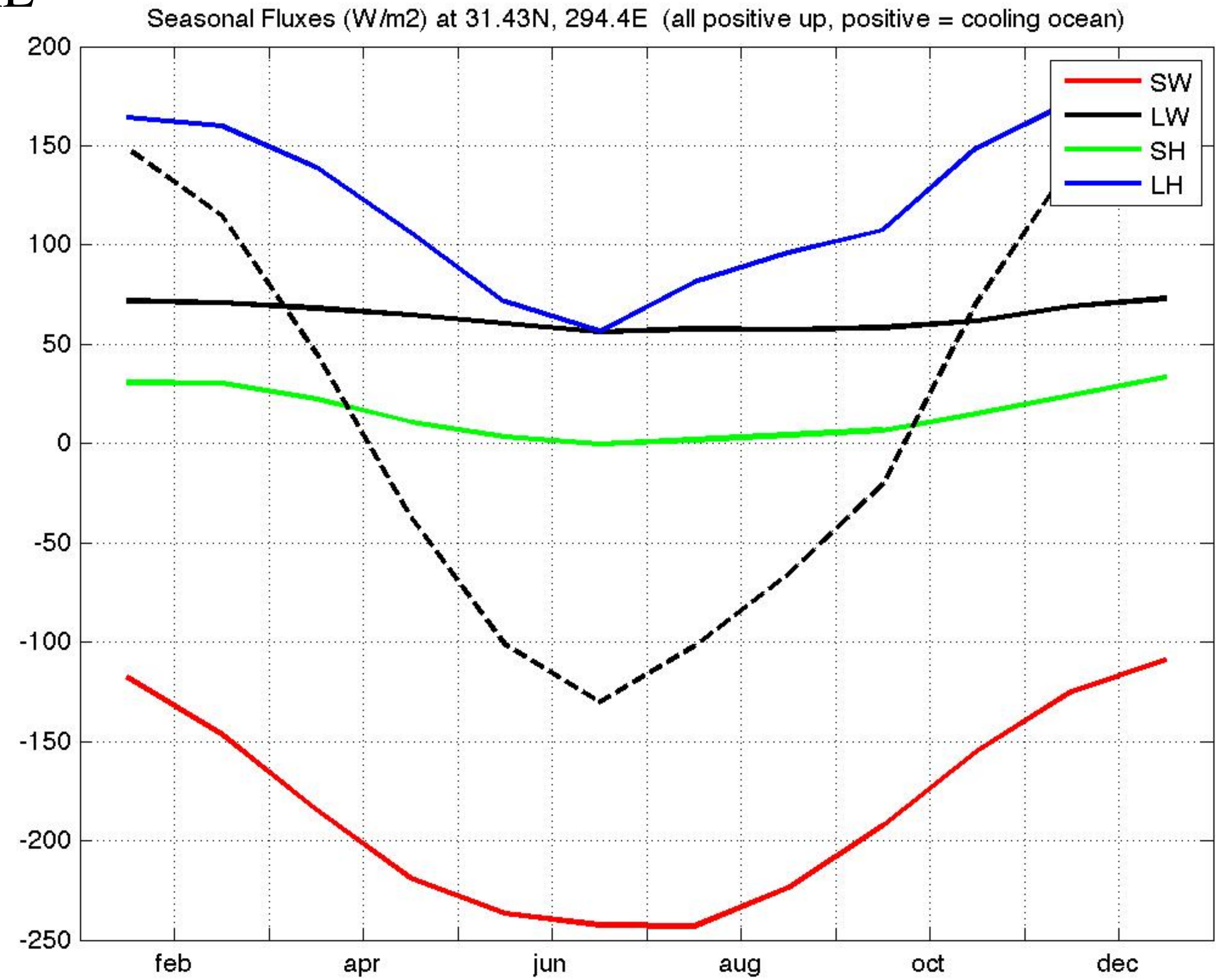


Figure 8.6. Observed stability frequency in the Pacific. **Left:** Stability of the deep thermocline east of the Kuroshio. **Right:** Stability of a shallow thermocline typical of the tropics. Note the change of scales.

The Seasonal Mixed Layer


radiative heating
radiative cooling
heat loss & evaporation
wind
Mixed Layer
convection
wind-driven turbulence
depth
T
entrainment
Thermocline
Abyss

BERMUDA SEASONAL FLUXES



Mixed Layer Cycle Near Bermuda

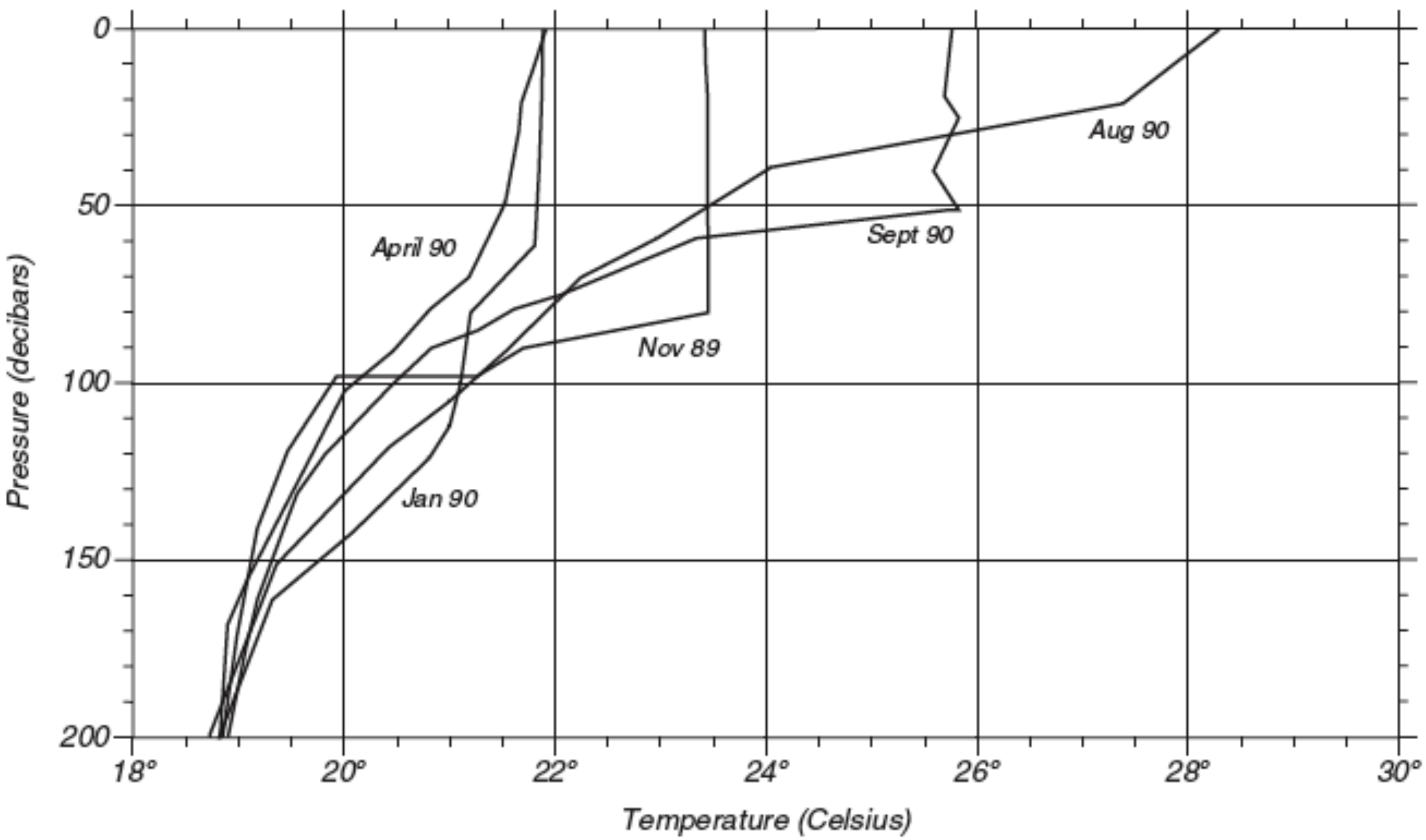
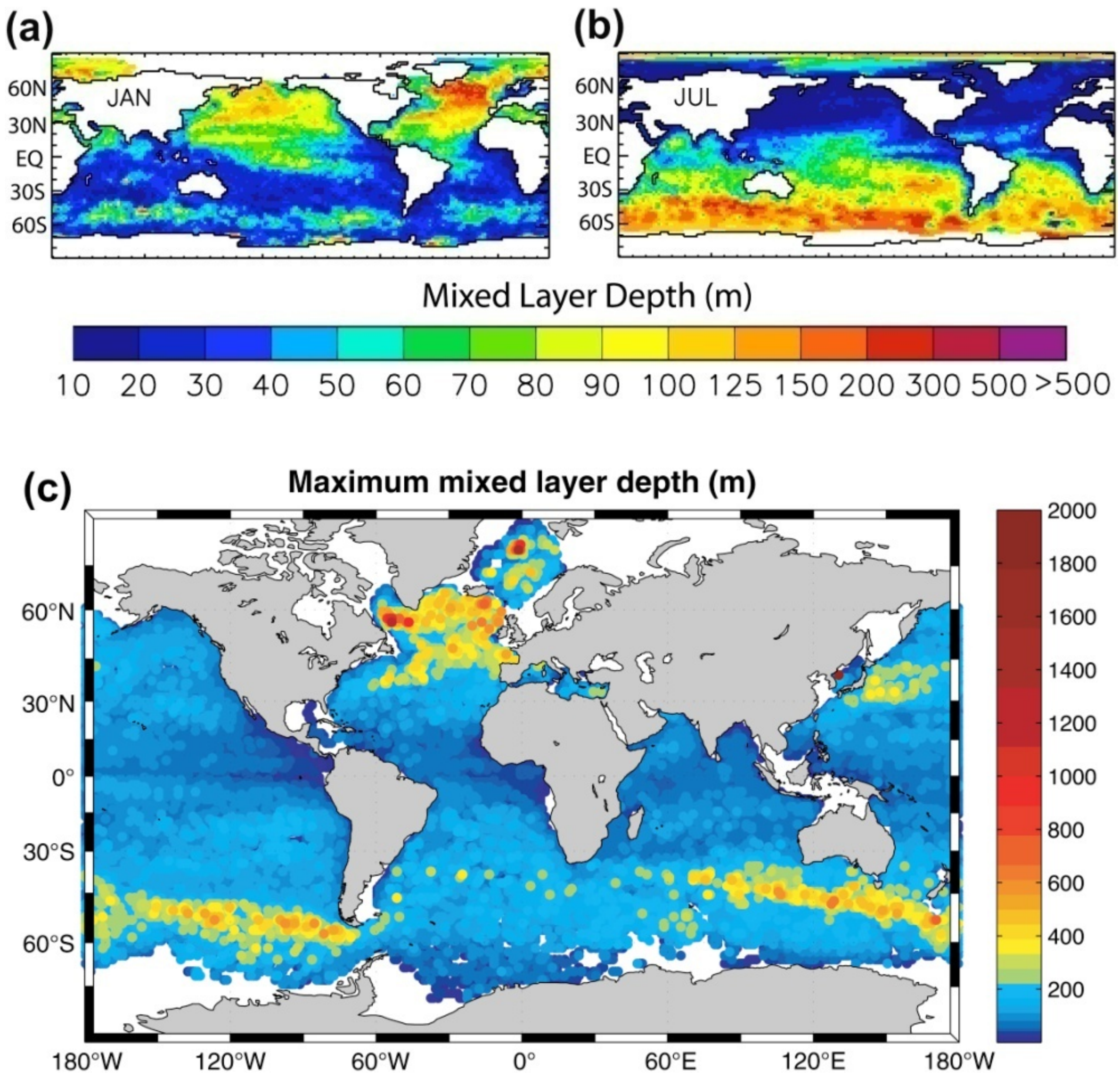


Figure 6.7 Growth and decay of the mixed layer and seasonal thermocline from November 1989 to September 1990 at the Bermuda Atlantic Time-series Station (BATS) at 31.8°N 64.1°W. Data were collected by the Bermuda Biological Station for Research, Inc. Note that pressure in decibars is nearly the same as depth in meters (see §6.8 for a definition of decibars).



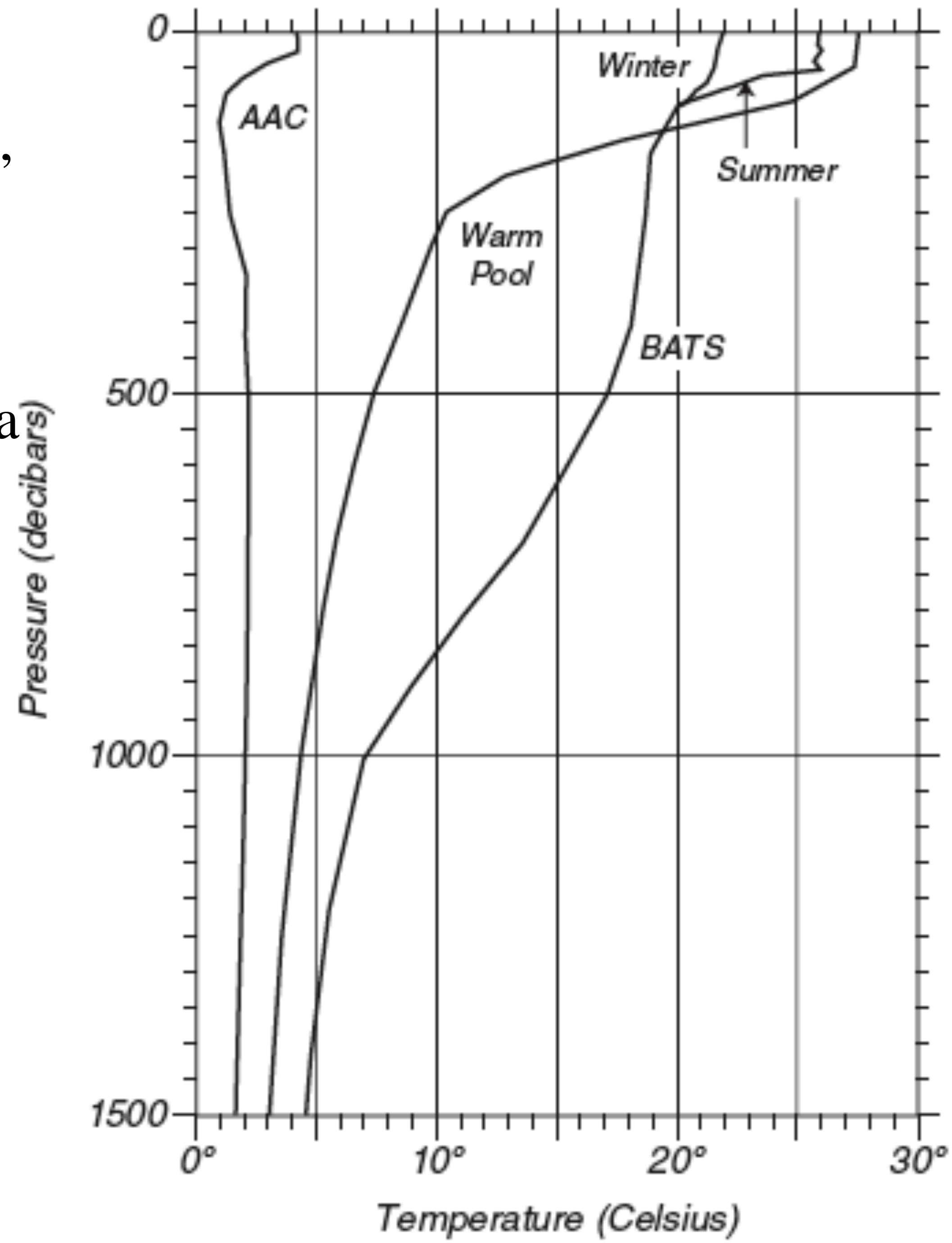
Mixed layer depth in (a) January and (b) July, based on a temperature difference of 0.2°C from the near-surface temperature. *Source: From deBoyer Montégut et al. (2004).* (c) Averaged maximum mixed layer depth, using the 5 deepest mixed layers in 1° × 1° bins from the Argo profiling float data set (2000-2009) and fitting the mixed layer structure as in Holte and Talley (2009). This figure can also be found in the color insert.

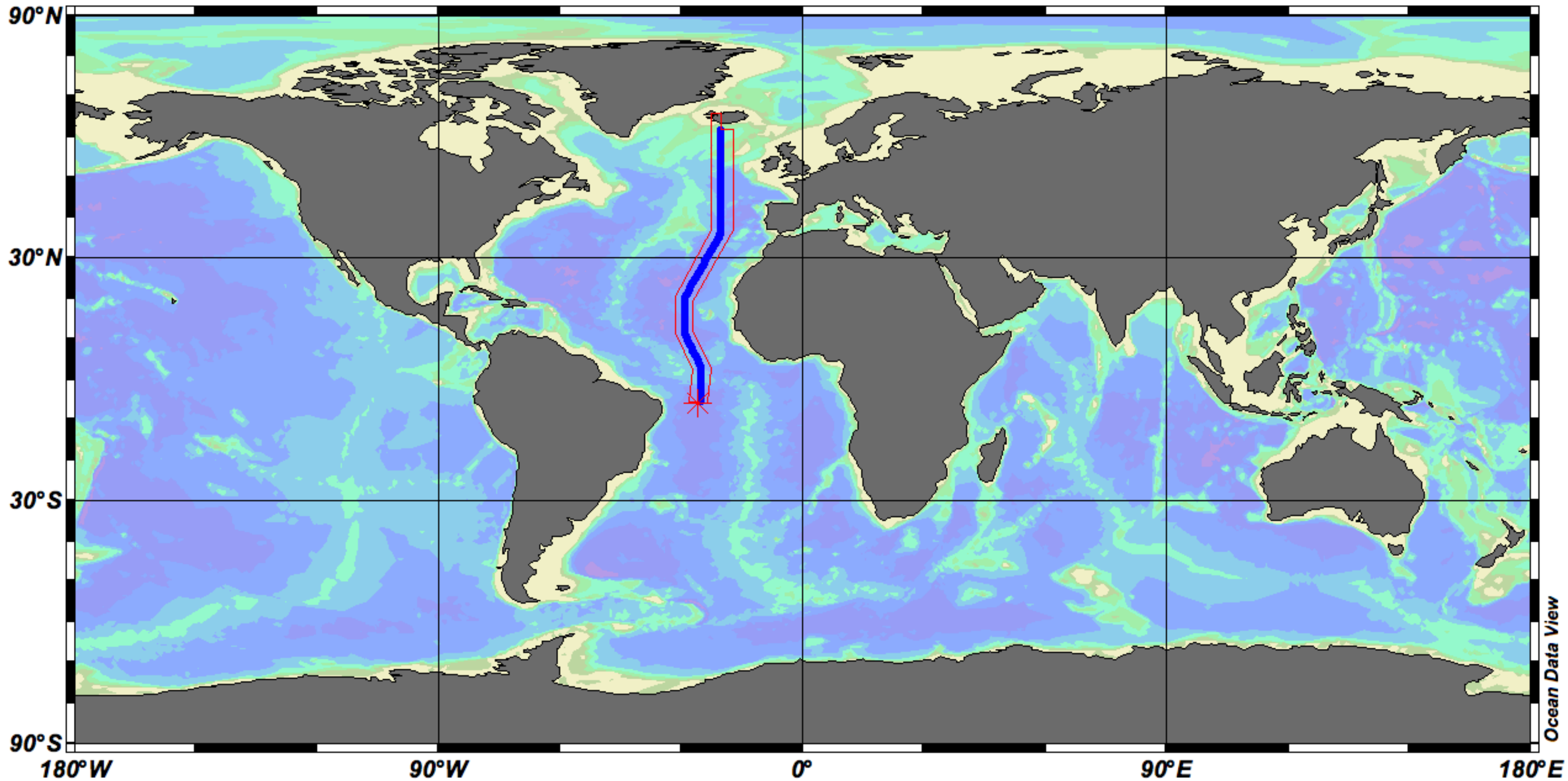
FIGURE 4.4

Over the global oceans, where do you expect

- Shallowest mixed layers?
- Deepest mixed layers?
- Largest seasonal variations?

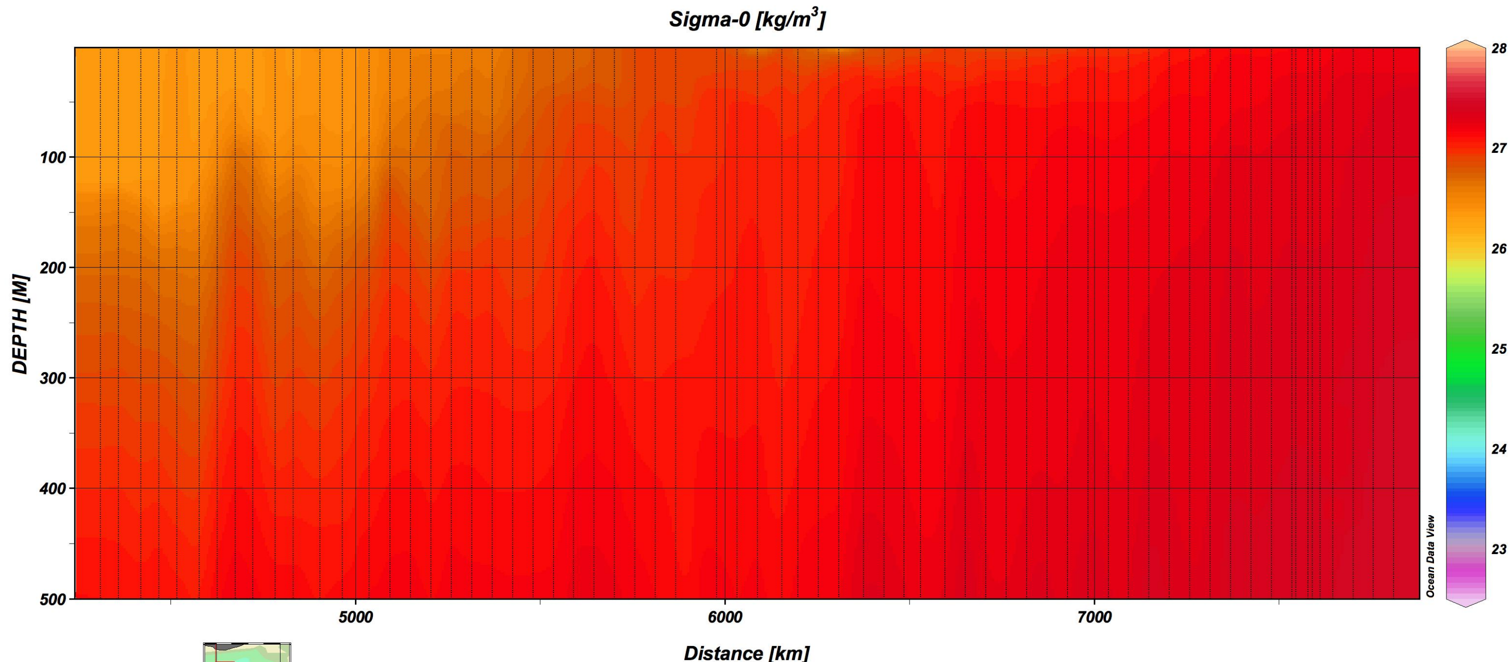
Typical Mixed layers in the ACC (summer), the Warm Pool of the western Pacific (annual), and seasonally at Bermuda (BATS)

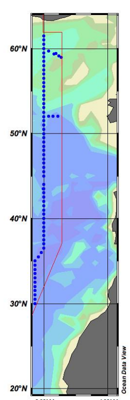




90°N
30°N
30°S
90°S
180°W
90°W
0°
90°E
180°E
Ocean Data View

May 1998, A16N, ~20-60N, σ_Θ

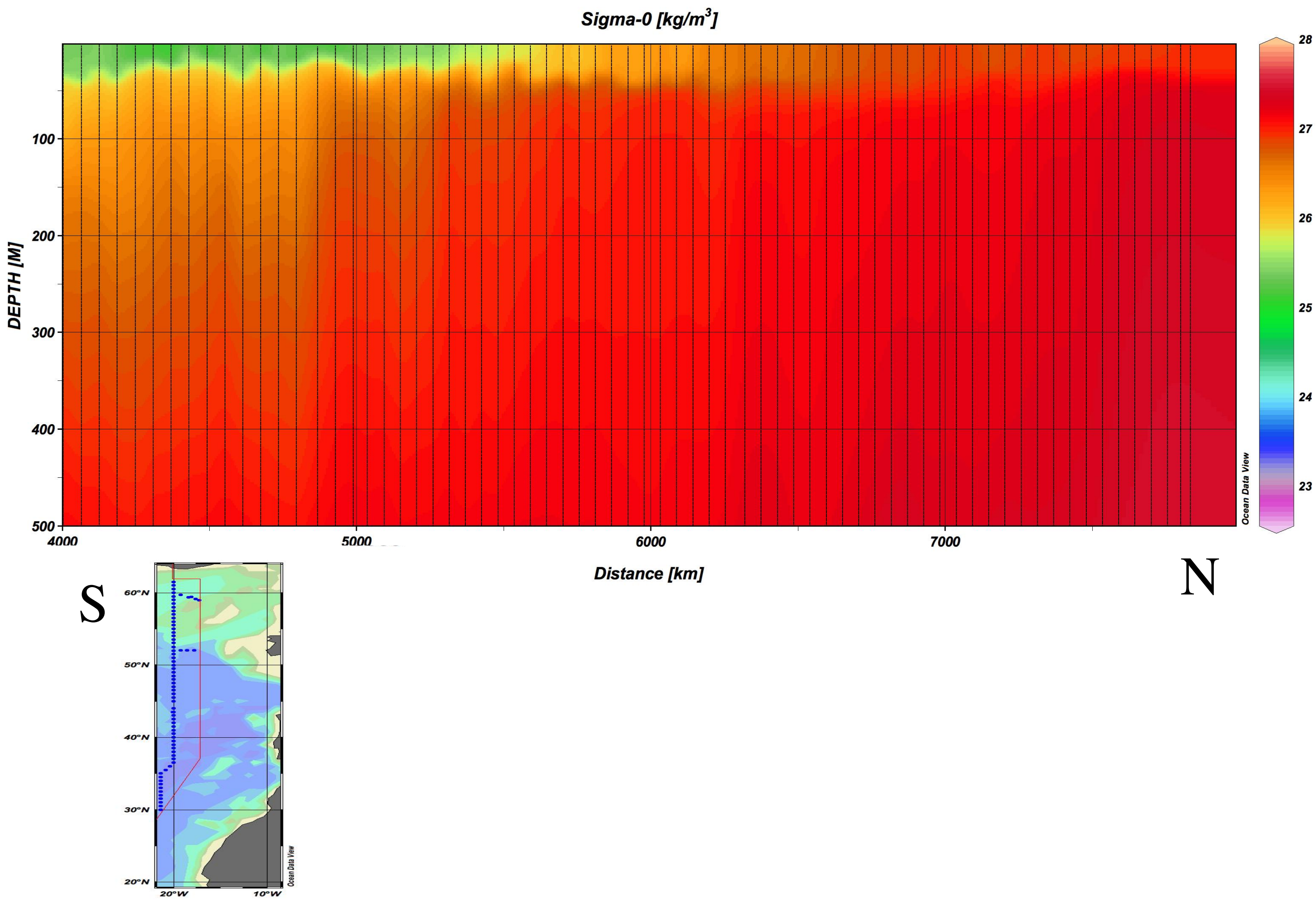




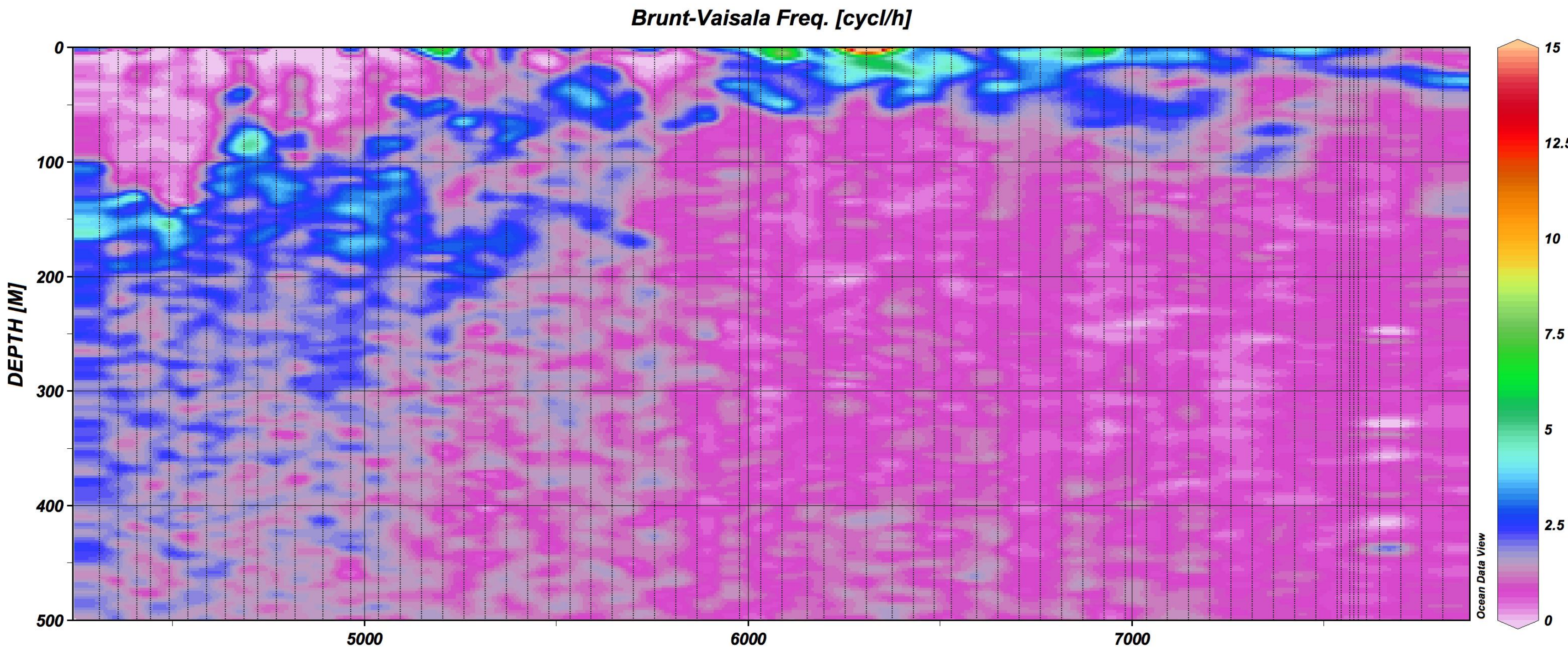
S

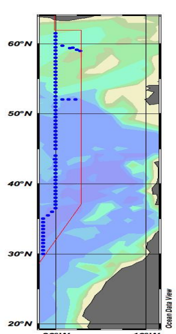
N

June 2003, A16N, ~20-60N, σ_Θ



N (cycle/hr)
May 1998, A16N, ~20-60N

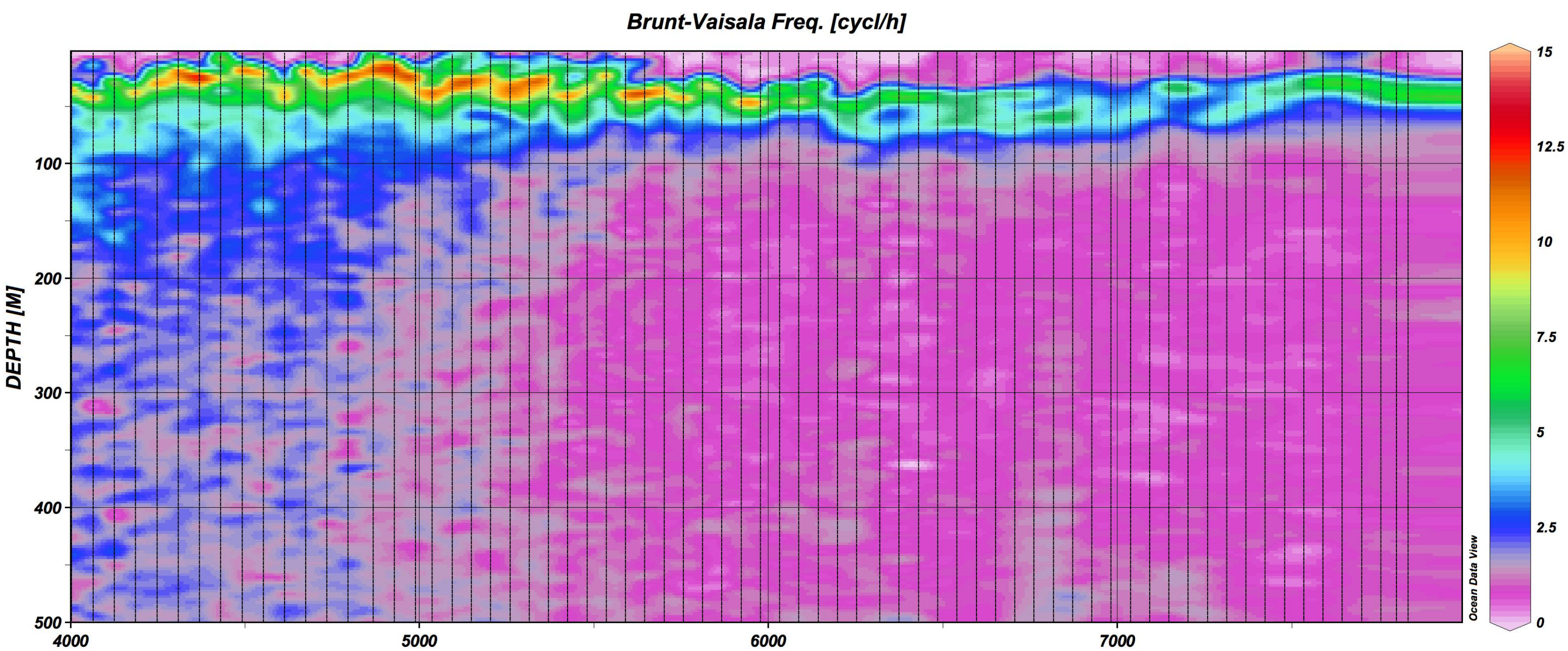




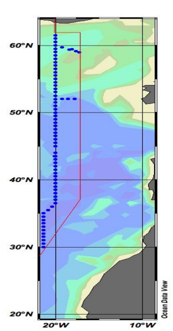
S

N

N (cycle/hr)
June 2003, A16N, ~20-60N

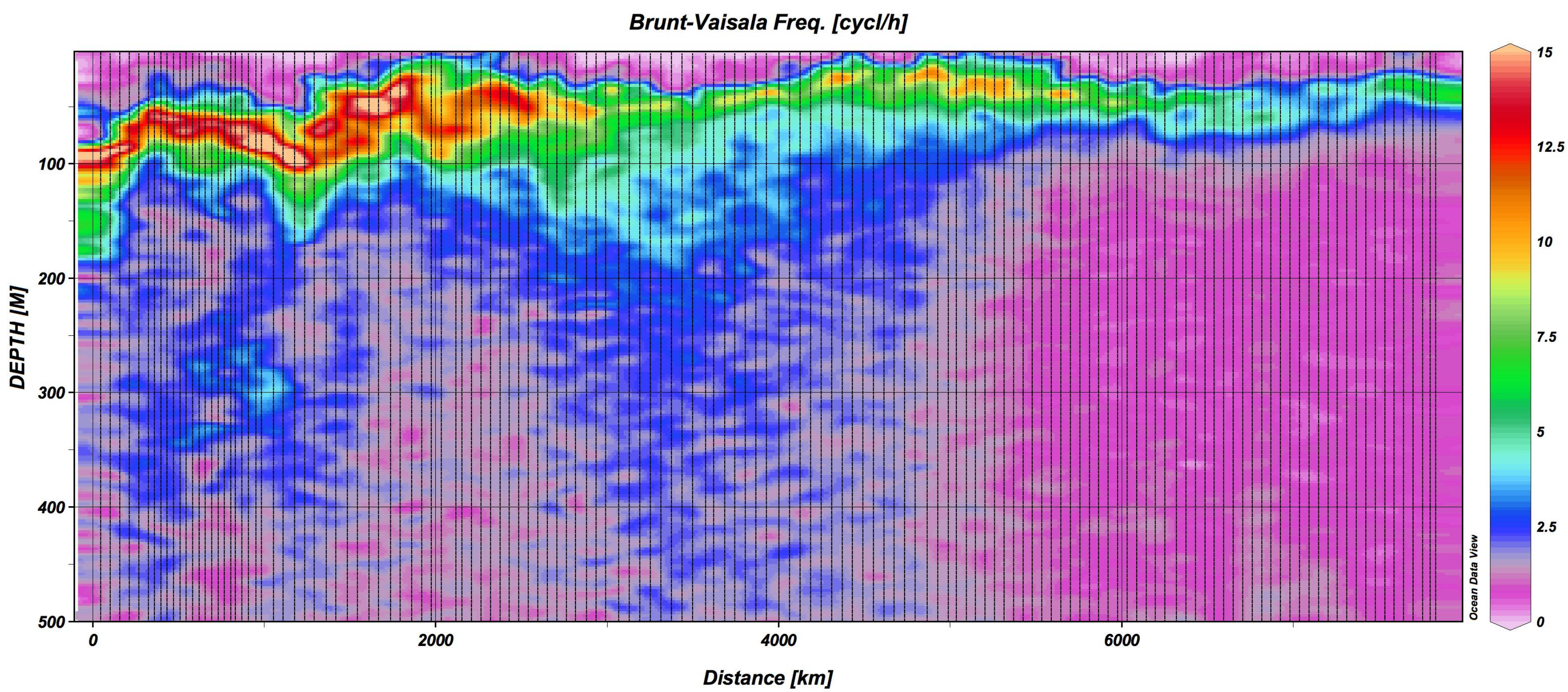


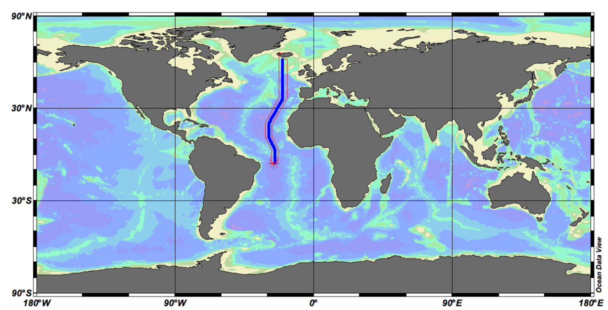
S



N

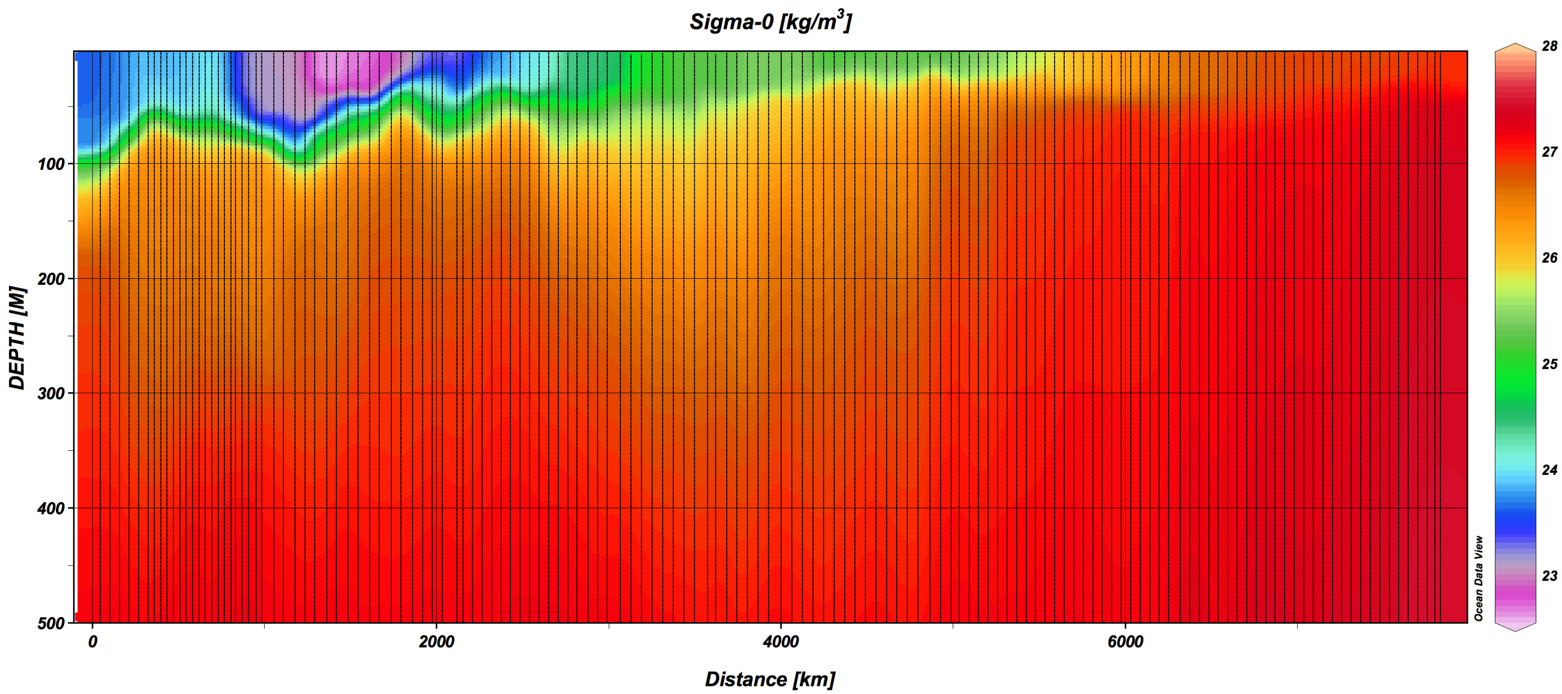
N (cycle/hr)
June 2003, A16N, extended south

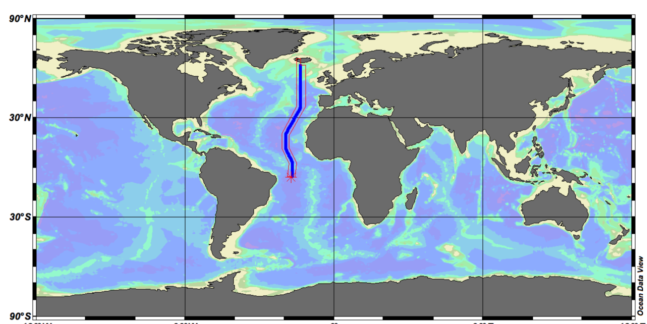




S N

June 2003, A16N, σ_Θ





S

N

Annual Average Forcing

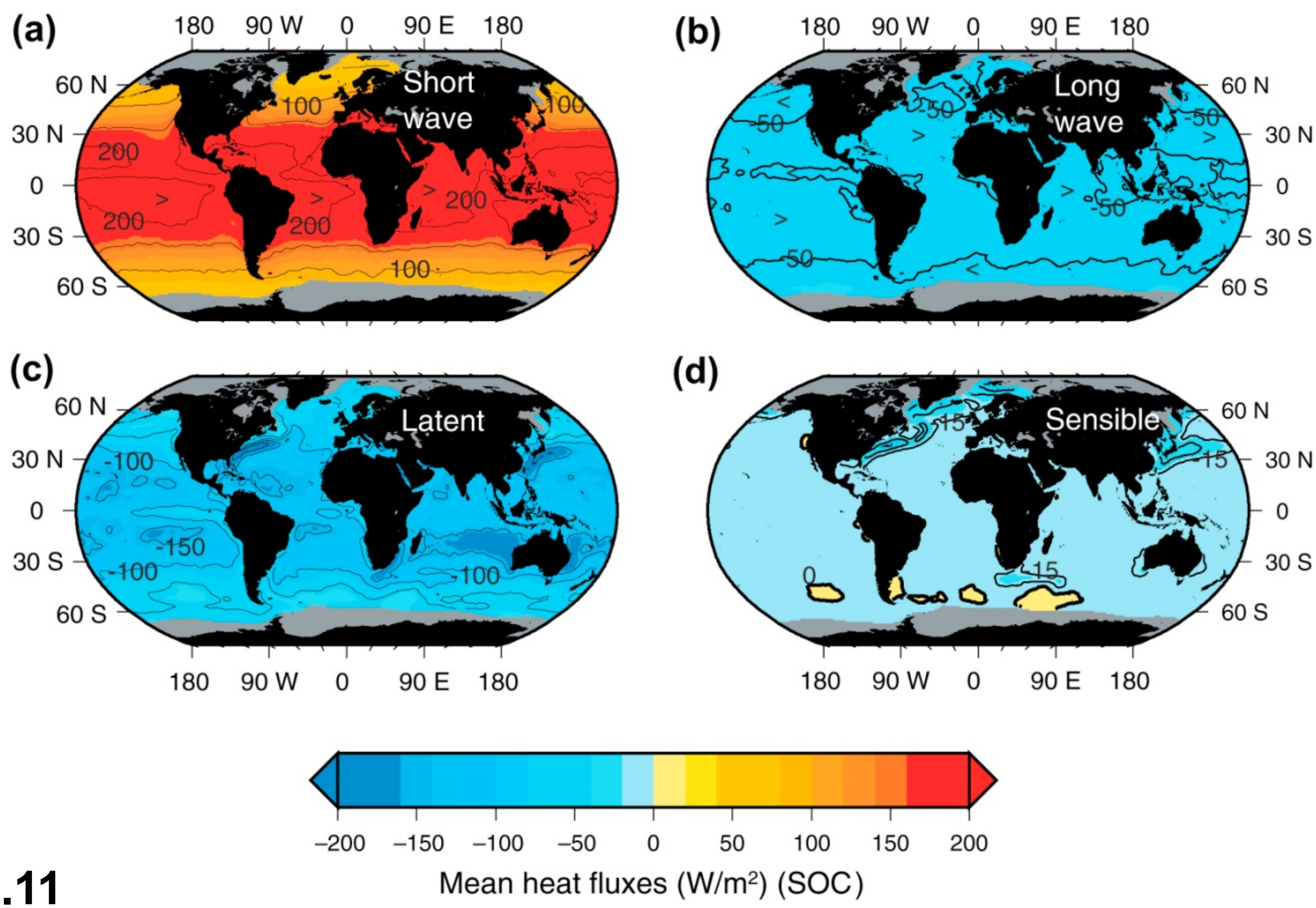
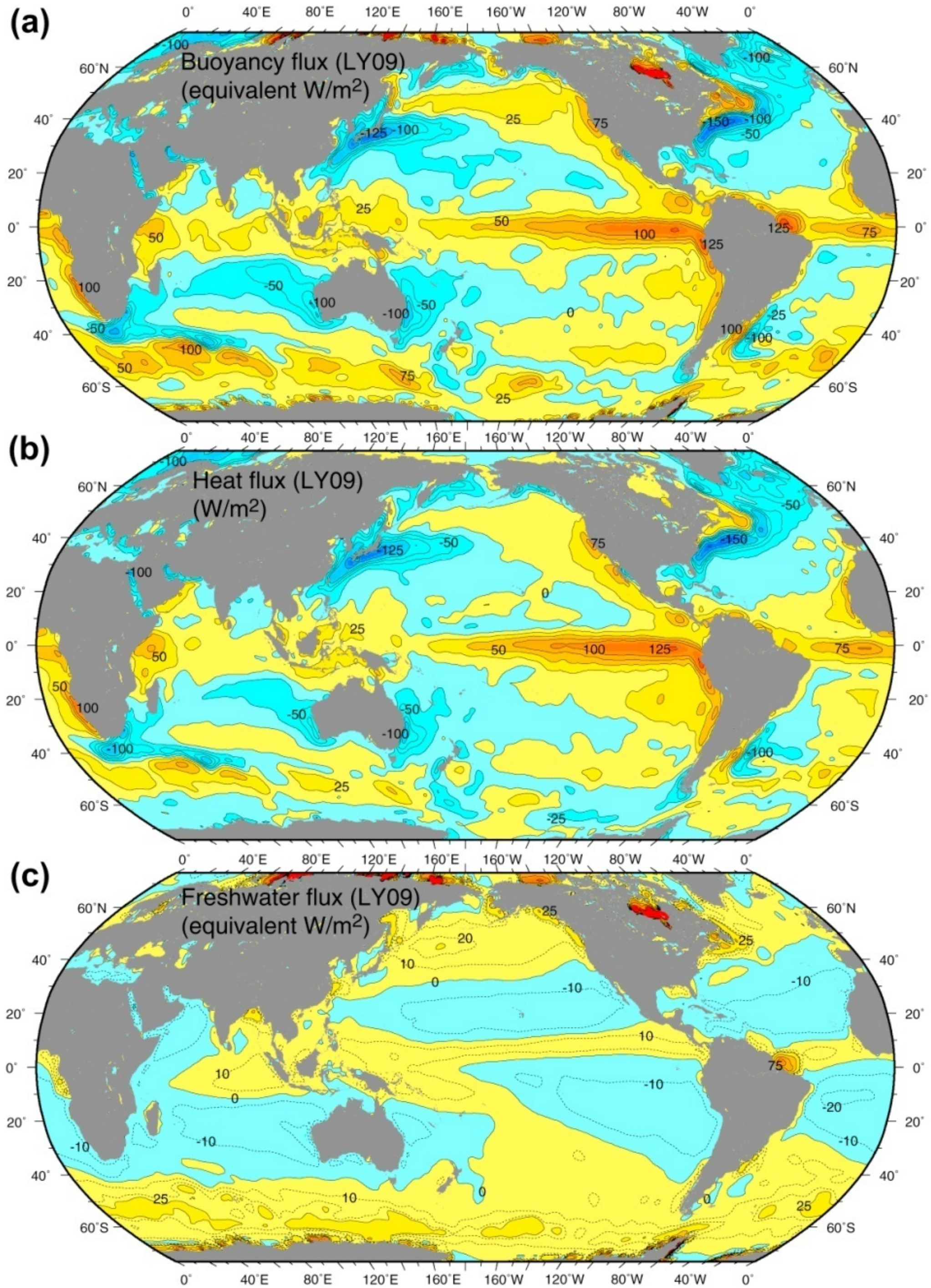


FIGURE 5.11

Annual average heat fluxes (W/m^2). (a) Shortwave heat flux Q_s. (b) Longwave (back radiation) heat flux Q_b. (c) Evaporative (latent) heat flux Q_e. (d) Sensible heat flux Q_h. Positive (yellows and reds): heat gain by the sea. Negative (blues): heat loss by the sea. Contour intervals are 50 W/m^2 in (a) and (c), 25 W/m^2 in (b), and 15 W/m^2 in (d). Data are from the National Oceanography Centre, Southampton (NOCS) climatology (Grist and Josey, 2003). This figure can also be found in the color insert.

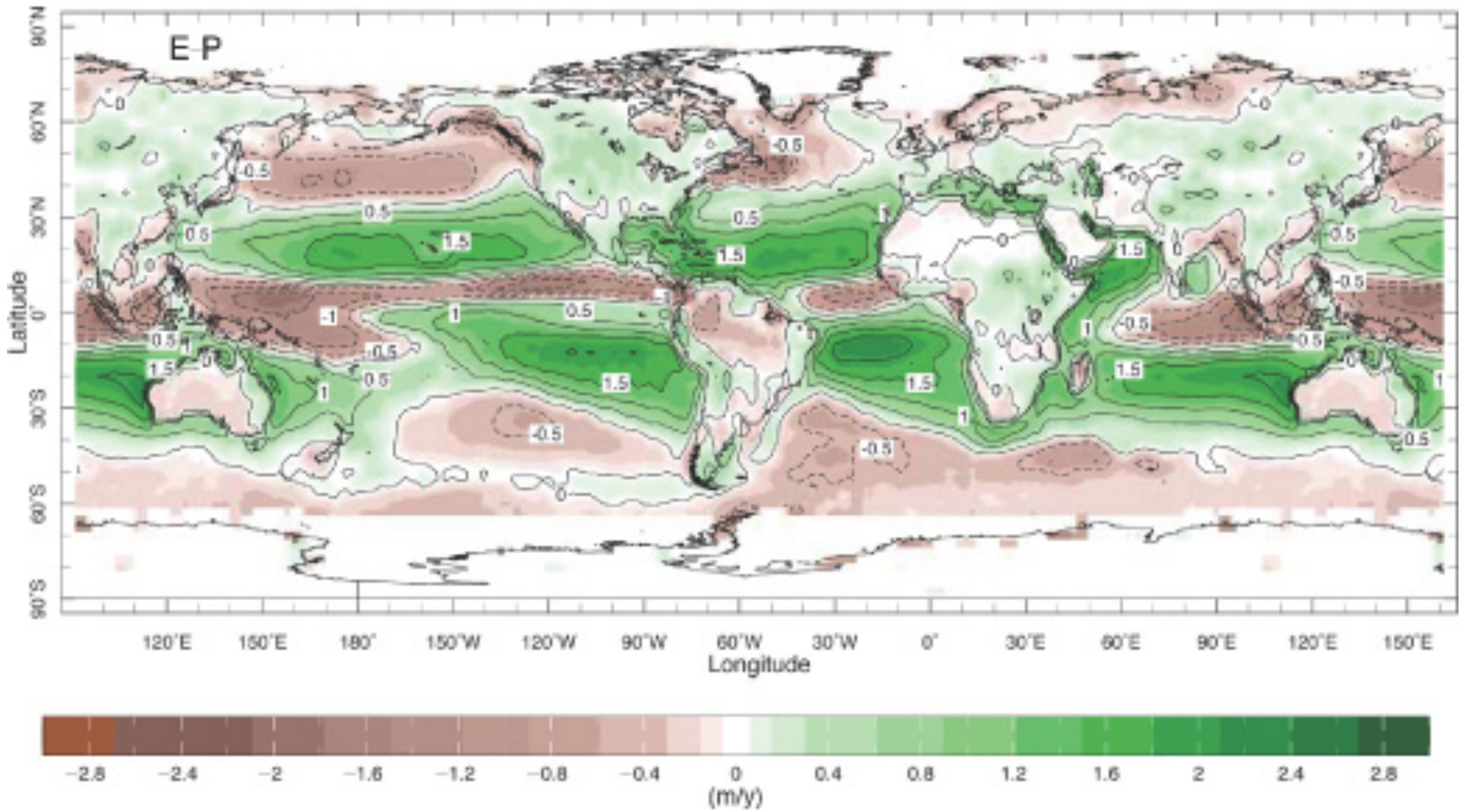


Annual mean air–sea (a) buoyancy flux, (b) heat flux, and (c) freshwater flux (precipitation, evaporation, and runoff) with the buoyancy and freshwater fluxes converted to equivalent heat fluxes (W/m^2), based on Large and Yeager (2009) air–sea fluxes. Positive values (yellows-reds) indicate that the ocean is becoming less dense, warmer, or fresher in the respective maps. Contour interval is 25 W/m^2; in (c) dotted contours are 10 and 20 W/m^2.

Net Salt Flux

Evaporation - Precipitation

E-P

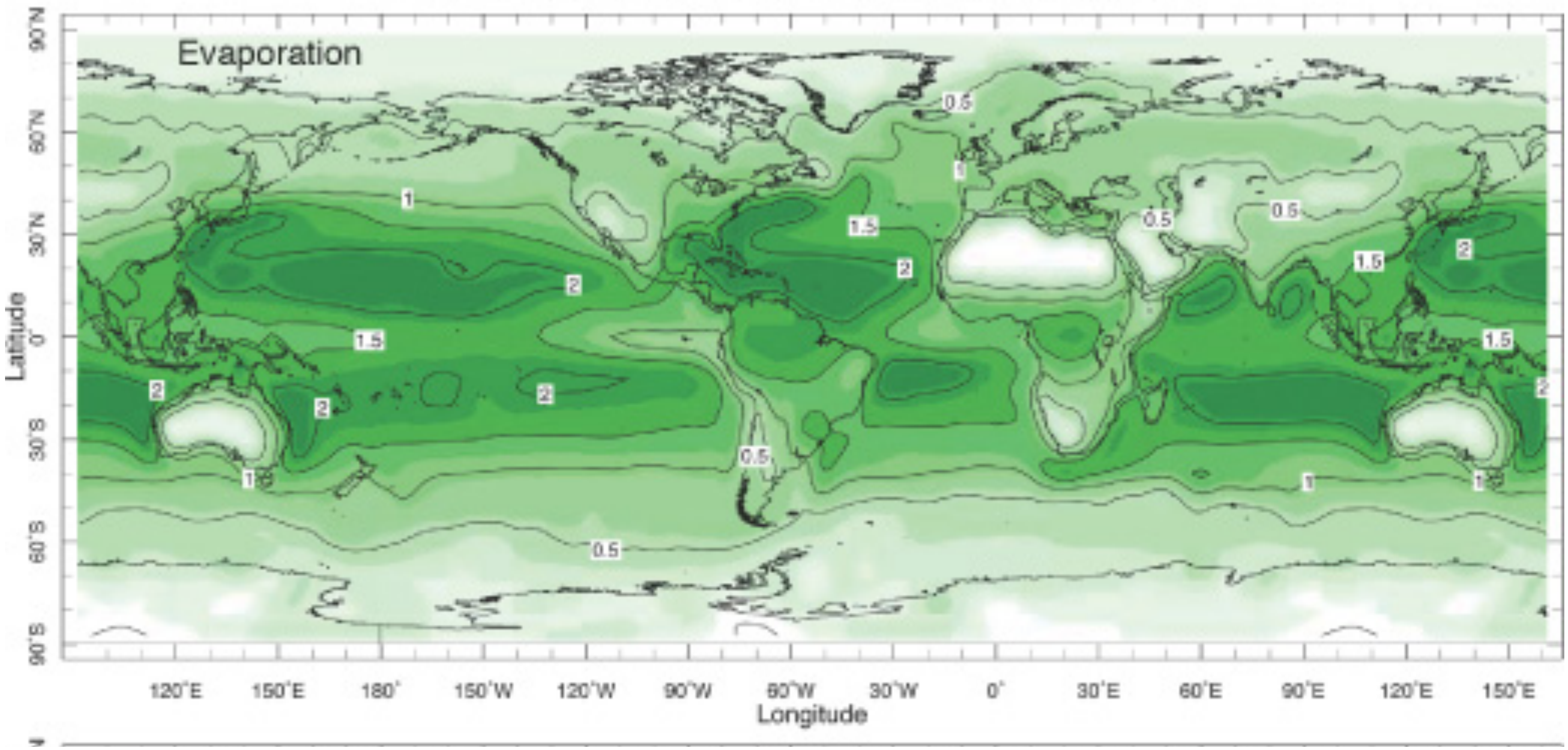


Ocean Buoyancy Gain

(From Kalnay et al. (1996).)

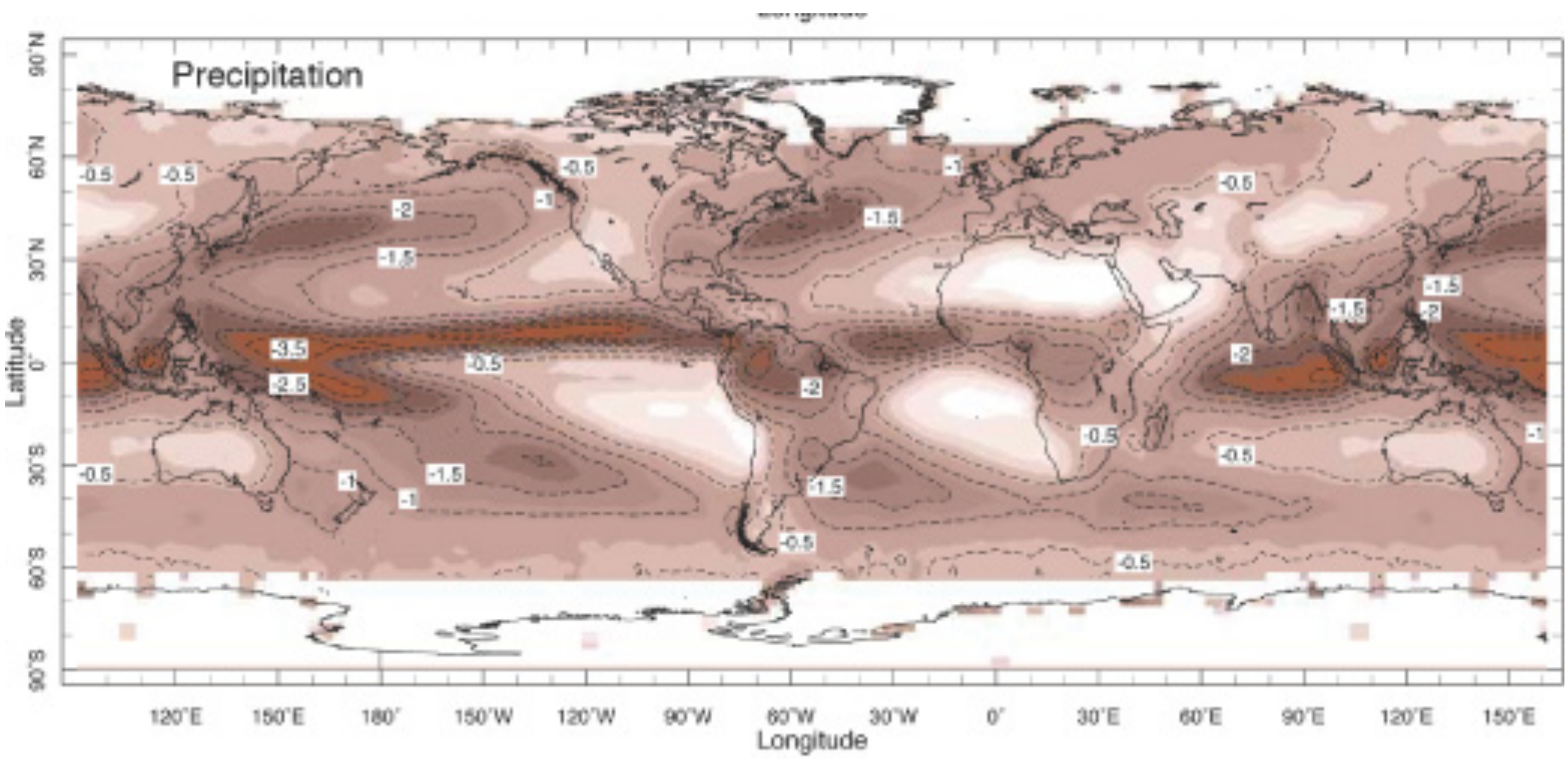
Ocean Buoyancy Loss

Evaporation (m/yr)



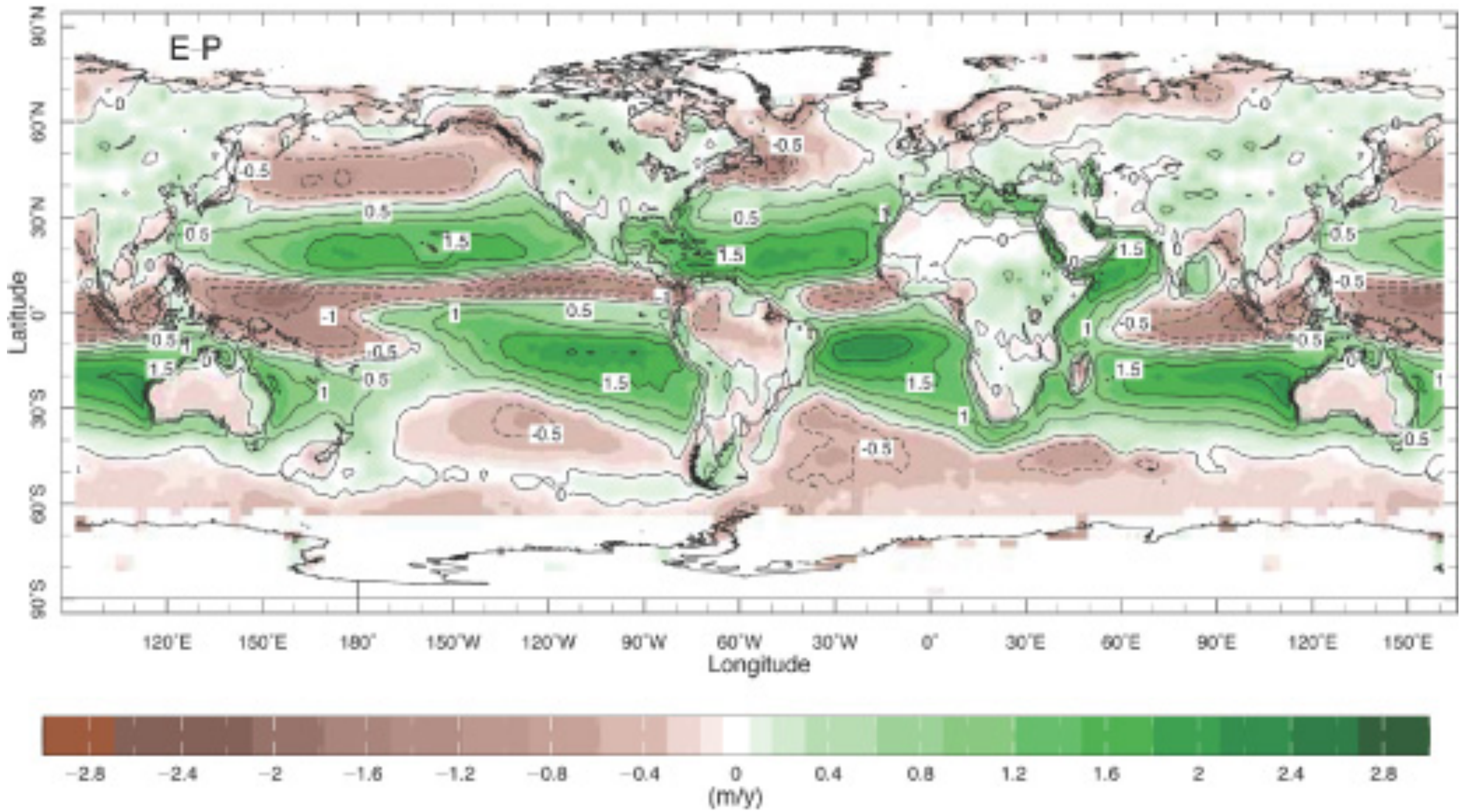
Ocean Buoyancy Loss

Precipitation (m/yr)



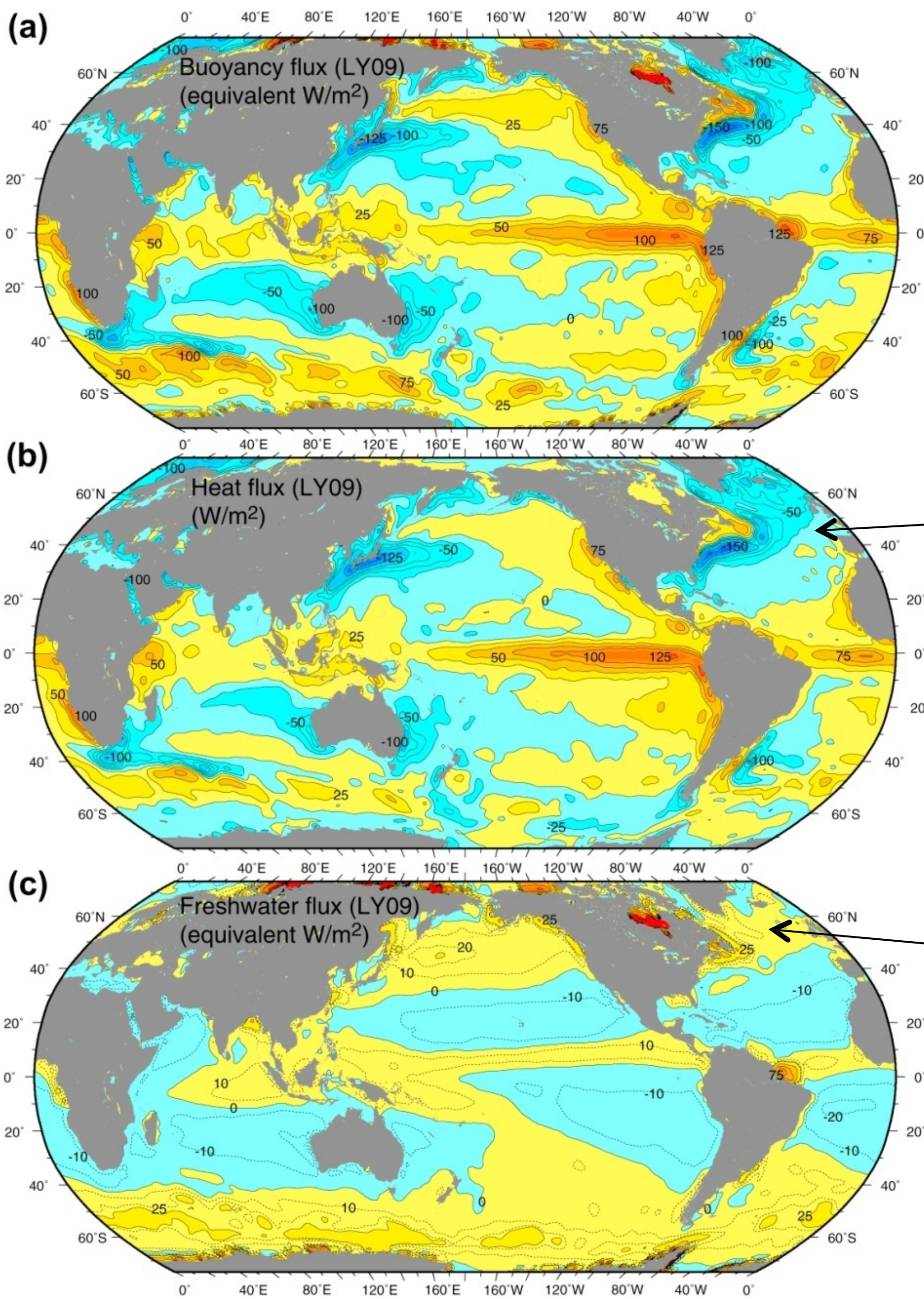
Ocean Buoyancy Gain

E-P



Ocean Buoyancy Gain (From Kalnay et al. (1996).) Ocean Buoyancy Loss

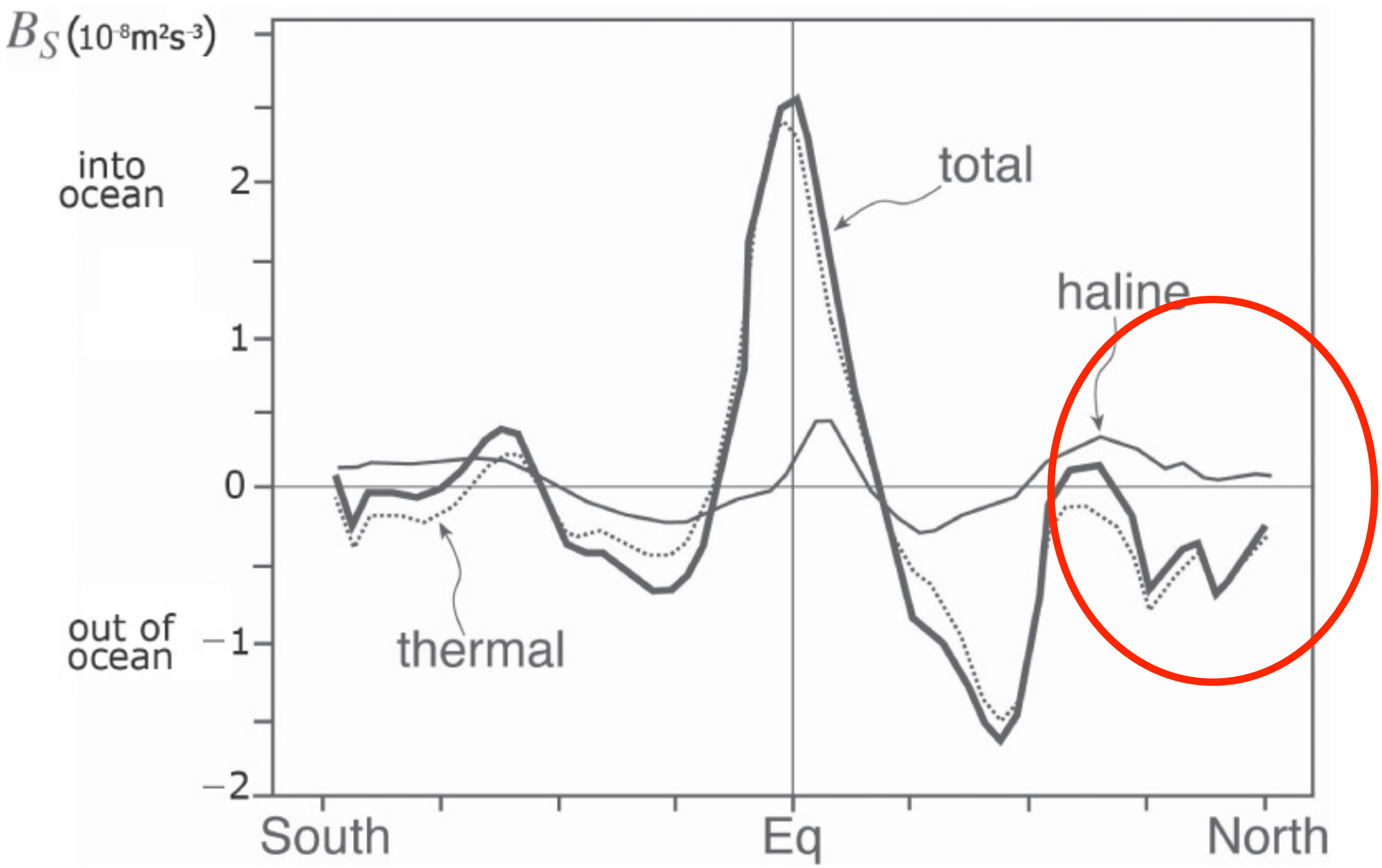
N. Atlantic: Competing Effects



Buoyancy Loss via heat

Buoyancy Gain (net Precip)

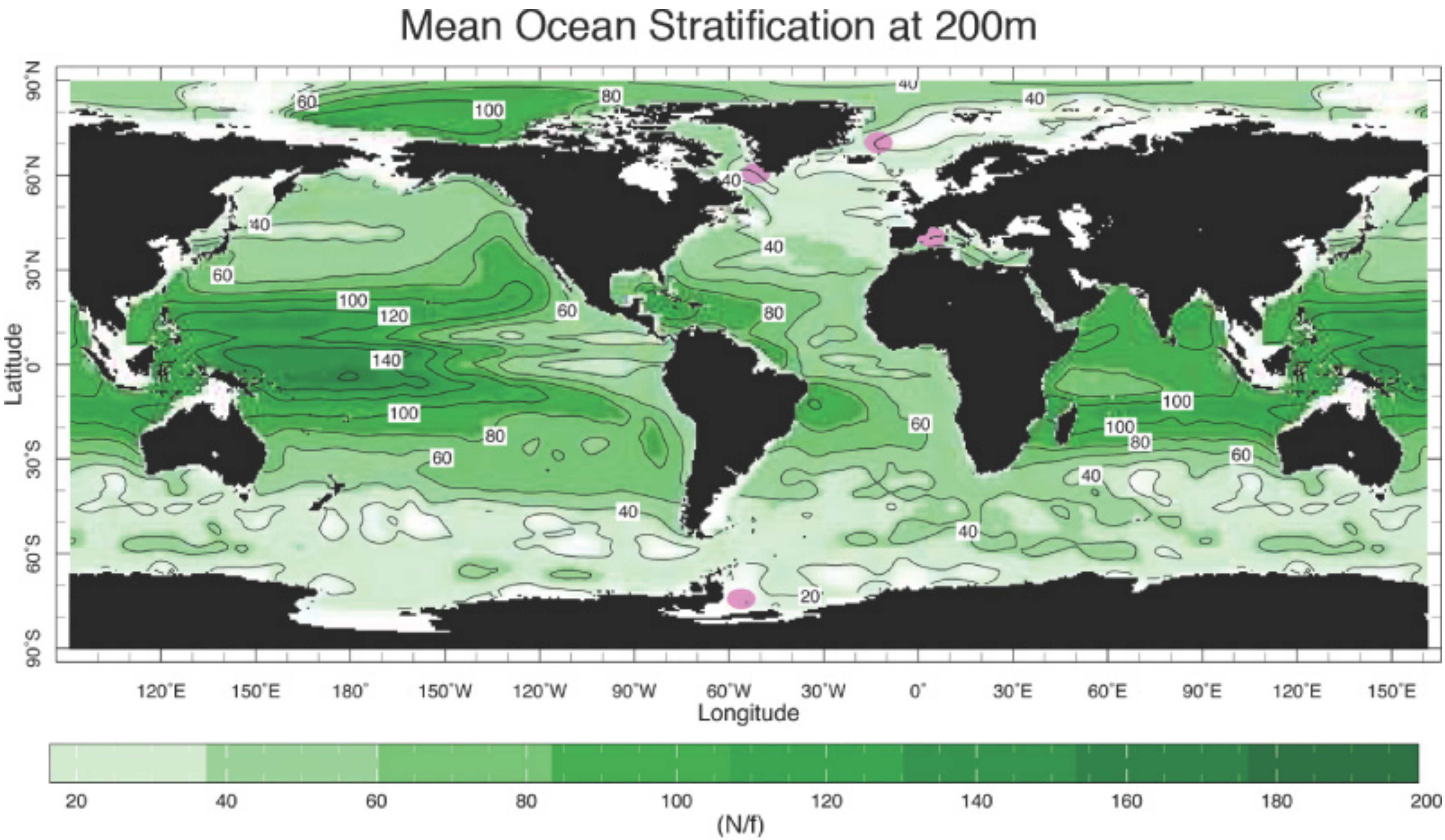
Net Buoyancy LOSS



(Data from Kalnay et al. (1996).)

Deep Convection

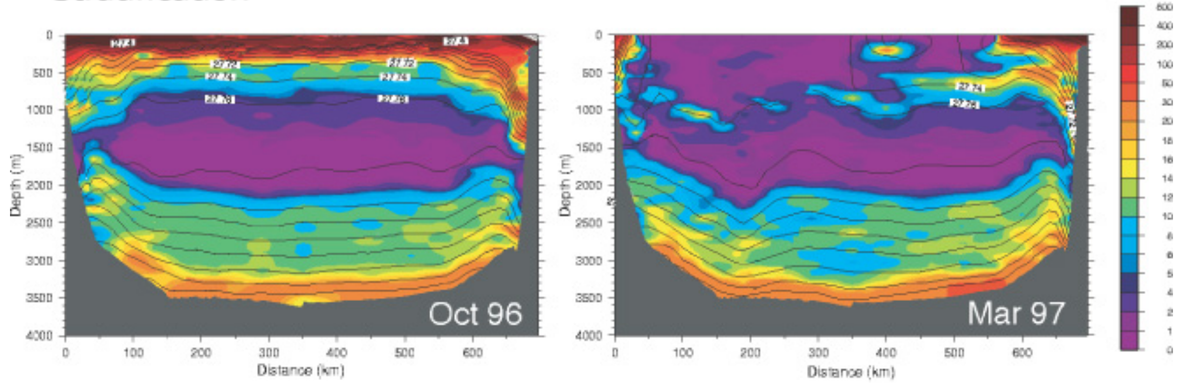
N/f_{ref}


Mean Ocean Stratification at 200m
Latitude
Longitude
90°N
60°N
30°N
0°
30°S
60°S
90°S
120°E
150°E
180°
150°W
120°W
90°W
60°W
30°W
0°
30°E
60°E
90°E
120°E
150°E
20
40
60
80
100
120
140
160
180
200
(N/f)

Lab Sea Experiment Feb-Mar 1997

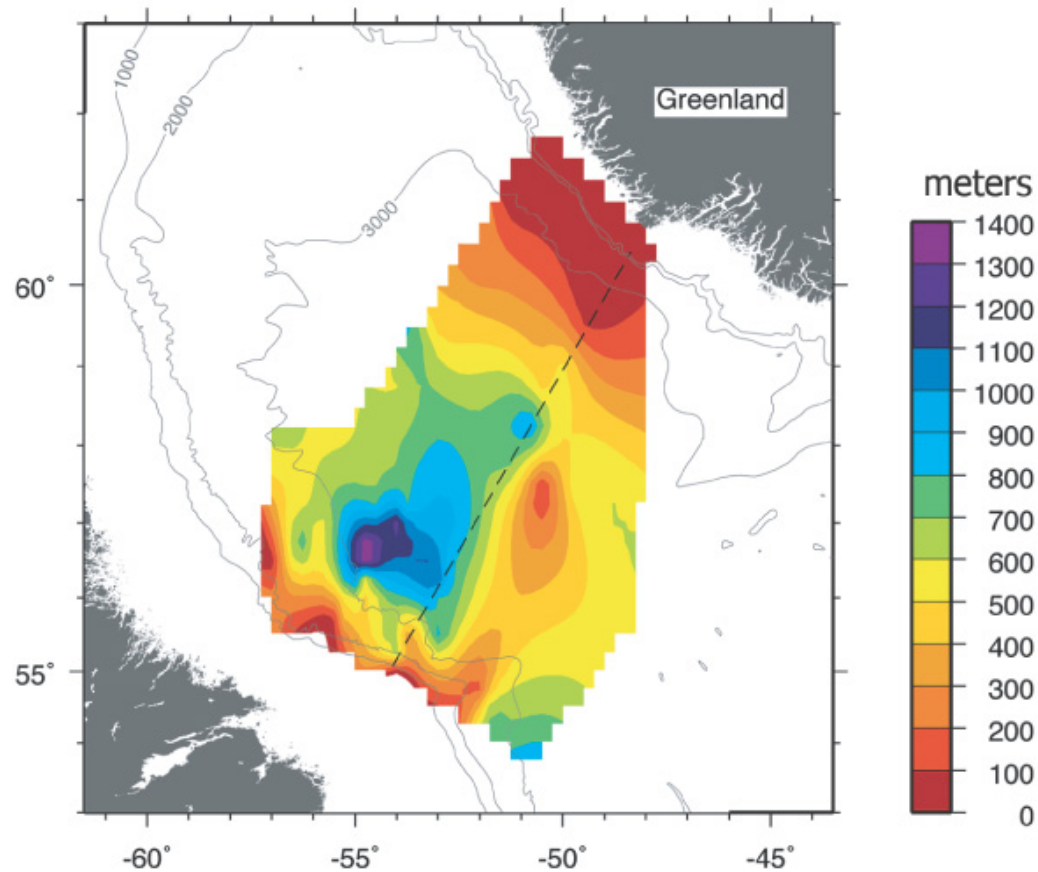
(Courtesy of Bob Pickart, WHOI.)

Stratification



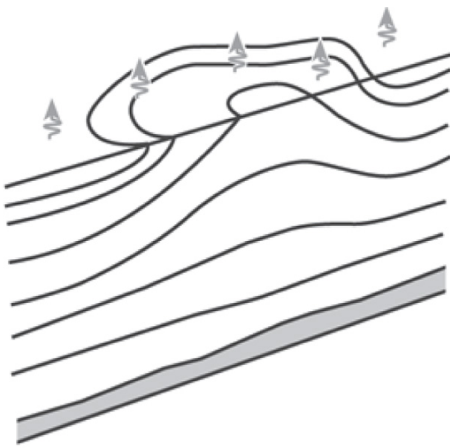
Mixed layer depth

Feb-Mar 1997



(Courtesy of Robert Pickart, WHOI.)

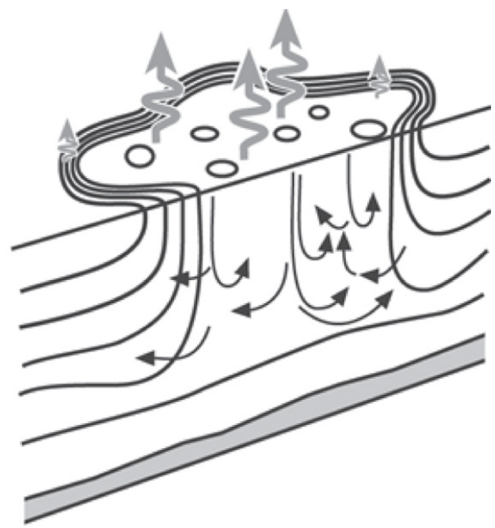
a



Preconditioning

(From Marshall and Schott (1999).)

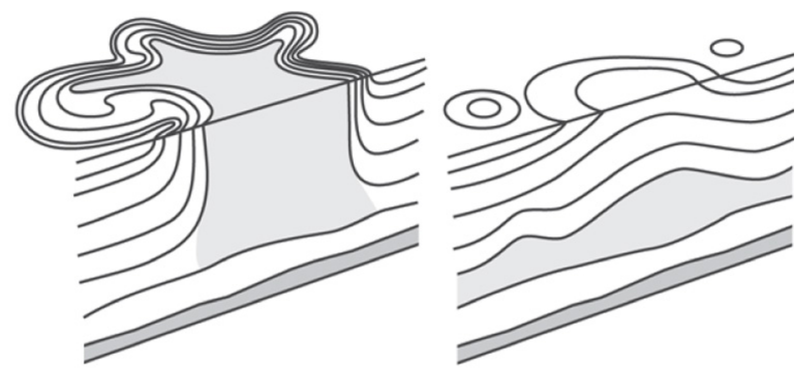
b



Convection and Mixing

(From Marshall and Schott (1999).)

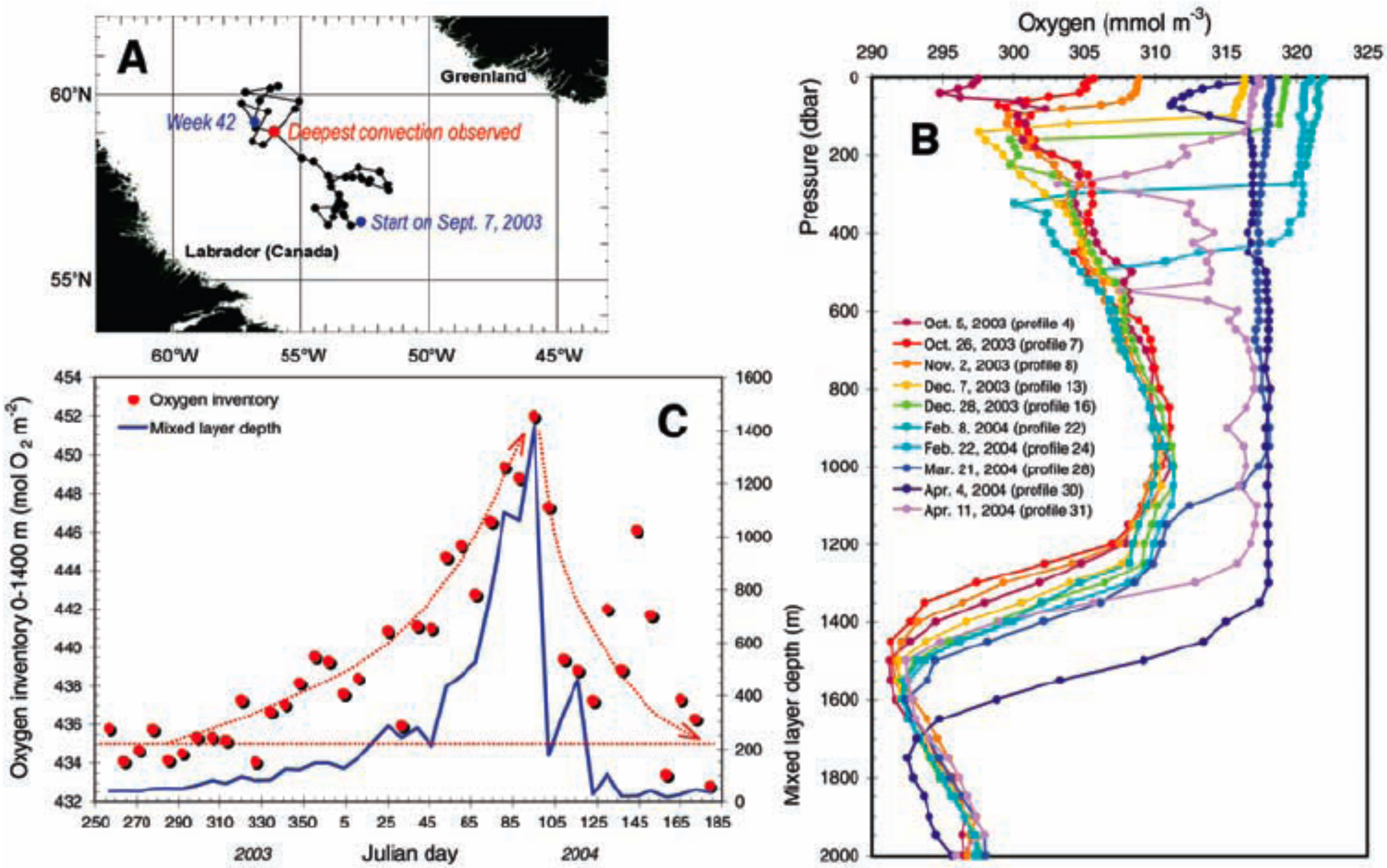
c



Sinking and Spreading

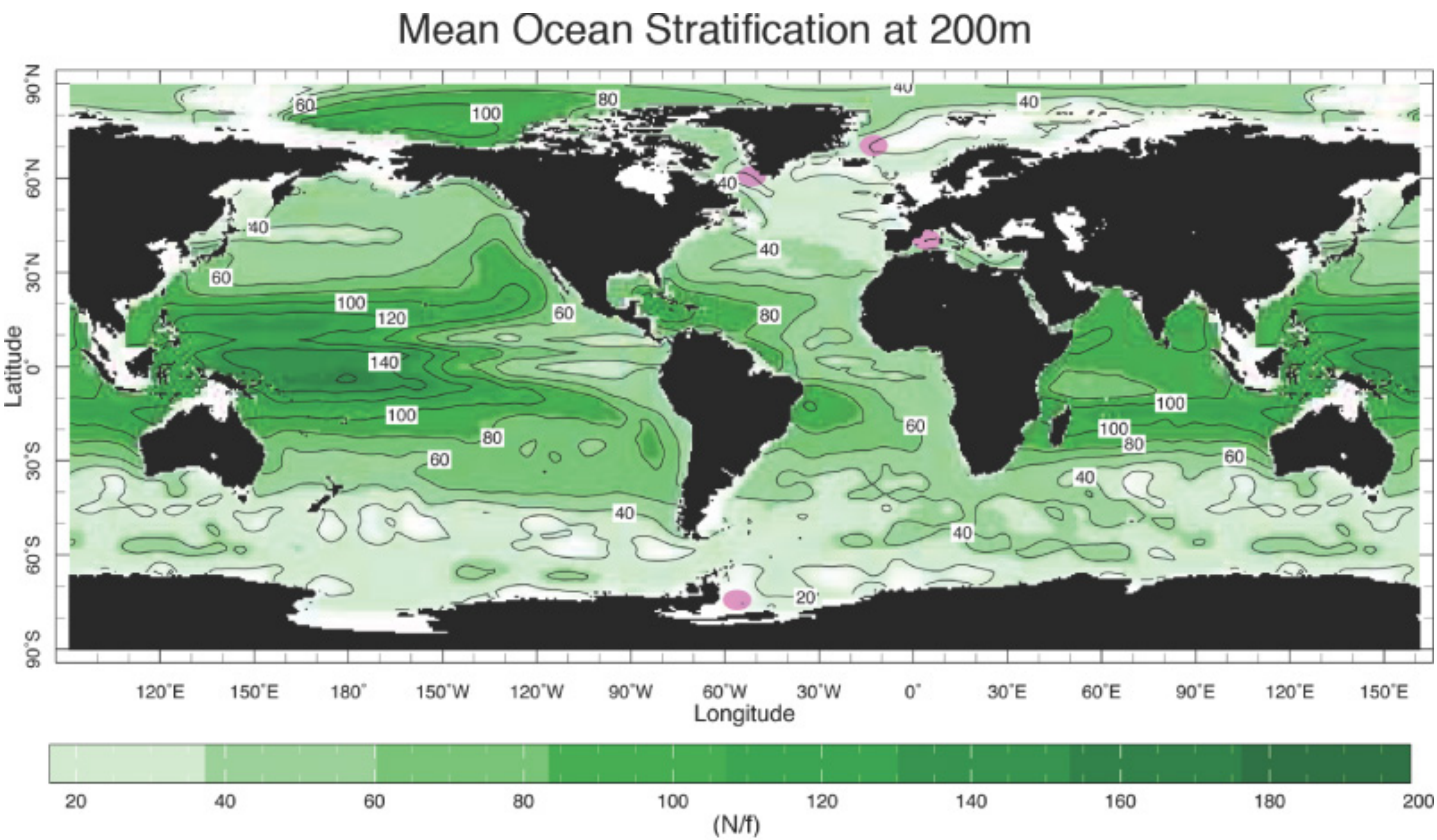
(From Marshall and Schott (1999).)

Labrador Sea Water formation, seen with oxygen



Kortzinger et al. 2004

N/f_{ref}


Mean Ocean Stratification at 200m
Latitude
90°N
60°N
30°N
0°
30°S
60°S
90°S
Longitude
120°E
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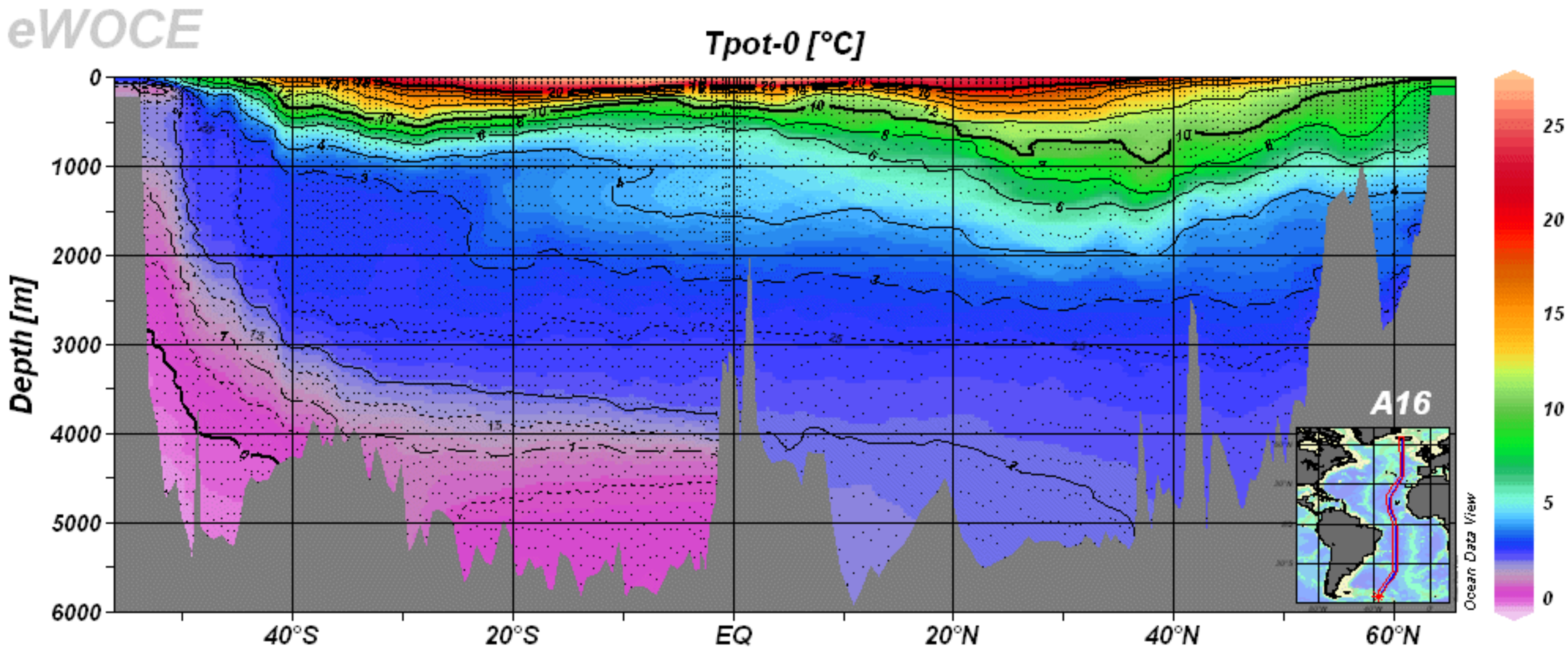
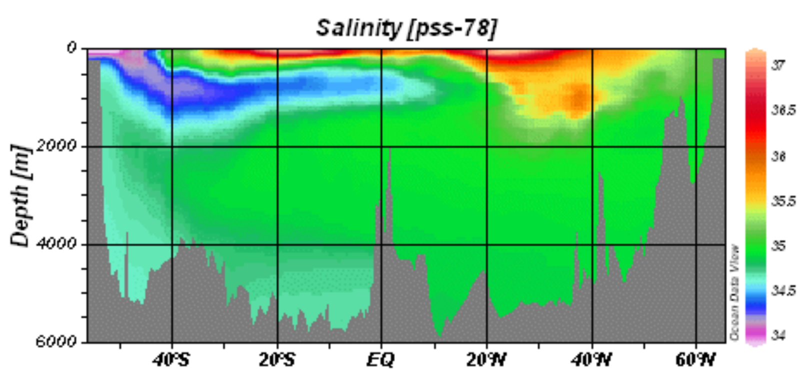
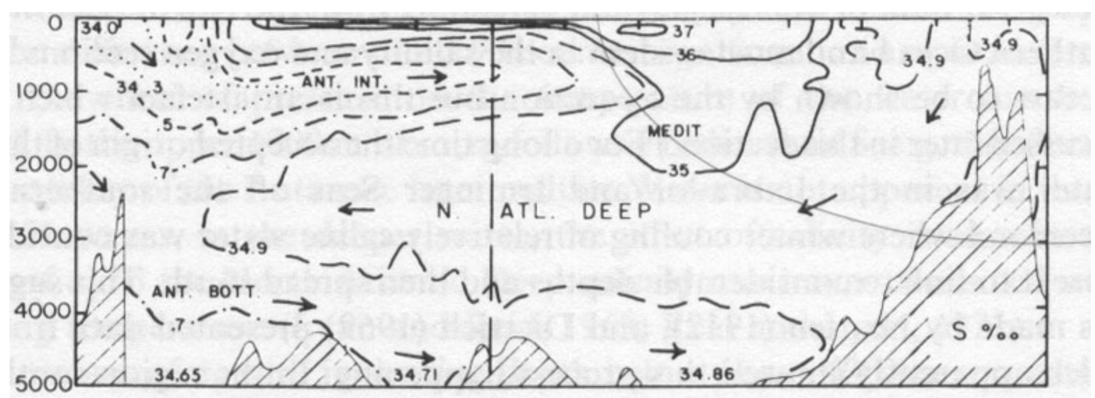
180°
150°W
120°W
90°W
60°W
30°W
0°
30°E
60°E
90°E
120°E
150°E
20
40
60
80
100
120
140
160
180
200
(N/f)

What happens to the mixed fluid?

An oceanographic section



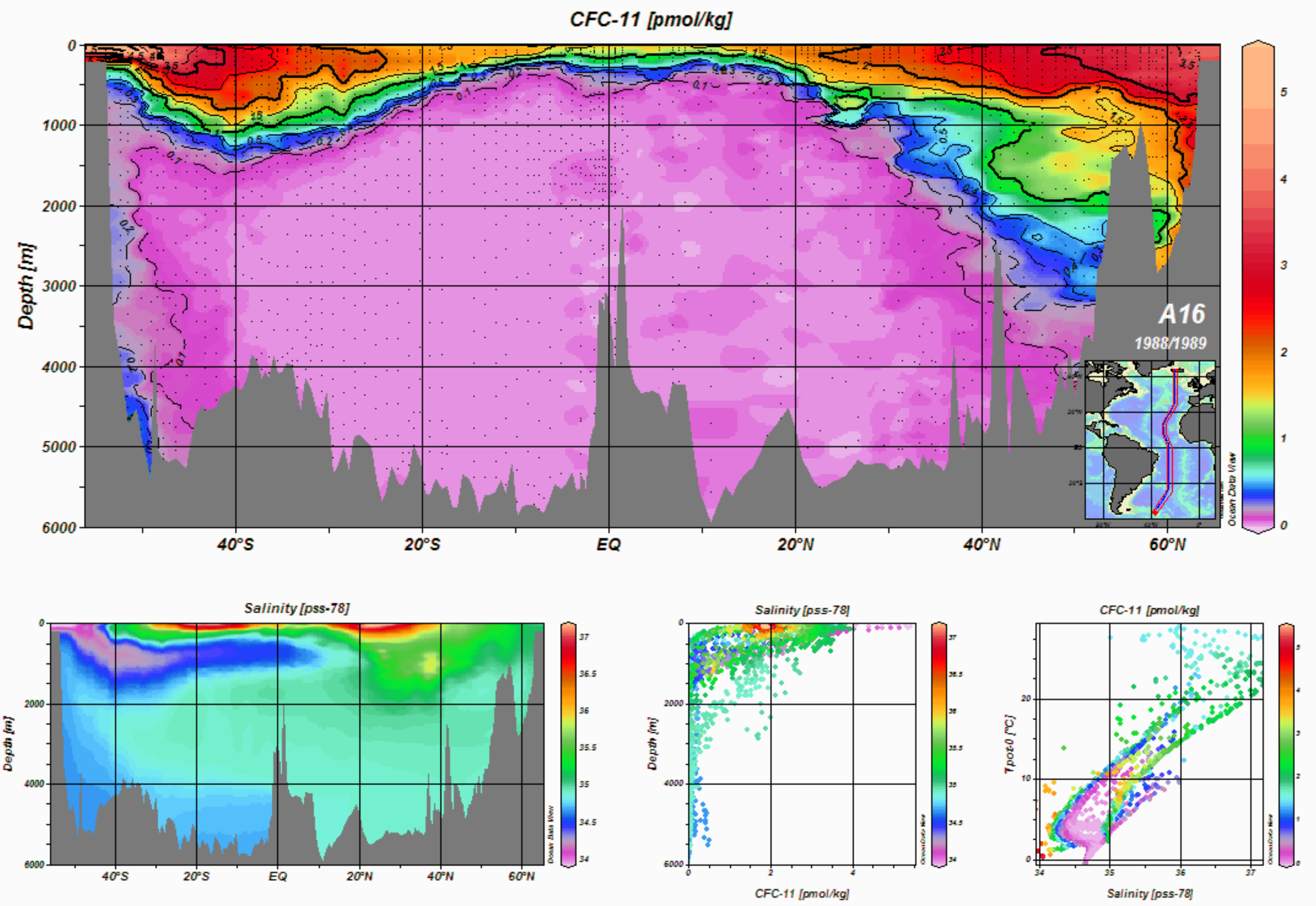




Conservative properties

- Without interior sources or sink of potential temperature and salinity, these properties are "conserved" away from the surface
- Thus they can be used to trace the origins of a body of water

- In modern oceanography, other tracers, such as CFCs, ^{14}C, O_2, nutrients are also used in more complex analyses

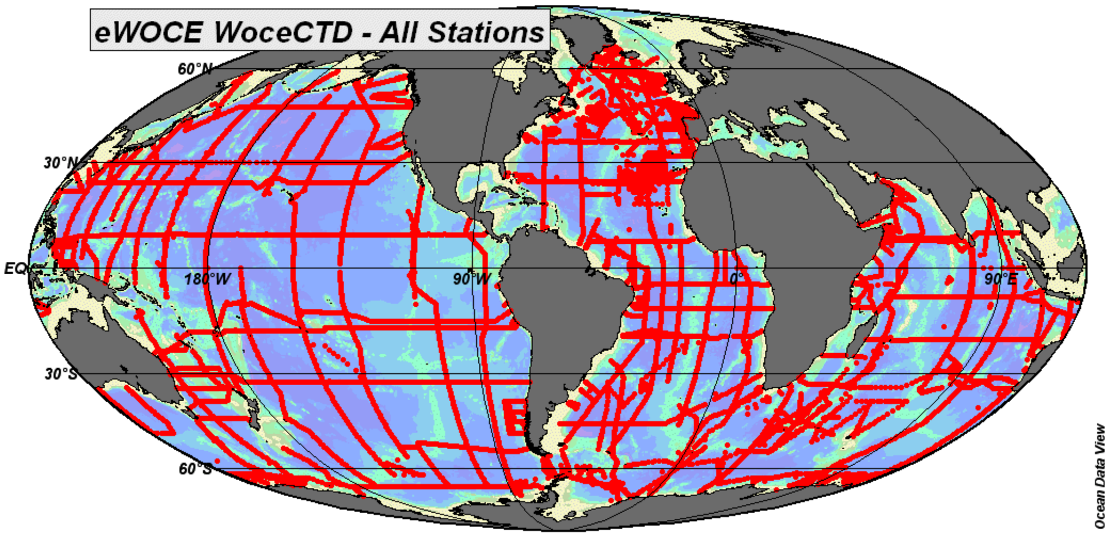

CFC-11 [pmol/kg]
Depth [m]
0
1000
2000
3000
4000
5000
6000
40°S
20°S
EQ
20°N
40°N
60°N
A16
1988/1989
Ocean Data View
Salinity [pss-78]
Depth [m]
CFC-11 [pmol/kg]
Salinity [pss-78]
Tpot-0 [°C]
Salinity [pss-78]

How do we observe the ocean?

Observing the Ocean

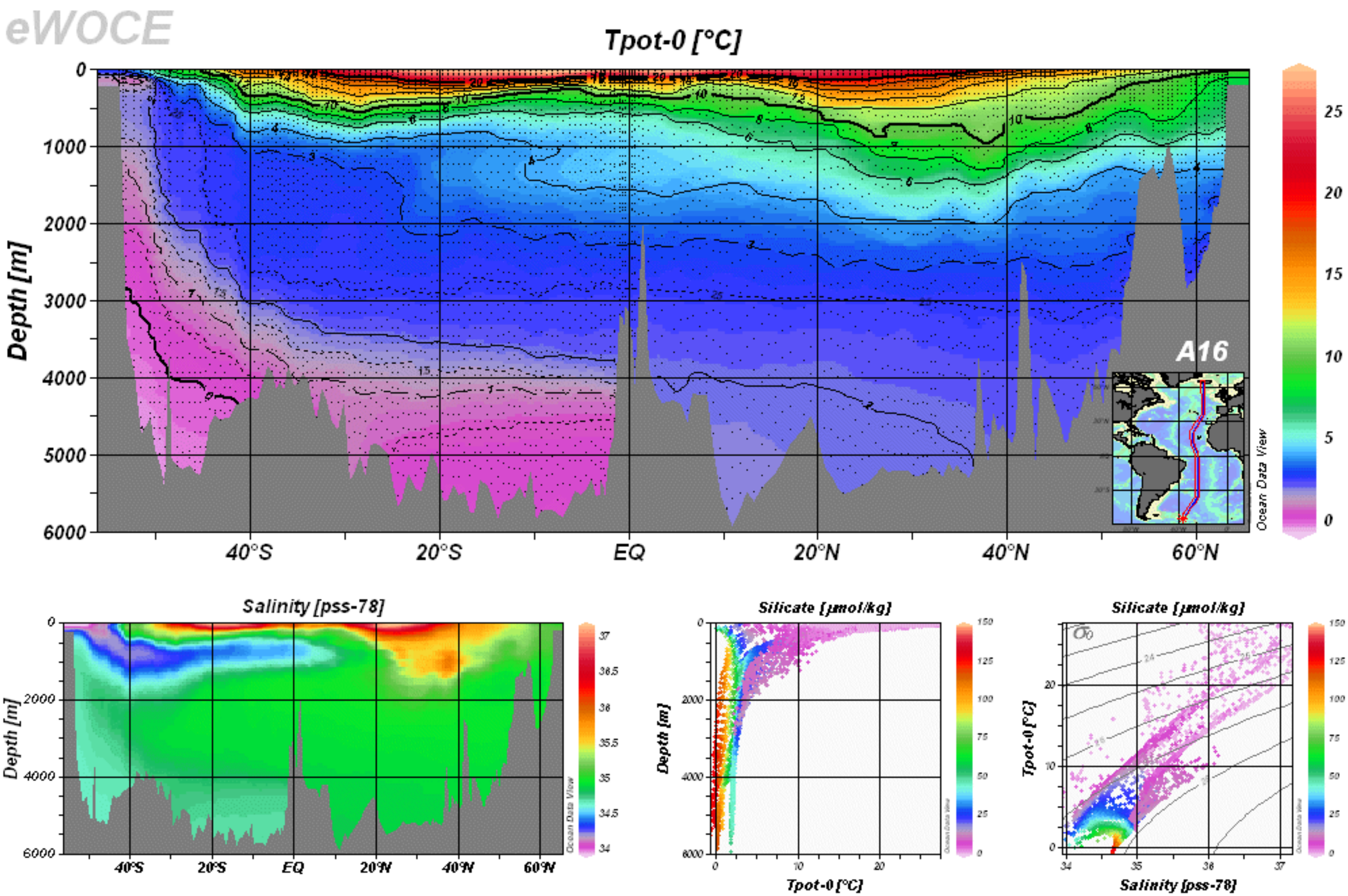
J. Botella

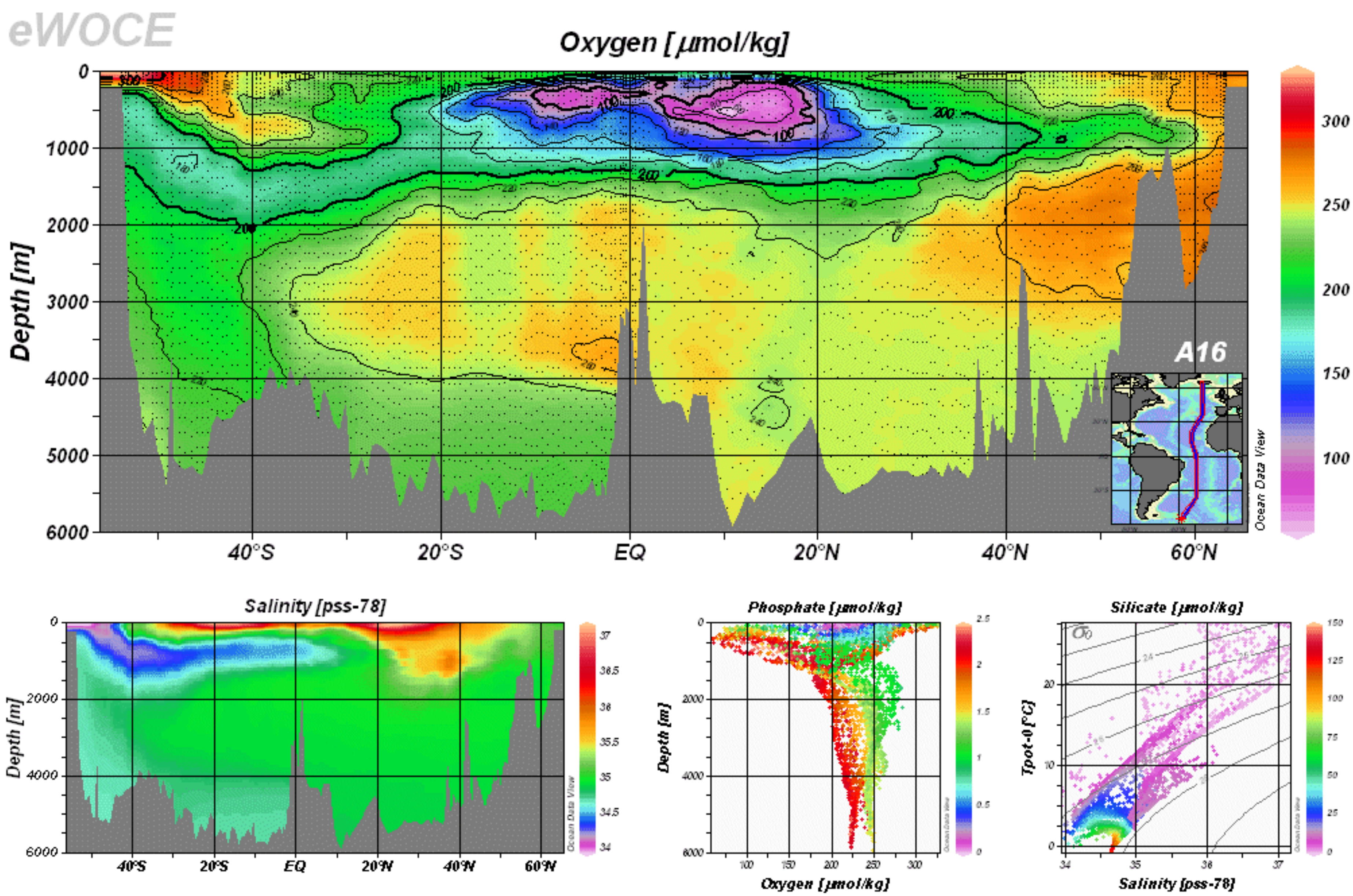
WHOI

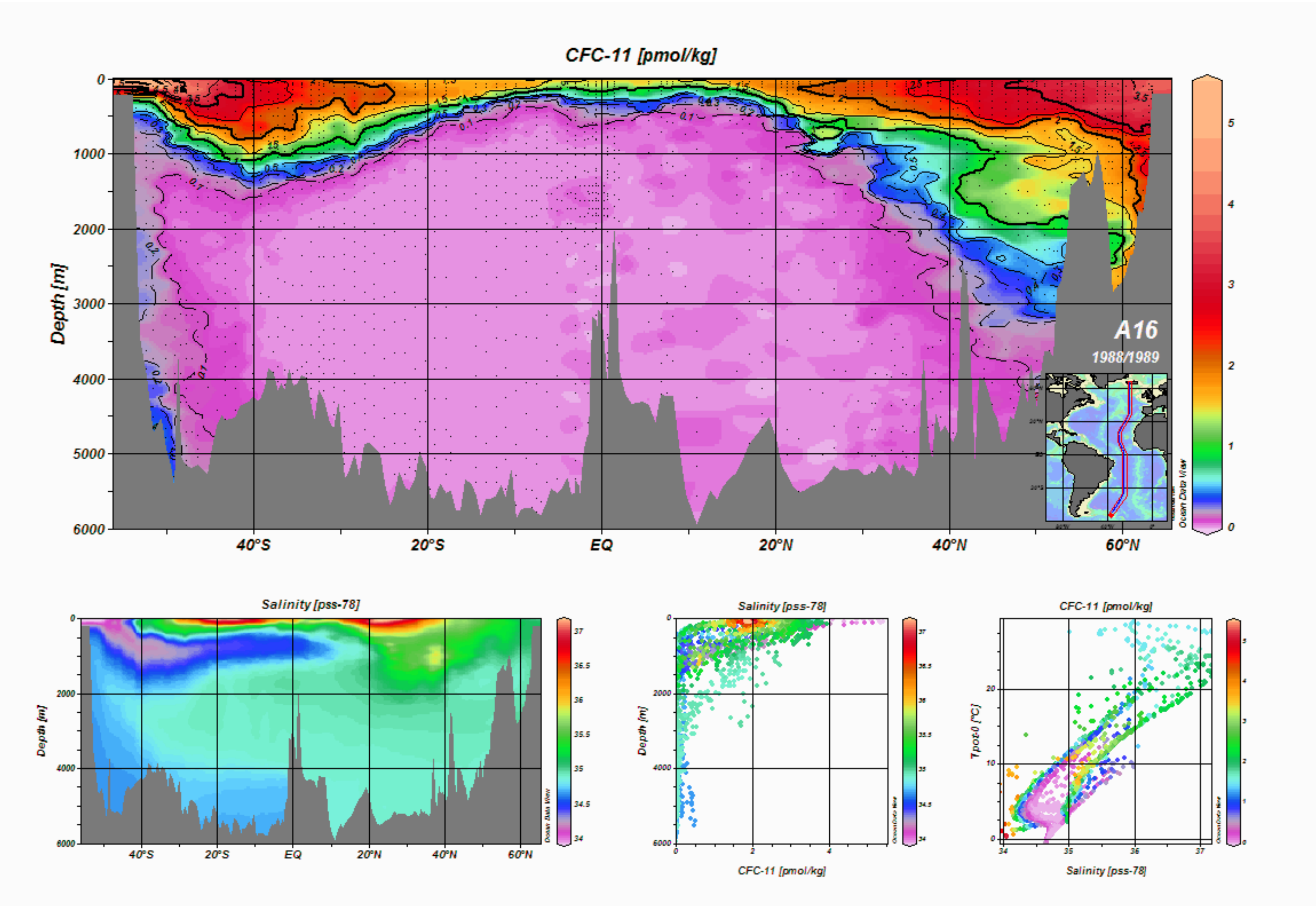


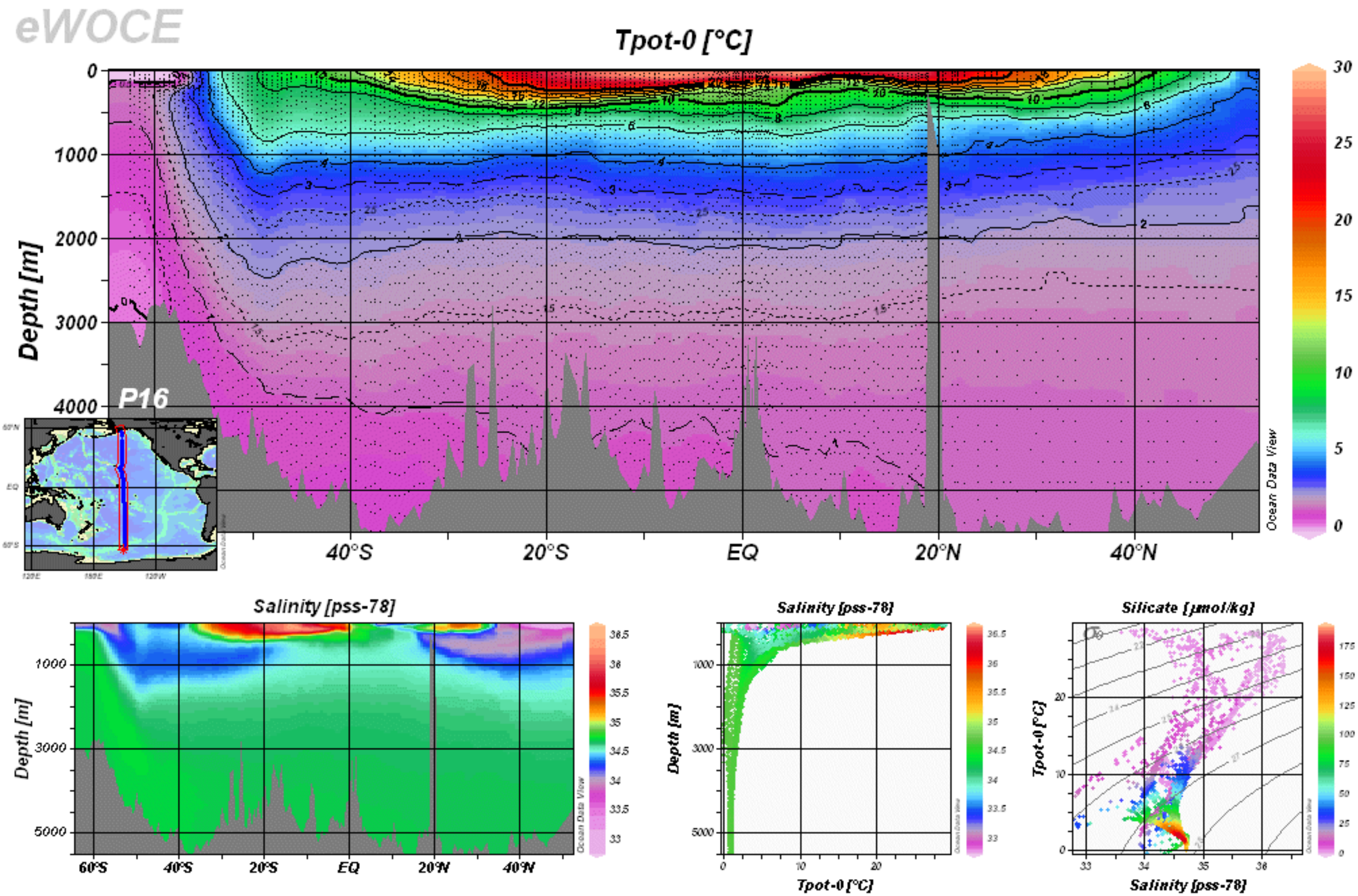
The comprehensive WOCE survey has been done once!

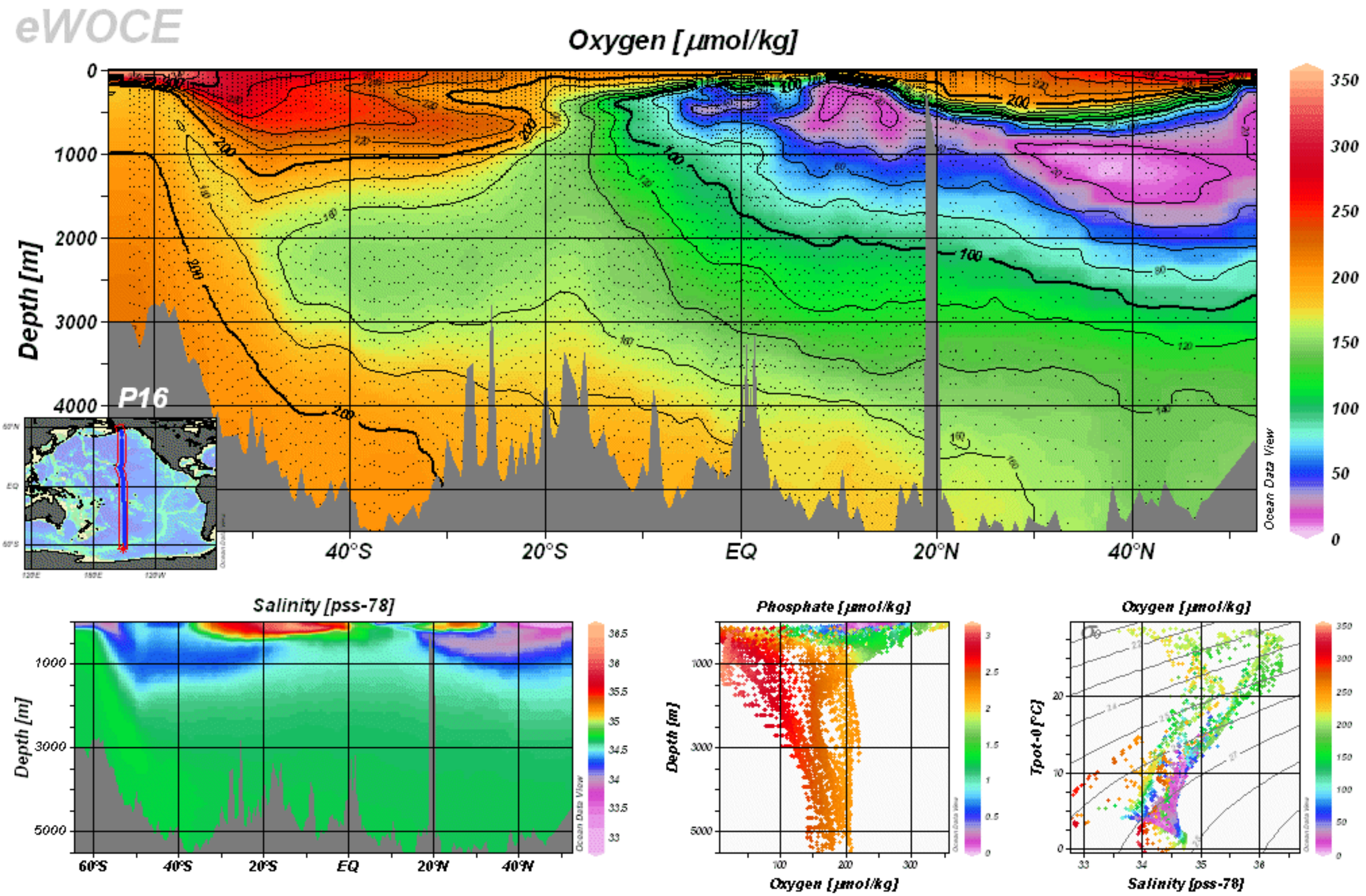
Ocean is significantly undersampled


eWOCE
Tpot-0 [°C]
Depth [m]
0
1000
2000
3000
4000
5000
6000
40°S
20°S
EQ
20°N
40°N
60°N
A16
Ocean Data View
25
20
15
10
5
0
Salinity [pss-78]
Silicate [µmol/kg]
Tpot-0 [°C]
Salinity [pss-78]
Silicate [µmol/kg]

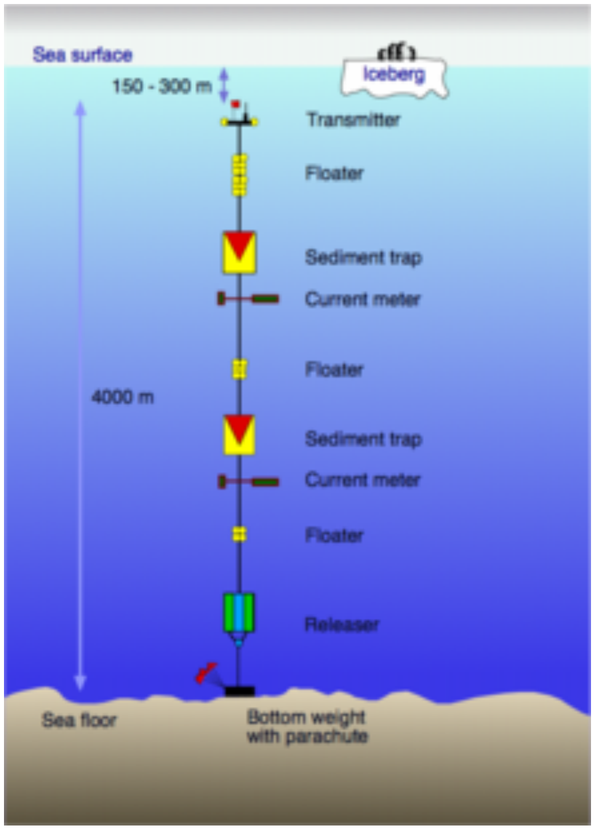

eWOCE
Oxygen [µmol/kg]
Depth [m]
A16
Ocean Data View
Salinity [pss-78]
Phosphate [µmol/kg]
Oxygen [µmol/kg]
Silicate [µmol/kg]
Tpot-0 [°C]
Salinity [pss-78]

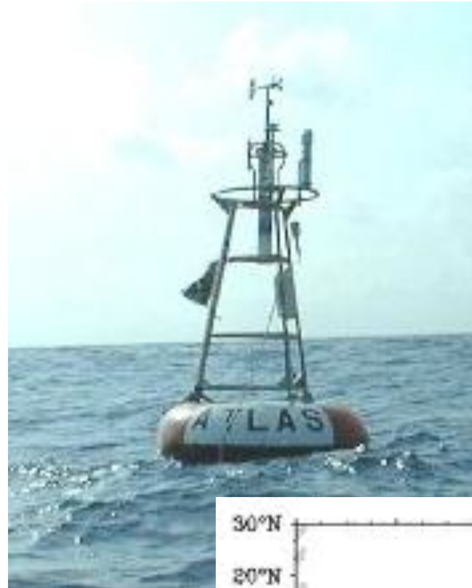

CFC-11 [pmol/kg]
Depth [m]
0
1000
2000
3000
4000
5000
6000
40°S
20°S
EQ
20°N
40°N
60°N
A16
1988/1989
Ocean Data View
0
1
2
3
4
5
Salinity [pss-78]
Depth [m]
34
34.5
35
35.5
36
36.5
37
Salinity [pss-78]
CFC-11 [pmol/kg]
CFC-11 [pmol/kg]
Tpot0 [°C]
Salinity [pss-78]

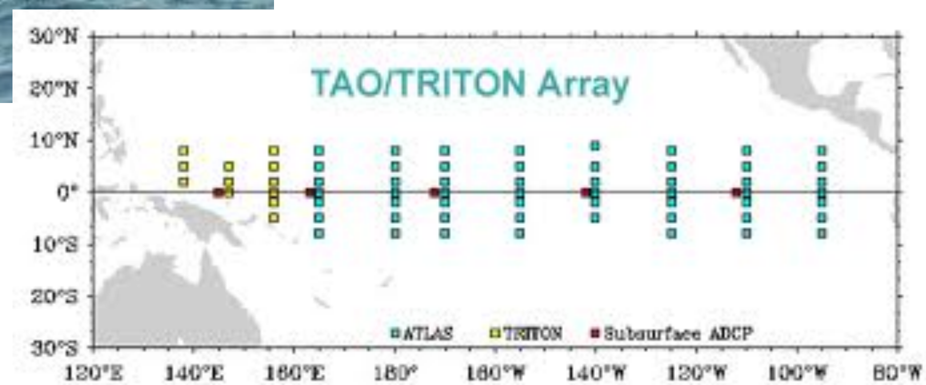

eWOCE
Tpot-0 [°C]
Depth [m]
P16
40°S
20°S
EQ
20°N
40°N
Ocean Data View
Salinity [pss-78]
Depth [m]
60°S
40°S
20°S
EQ
20°N
40°N
Salinity [pss-78]
Depth [m]
Tpot-0 [°C]
Silicate [µmol/kg]
Tpot-0 [°C]
Salinity [pss-78]


eWOCE
Oxygen [µmol/kg]
Depth [m]
P16
40°S
20°S
EQ
20°N
40°N
Ocean Data View
Salinity [pss-78]
60°S
Phosphate [µmol/kg]
Oxygen [µmol/kg]
Tpot-0 [°C]
Salinity [pss-78]

Moorings for temporal resolution





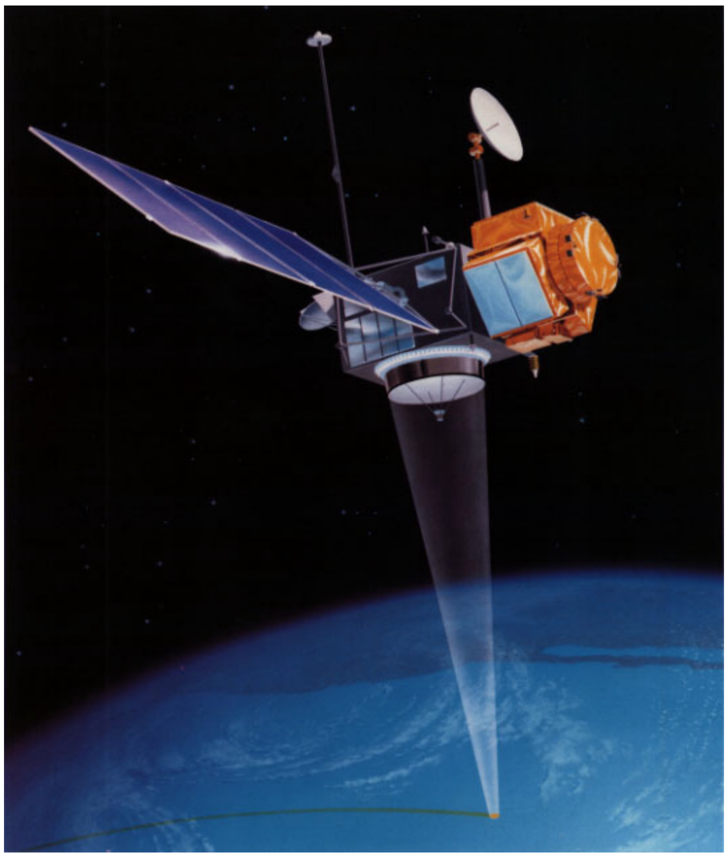


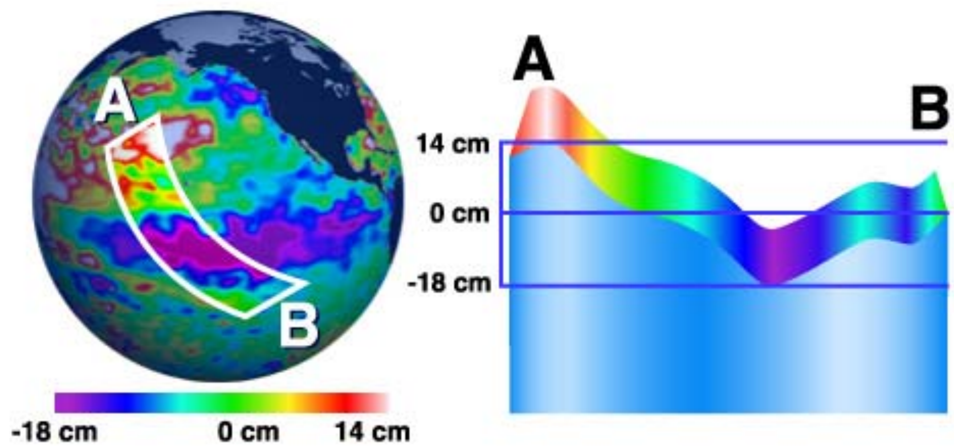
Data at: http://www.pmel.noaa.gov/tao/

From Space: US Earth Science Missions

Surface Currents from Space

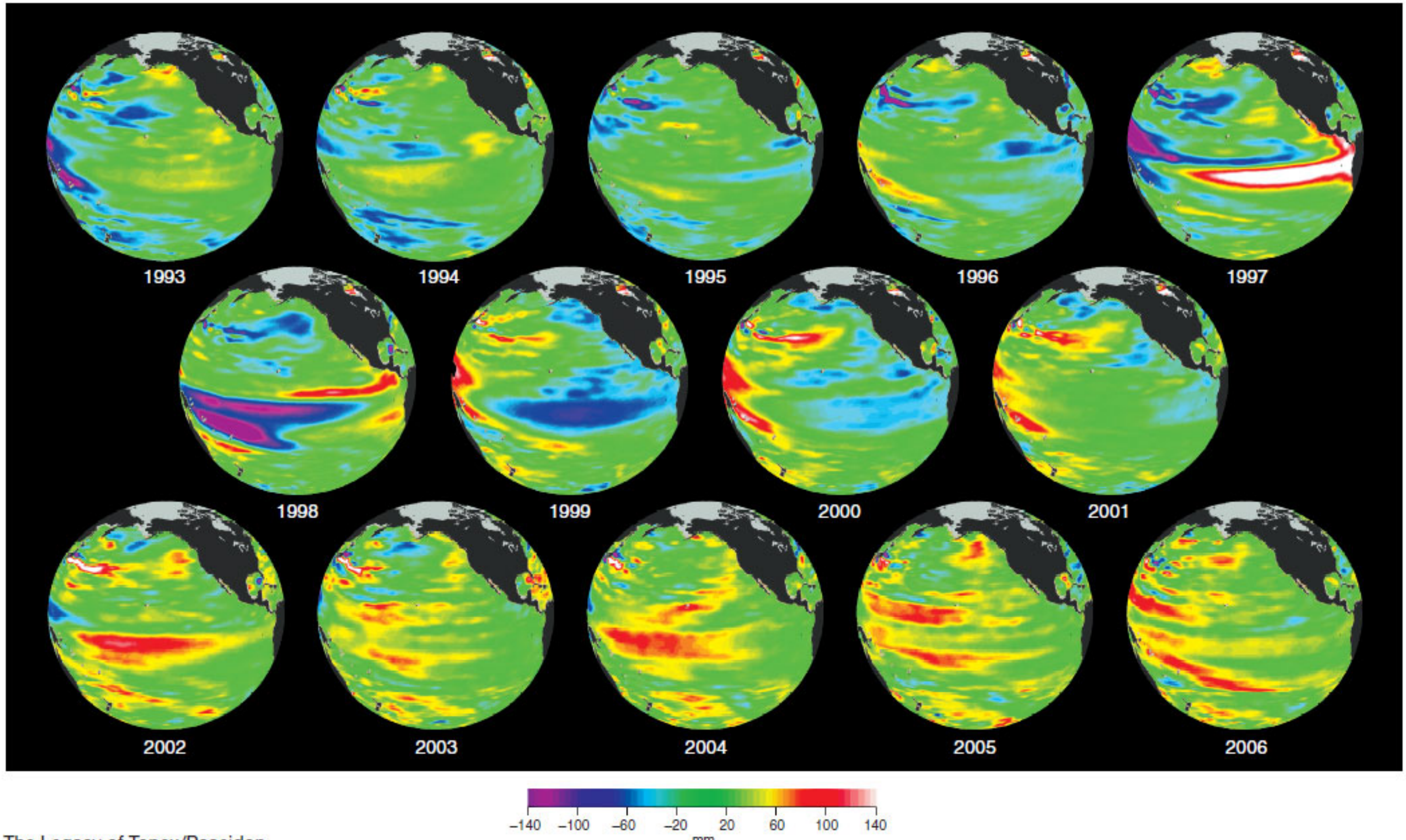
(e.g. TOPEX/Poseidon, JASON, JASON-2)





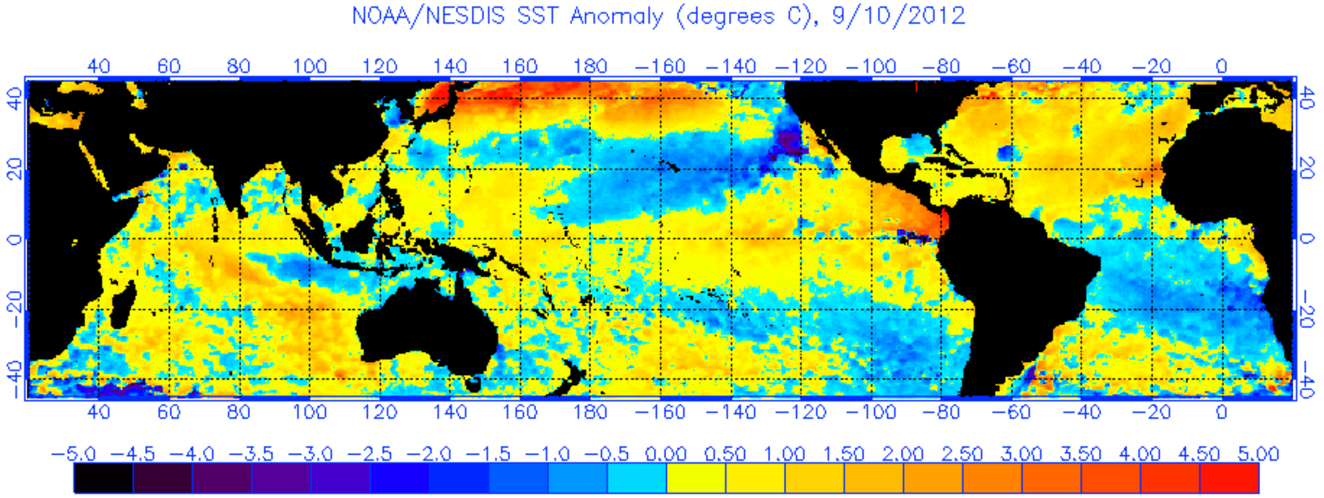
NASA

TOPEX/Poseidon Results: El Niño / La Niña

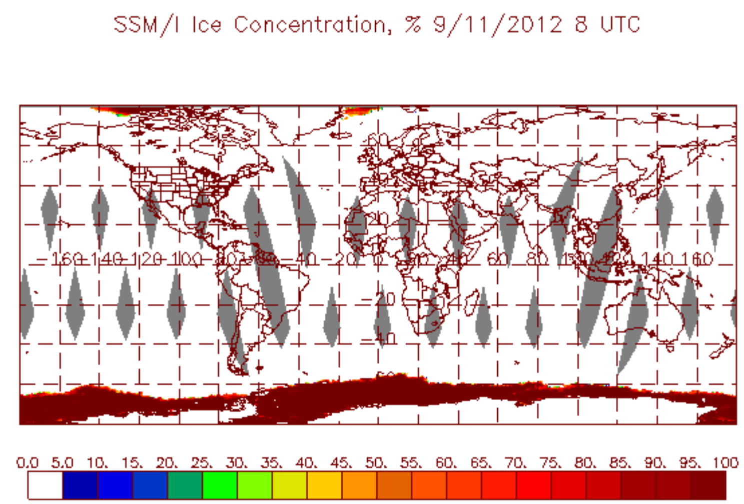


The Legacy of Topex/Poseidon

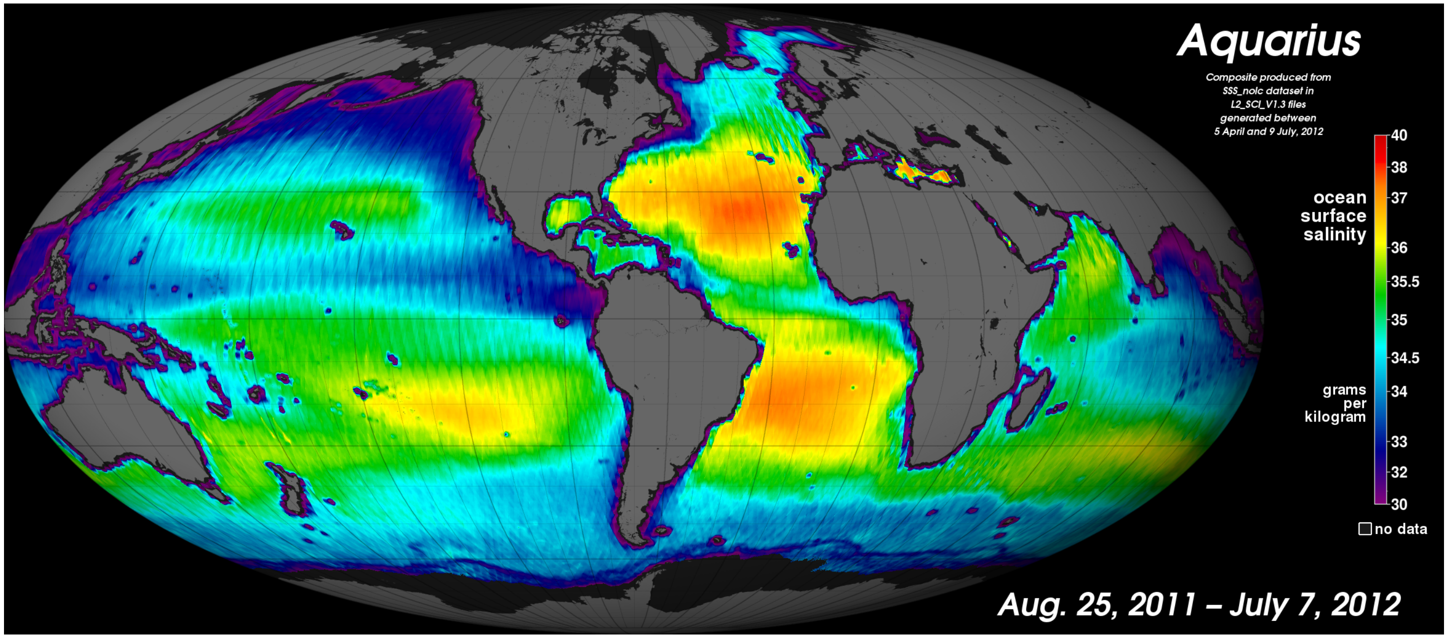
Other Physical Products from Space

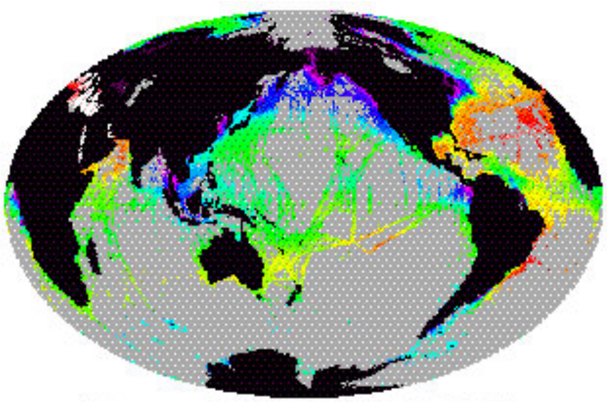


- SST (AVHRR on multiple platforms)
- Sea and Lake Ice (SSM/I)
- Winds (JASON-2, ASCAT, QuikSCAT, SSM/I)

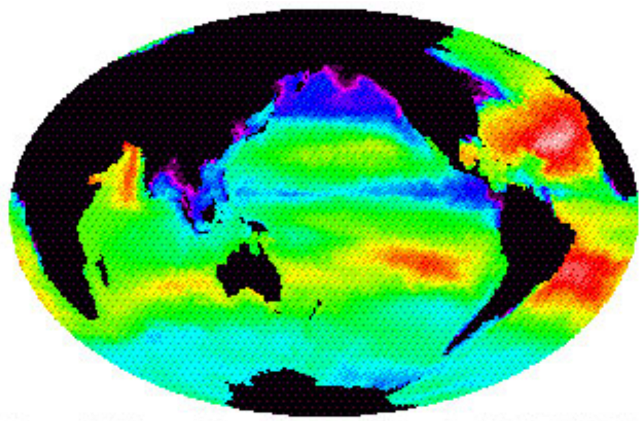


Since mid-2011: Aquarius for SSS





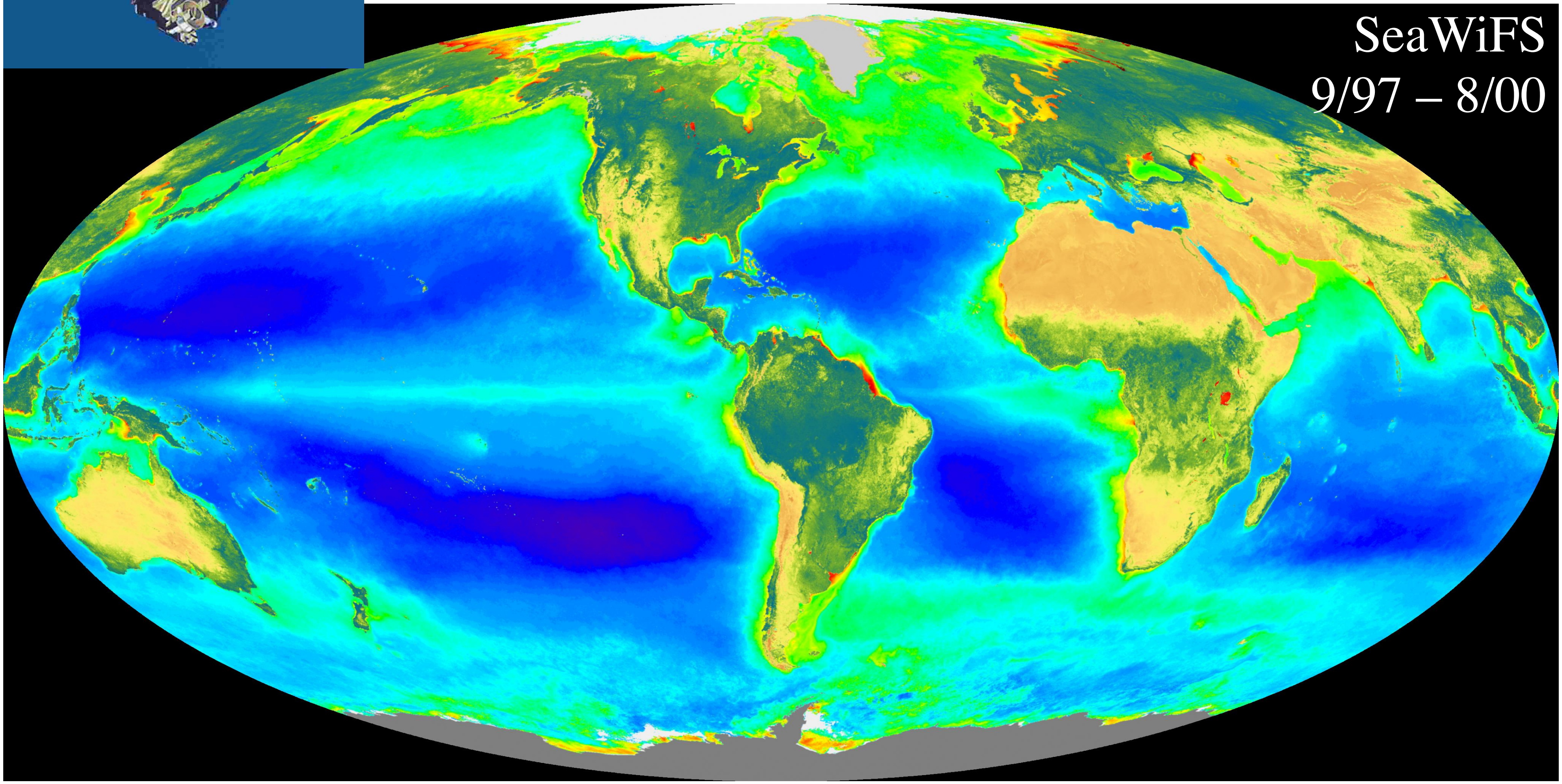
100 years of Sea Surface Salinity (SSS) measurements averaged over one month



Example 7 days of Aquarius Sea Surface Salinity (SSS) data

Ocean Biosphere

CZCS (1978-1986); SeaWiFS (1997-2010); MODIS (2002-present); PACE (launch ~2017)

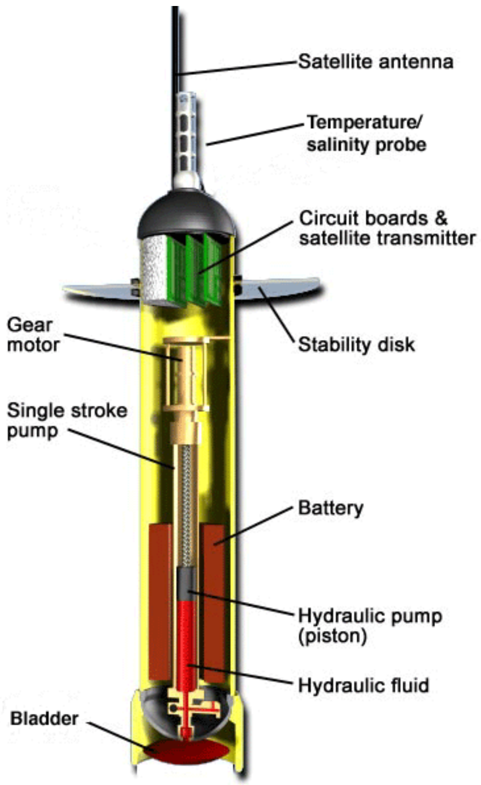


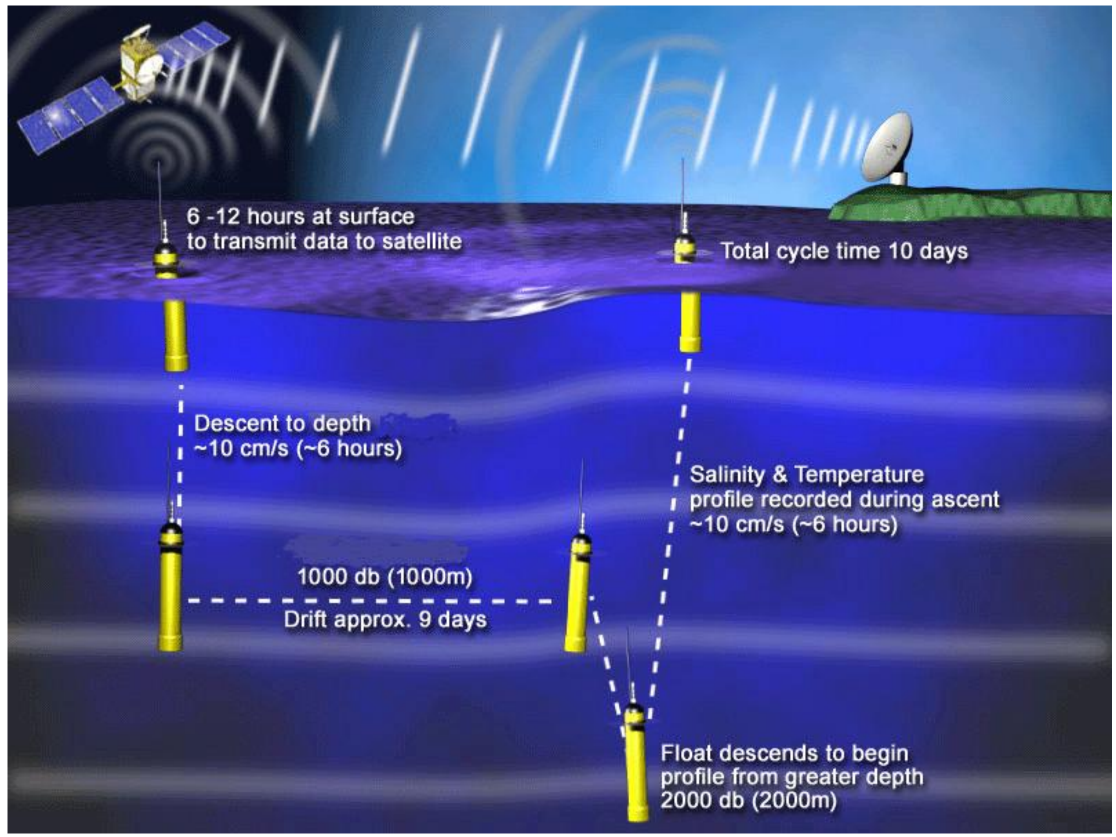
97-05 animation at

http://oceancolor.gsfc.nasa.gov/SeaWiFS/MOVIES/SeaWiFS.BiosphereAnimation.Sep1997-Jul2005.70W.gif

But ships are expensive,
moorings are spatially limited,
and satellites only see the surface

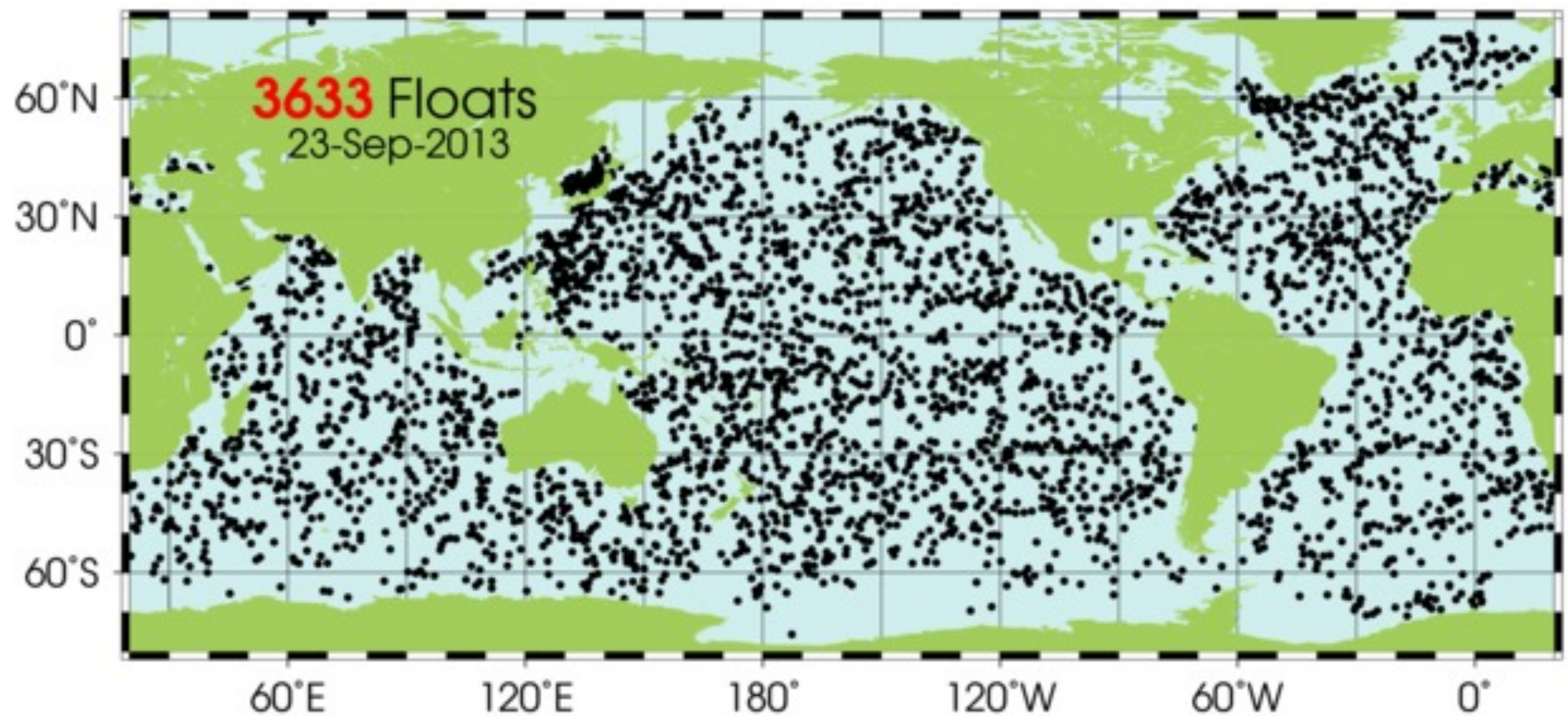
Observing S and T autonomously



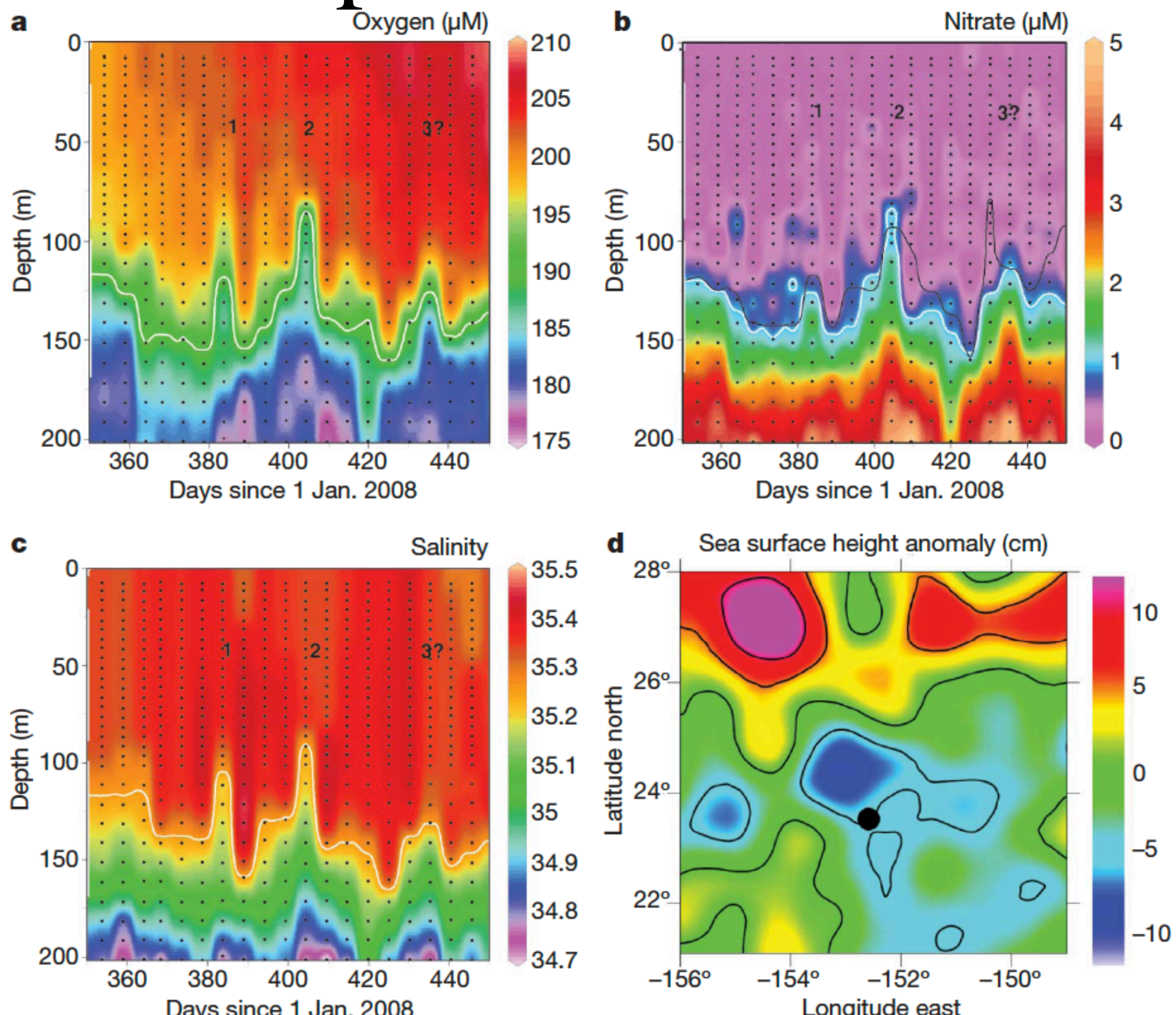


ARGO program: http://www.argo.ucsd.edu

Floats in the water on 23 Sept 2013



Not just T and S from floats!
Subtropical North Pacific



Johnson et al. 2010, Nature