Exploring the Weather-Climate Connection: Probabilistic Climate Dynamics Part I : An Introduction to the Climate System

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School of Earth and Ocean Sciences, University of Victoria

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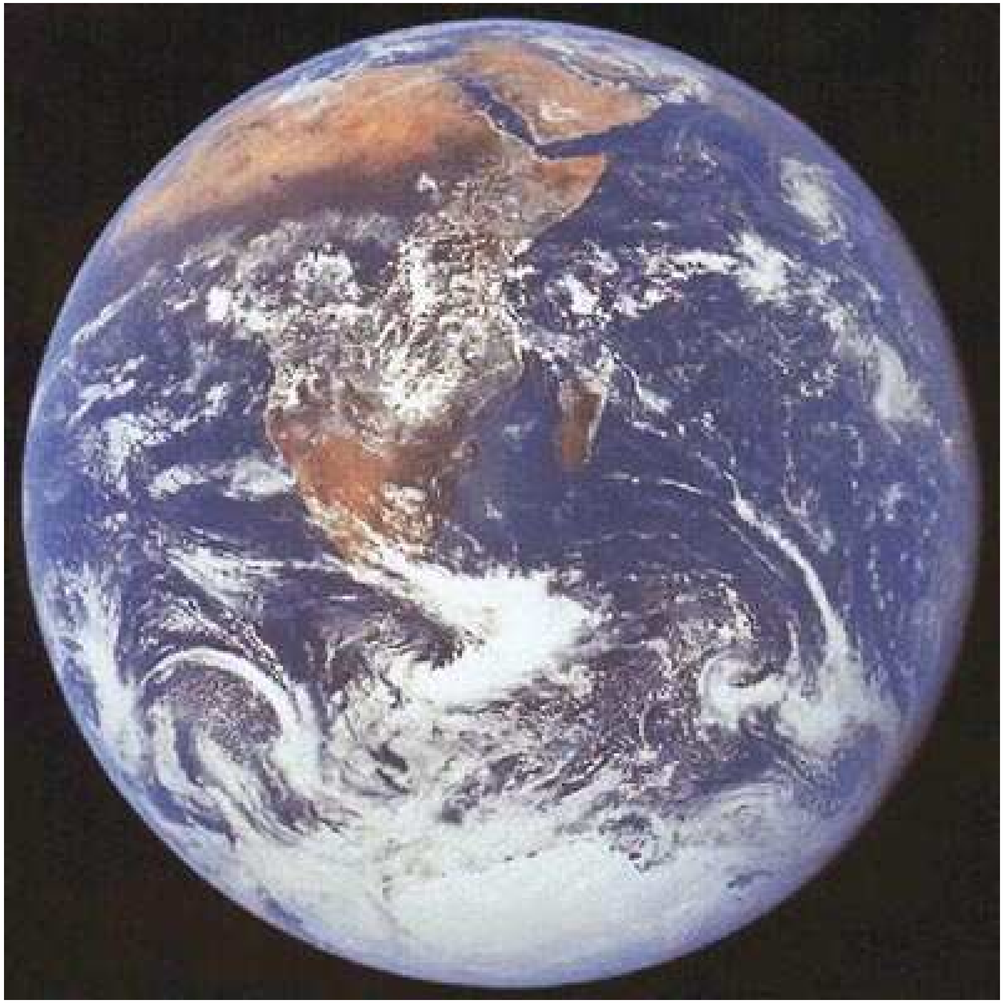
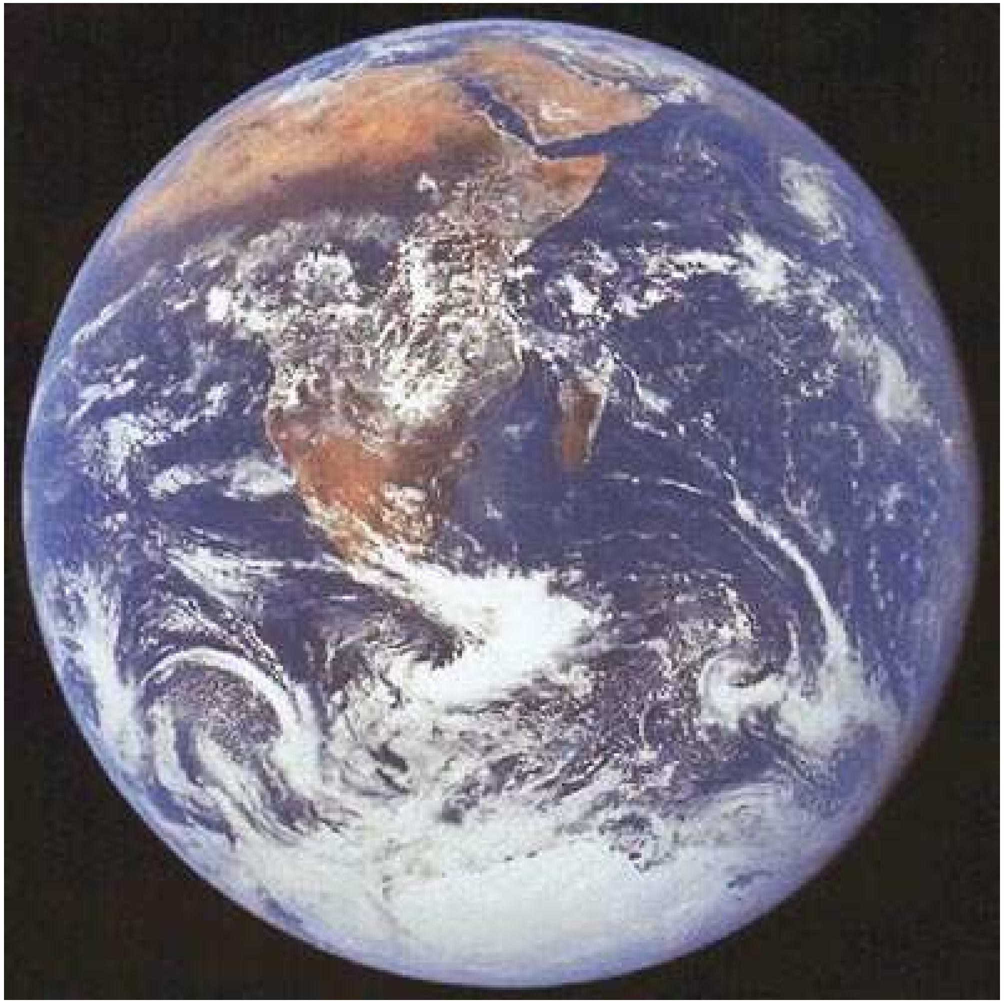
    - Climate change
    - Multiple scales of variability
    - Weather, climate, and probability

Earth, Ocean, Atmosphere: Scale



- Important facts:

Earth, Ocean, Atmosphere: Scale



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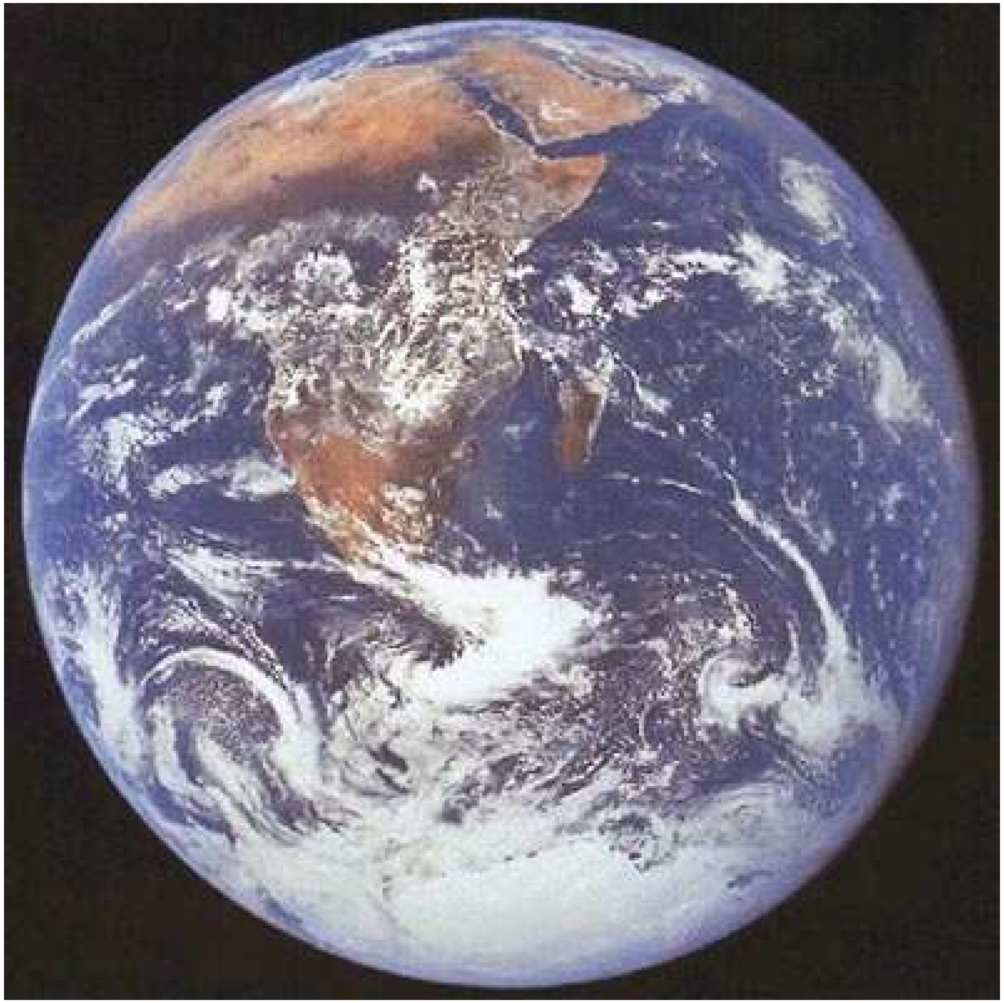

- Important facts:
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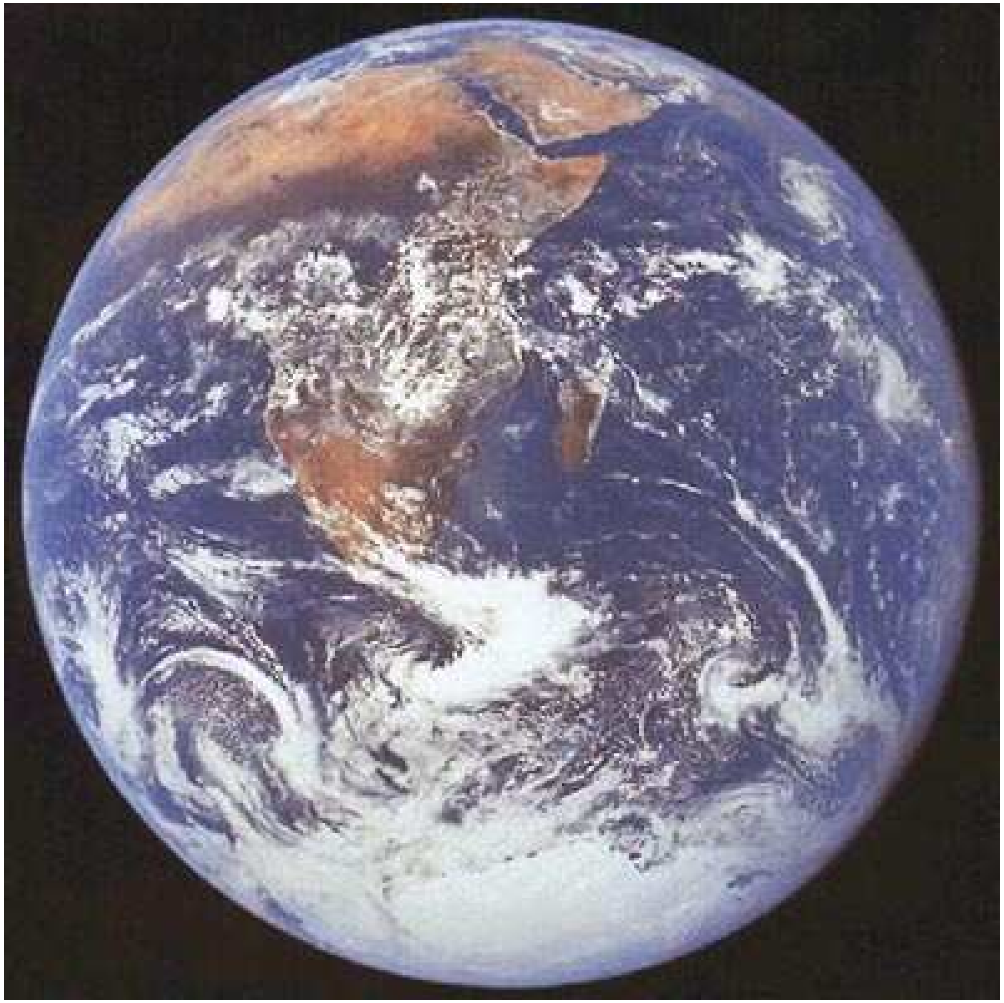
  - average radius $\sim$ 6400 km

Earth, Ocean, Atmosphere: Scale



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  - 80% of atmospheric mass within $\sim$ 10 km of surface

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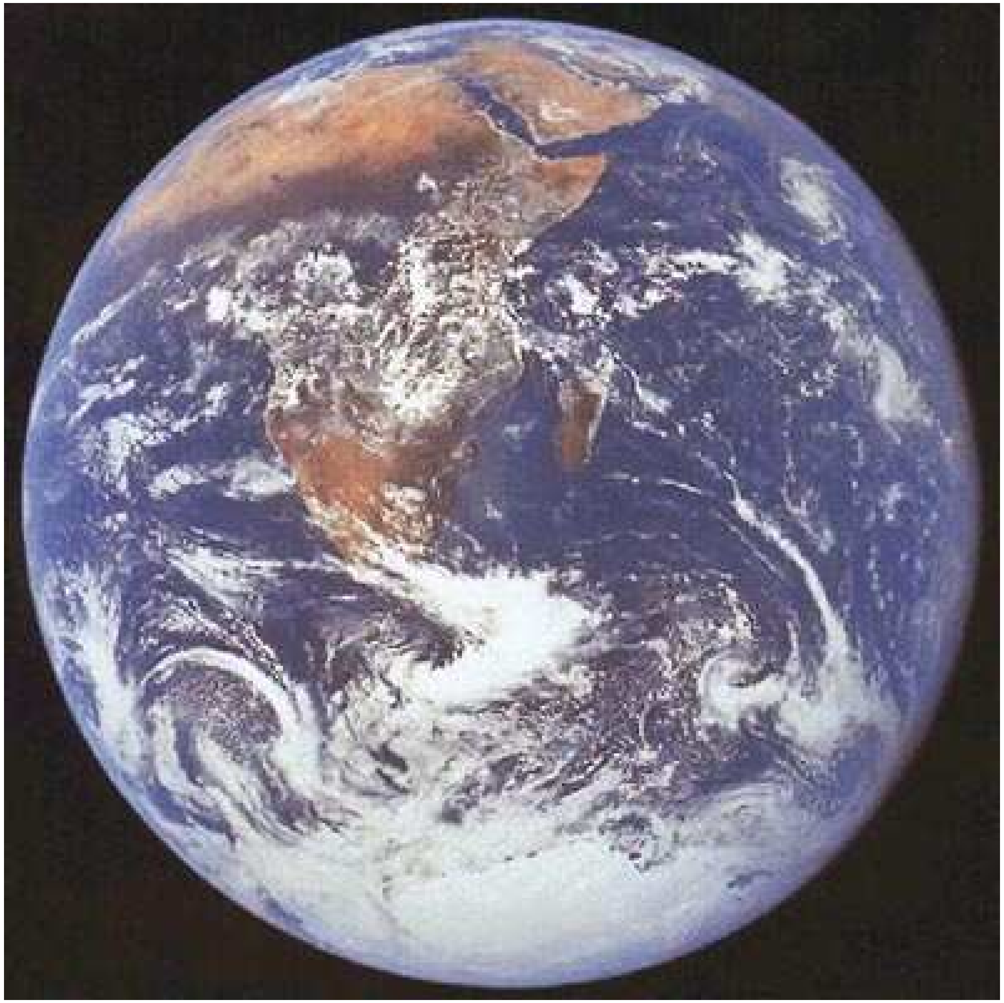

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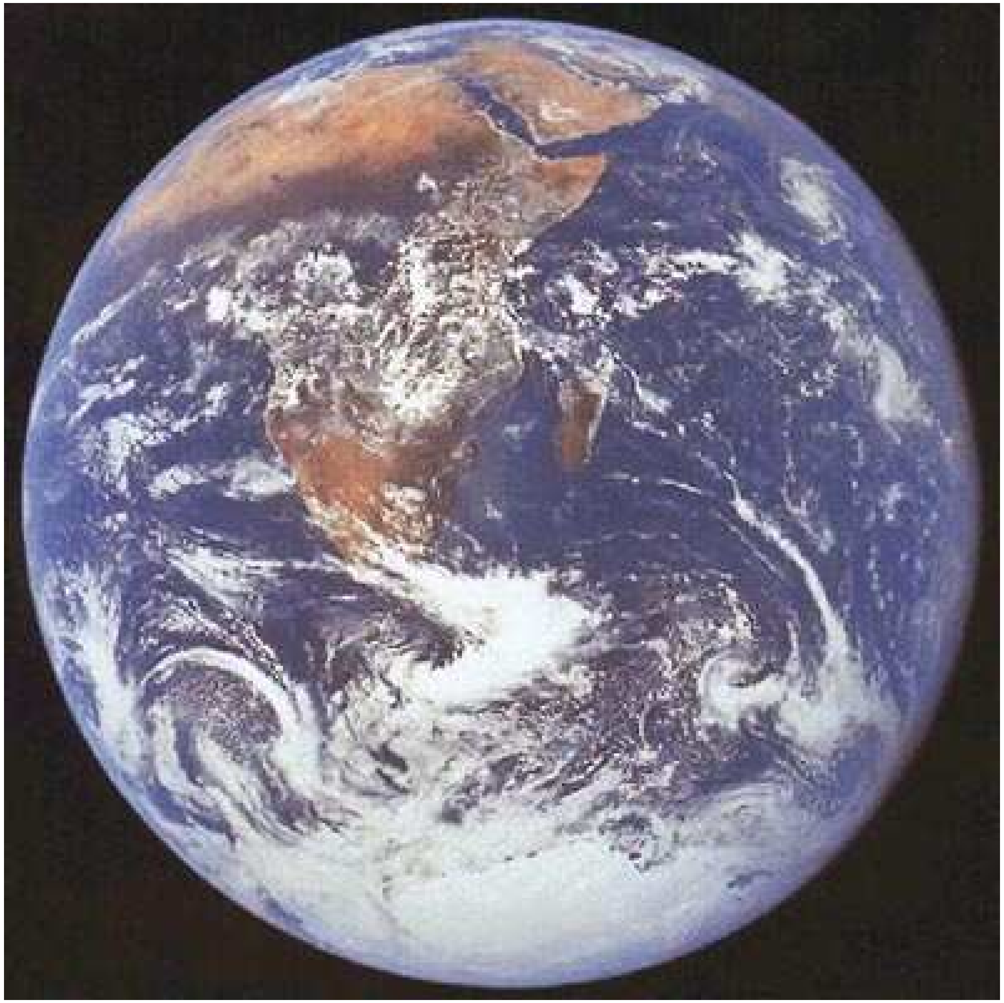

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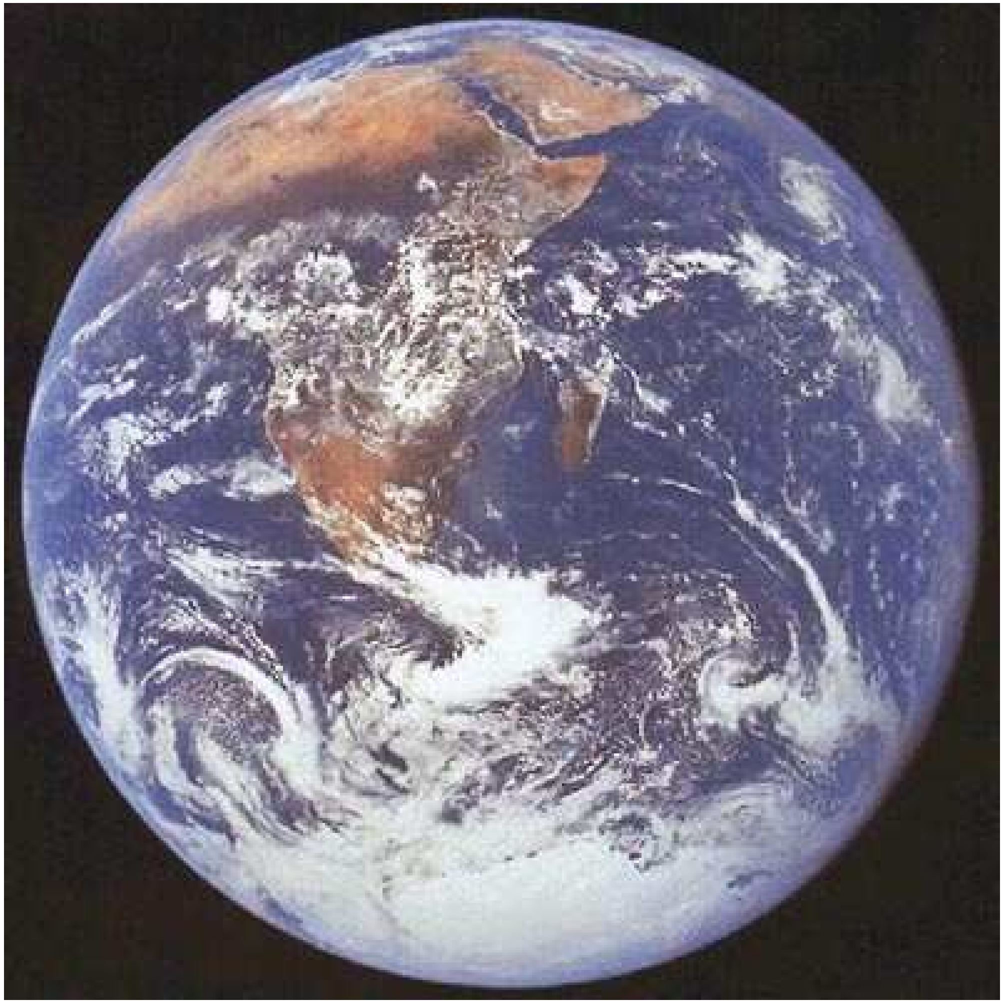

- Important facts:
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  - average radius ∼ 6400 km
  - 80% of atmospheric mass within ∼ 10 km of surface
  - average ocean depth ∼ 4 km
  - atmosphere, ocean (normally) stably stratified

⇒ atmosphere and ocean are thin “onion-skins" around solid earth

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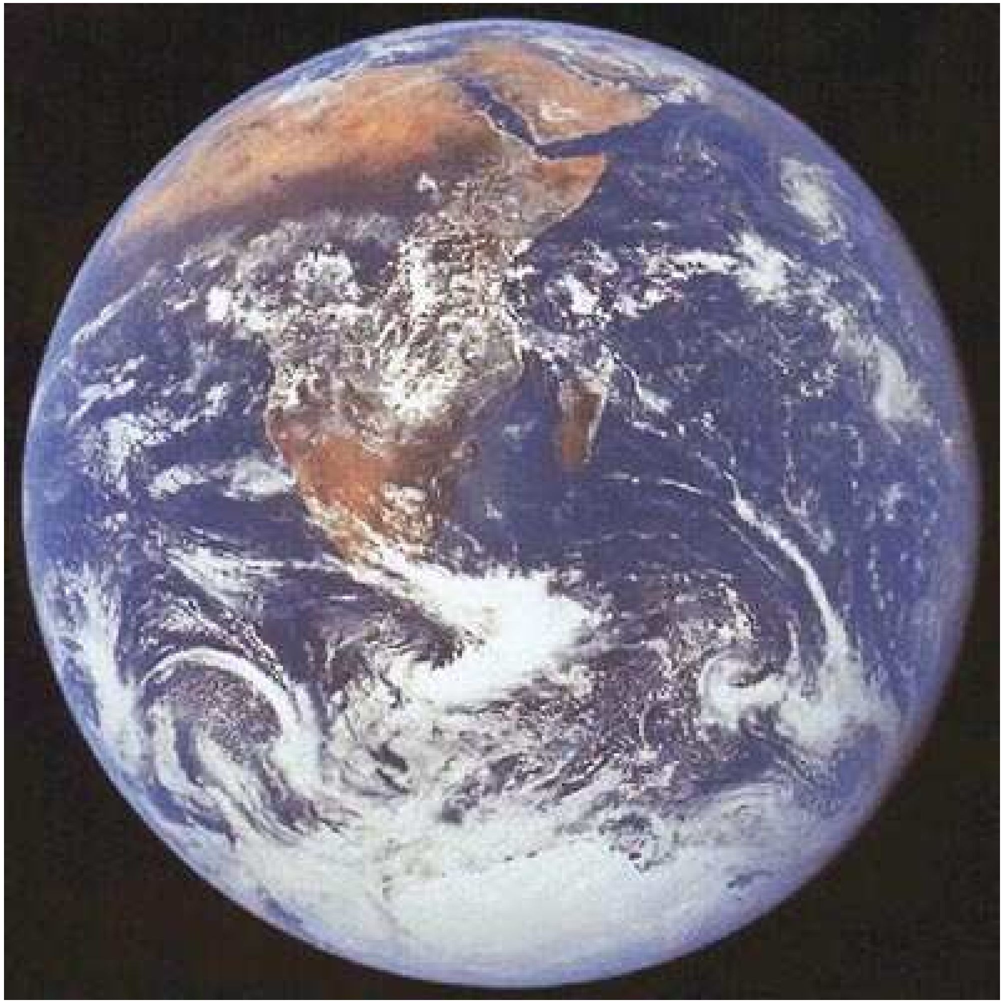
Earth, Ocean, Atmosphere: Scale



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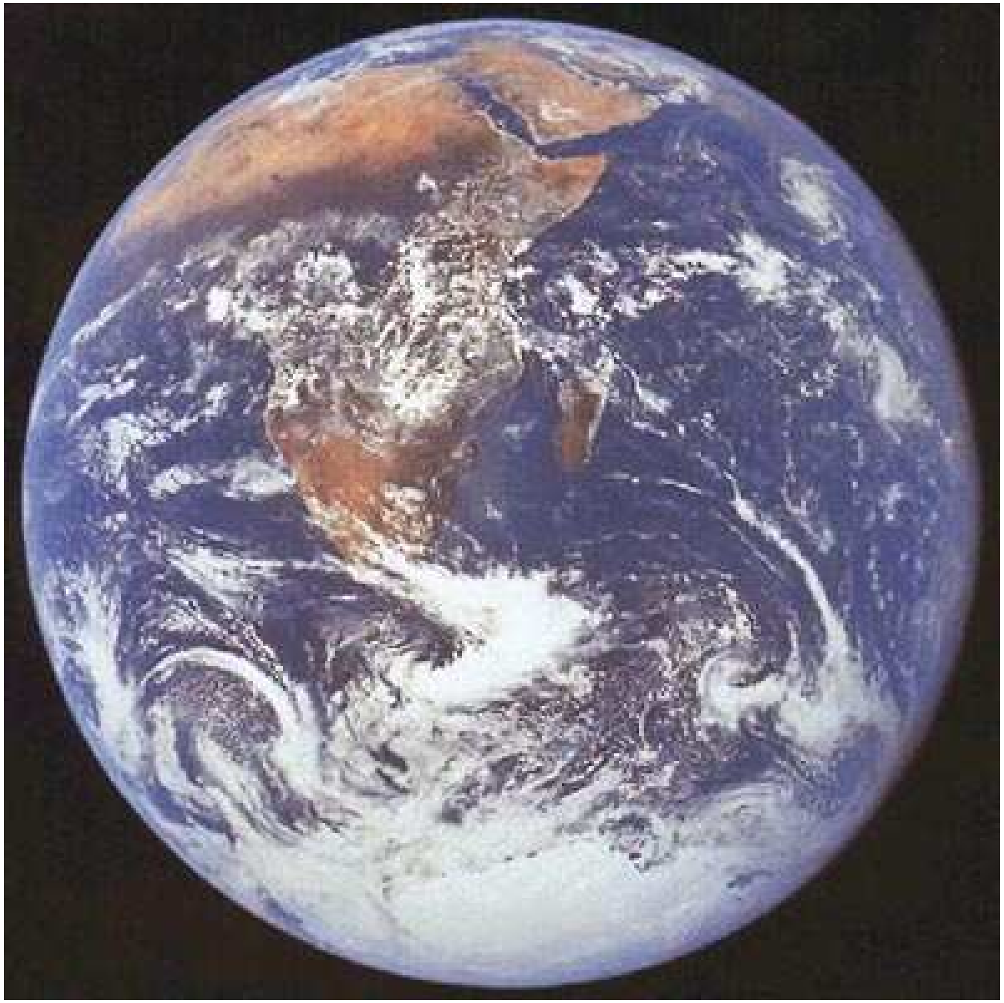
$\Rightarrow$ atmosphere and ocean are thin “onion-skins" around solid earth

$\Rightarrow$ large-scale motions quasi-2D

Earth, Ocean, Atmosphere: Scale



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$\Rightarrow$ large-scale motions quasi-2D

- “Vertical" motion tends to be episodic, localised, turbulent

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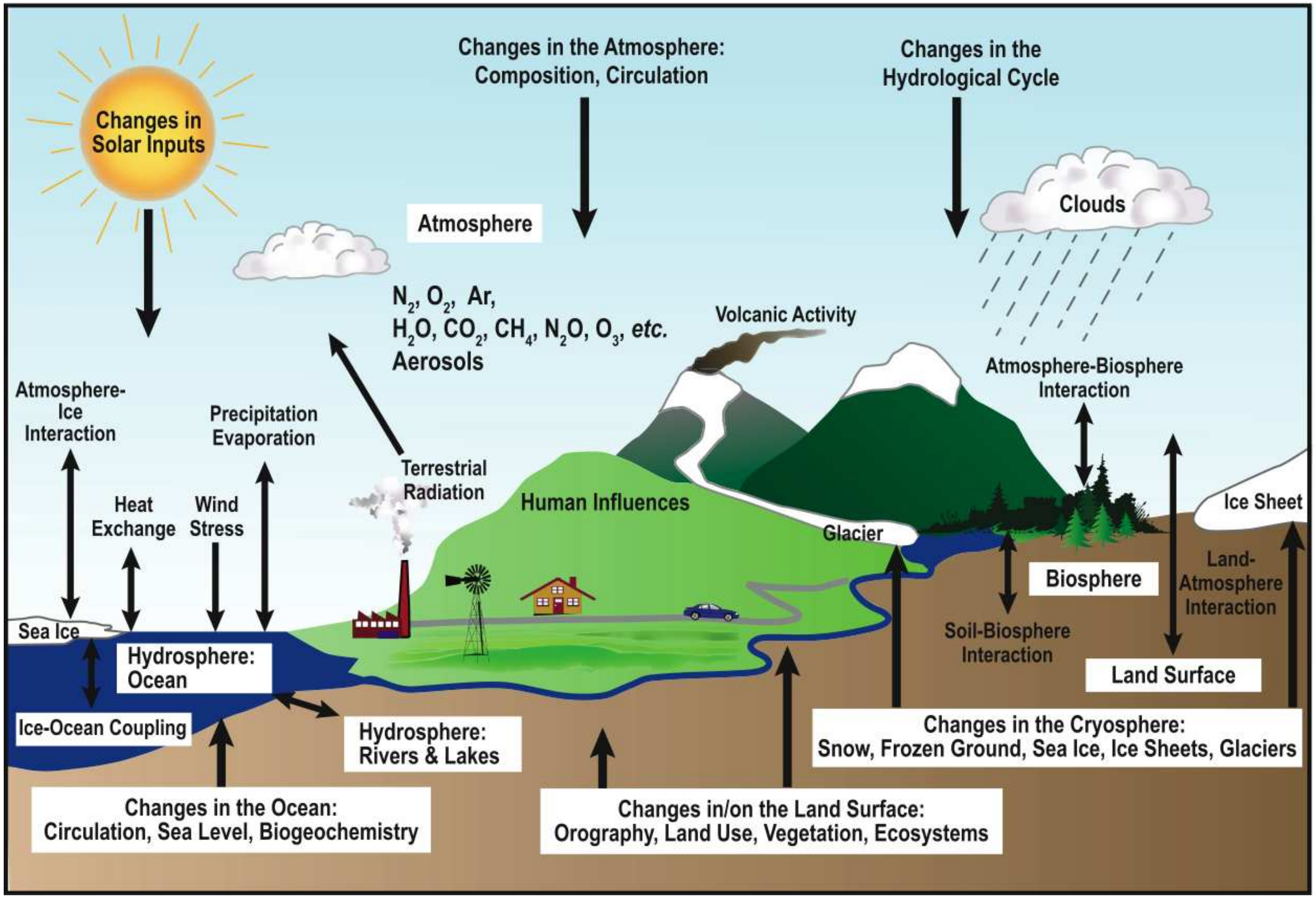
Earth, Ocean, Atmosphere: Scale

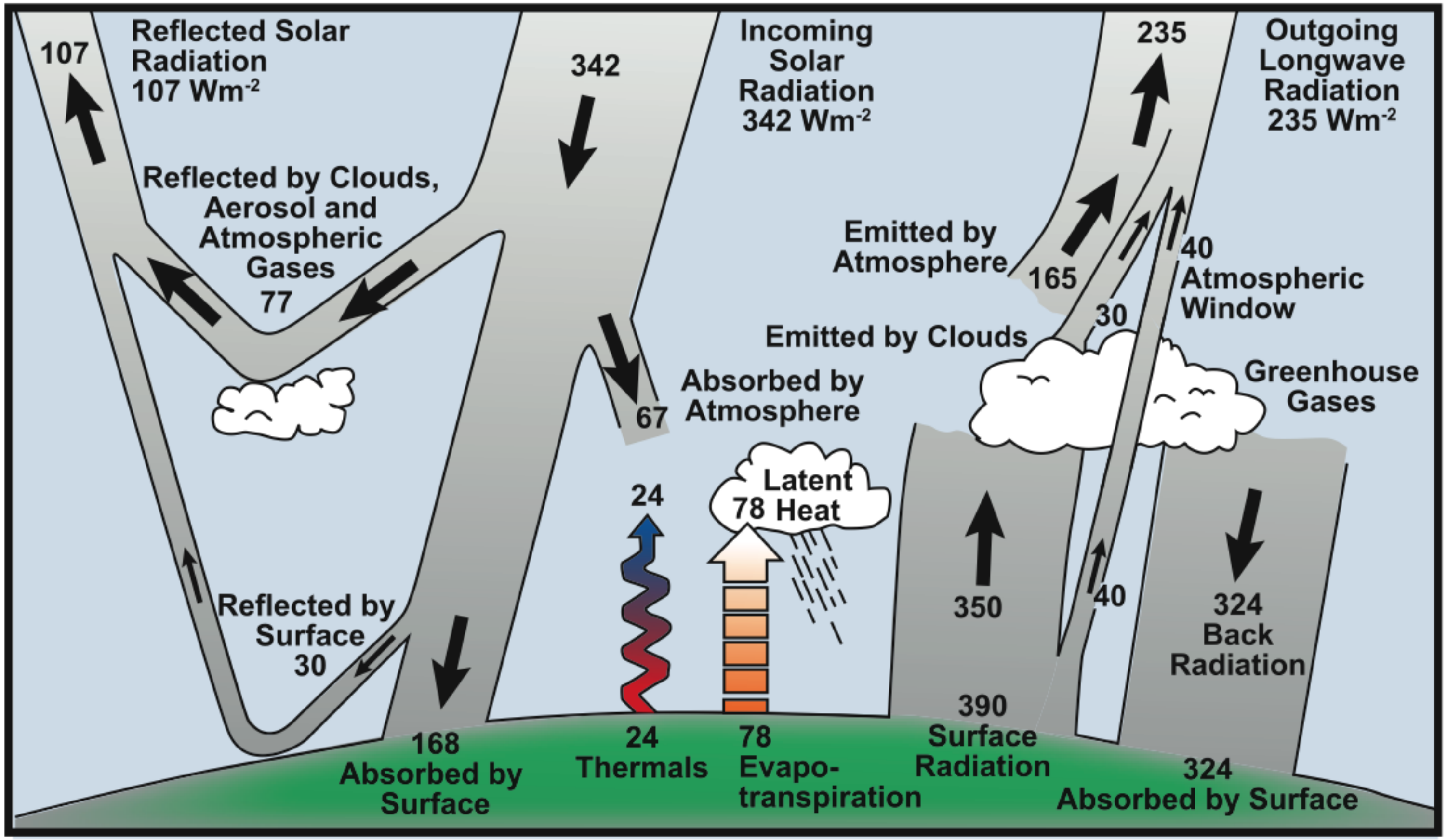
Earth, Ocean, Atmosphere: The Climate System


Changes in Solar Inputs
Changes in the Atmosphere: Composition, Circulation
Changes in the Hydrological Cycle
Clouds
Atmosphere
N_2, O_2, Ar,
H_2O, CO_2, CH_4, N_2O, O_3, *etc.*
Aerosols
Volcanic Activity
Atmosphere-Biosphere Interaction
Atmosphere-Ice Interaction
Precipitation Evaporation
Terrestrial Radiation
Heat Exchange
Wind Stress
Human Influences
Glacier
Ice Sheet
Biosphere
Land-Atmosphere Interaction
Sea Ice
Hydrosphere: Ocean
Soil-Biosphere Interaction
Land Surface
Ice-Ocean Coupling
Hydrosphere: Rivers & Lakes
Changes in the Cryosphere: Snow, Frozen Ground, Sea Ice, Ice Sheets, Glaciers
Changes in the Ocean: Circulation, Sea Level, Biogeochemistry
Changes in/on the Land Surface: Orography, Land Use, Vegetation, Ecosystems

From IPCC AR4 http://www.ipcc.ch

FAQ 1.2, Figure 1

Earth’s Radiation Balance

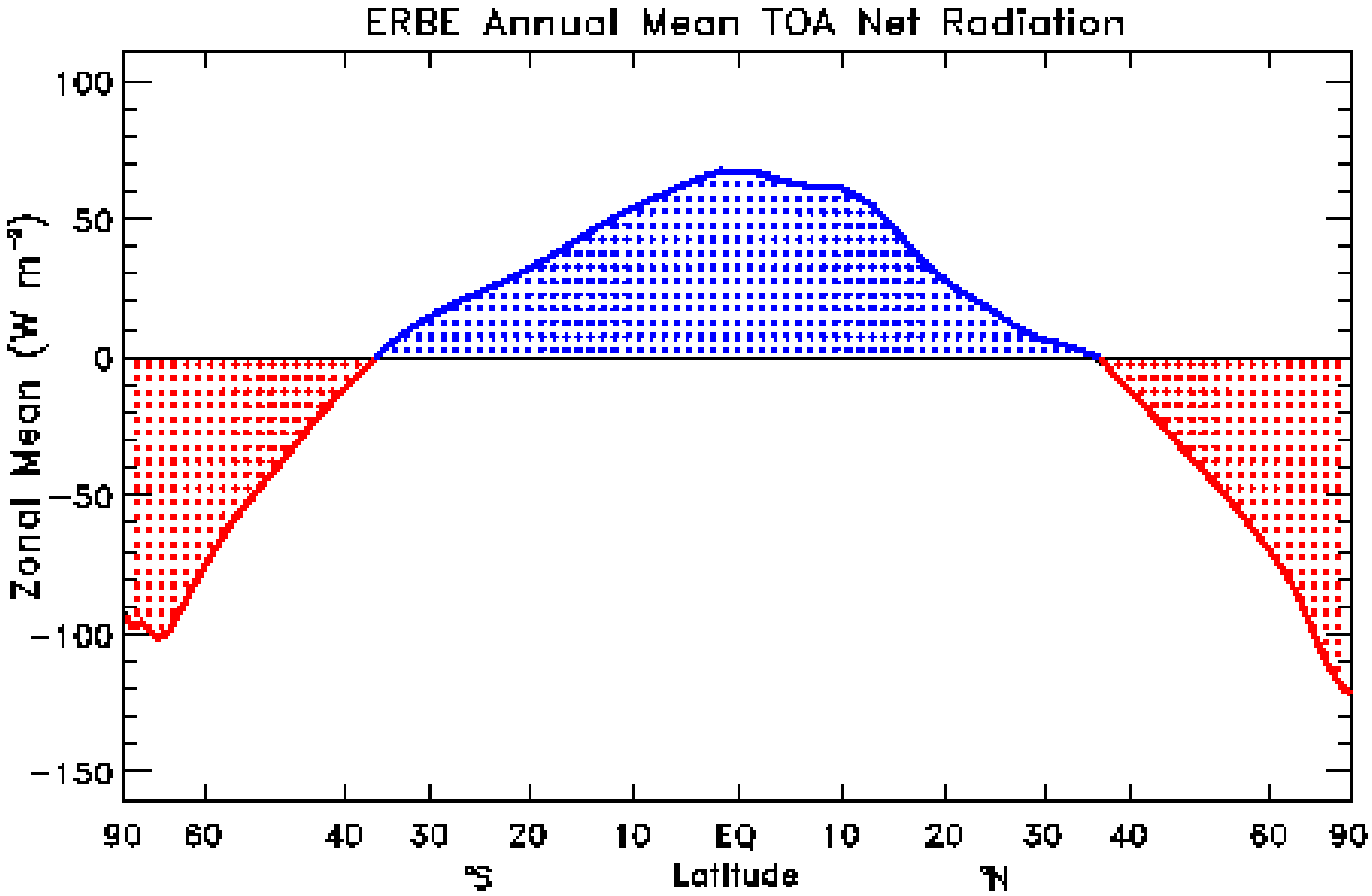

107
Reflected Solar Radiation 107 Wm-2
342
Incoming Solar Radiation 342 Wm-2
235
Outgoing Longwave Radiation 235 Wm-2
Reflected by Clouds, Aerosol and Atmospheric Gases 77
Emitted by Atmosphere
165
30
40
Atmospheric Window
Emitted by Clouds
Greenhouse Gases
Absorbed by Atmosphere
67
24
Latent 78 Heat
350
40
324 Back Radiation
Reflected by Surface 30
390 Surface Radiation
168 Absorbed by Surface
24 Thermals
78 Evapo-transpiration
324 Absorbed by Surface

From IPCC AR4 http://www.ipcc.ch

FAQ 1.1, Figure 1

Earth As A Heat Engine

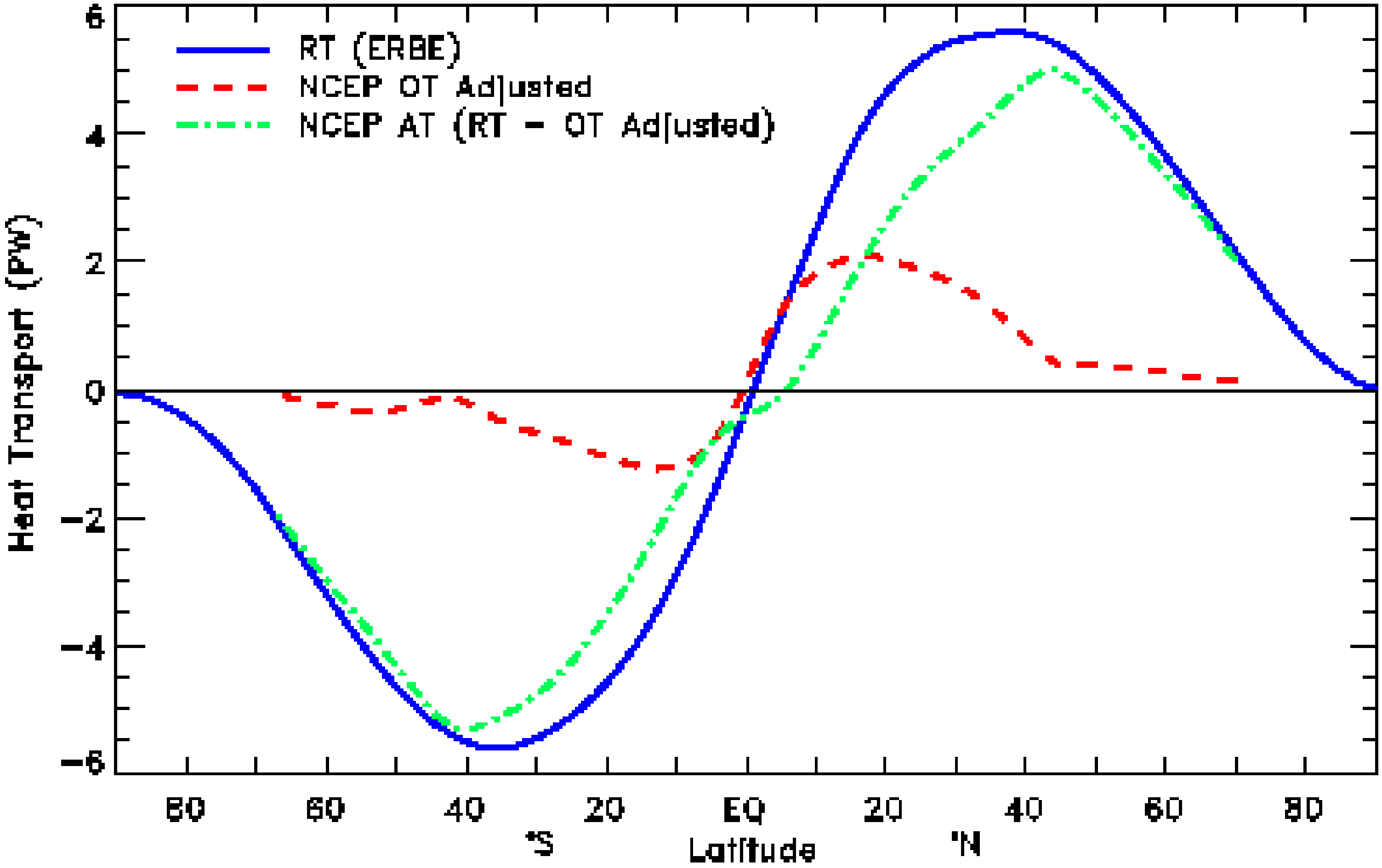
Solar energy in - terrestrial energy out



From Trenberth and Caron, J. Clim, 2001

Earth As A Heat Engine

Meridional (northwards) equilibrium heat transport



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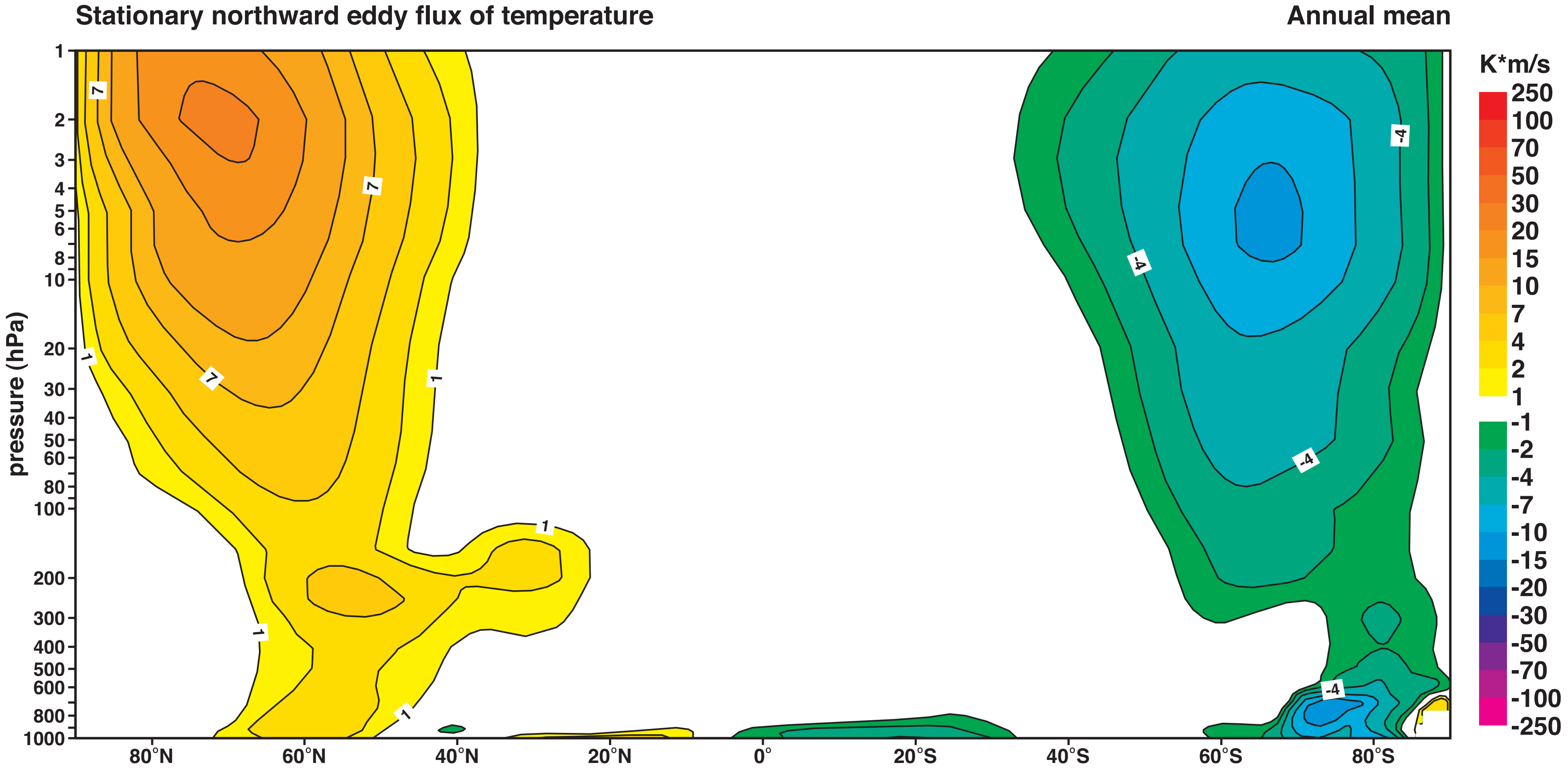
Earth As A Heat Engine

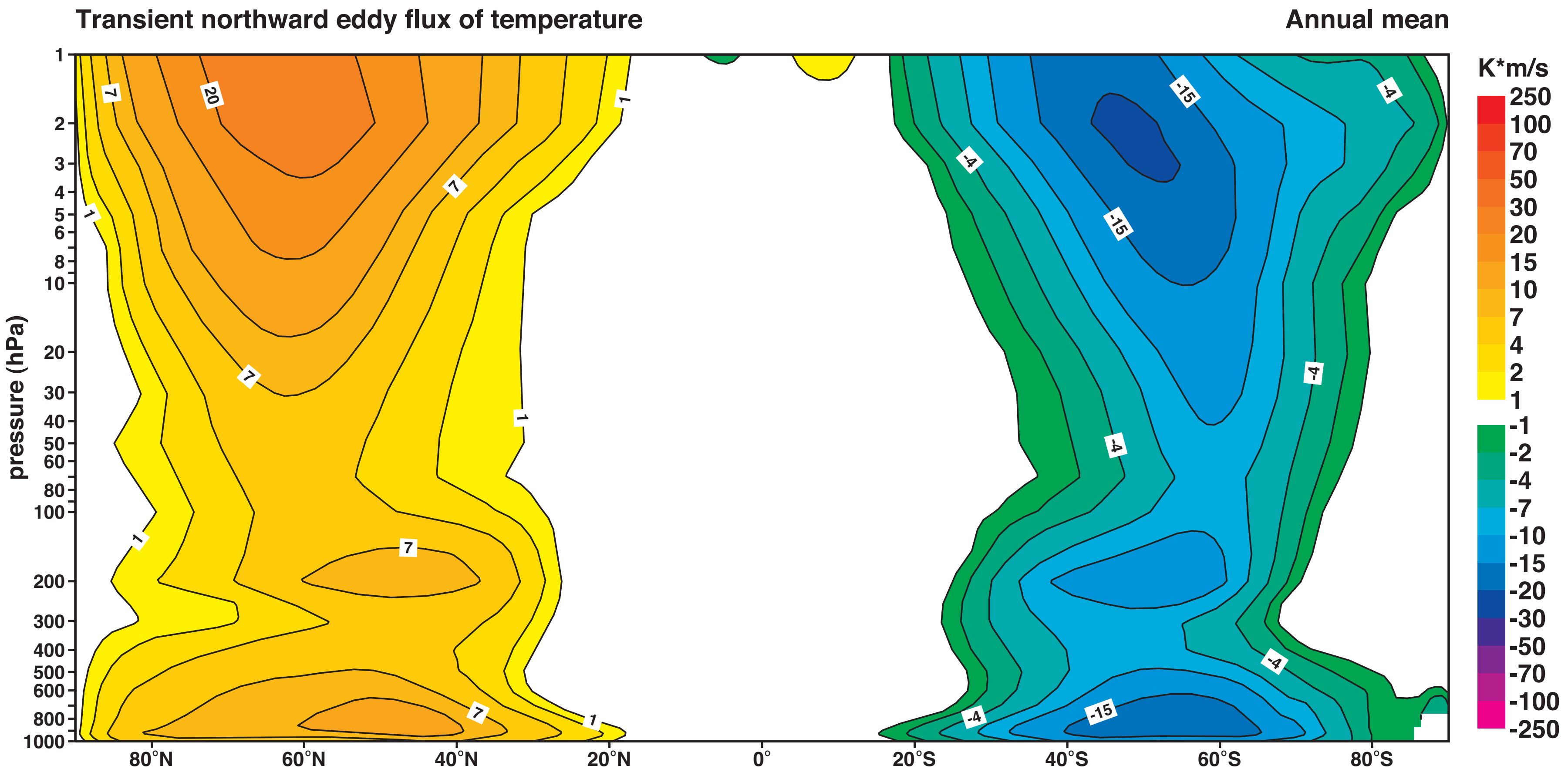
Mean northwards heat flux by mean state



From ERA 40 Reanalysis Atlas

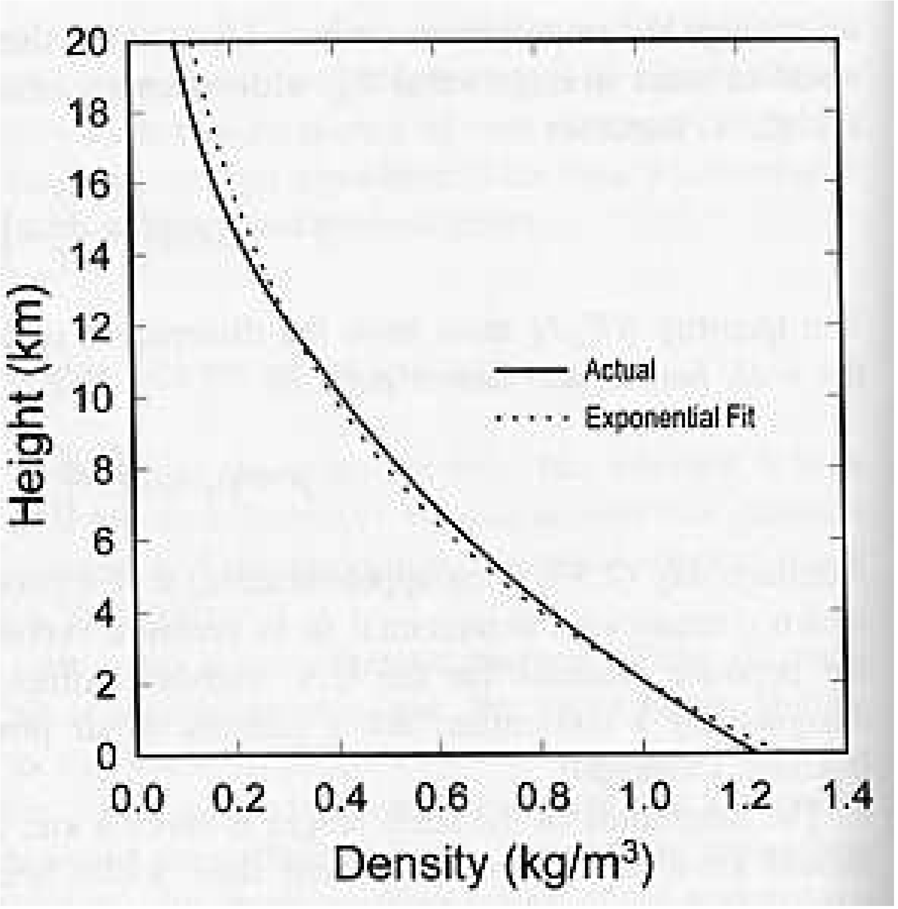
Earth As A Heat Engine

Mean northwards heat flux by transient variability

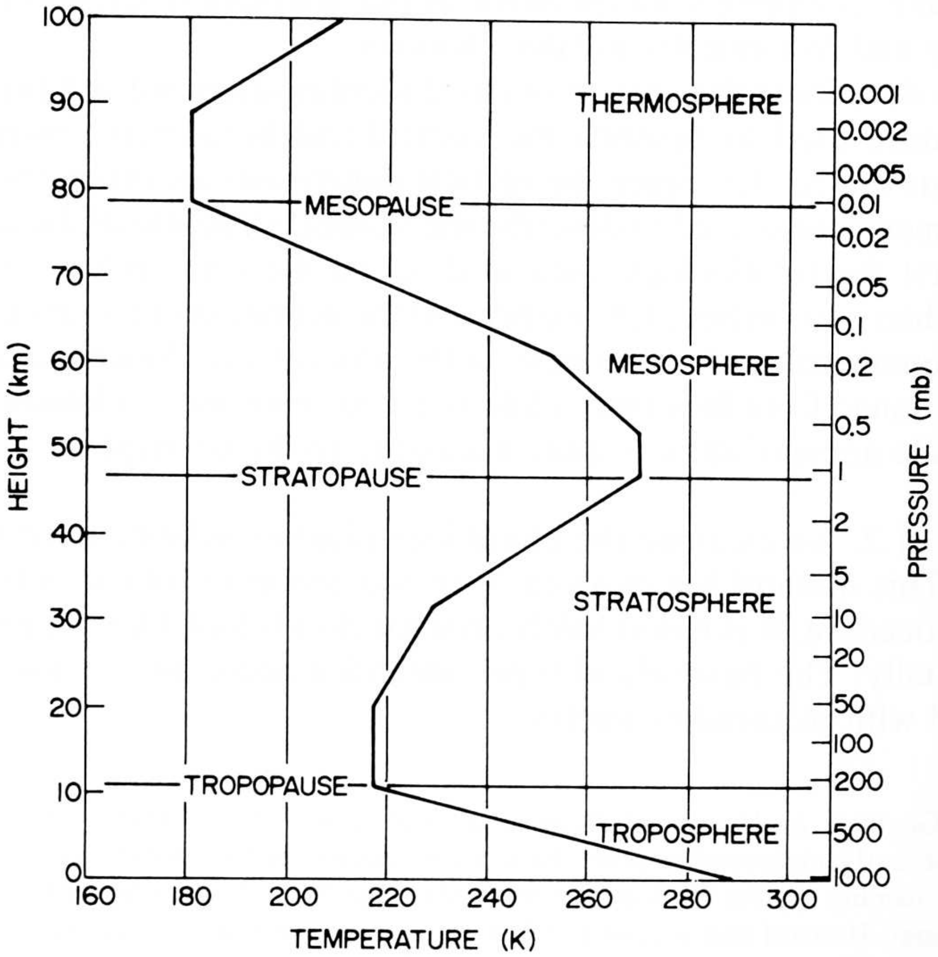


From ERA 40 Reanalysis Atlas

Atmosphere: Mean Vertical Structure

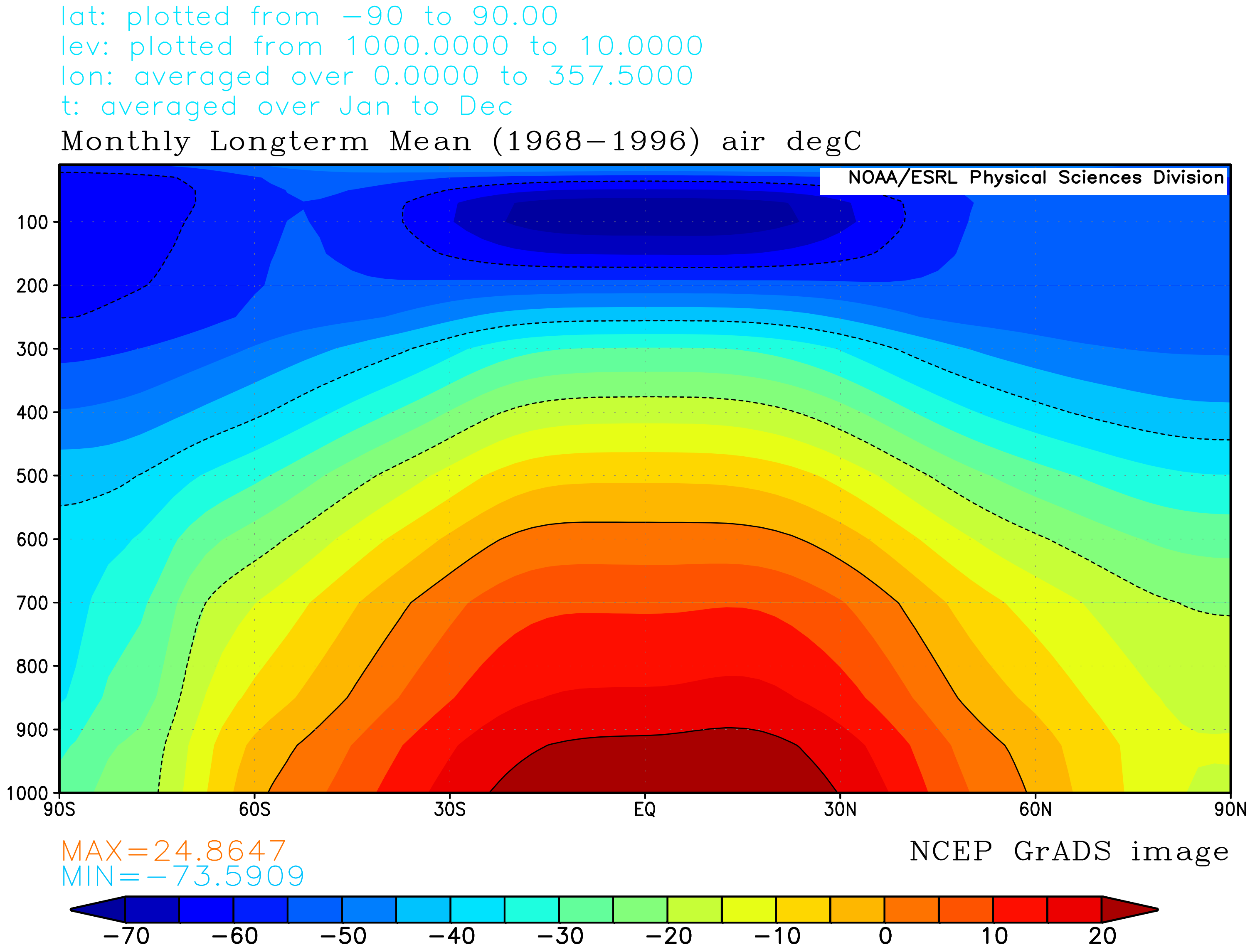


From Bohren & Albrecht 1998

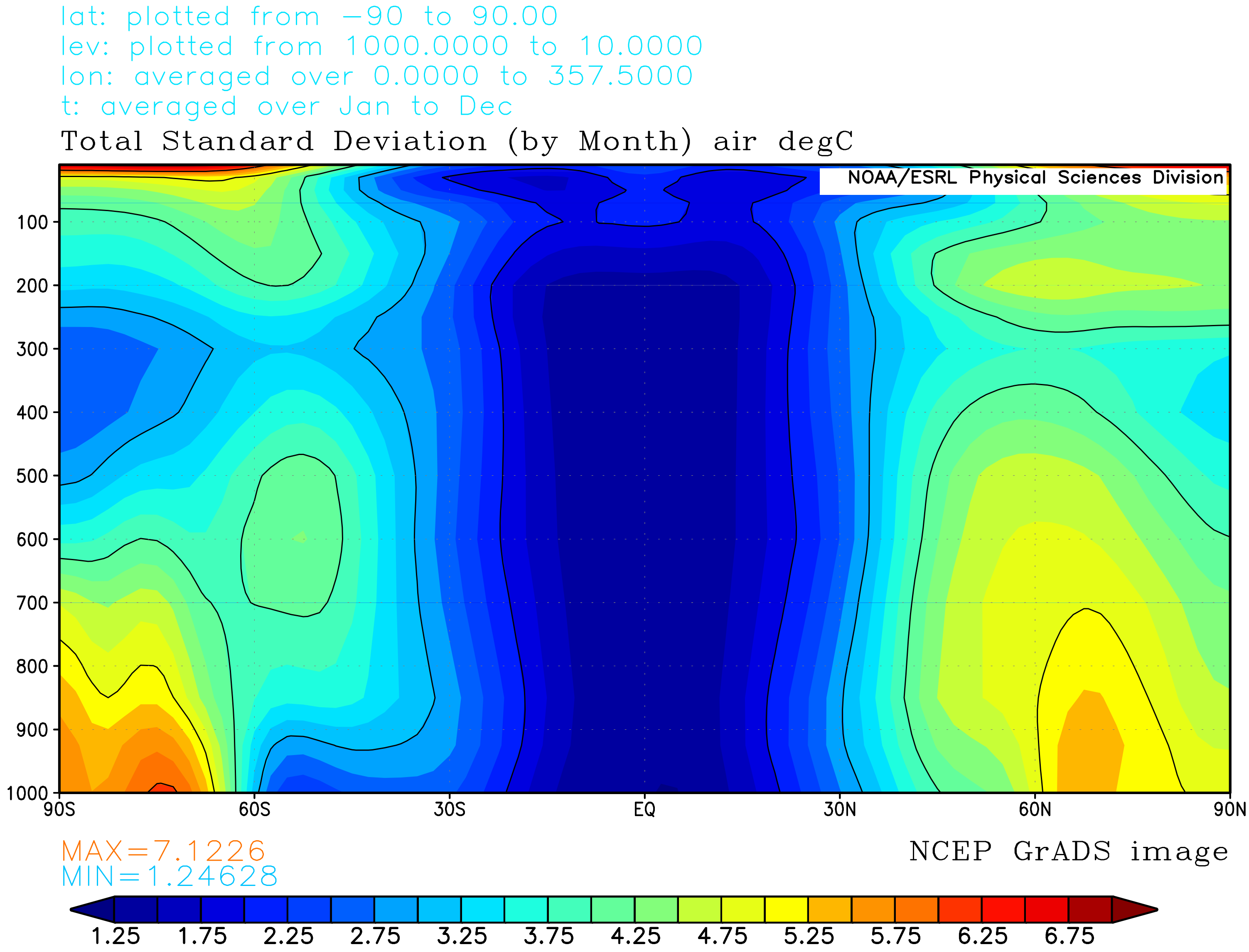


From Wallace & Hobbs 1977

Atmosphere: Mean Air Temperature

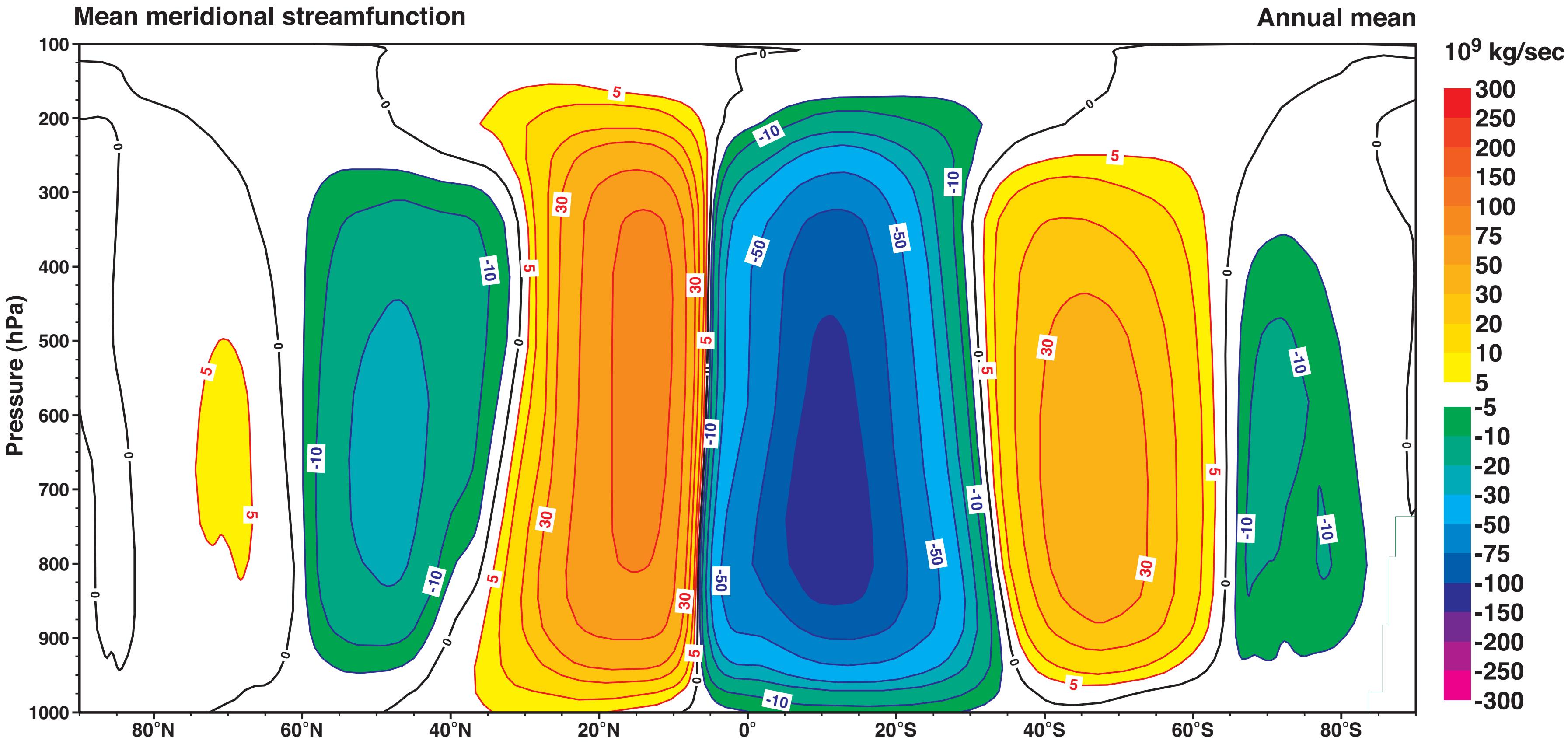


Atmosphere: Standard Deviation of Air Temperature



Atmosphere: Mean Meridional Circulation

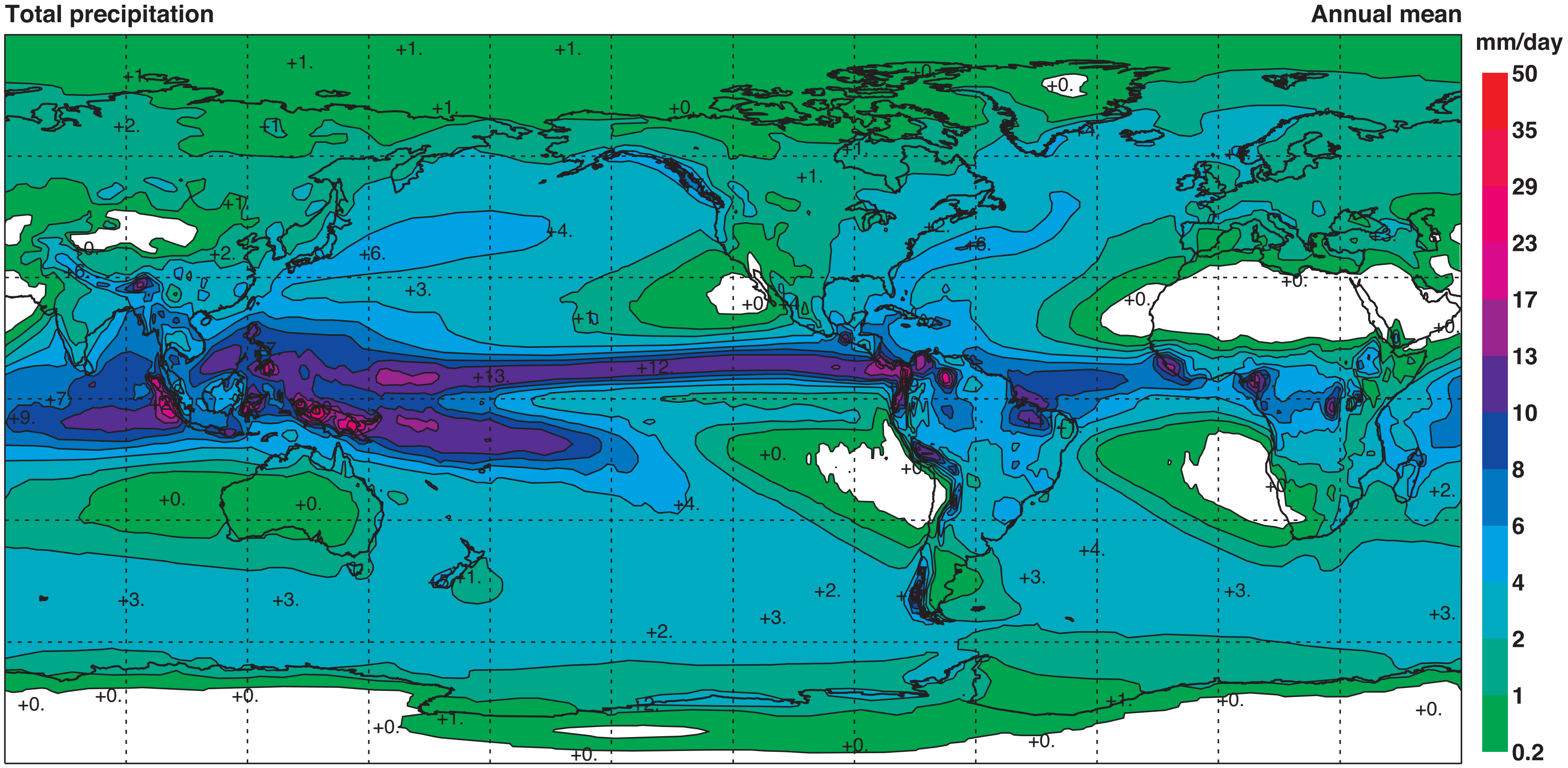
Zonal mean meridional circulation



From ERA 40 Reanalysis Atlas

Atmosphere: Mean Precipitation

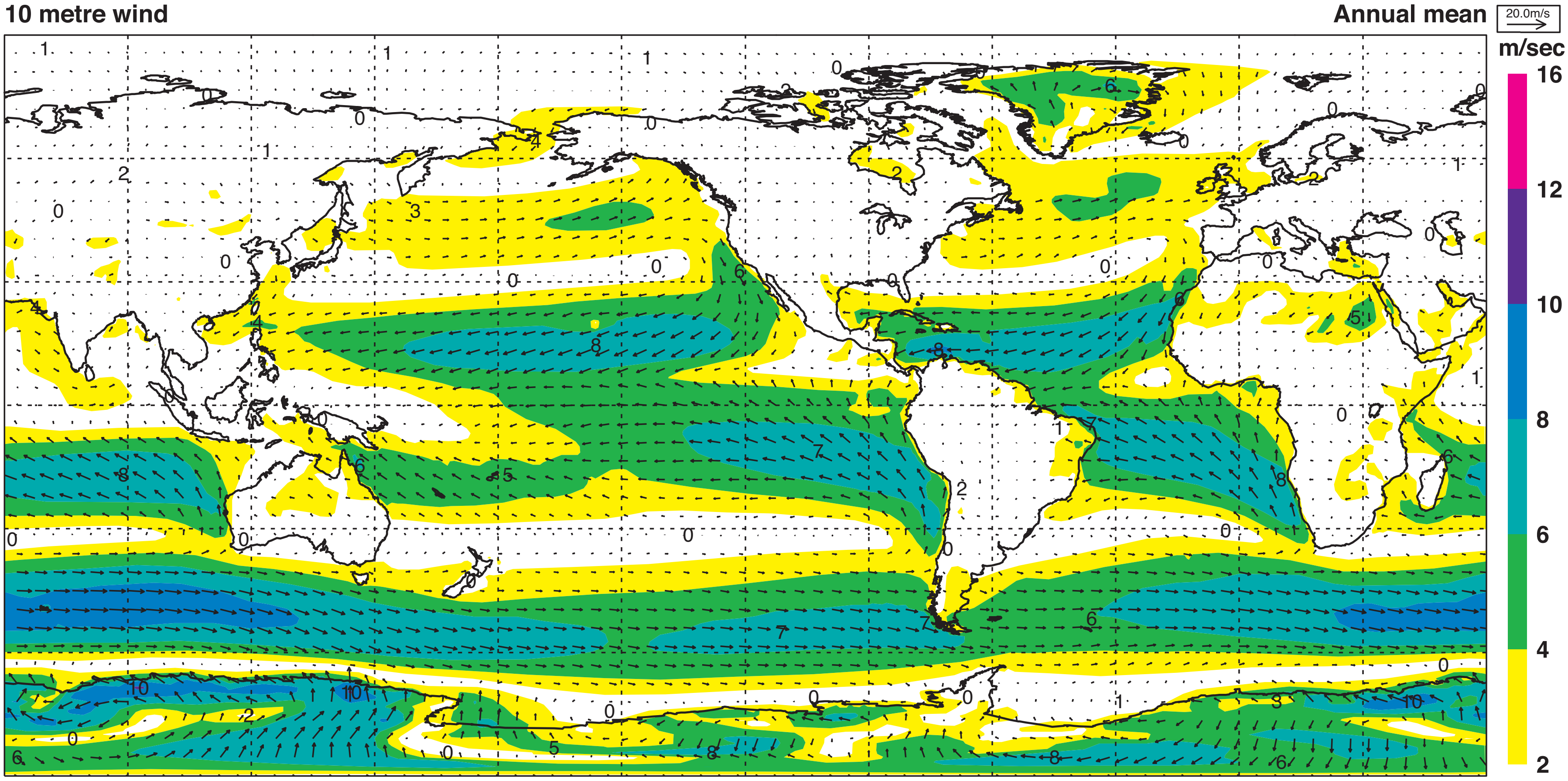
Annual mean precipitation


Total precipitation
Annual mean
mm/day
50
35
29
23
17
13
10
8
6
4
2
1
0.2

From ERA 40 Reanalysis Atlas

Atmosphere: Mean Surface Winds

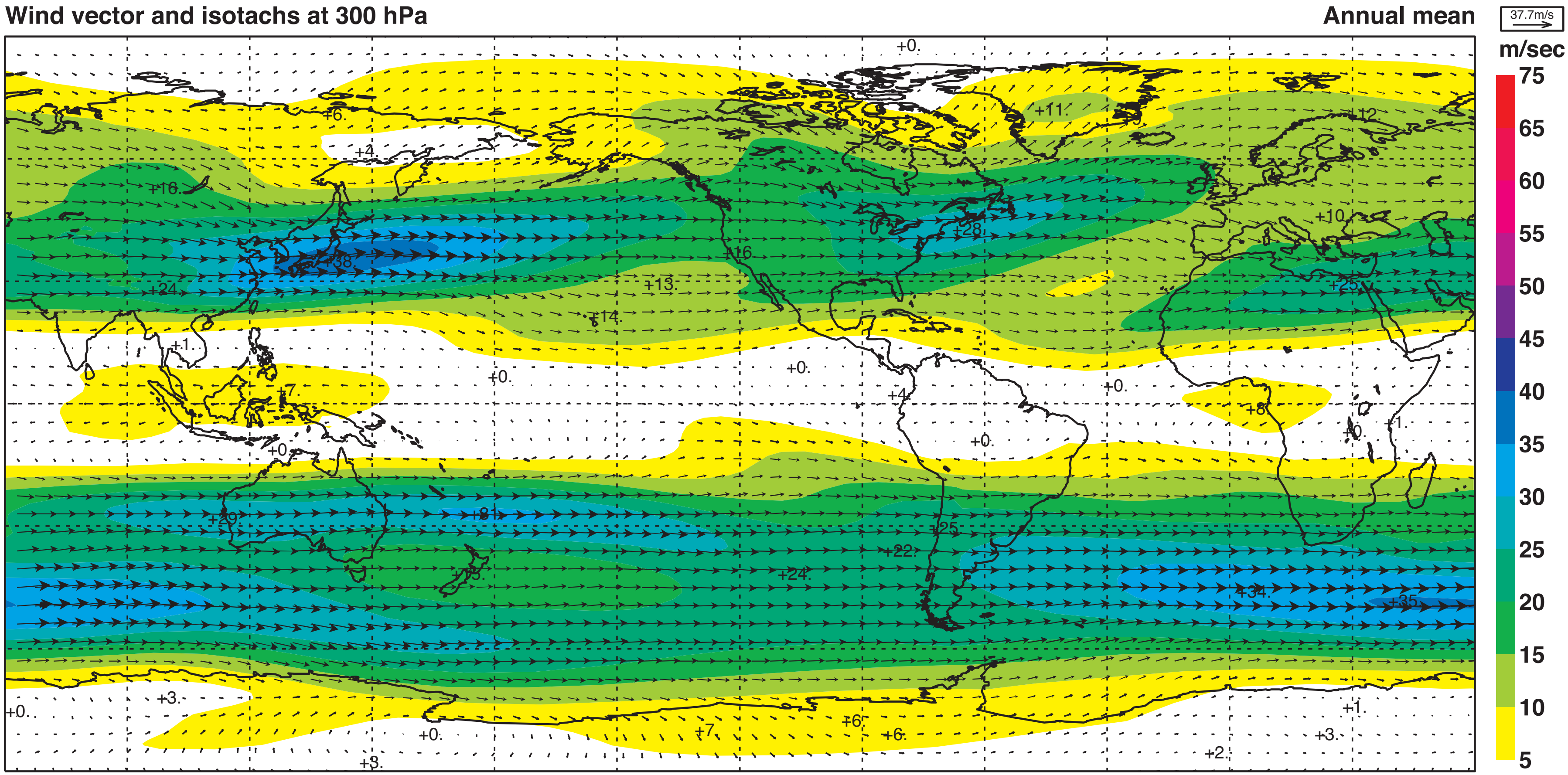
Mean 10 m surface winds


10 metre wind
Annual mean
20.0m/s
m/sec
16
12
10
8
6
4
2

From ERA 40 Reanalysis Atlas

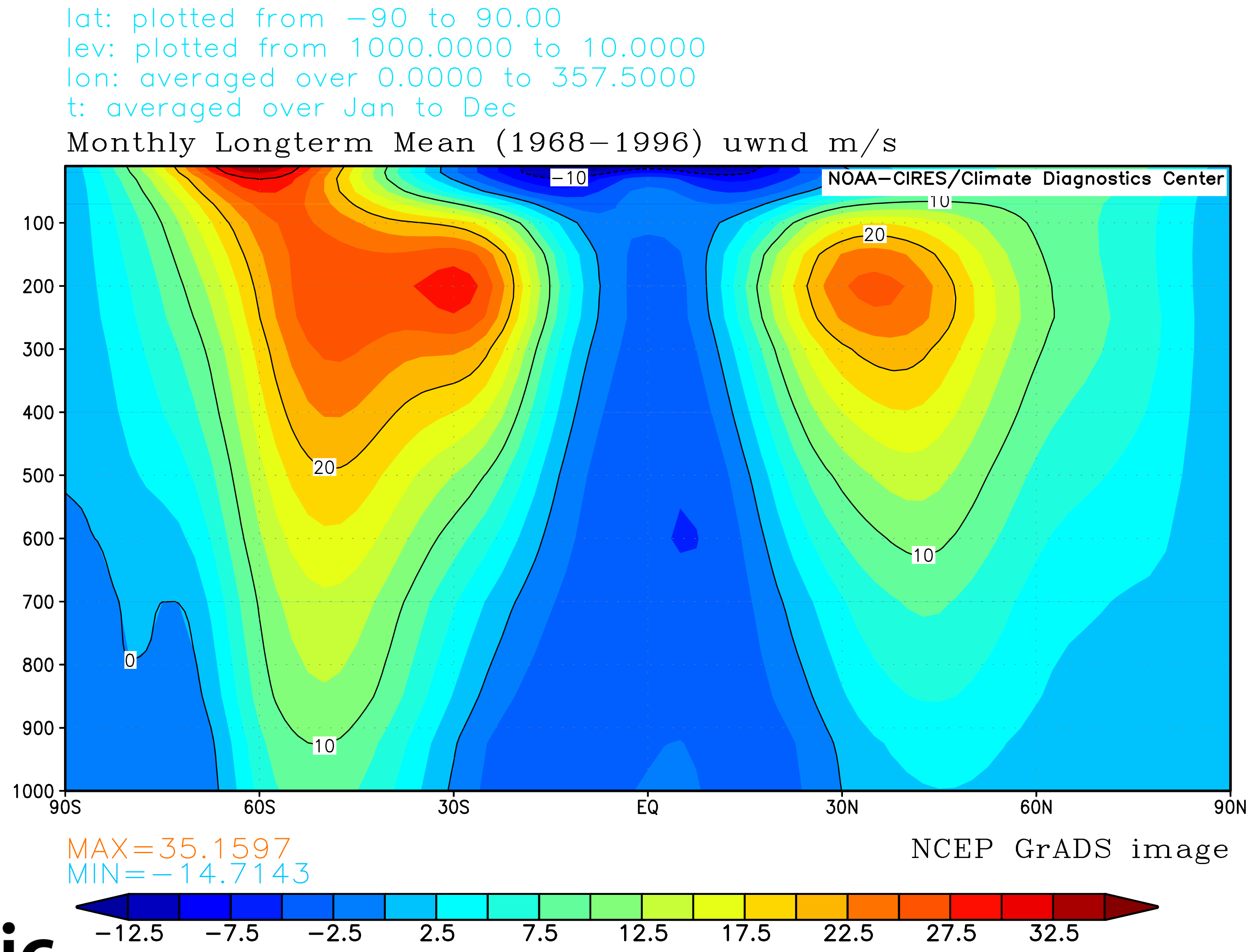
Atmosphere: Mean Upper Tropospheric Winds

Mean 300 hPa winds

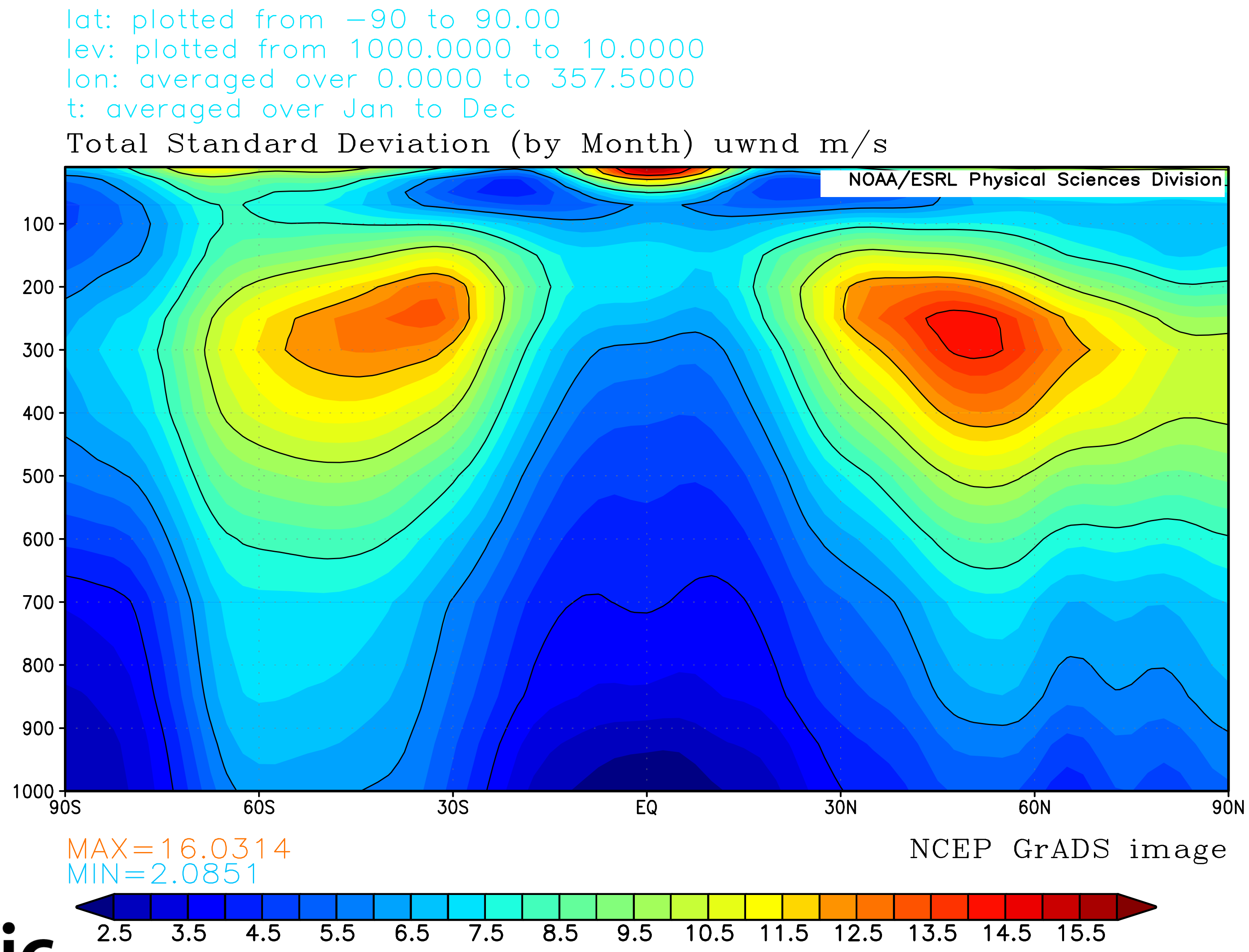

Wind vector and isotachs at 300 hPa
Annual mean
37.7m/s
m/sec
75
65
60
55
50
45
40
35
30
25
20
15
10
5

From ERA 40 Reanalysis Atlas

Atmosphere: Mean Zonal Wind

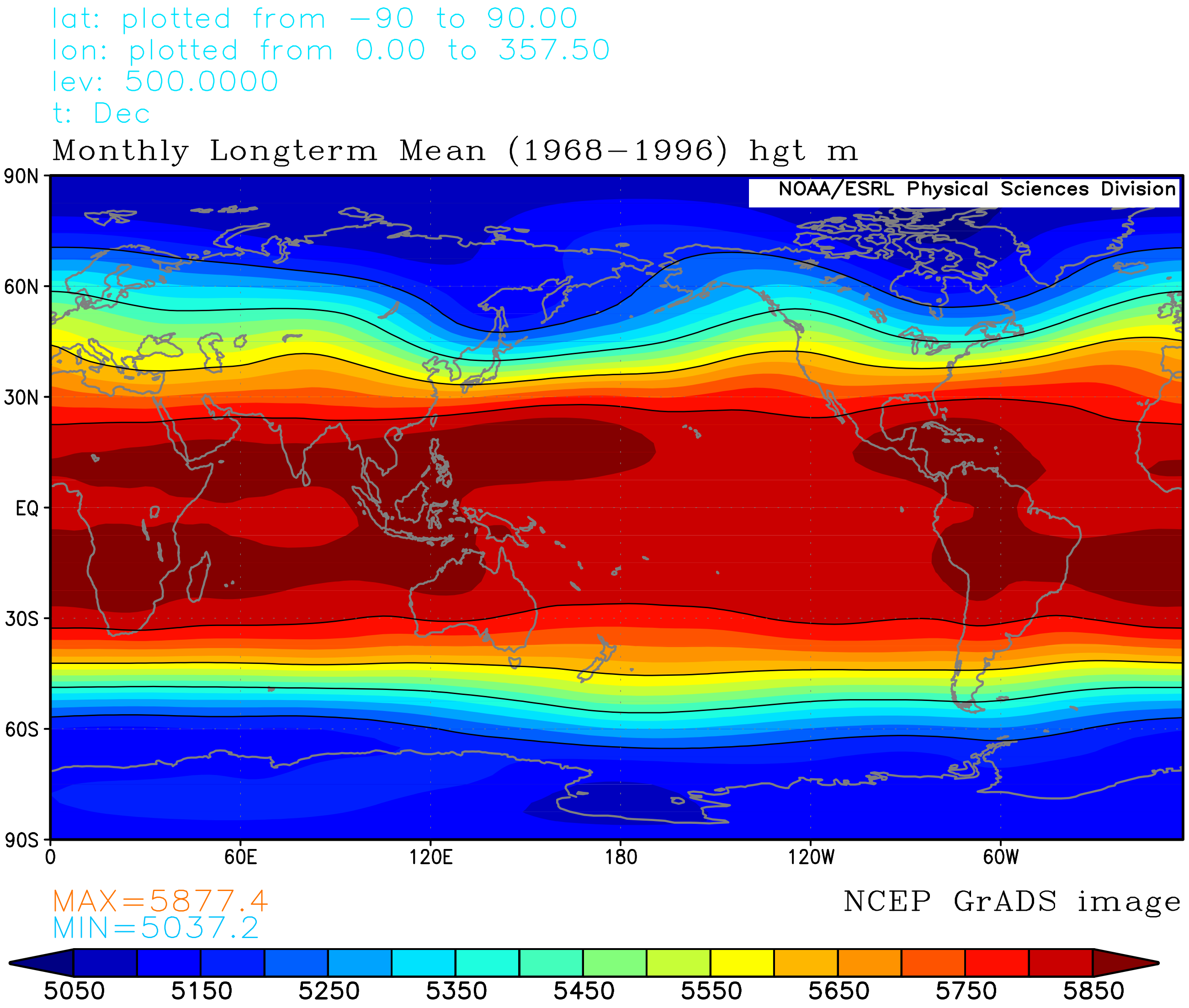


Atmosphere: Standard Deviation of Zonal Wind



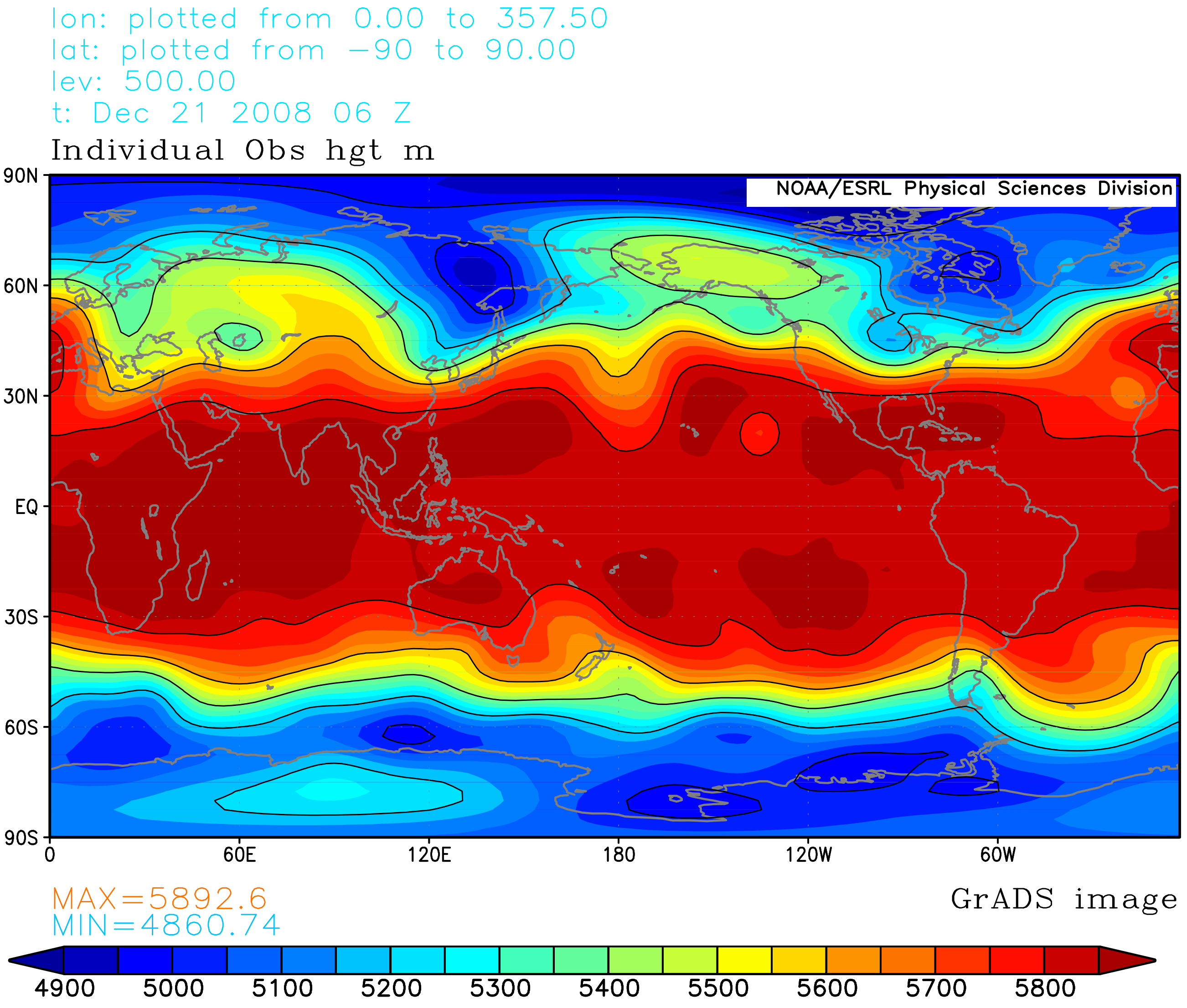
Atmosphere: Mid-Troposphere Streamlines

Time-mean December geopotential height


lat: plotted from -90 to 90.00
lon: plotted from 0.00 to 357.50
lev: 500.0000
t: Dec
Monthly Longterm Mean (1968-1996) hgt m
NOAA/ESRL Physical Sciences Division
90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
MAX=5877.4
MIN=5037.2
NCEP GrADS image
5050
5150
5250
5350
5450
5550
5650
5750
5850

Atmosphere: Mid-Troposphere Streamlines

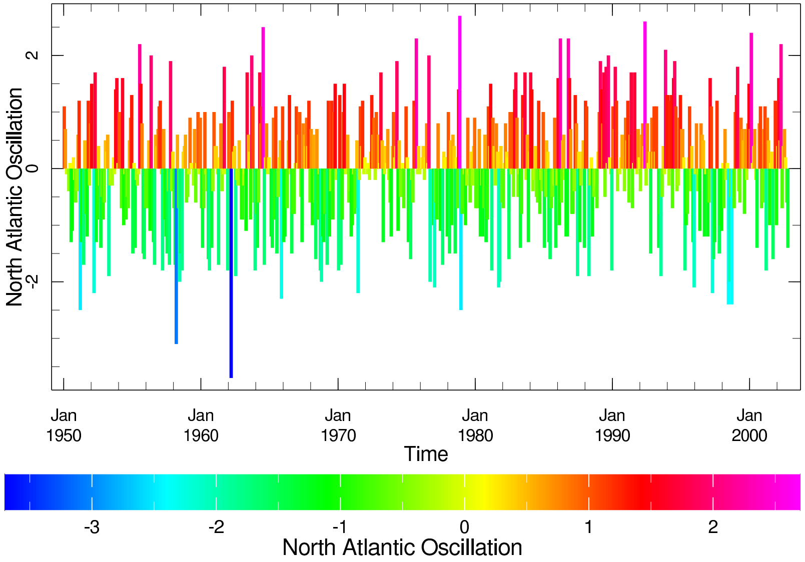
December 21 2008 geopotential height

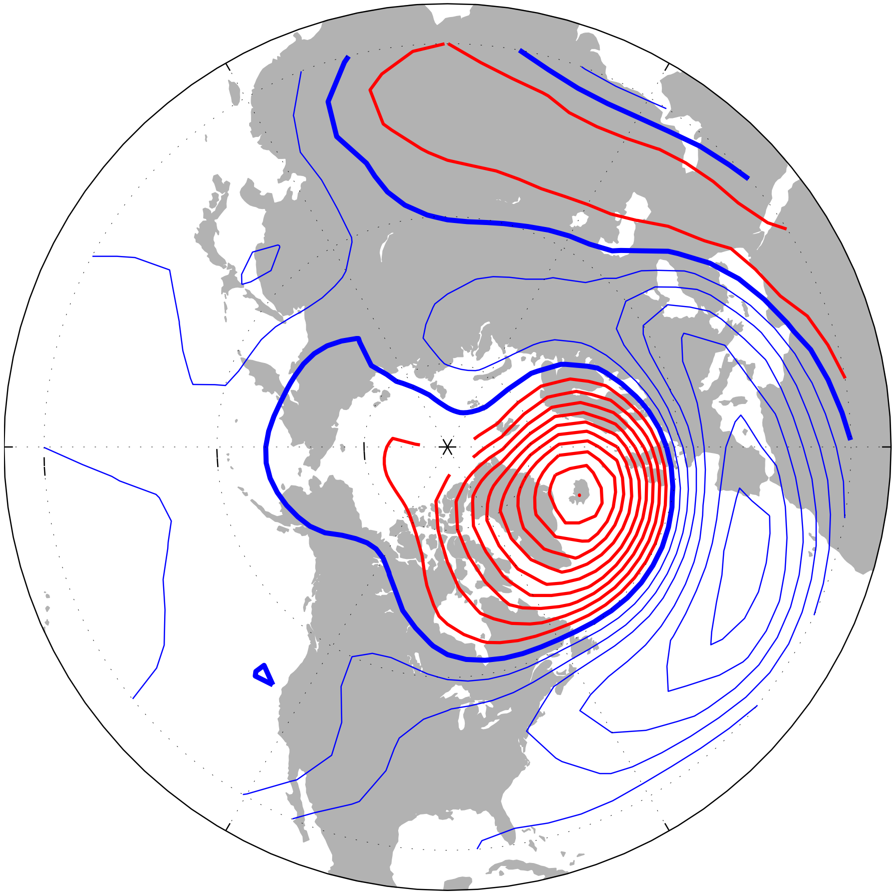

lon: plotted from 0.00 to 357.50
lat: plotted from −90 to 90.00
lev: 500.00
t: Dec 21 2008 06 Z
Individual Obs hgt m
NOAA/ESRL Physical Sciences Division
90N
60N
30N
EQ
30S
60S
90S
0
60E
120E
180
120W
60W
MAX=5892.6
MIN=4860.74
GrADS image
4900
5000
5100
5200
5300
5400
5500
5600
5700
5800

Atmosphere: Large-Scale Teleconnections

Teleconnections: hemispheric-scale structures of atmospheric variability

North Atlantic Oscillation (NAO)

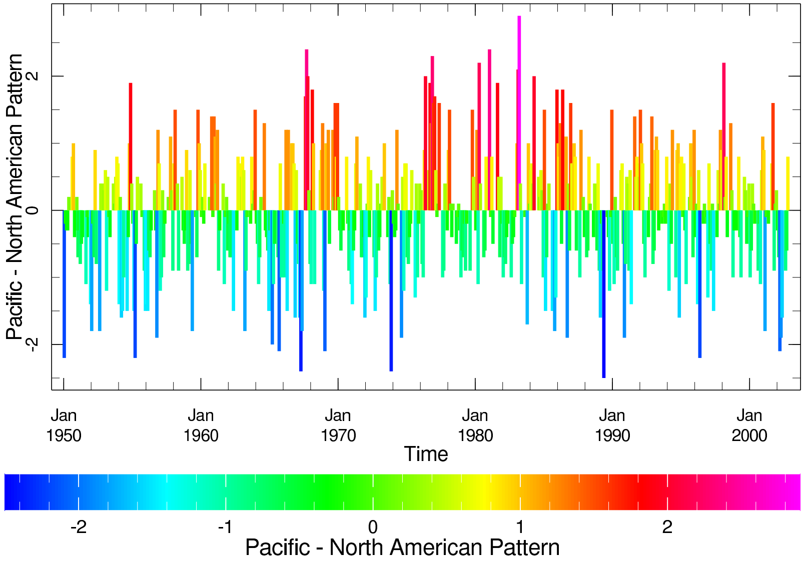



One−Point Correlation Map

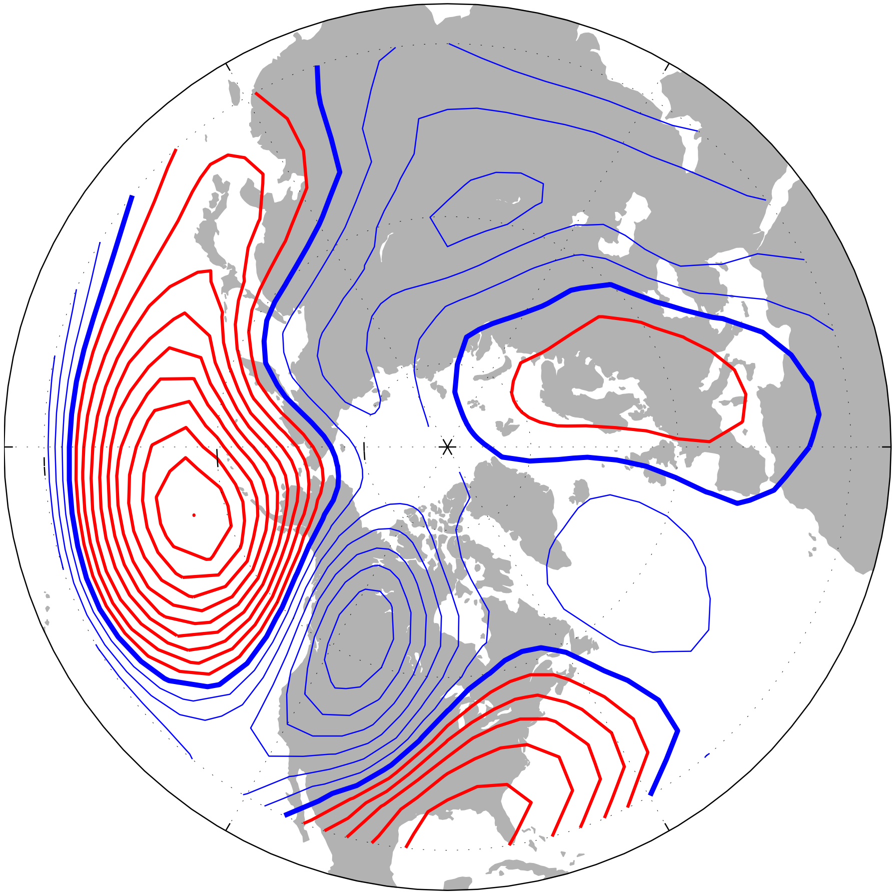
Atmosphere: Large-Scale Teleconnections

Teleconnections: hemispheric-scale structures of atmospheric variability

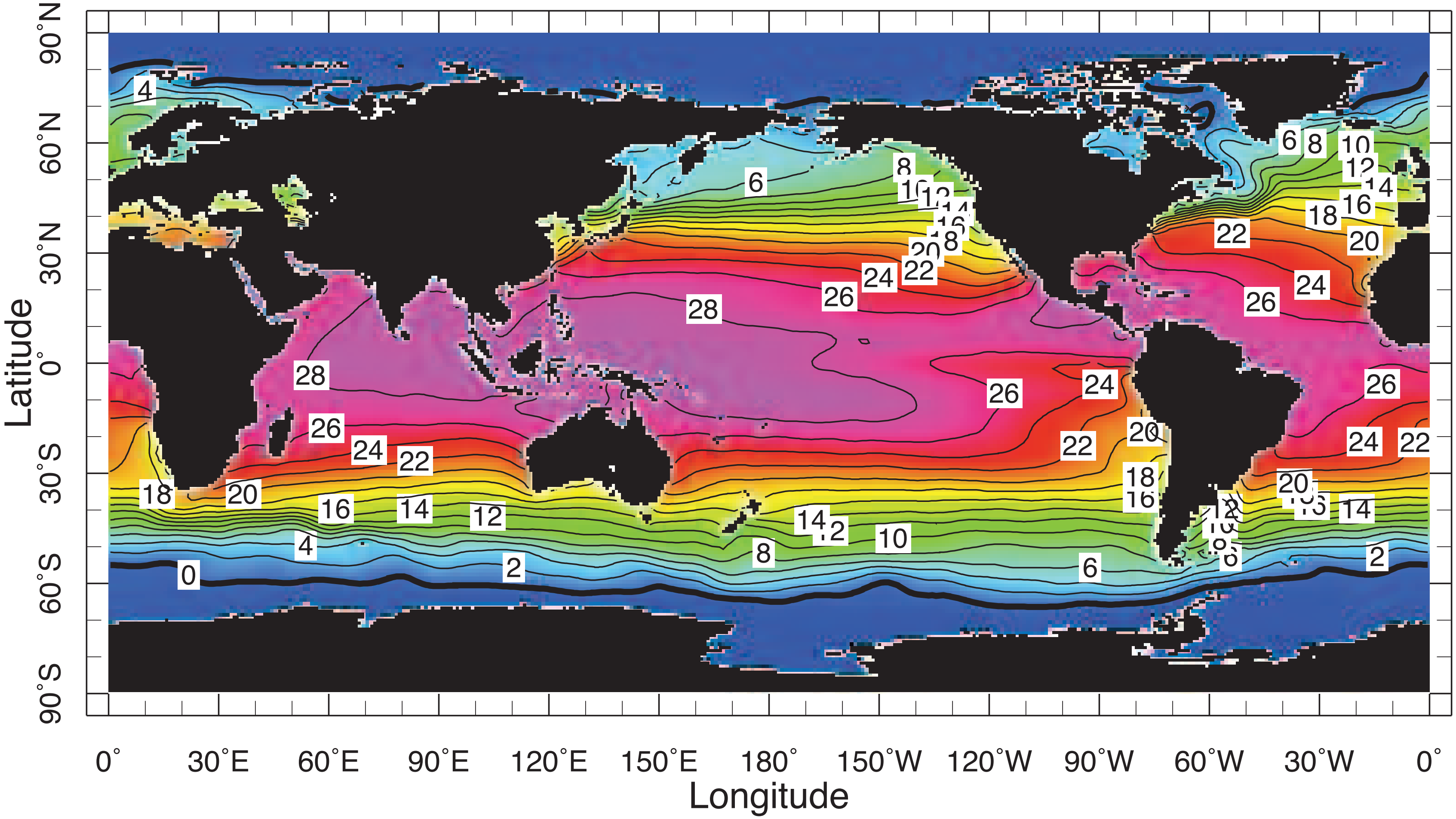
Pacific-North America (PNA) Pattern



One−Point Correlation Map



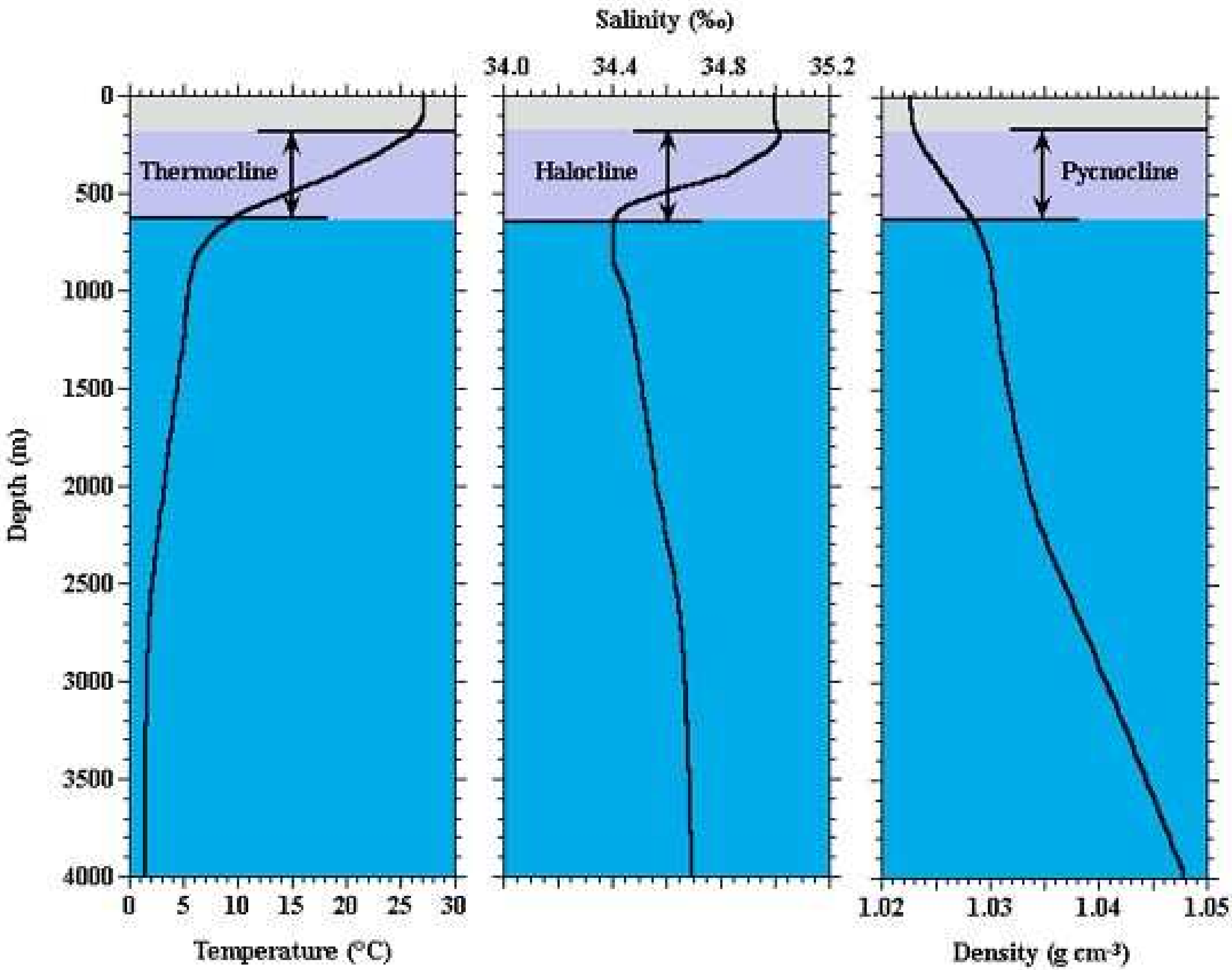
Ocean: Mean Sea Surface Temperature


Latitude
Longitude
90˚N
60˚N
30˚N
0˚
30˚S
60˚S
90˚S
0˚
30˚E
60˚E
90˚E
120˚E
150˚E
180˚
150˚W
120˚W
90˚W
60˚W
30˚W
0˚
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28

0.0 m

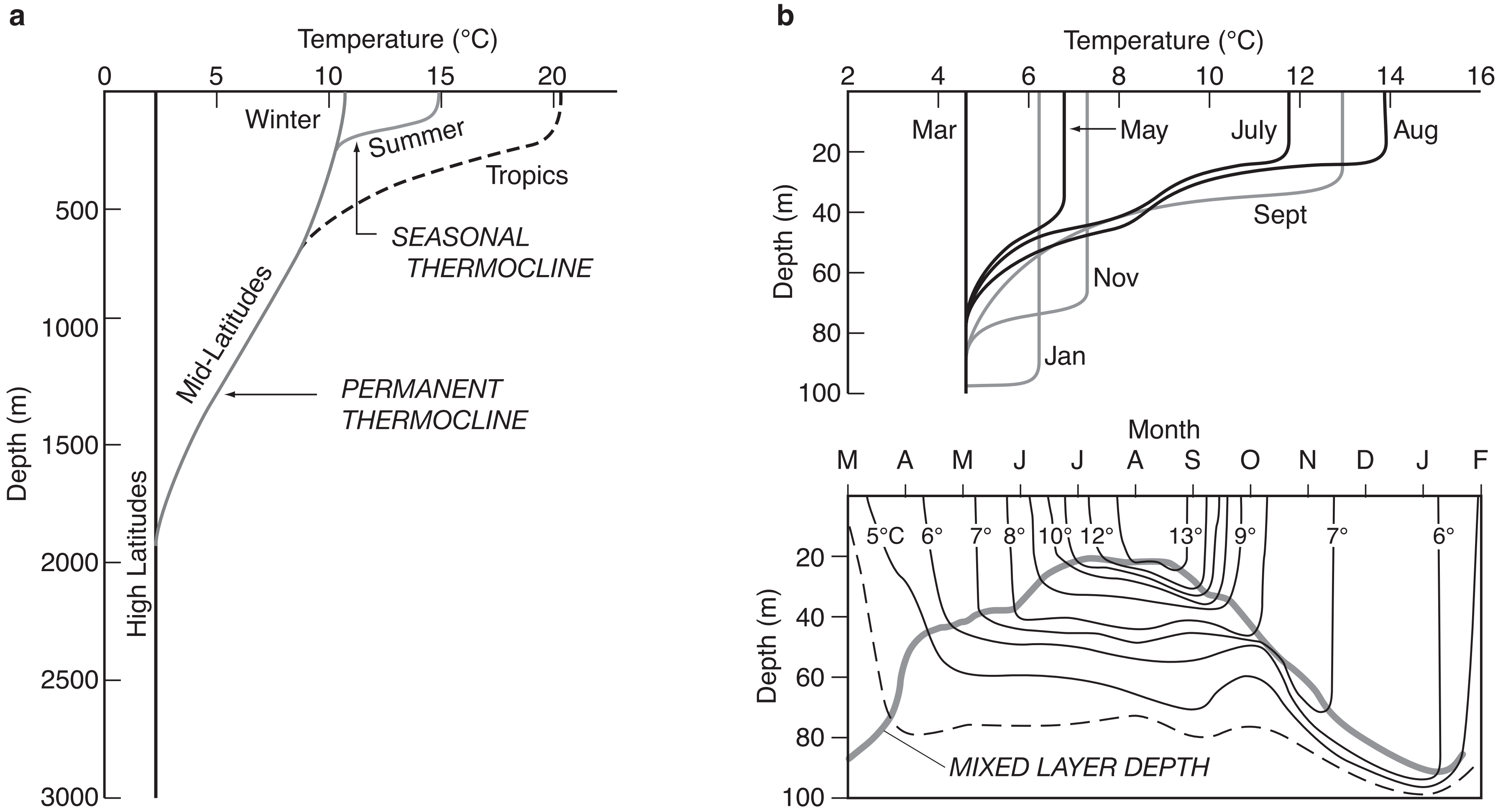
From World Ocean Atlas 2005 http://ingrid.ldeo.columbia.edu

Ocean: Typical Stratification



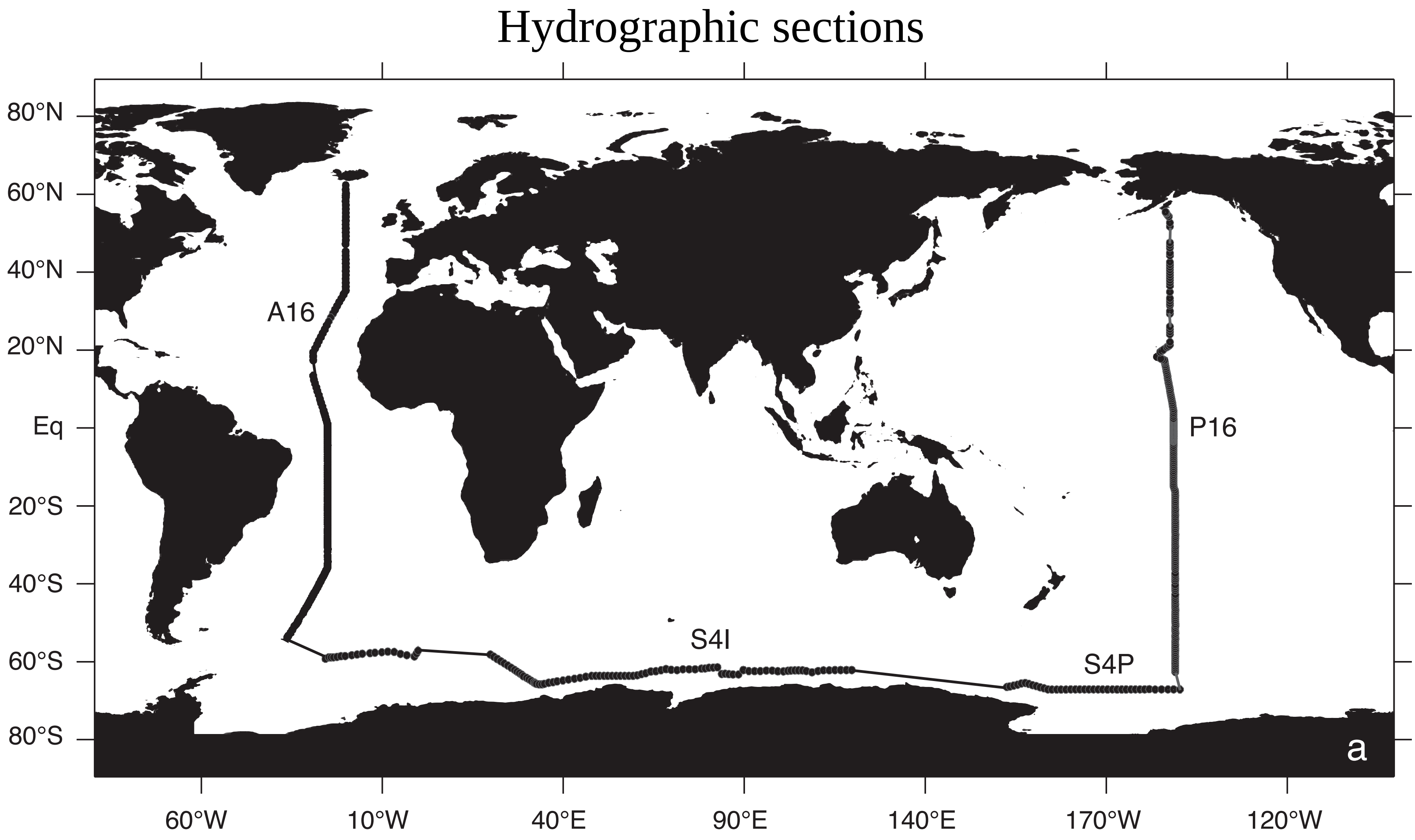
From http://ocp.ldeo.columbia.edu/climatekidscorner/ocean_stratification.jpg

Ocean: Mixed Layer Depth Variability



From Sarmiento & Gruber, Ocean Biogeochemical Dynamics, 2006

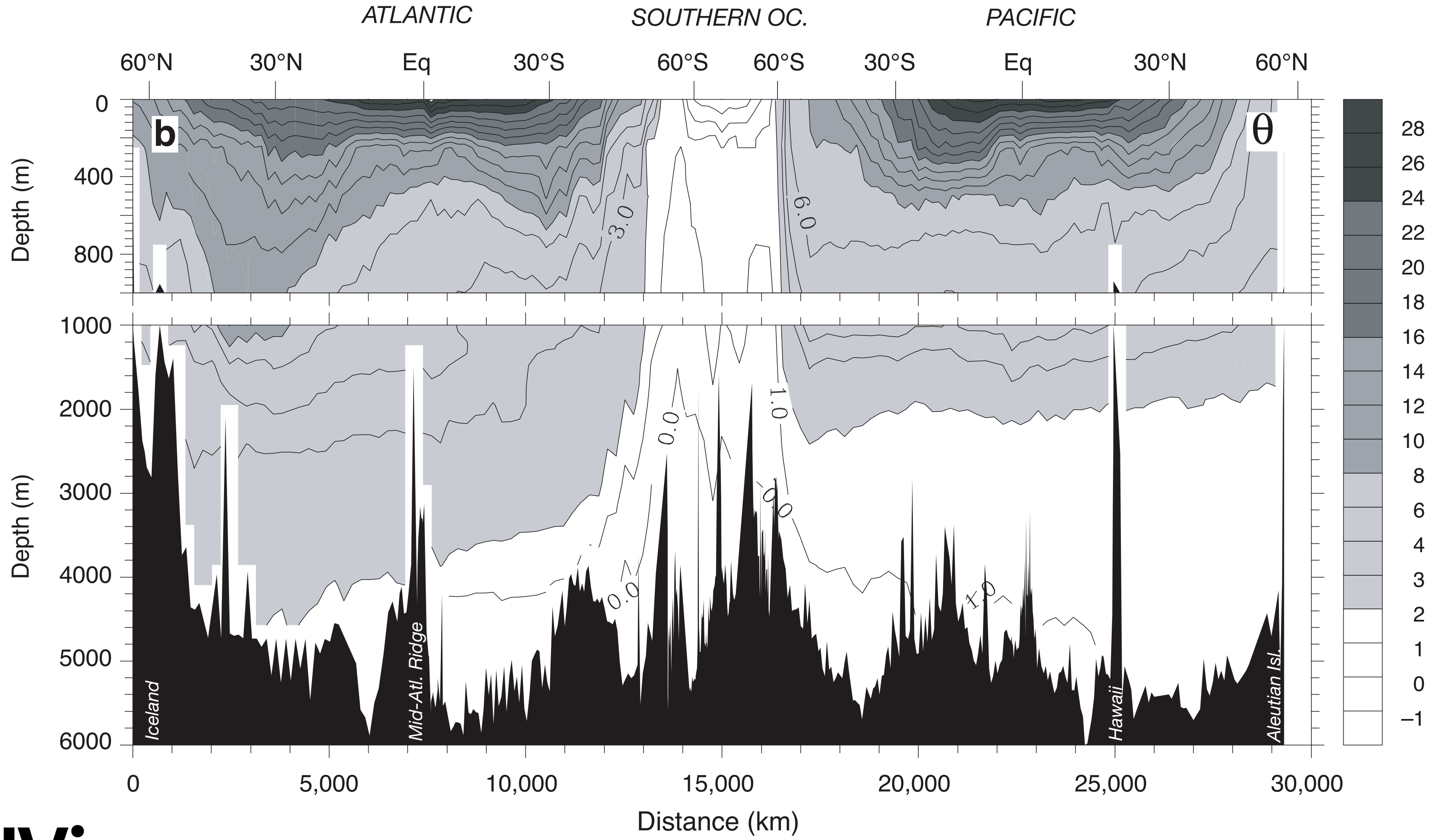
Ocean: Mean Thermal Structure


Hydrographic sections
80°N
60°N
40°N
20°N
Eq
20°S
40°S
60°S
80°S
A16
P16
S4I
S4P
a
60°W
10°W
40°E
90°E
140°E
170°W
120°W

From Sarmiento & Gruber, Ocean Biogeochemical Dynamics, 2006

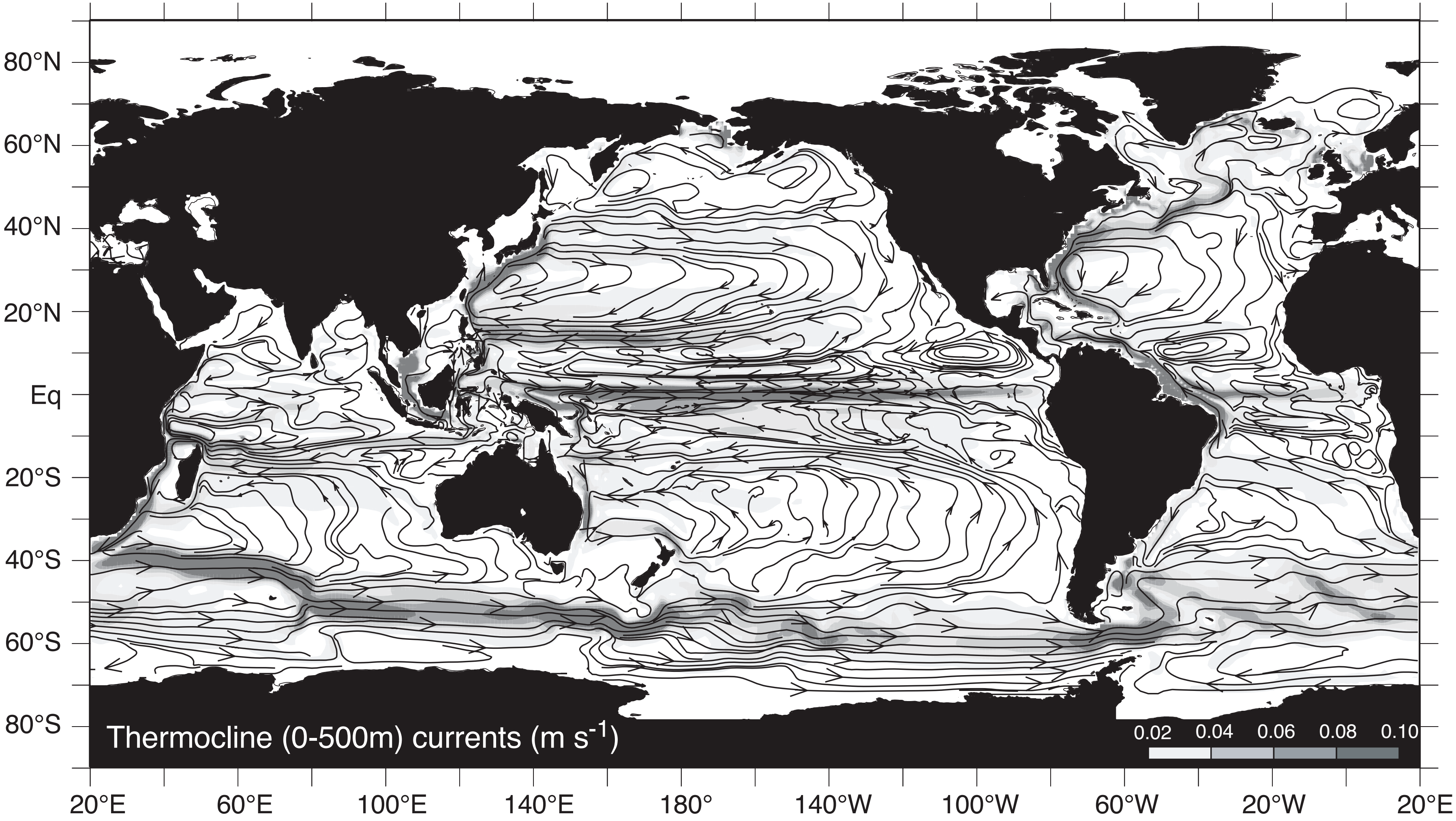
Ocean: Mean Thermal Structure

Potential temperature



From Sarmiento & Gruber, Ocean Biogeochemical Dynamics, 2006

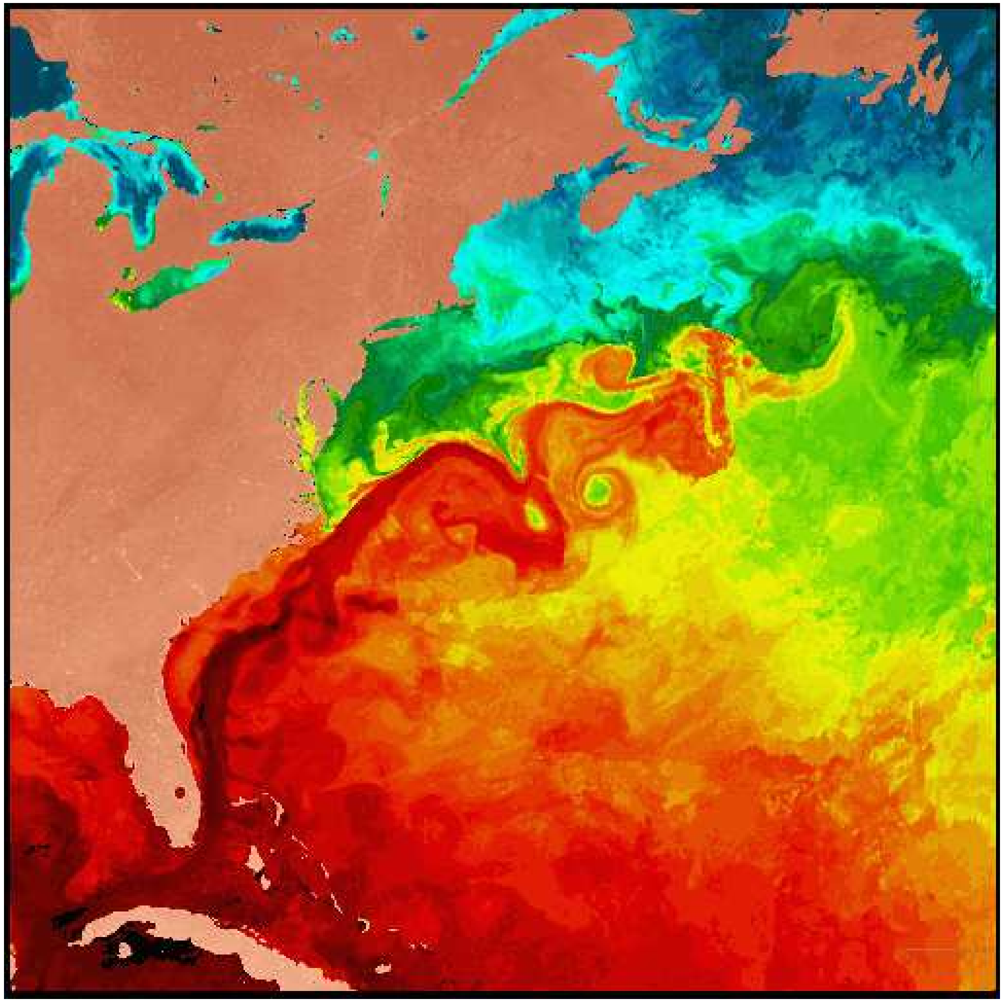
Ocean: Mean Wind-Driven Currents


80°N
60°N
40°N
20°N
Eq
20°S
40°S
60°S
80°S
20°E
60°E
100°E
140°E
180°
140°W
100°W
60°W
20°W
20°E
Thermocline (0-500m) currents (m s^{-1})
0.02
0.04
0.06
0.08
0.10

From Sarmiento & Gruber, Ocean Biogeochemical Dynamics, 2006

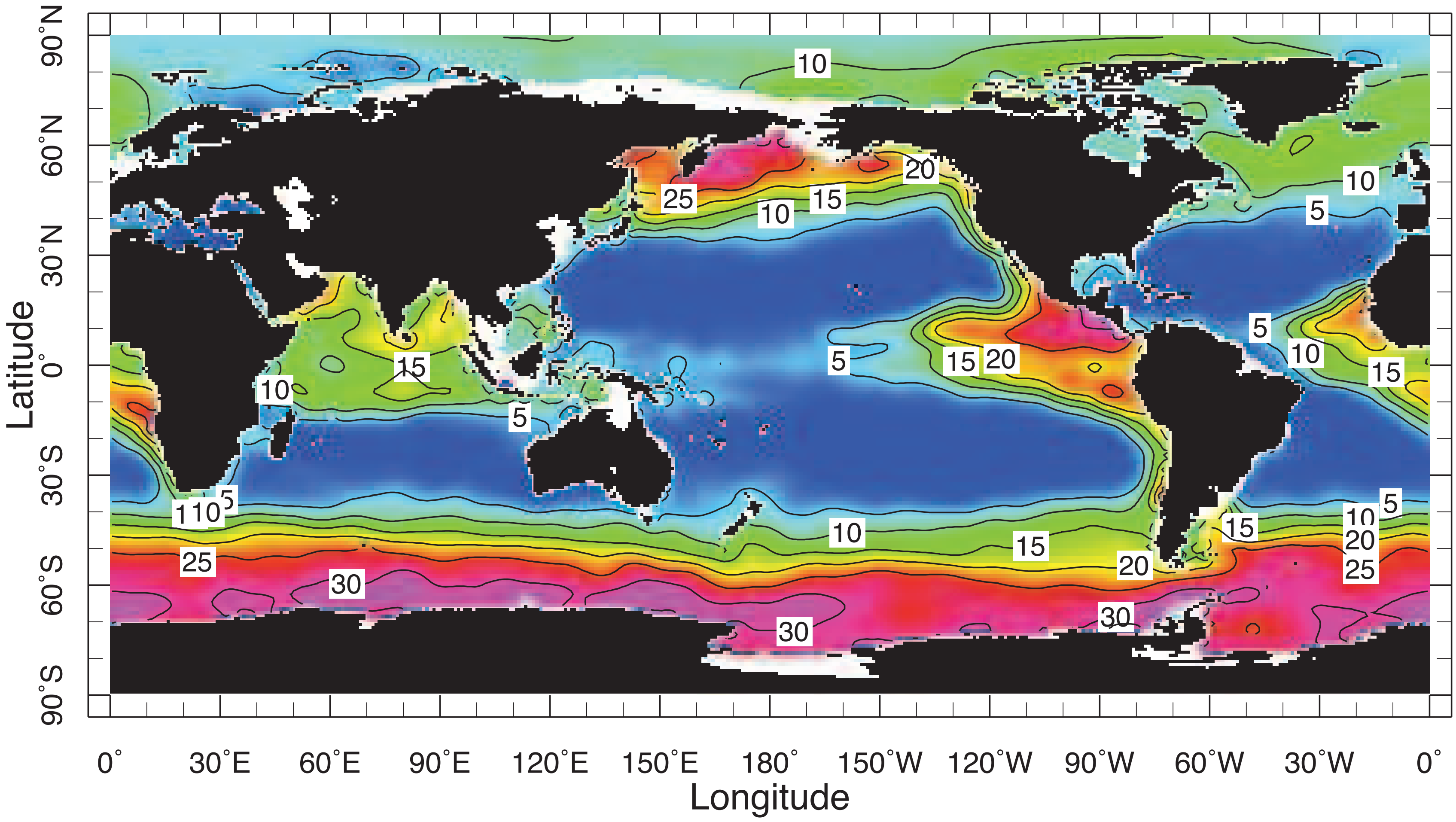
Ocean: Variability in Wind-Driven Currents

False colour SST image showing Gulf Stream eddies



From http://www.knmi.nl

Ocean: Mean 100m Nitrate Concentration


Latitude
90˚N
60˚N
30˚N
0˚
30˚S
60˚S
90˚S
Longitude
0˚
30˚E
60˚E
90˚E
120˚E
150˚E
180˚
150˚W
120˚W
90˚W
60˚W
30˚W
0˚
10
20
25
10
15
10
5
15
10
5
5
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10
20
25
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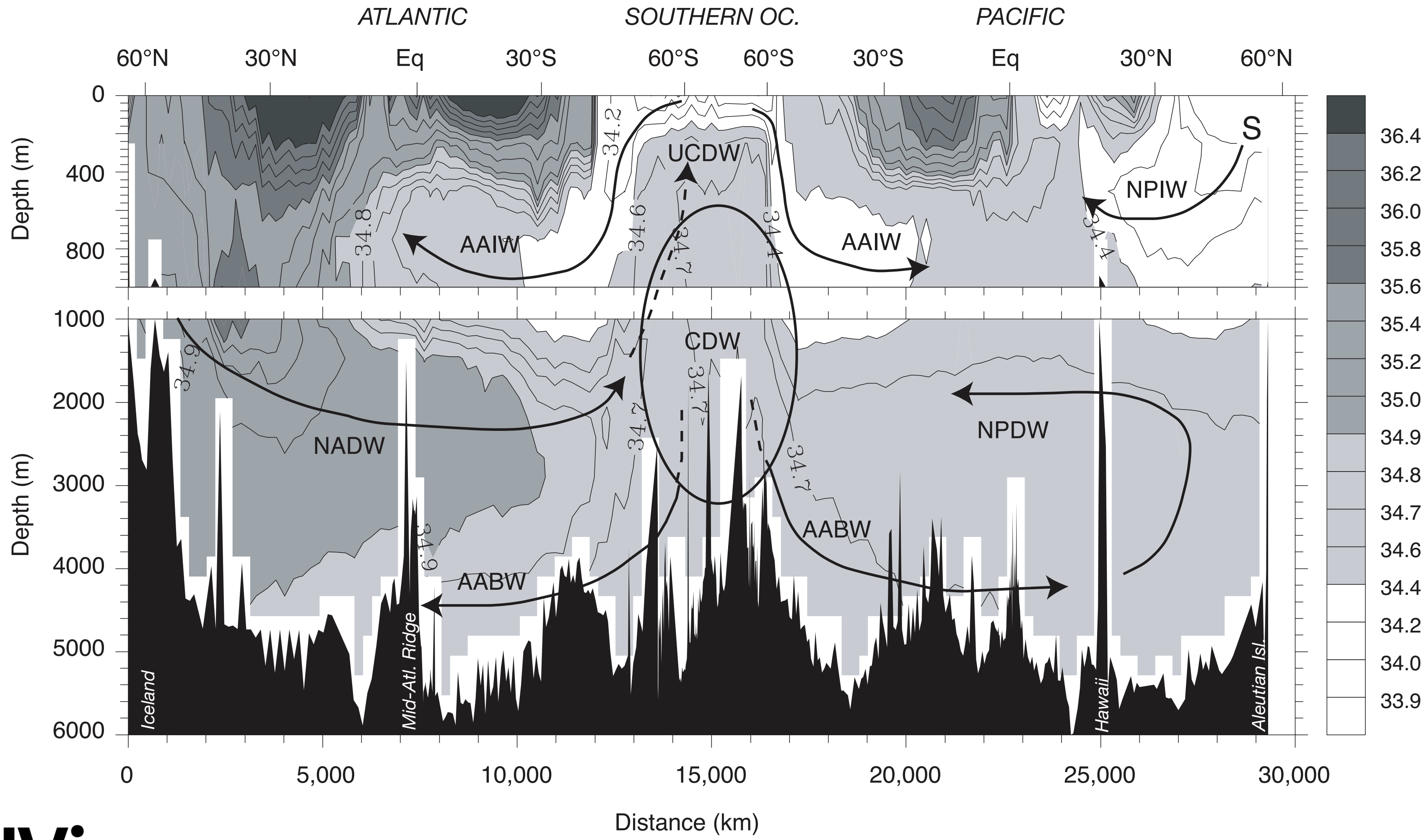
30

100. m

From World Ocean Atlas 2005 http://ingrid.ldeo.columbia.edu

Ocean: Deep Circulation

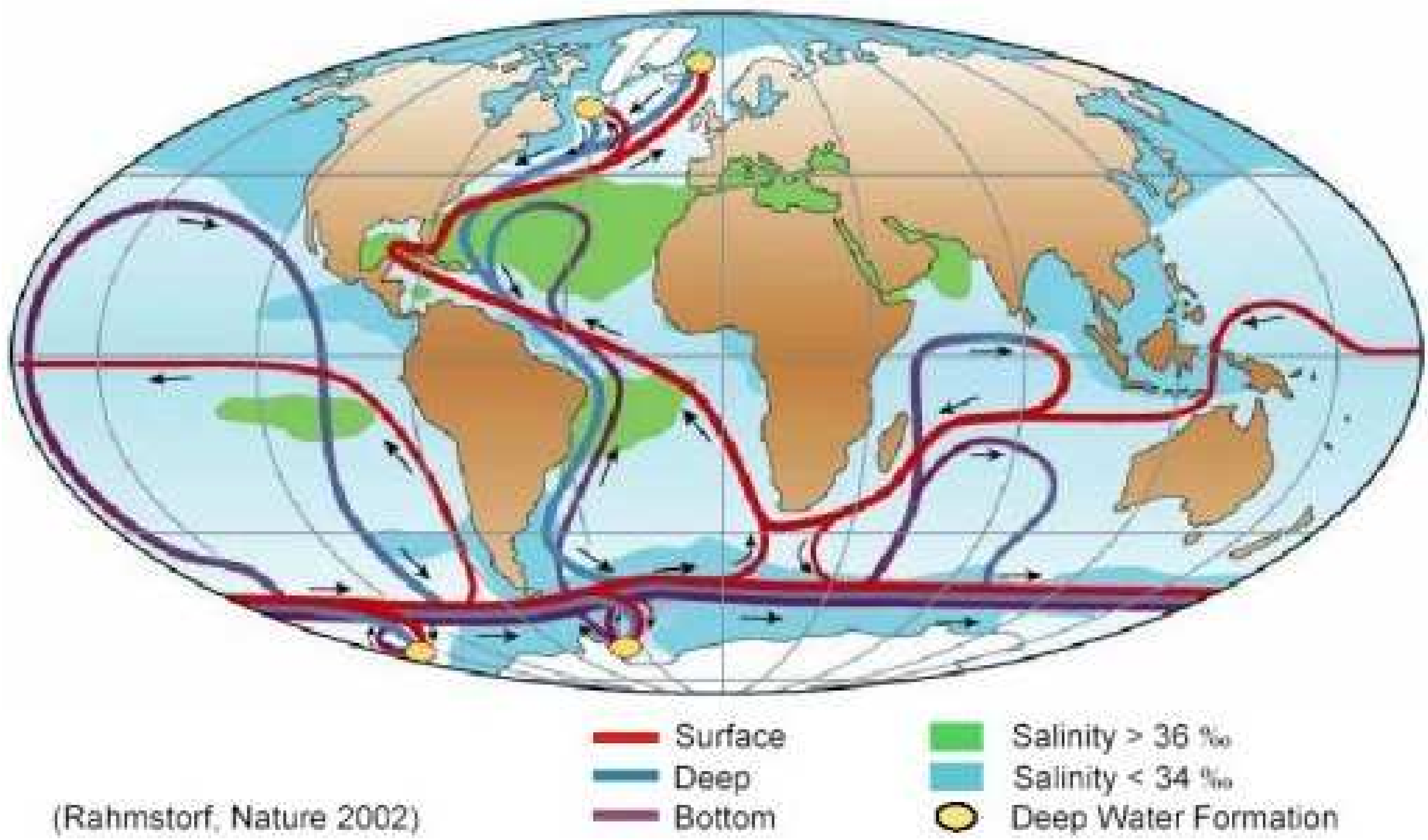
Density distribution and water mass formation



From Sarmiento & Gruber, Ocean Biogeochemical Dynamics, 2006

Ocean: Deep Circulation

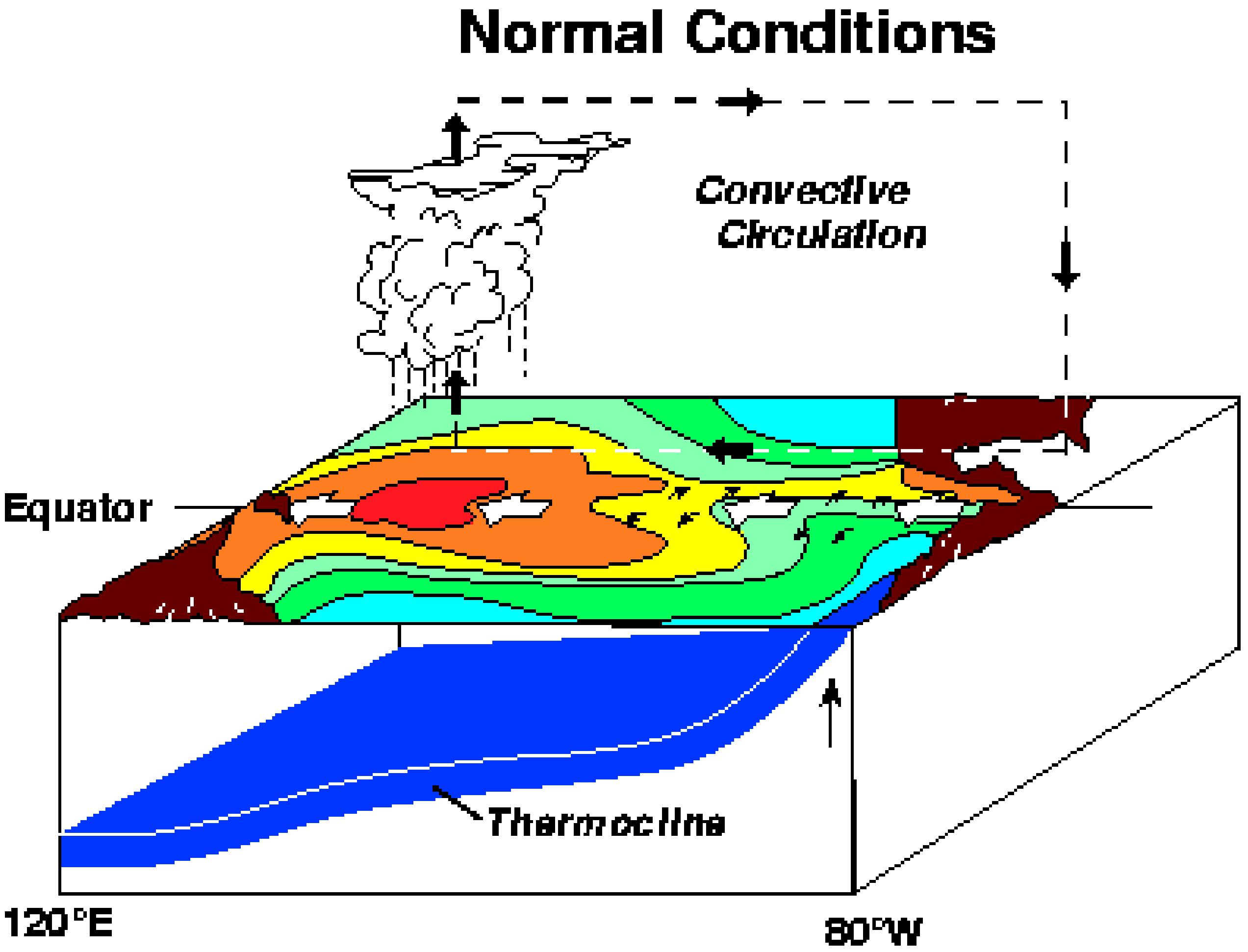
Thermohaline circulation “conveyor belt"


Surface
Deep
Bottom
Salinity > 36 ‰
Salinity < 34 ‰
Deep Water Formation
(Rahmstorf, Nature 2002)

From Kuhlbrodt et al., *Rev. Geophys.*, 2007

Coupled Atmosphere-Ocean Processes: ENSO

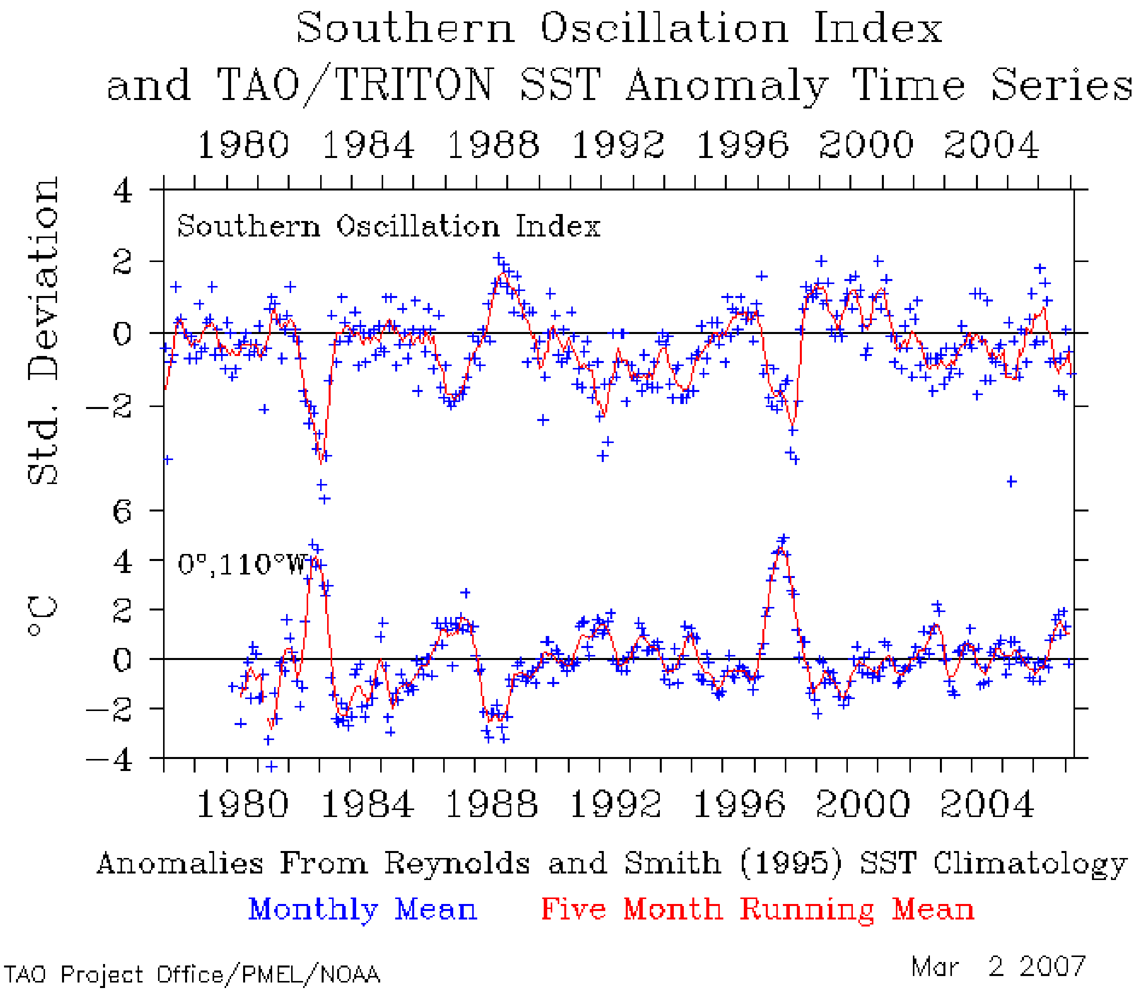
Mean State of Tropical Pacific


Normal Conditions
Convective Circulation
Equator
Thermocline
120°E
80°W

From http://www.pmel.noaa.gov/tao/elnino/nino-home.html

Coupled Atmosphere-Ocean Processes: ENSO

Tropical Pacific variability: Southern Oscillation Index & Nino 3.4 Index



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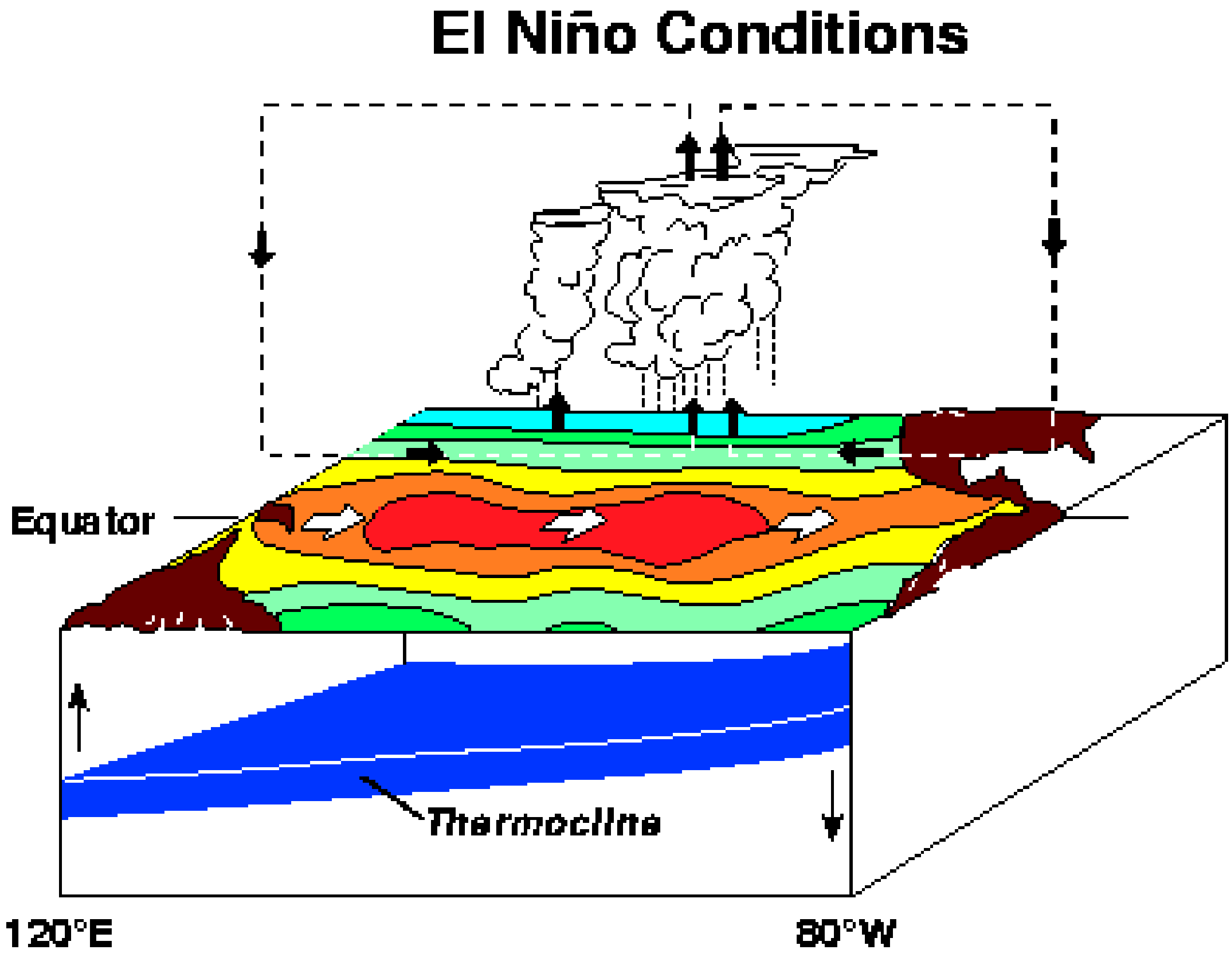
Coupled Atmosphere-Ocean Processes: ENSO

El Niño State


El Niño Conditions
Equator
Thermocline
120°E
80°W

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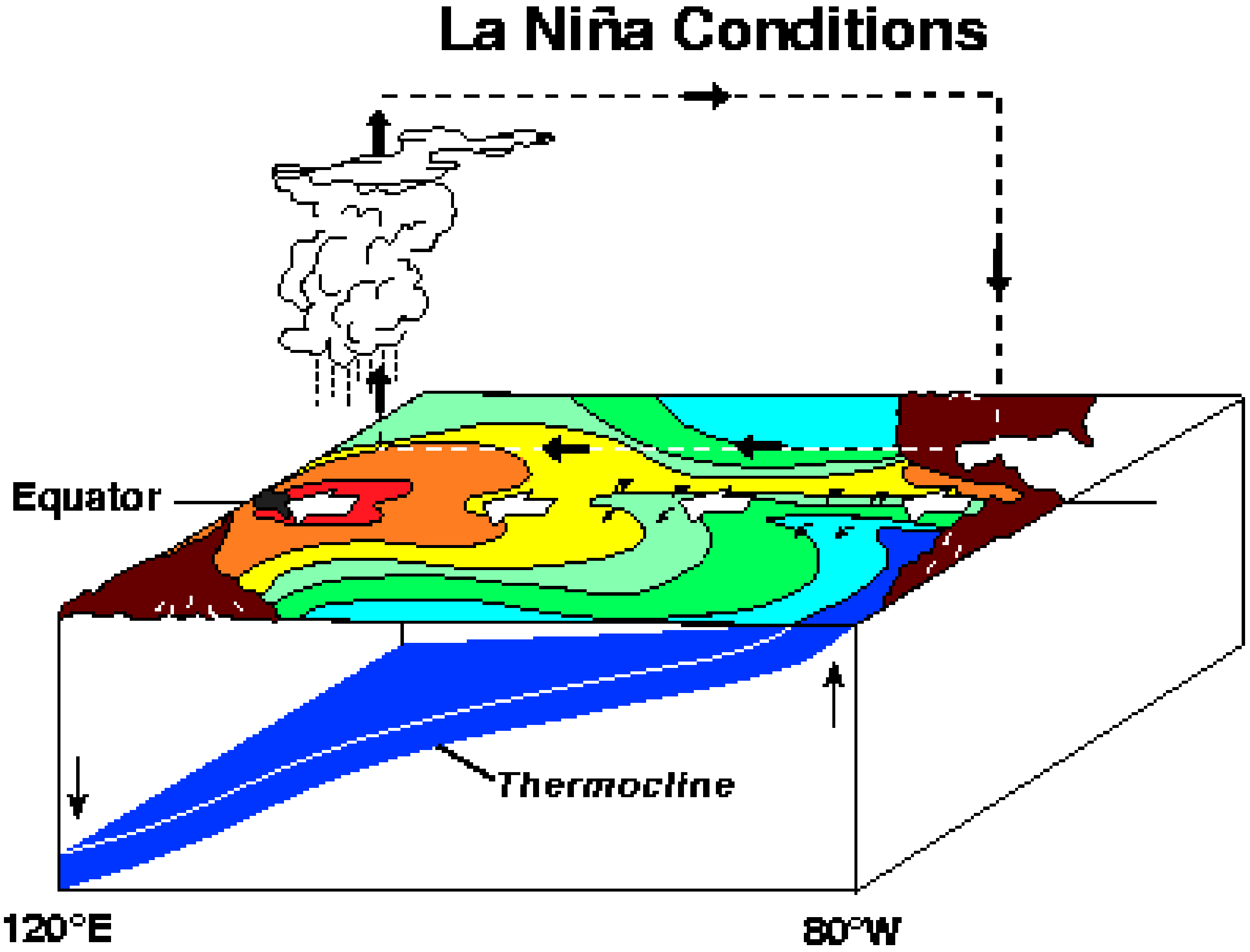
Coupled Atmosphere-Ocean Processes: ENSO

La Niña State


La Niña Conditions
Equator
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From http://www.pmel.noaa.gov/tao/elnino/nino-home.html

The Rest of the Climate System

- Atmosphere and ocean only two parts of coupled climate system

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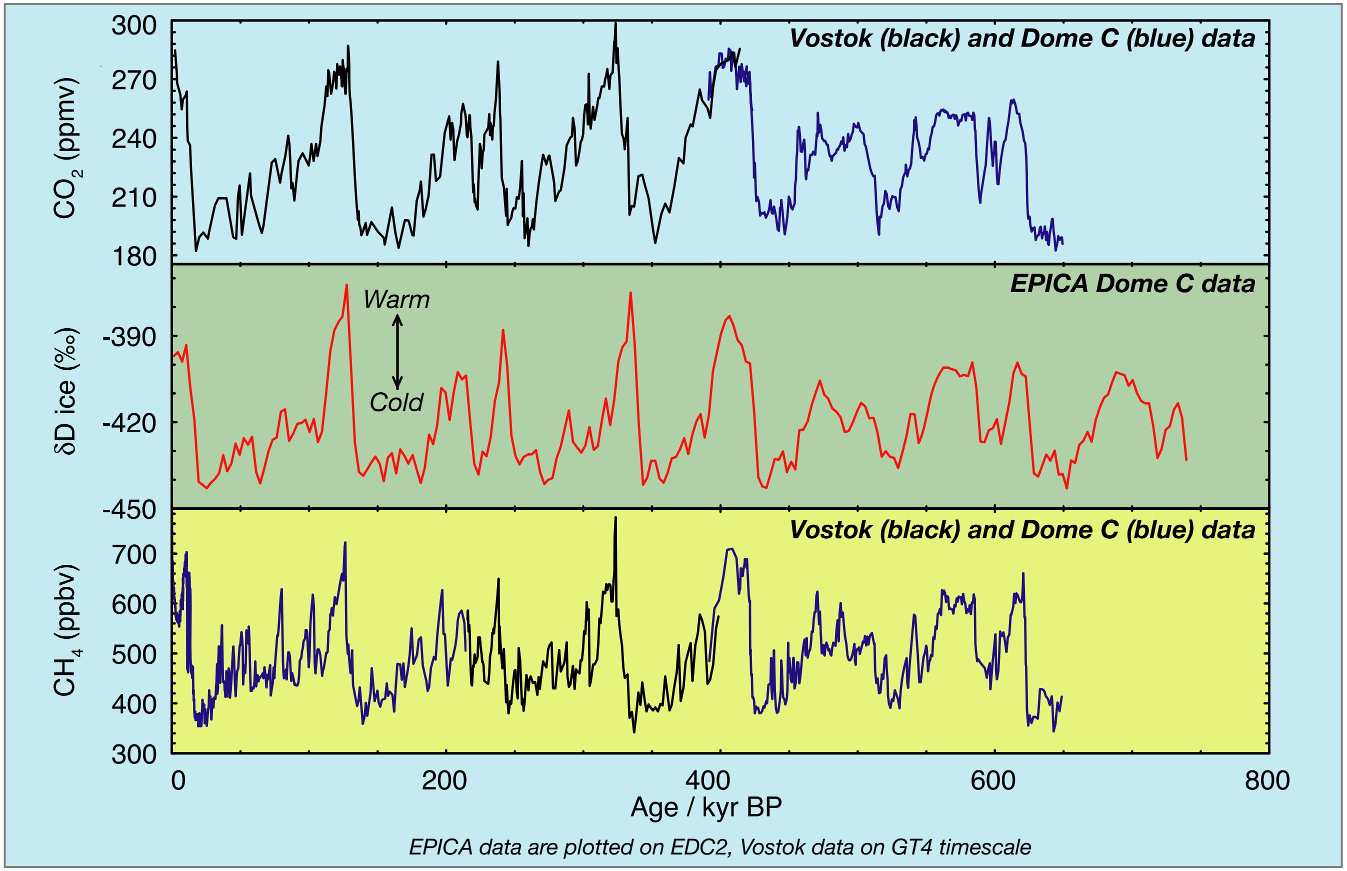
- Comprehensive studies of the system try to take all of these into account

Climate Change

Ice core records: atmospheric composition and temperature

Antarctic ice core records: Vostok and EPICA CO_2, CH_4 and δD

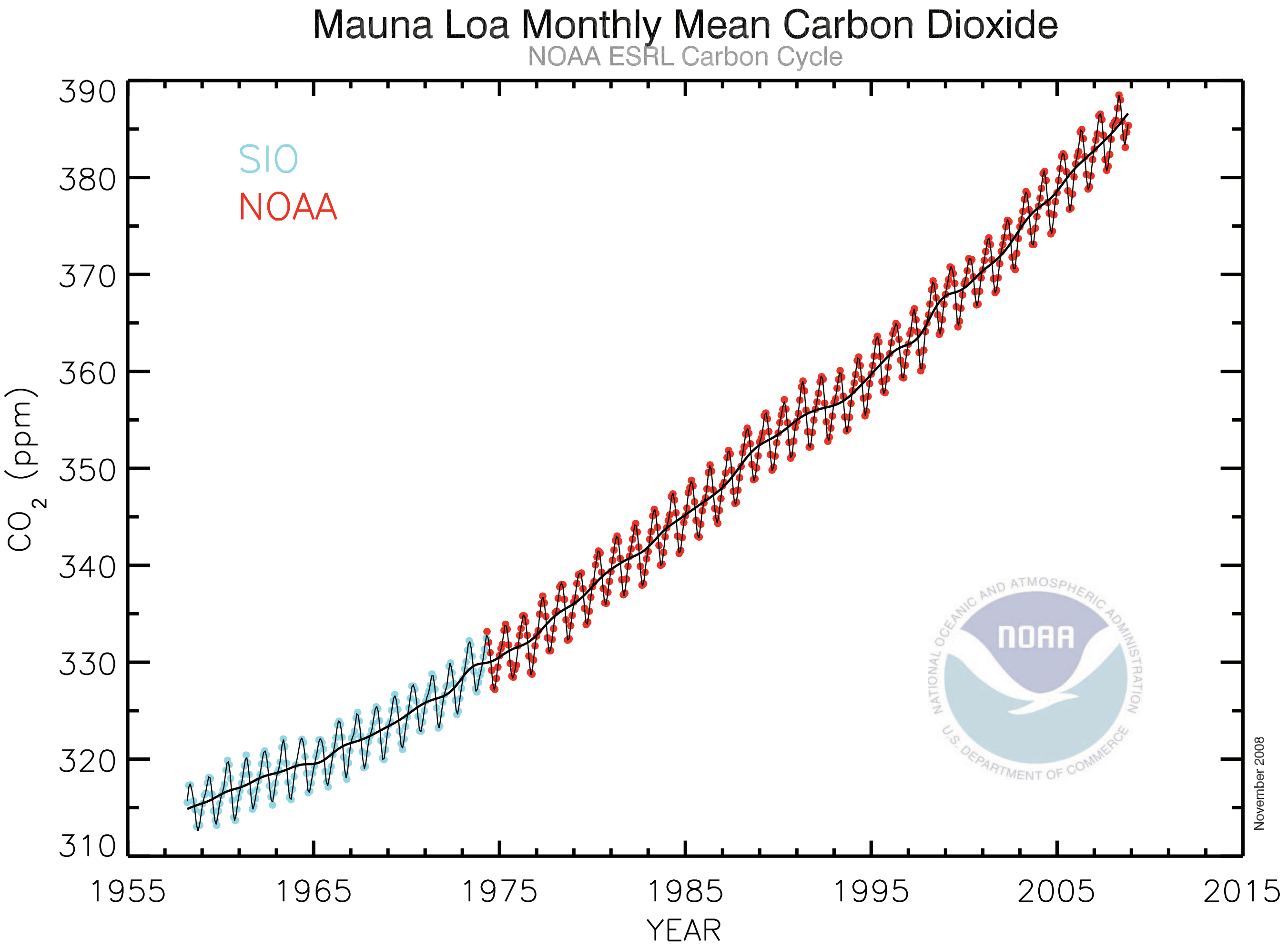


EPICA data are plotted on EDC2, Vostok data on GT4 timescale

Petit et al., 1999 (Vostok), Siegenthaler et al., 2005 (Dome C - CO_2),
Spahni et al., 2005 (Dome C - CH_4), EPICA community members, 2004 (δD)

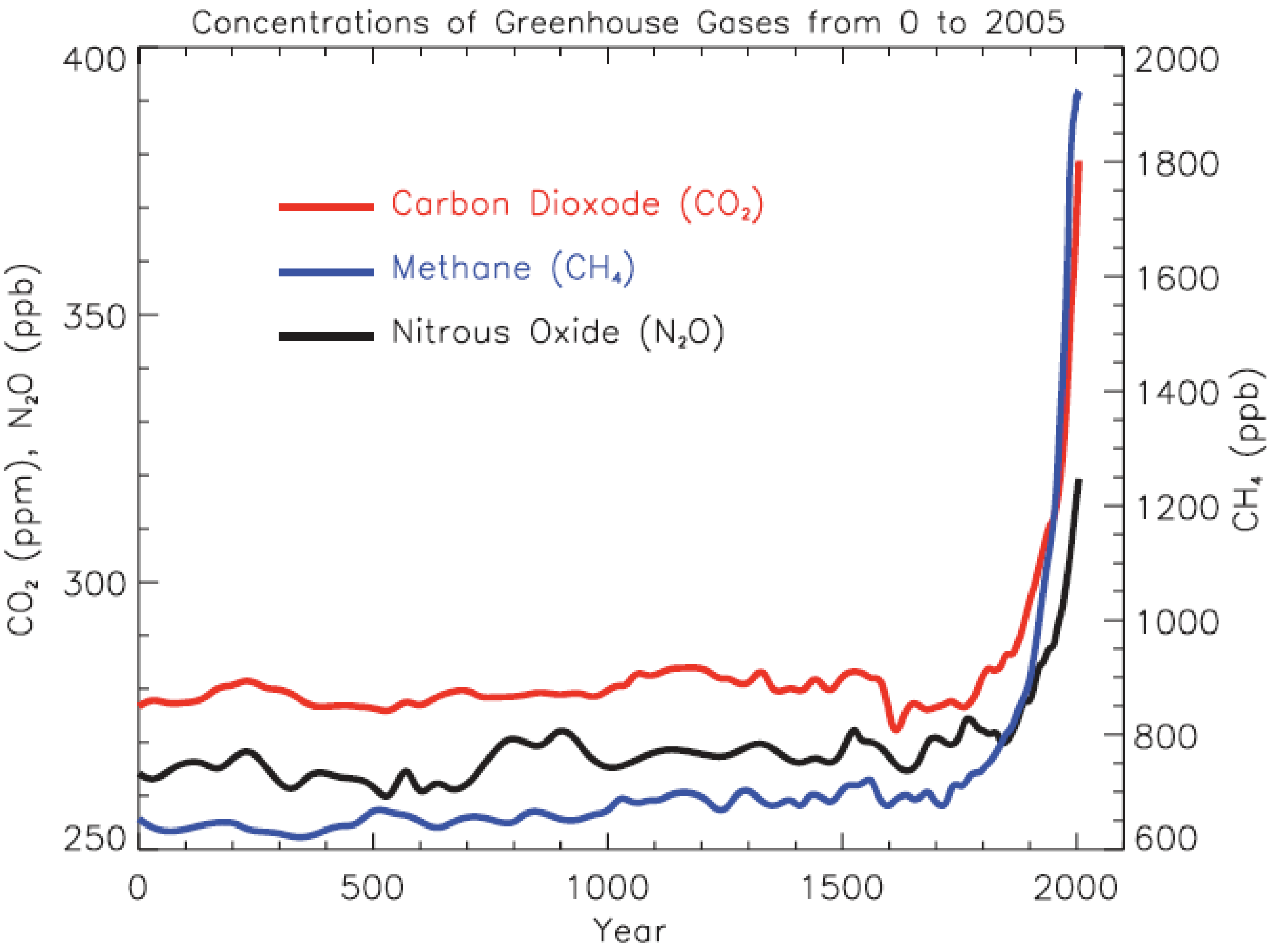
Climate Change

Mauna Loa CO_2 Record (the “Keeling Curve")



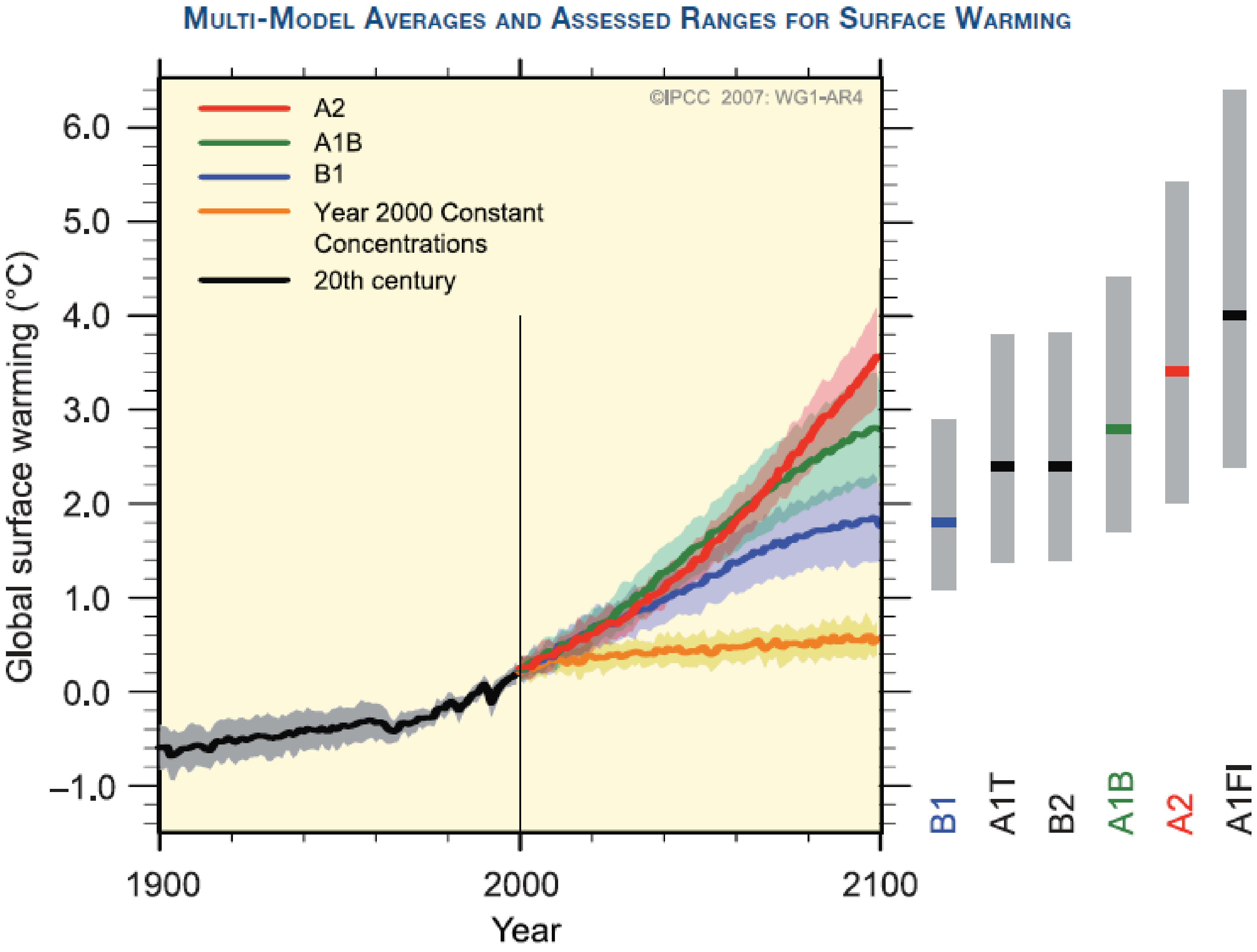
Atmospheric carbon dioxide monthly mean mixing ratios. Data prior to May 1974 are from the Scripps Institution of Oceanography (SIO, blue), data since May 1974 are from the National Oceanic and Atmospheric Administration (NOAA, red). A long-term trend curve is fitted to the monthly mean values. Contact: Dr. Pieter Tans, NOAA ESRL Carbon Cycle, Boulder, Colorado, (303) 497-6678, pieter.tans@noaa.gov, and Dr. Ralph Keeling, SIO GRD, La Jolla, California, (858) 534-7582, rkeeling@ucsd.edu.

Climate Change



From IPCC AR4 www.ipcc.ch

Climate Change



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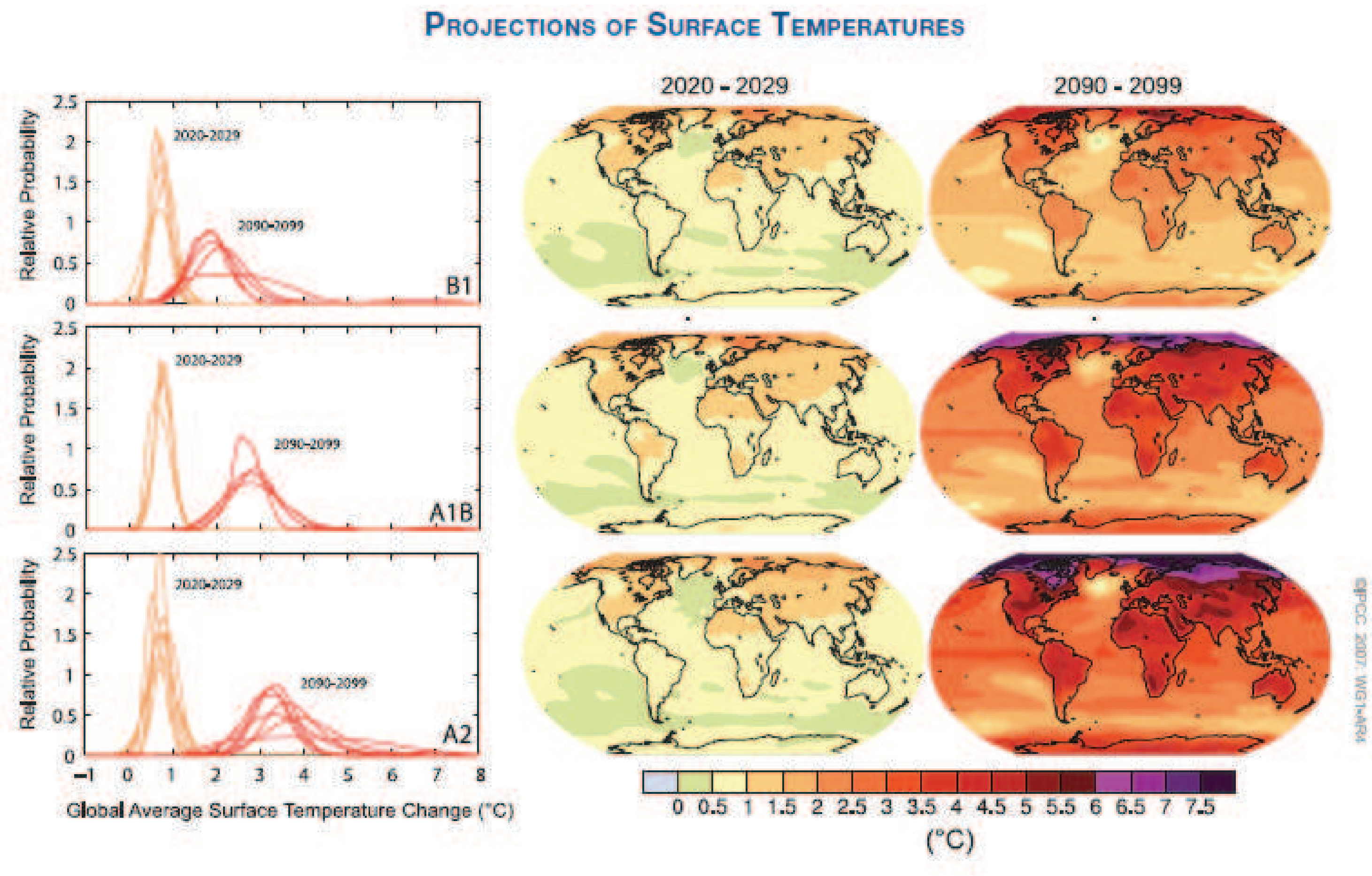
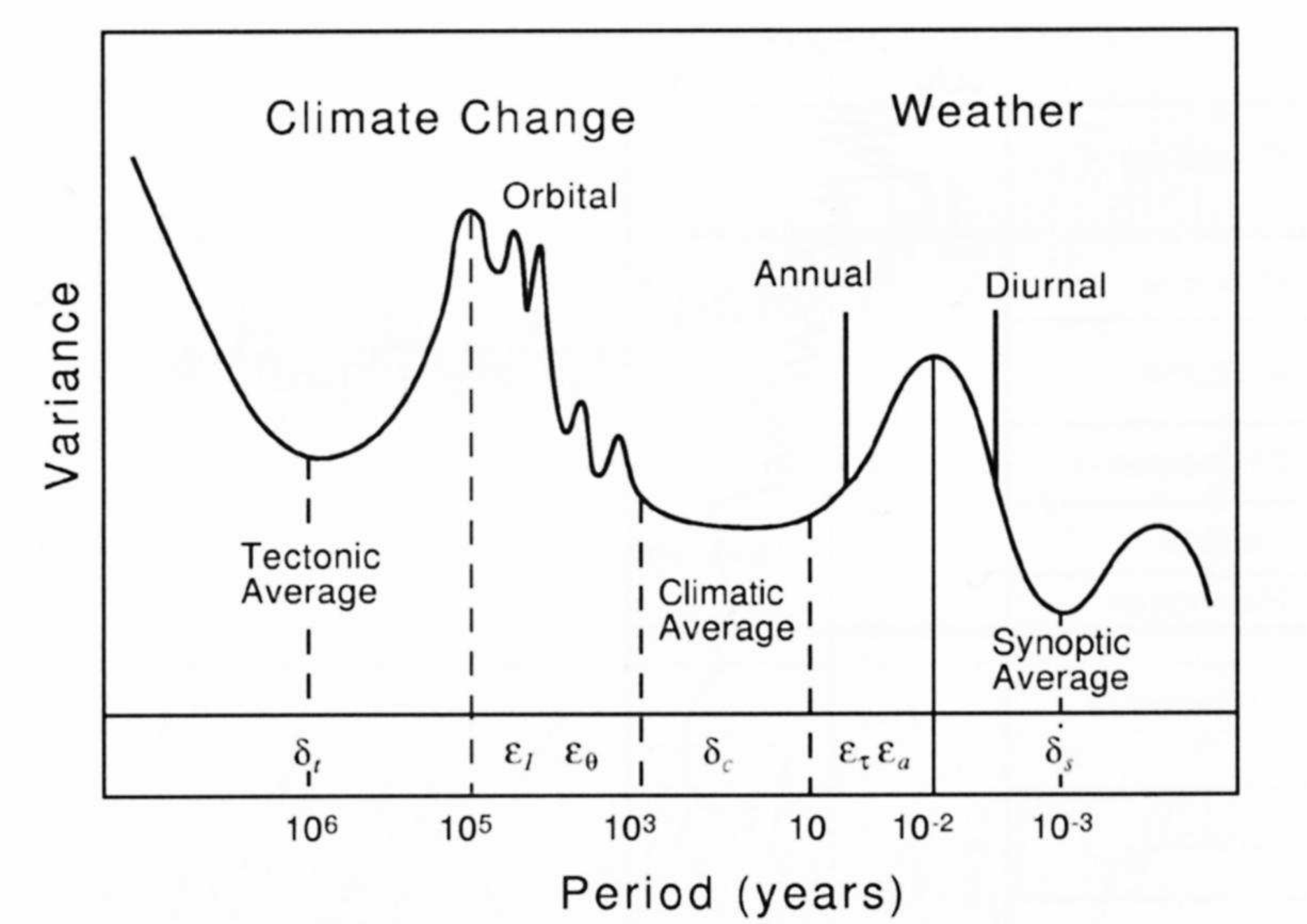


From IPCC AR4 www.ipcc.ch

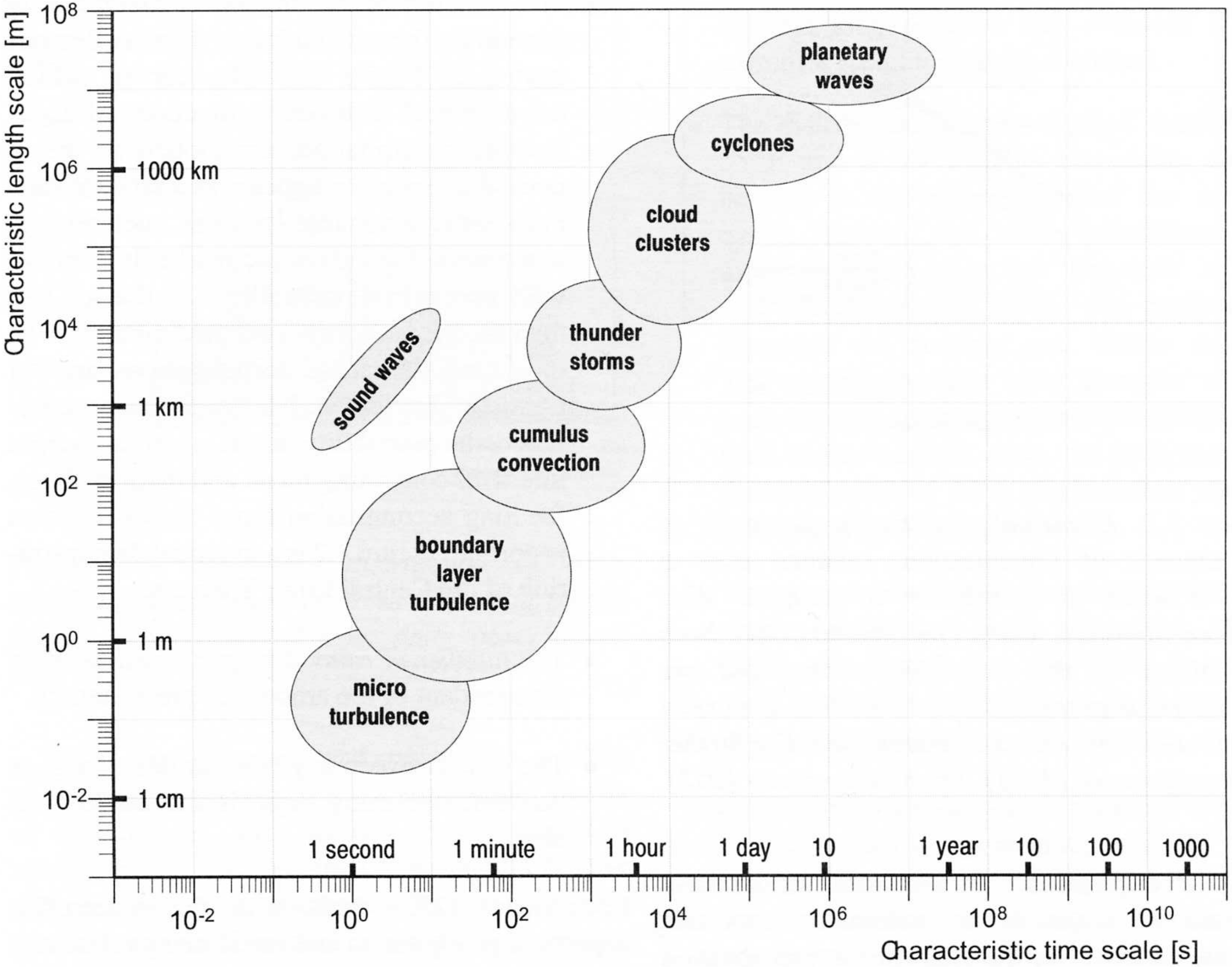
Multiple Scales of Variability

Climate system displays variability over broad range of space and time scales



From Saltzman, 2002

Multiple Scales of Variability



From von Storch and Zwiers, 1999

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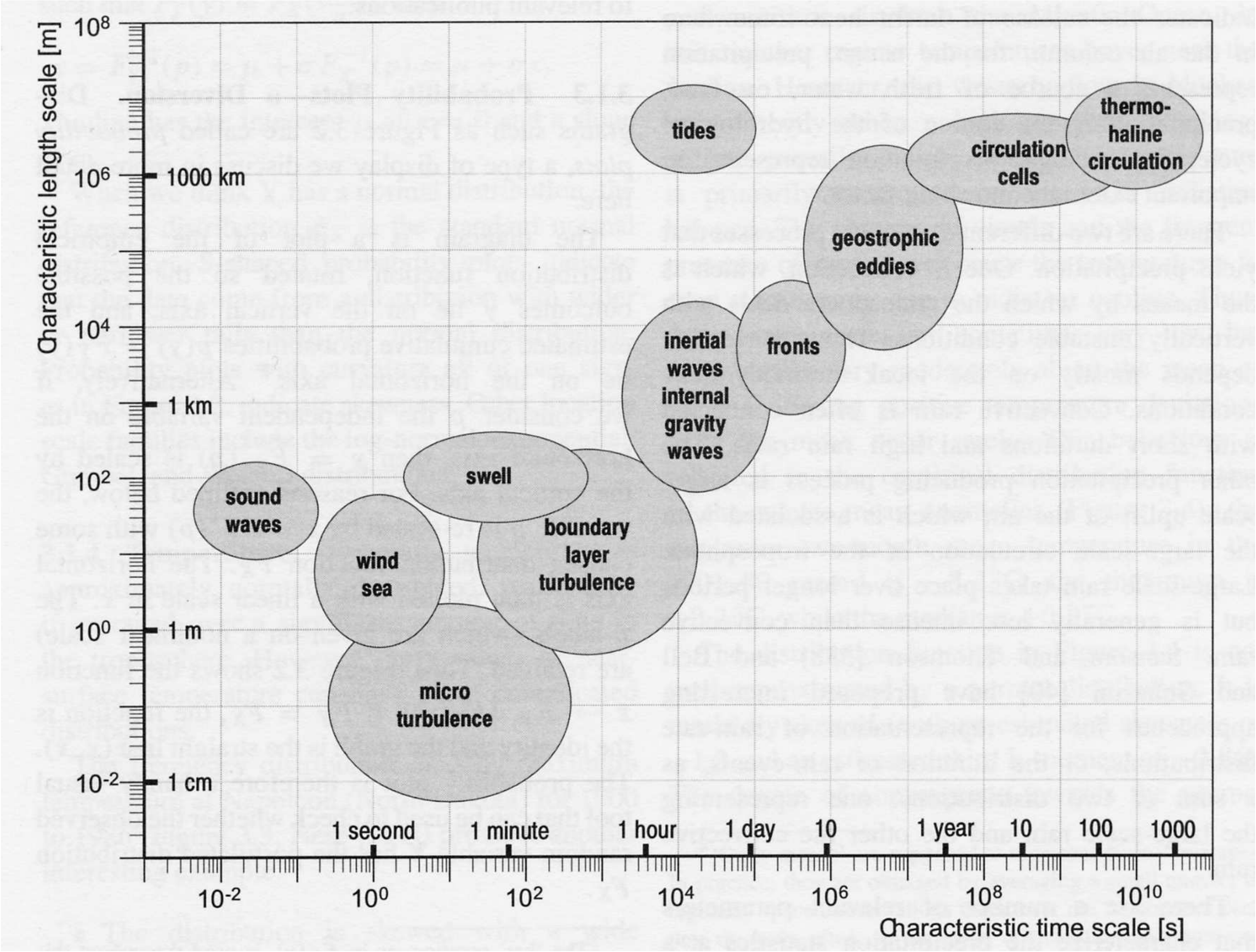

From von Storch and Zwiers, 1999

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  - predictability
    [evolution of trajectory (“weather prediction”) **and** response of measure to forcing (“climate prediction”)]

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- A fundamental complication of the weather-climate connection is that **variability is coupled across scales**: fast weather influences the climate, and slow climate modulates the weather