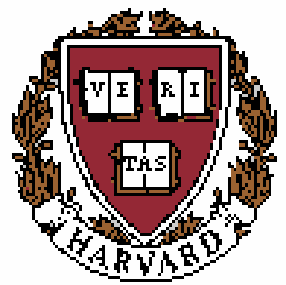
Ocean Dynamics and Climate Dynamics



Allan R. Robinson

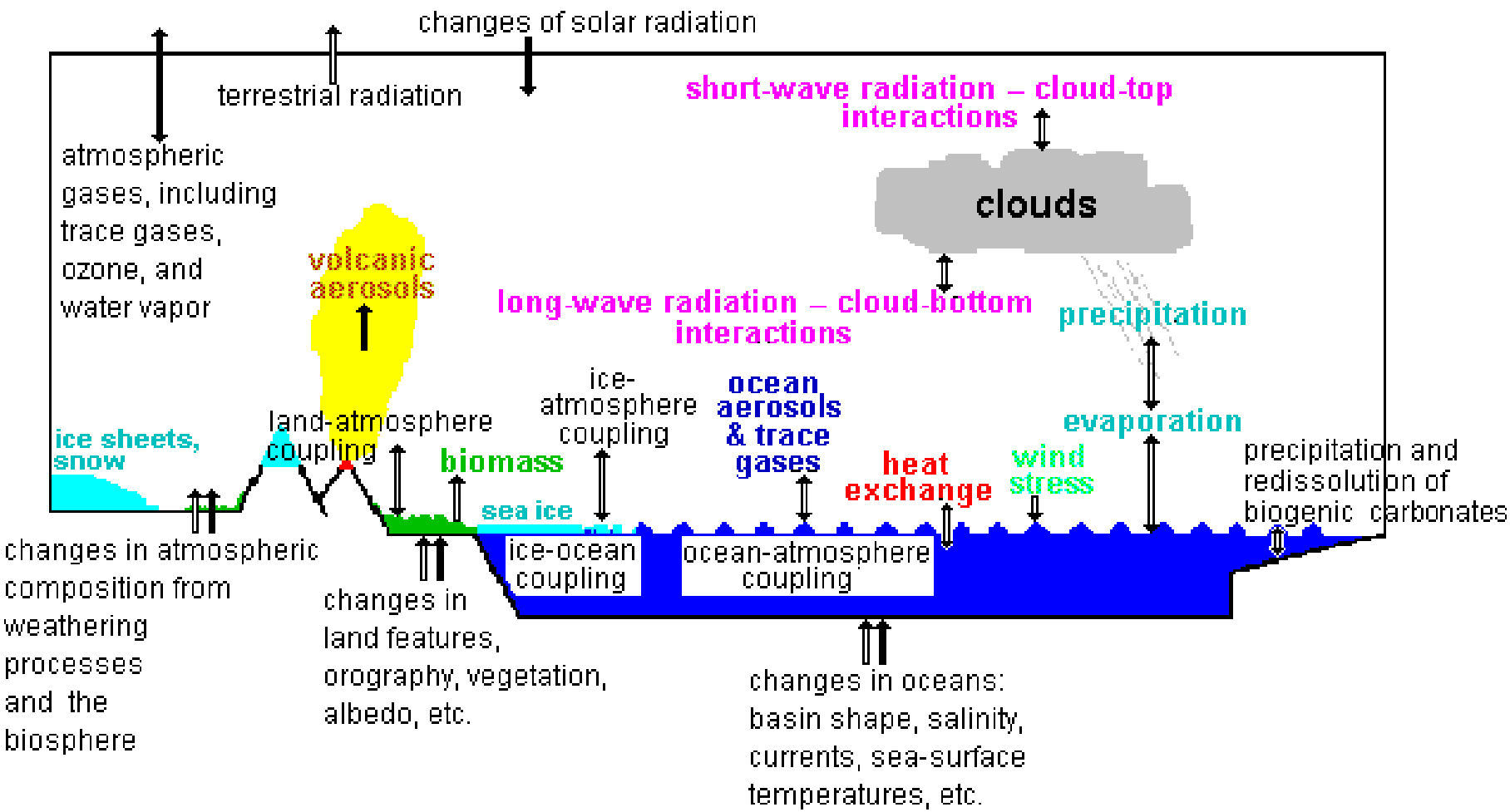
Division of Engineering and Applied Sciences

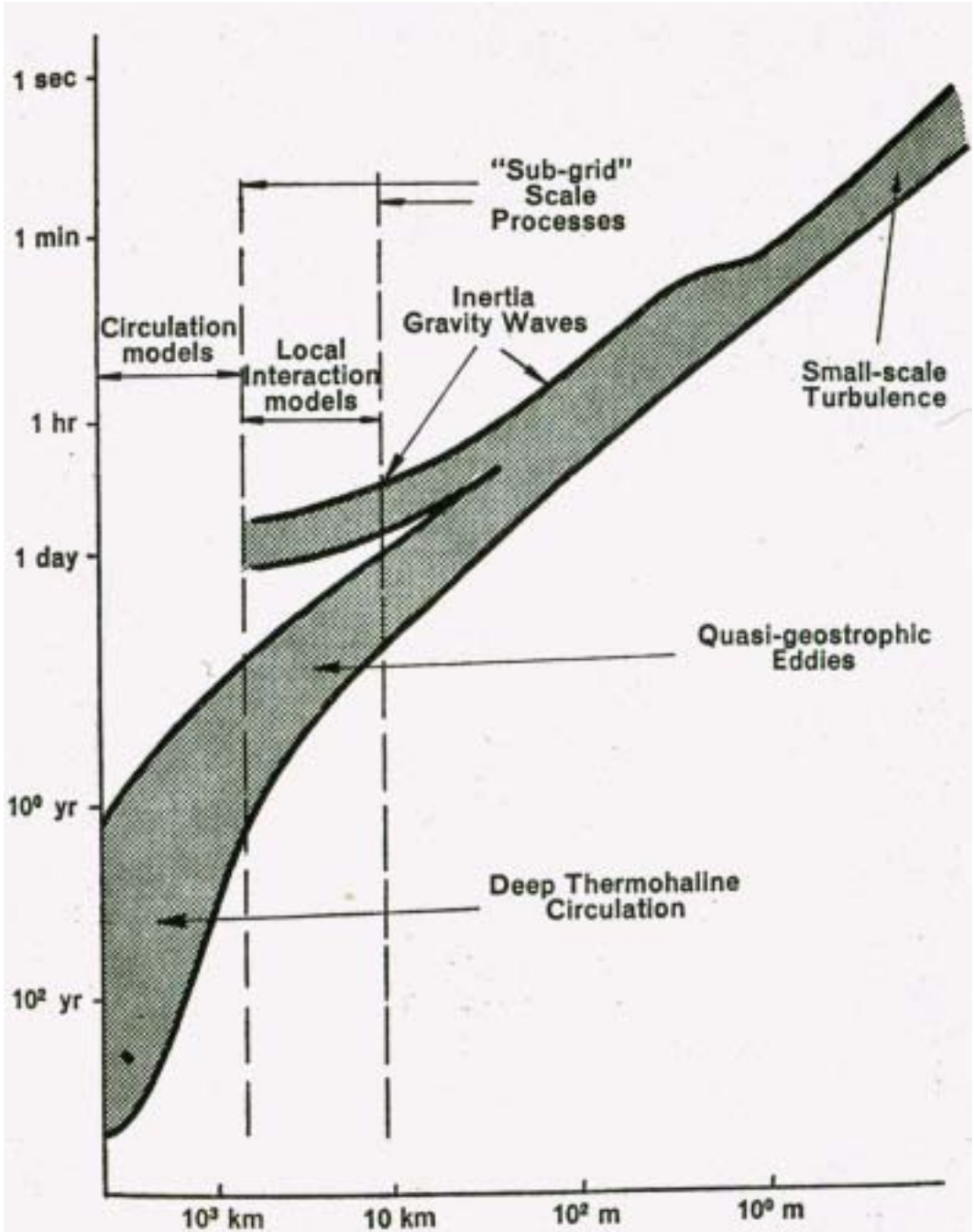
Department of Earth and Planetary Sciences

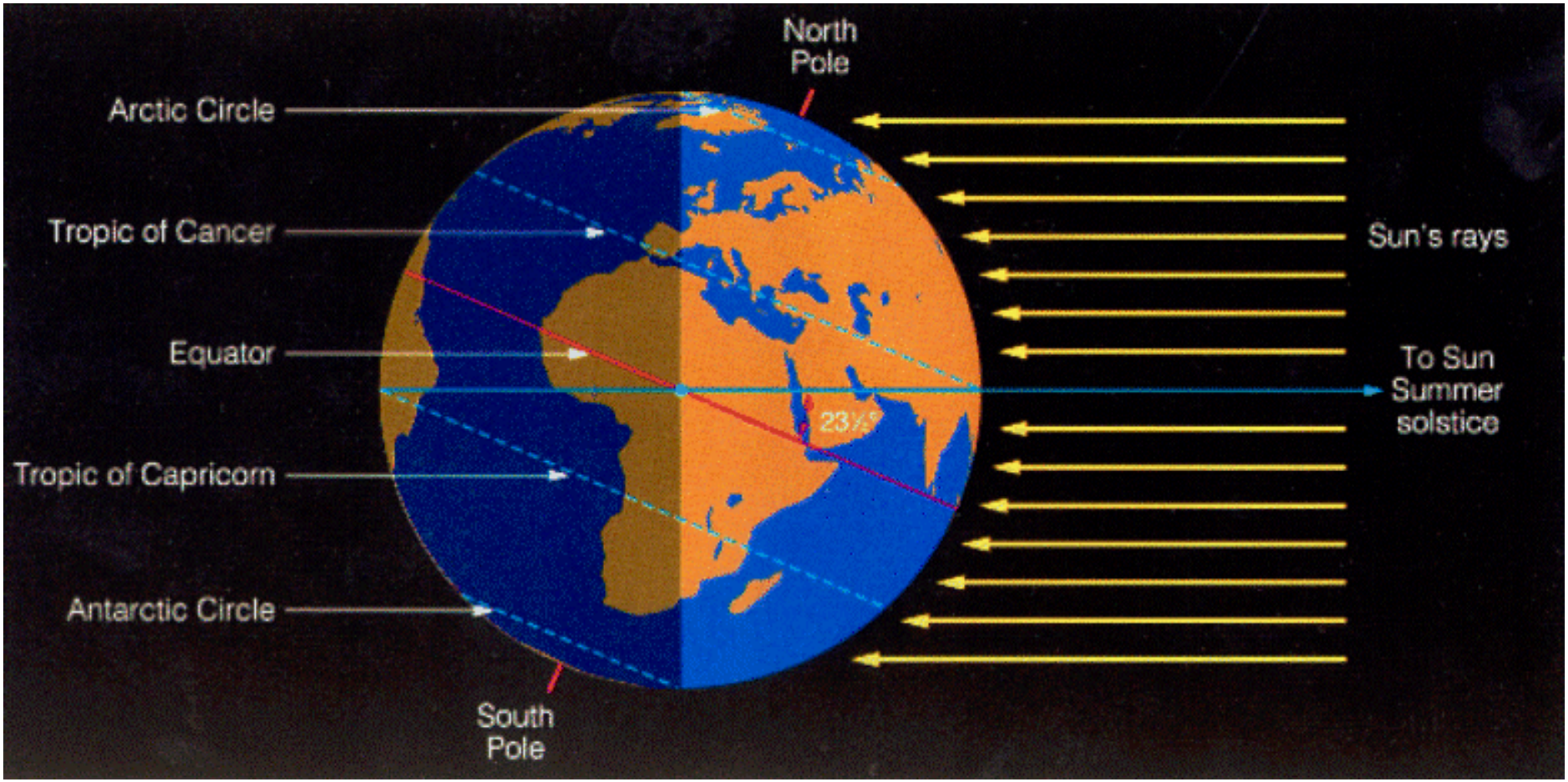
Harvard University

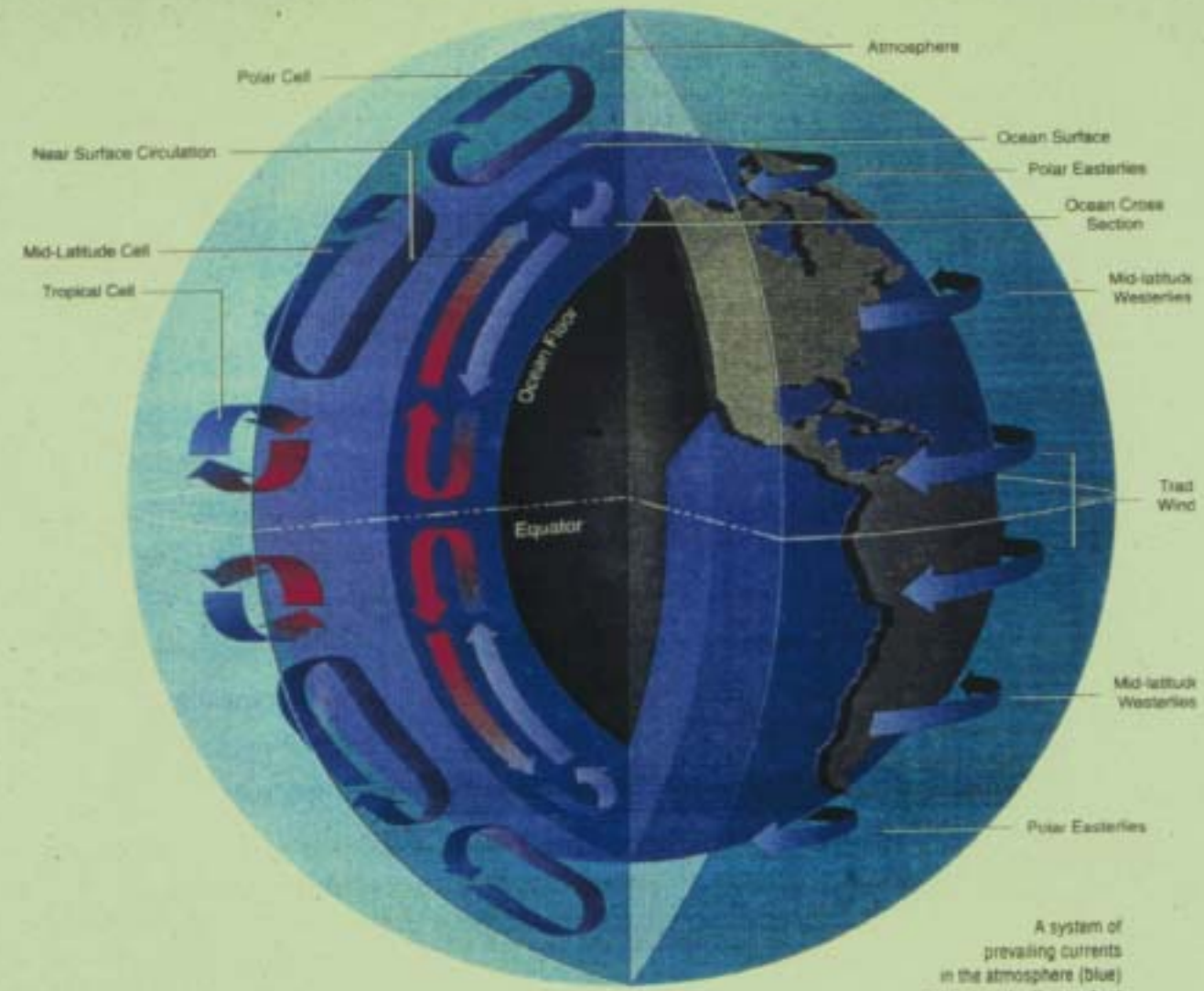
25 January 2003

- **Climate System Dynamics and Variabilities**
- **Coupled Circulation of the Atmosphere and Ocean – Seasonal Cycle and Year to Year Changes**
- **Multiple Equilibria of the Thermohaline Circulation and Internal Dynamical Instability**

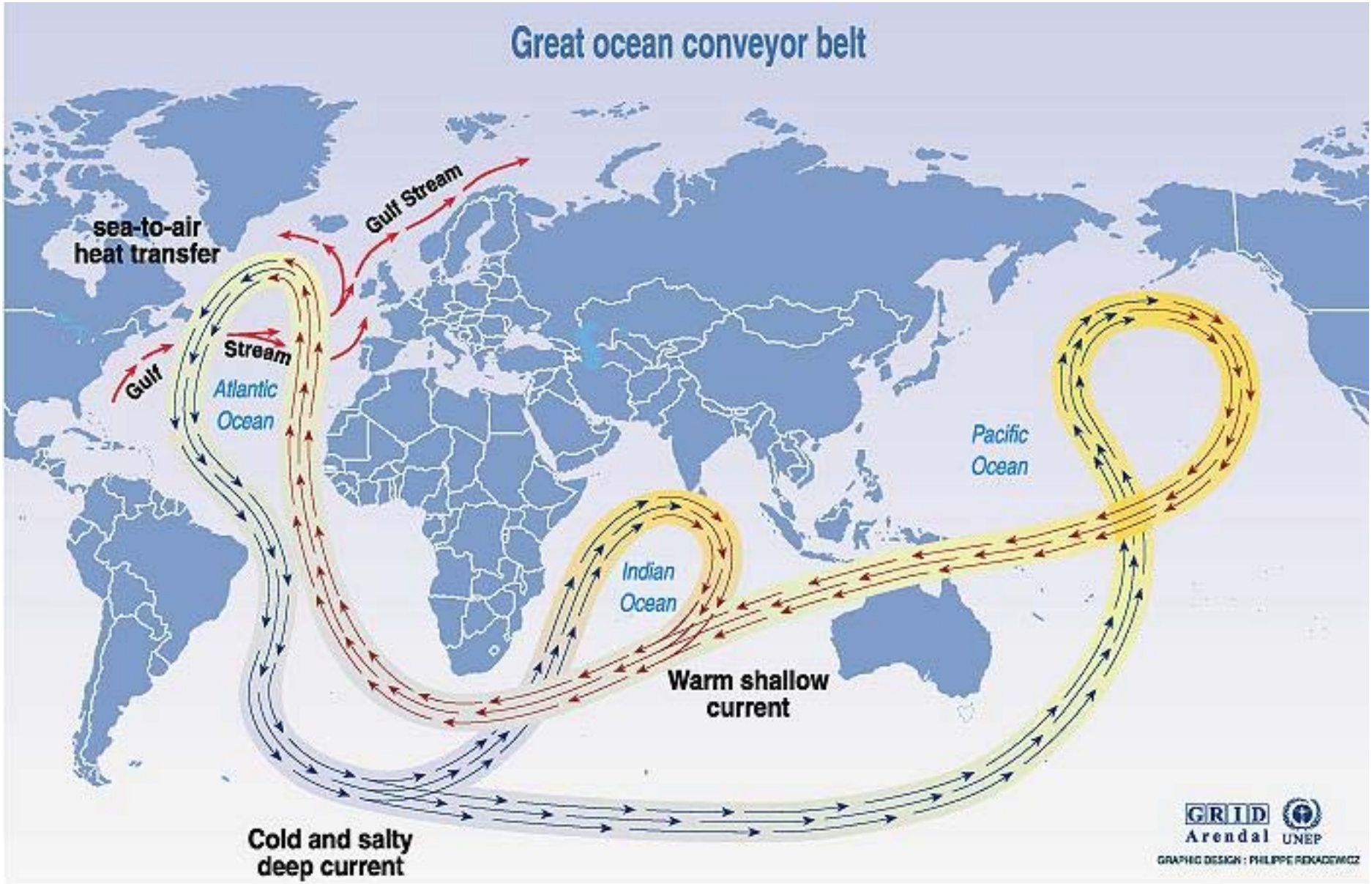

changes of solar radiation
terrestrial radiation
short-wave radiation – cloud-top interactions
atmospheric gases, including trace gases, ozone, and water vapor
clouds
volcanic aerosols
long-wave radiation – cloud-bottom interactions
precipitation
ice-atmosphere coupling
ocean aerosols & trace gases
evaporation
land-atmosphere coupling
ice sheets, snow
biomass
heat exchange
wind stress
precipitation and redissolution of biogenic carbonates
sea ice
changes in atmospheric composition from weathering processes and the biosphere
ice-ocean coupling
ocean-atmosphere coupling
changes in land features, orography, vegetation, albedo, etc.
changes in oceans: basin shape, salinity, currents, sea-surface temperatures, etc.


1 sec
1 min
1 hr
1 day
10⁰ yr
10² yr
"Sub-grid" Scale Processes
Circulation models
Local Interaction models
Inertia Gravity Waves
Small-scale Turbulence
Quasi-geostrophic Eddies
Deep Thermohaline Circulation
10³ km
10 km
10² m
10⁰ m

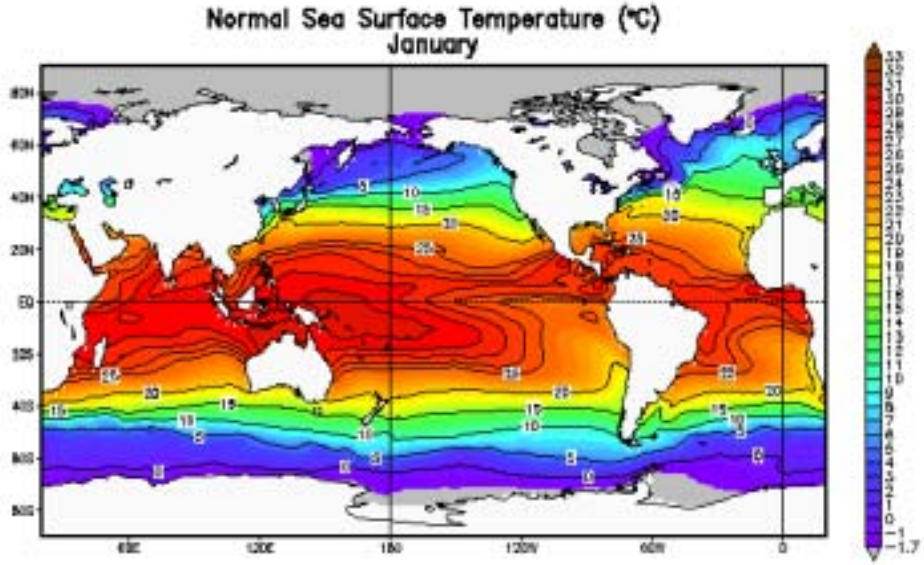

North Pole
Arctic Circle
Tropic of Cancer
Sun's rays
Equator
To Sun
Summer
solstice
23½°
Tropic of Capricorn
Antarctic Circle
South Pole

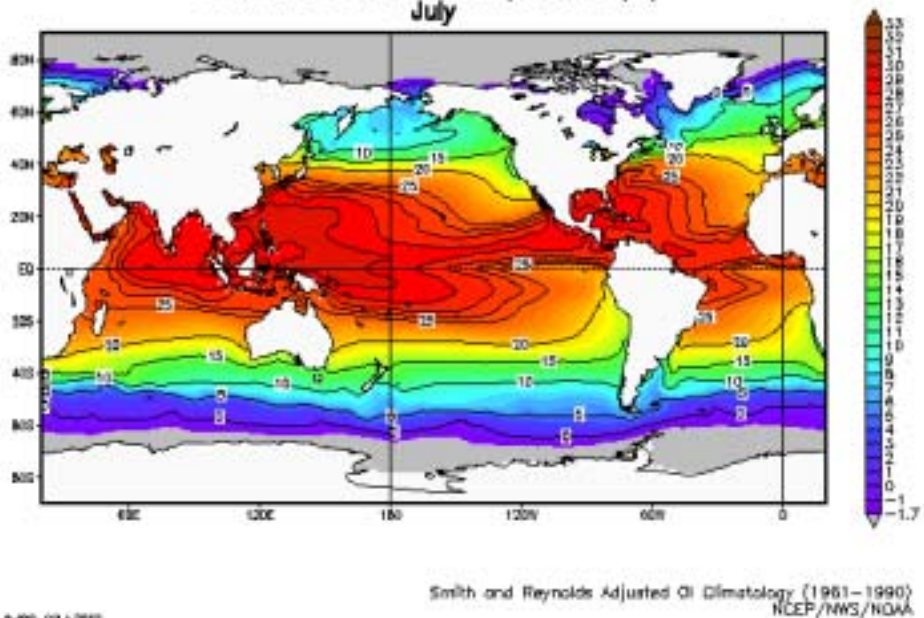


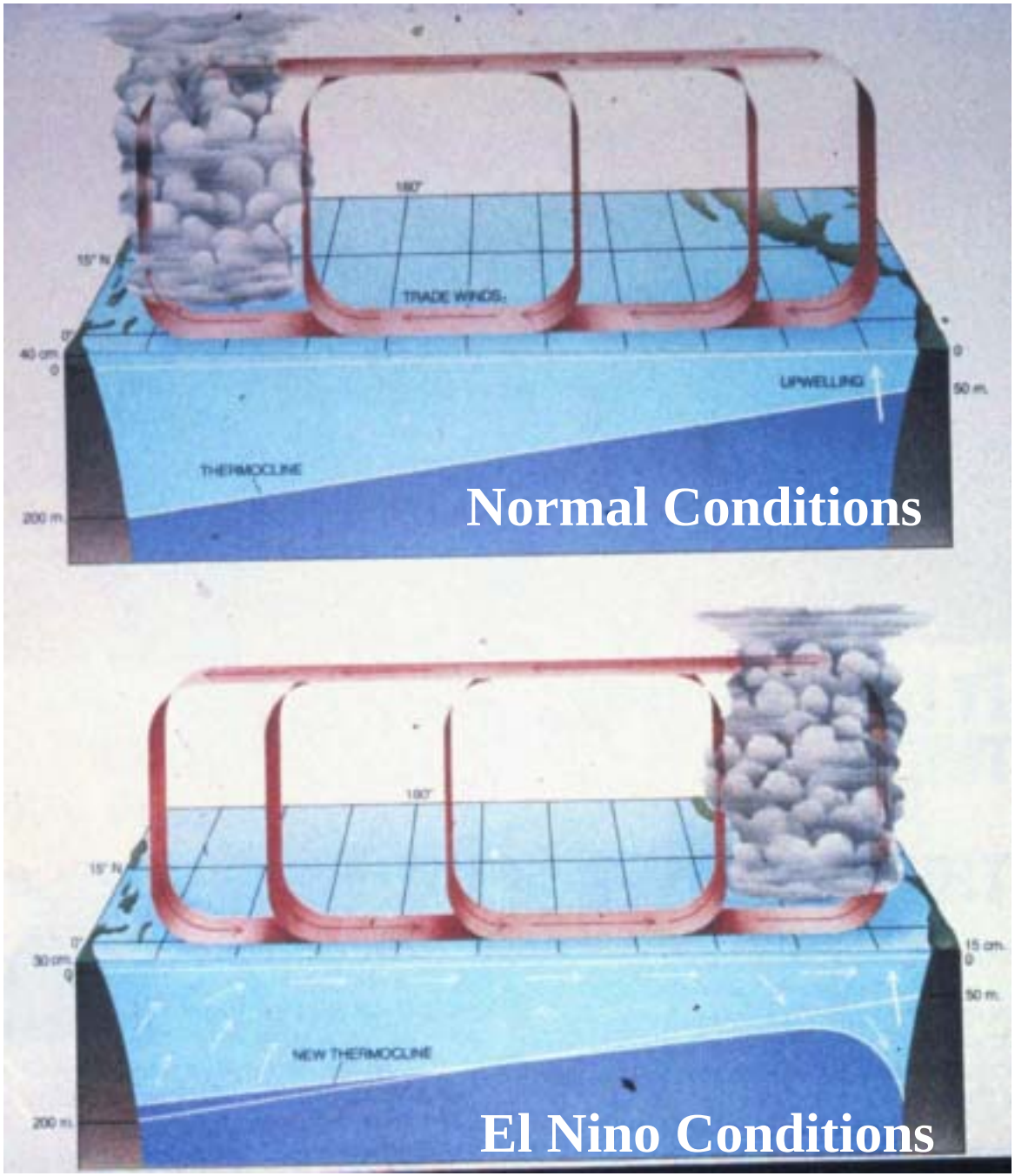
A system of prevailing currents in the atmosphere (blue) and oceans (red) carry heat from one part of the planet to another. The forces that drive them are provided by incoming solar energy and the spinning motion of the Earth.



Source: Broecker, 1991, in Climate change 1995, Impacts, adaptations and mitigation of climate change: scientific-technical analyses, contribution of working group 2 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge press university, 1996.


Normal Sea Surface Temperature (°C)
January
Smith and Reynolds Adjusted OI Climatology (1961-1990)
NCEP/NWS/NOAA


Normal Sea Surface Temperature (°C)
July
Smith and Reynolds Adjusted OI Climatology (1961-1990)
NCEP/NWS/NOAA


180°
15° N
0°
TRADE WINDS
40 cm.
0
0
UPWELLING
50 m.
THERMOCLINE
200 m.
Normal Conditions
180°
15° N
0°
30 cm.
0
15 cm.
0
50 m.
NEW THERMOCLINE
200 m.
El Nino Conditions

INDONESIA

WORLDWIDE IMPACT As brush fires raged in drought-stricken Sumatra, motorists were shrouded in smoke, and clinics were filled with patients (above). Flames charred trees and utility poles in Bunnell, Florida (below left), which endured severe drought last summer. Too much winter rain near Chino, California (below right), sent rescuers in front loaders to save cattle neck deep in mud. Fires fueled by droughts claimed more than 19,000 square miles of

UNITED STATES

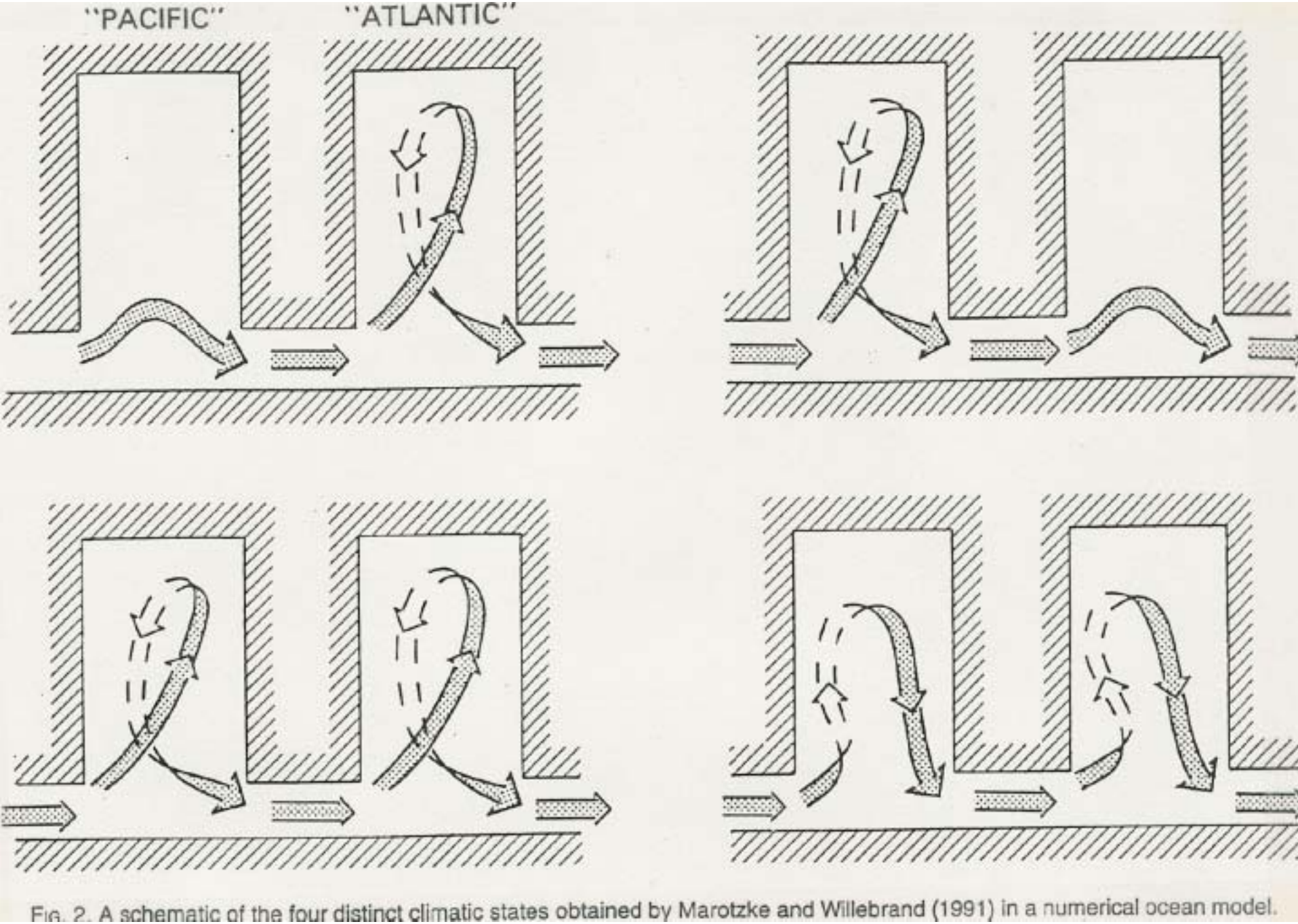
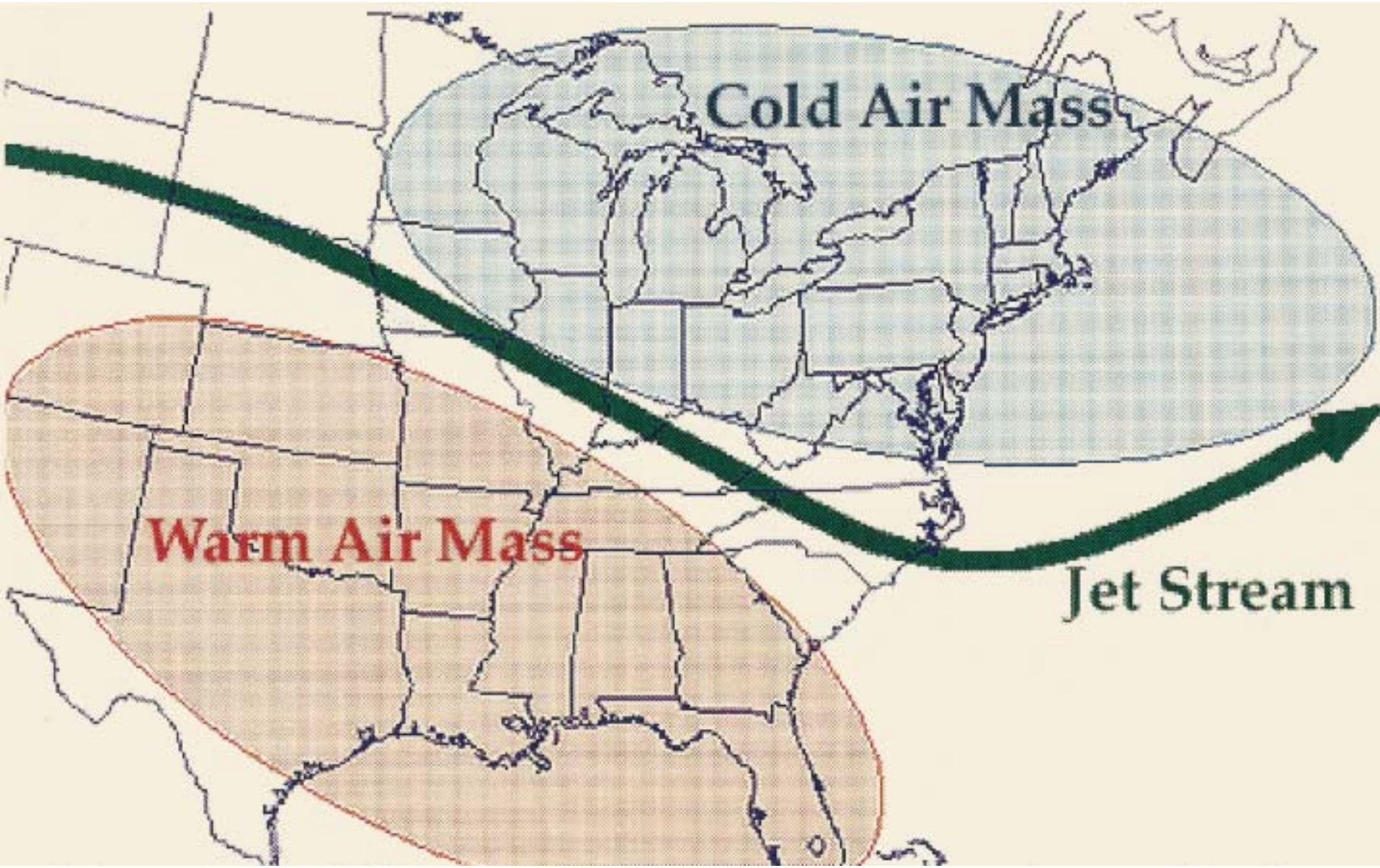
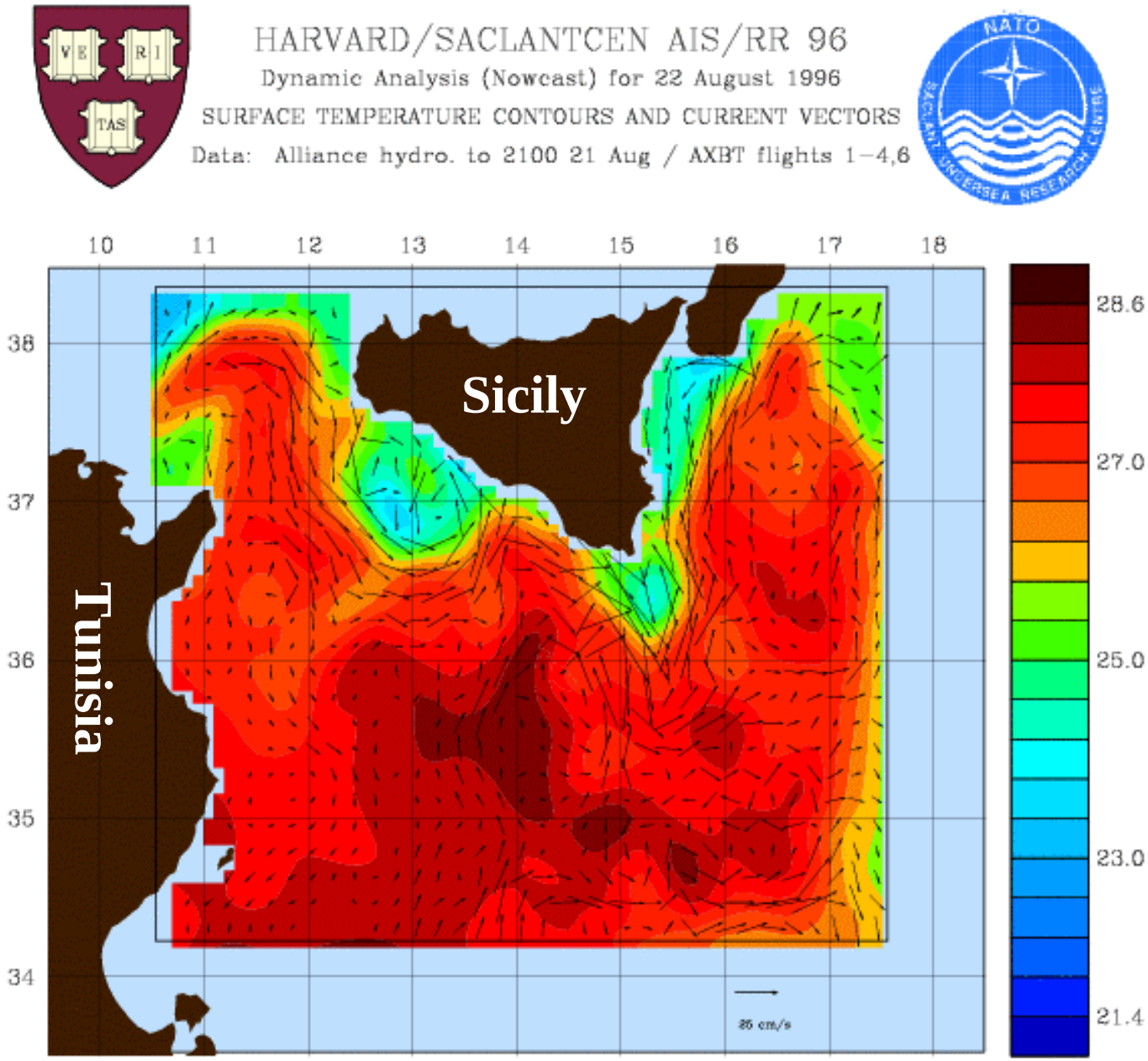


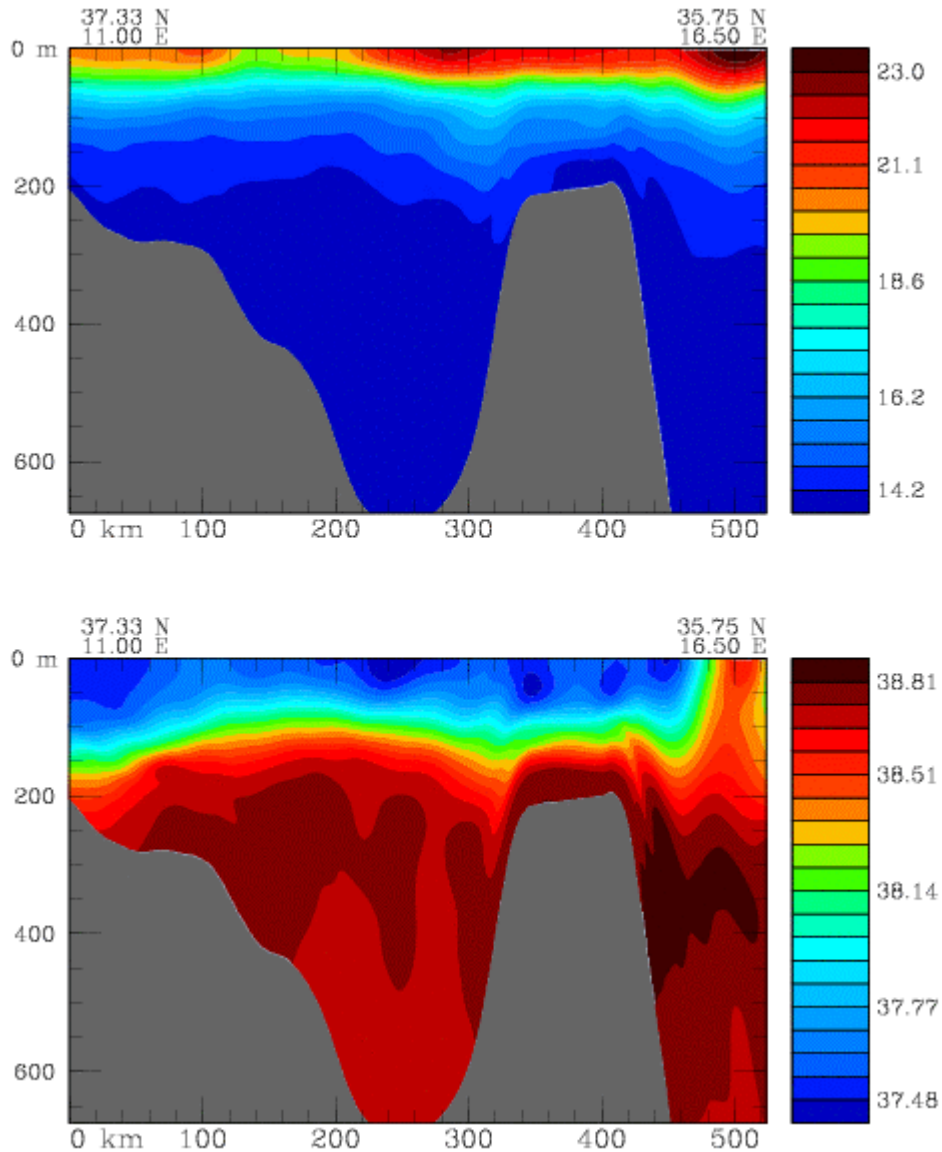
Fig. 2. A schematic of the four distinct climatic states obtained by Marotzke and Willebrand (1991) in a numerical ocean model.

- **Internal Weather of the Sea – the Most Energetic Motions**
- **Powerful Synoptical Dynamical Events Occur and Statistically Mediate Important Aspects of the Ocean Climate**
- **HOPS – Harvard Ocean Prediction System**


Cold Air Mass
Warm Air Mass
Jet Stream

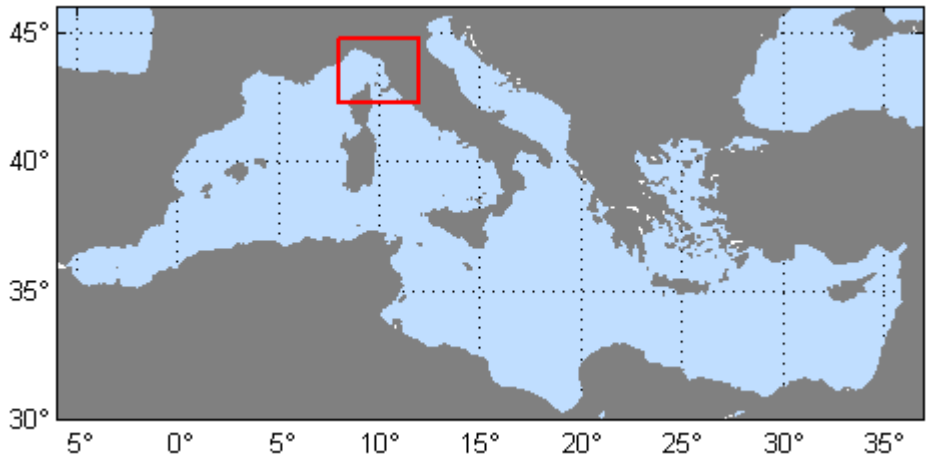

HARVARD/SACLANTCEN AIS/RR 96
Dynamic Analysis (Nowcast) for 22 August 1996
SURFACE TEMPERATURE CONTOURS AND CURRENT VECTORS
Data: Alliance hydro. to 2100 21 Aug / AXBT flights 1–4,6
NATO
SACLANT UNDERSEA RESEARCH CENTRE
10
11
12
13
14
15
16
17
18
38
37
36
35
34
Sicily
Tunisia
25 cm/s
28.6
27.0
25.0
23.0
21.4

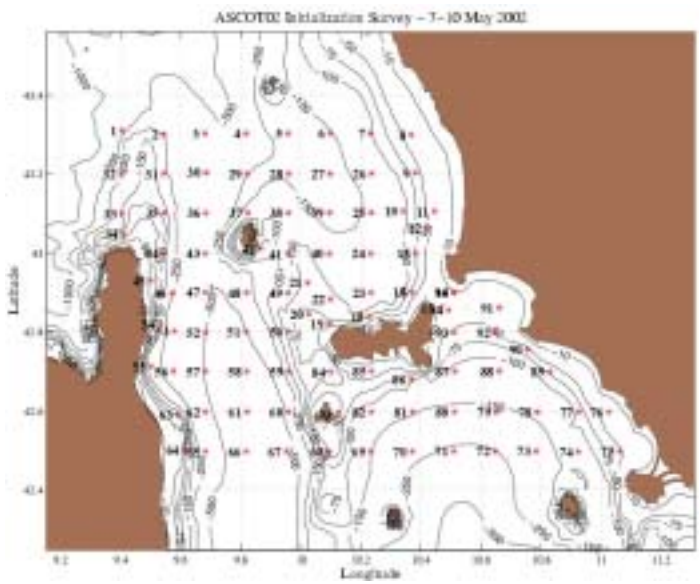
Vertical section of Temperature (top) and Salinity (bottom) during Rapid Response 1996

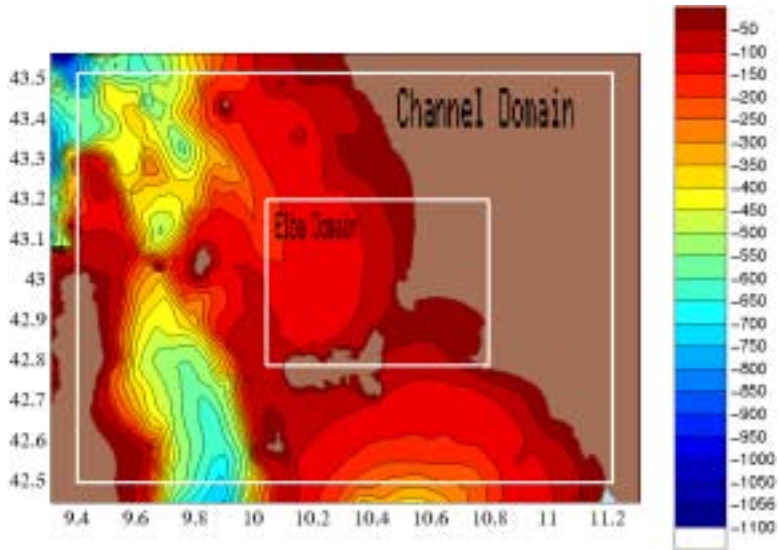


ASCOT-02 Data and Modeling Domains

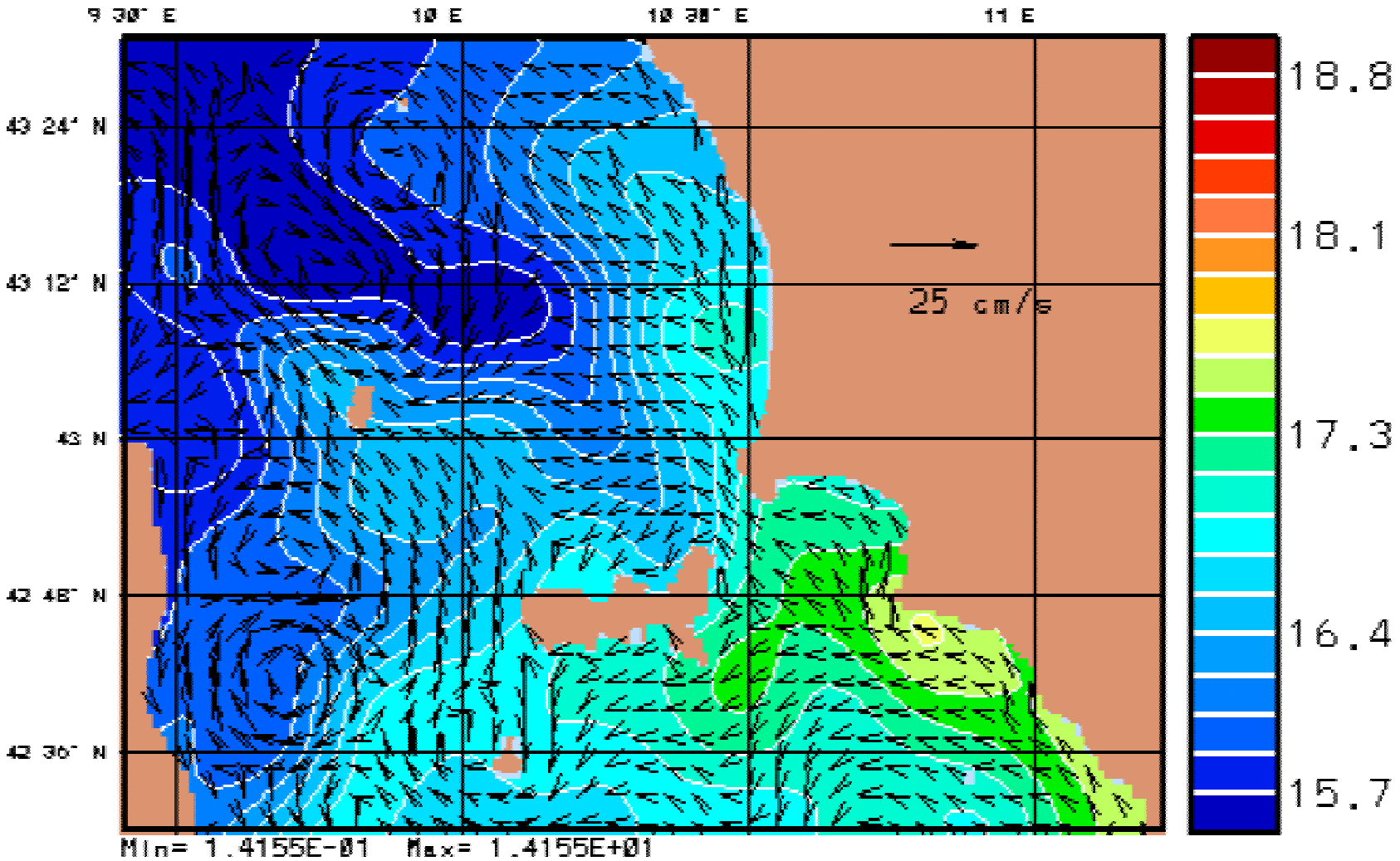
7-17 May 2002



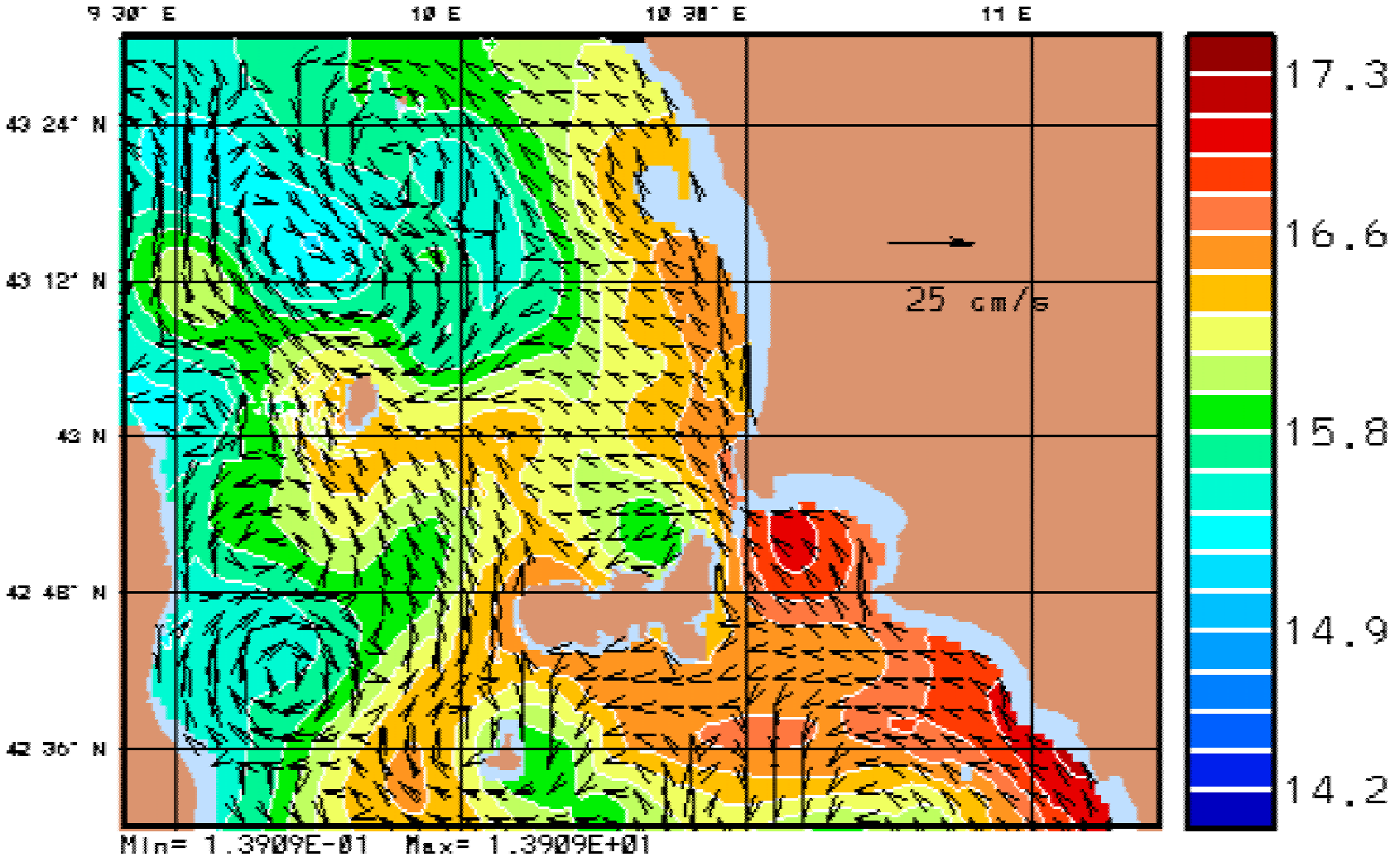




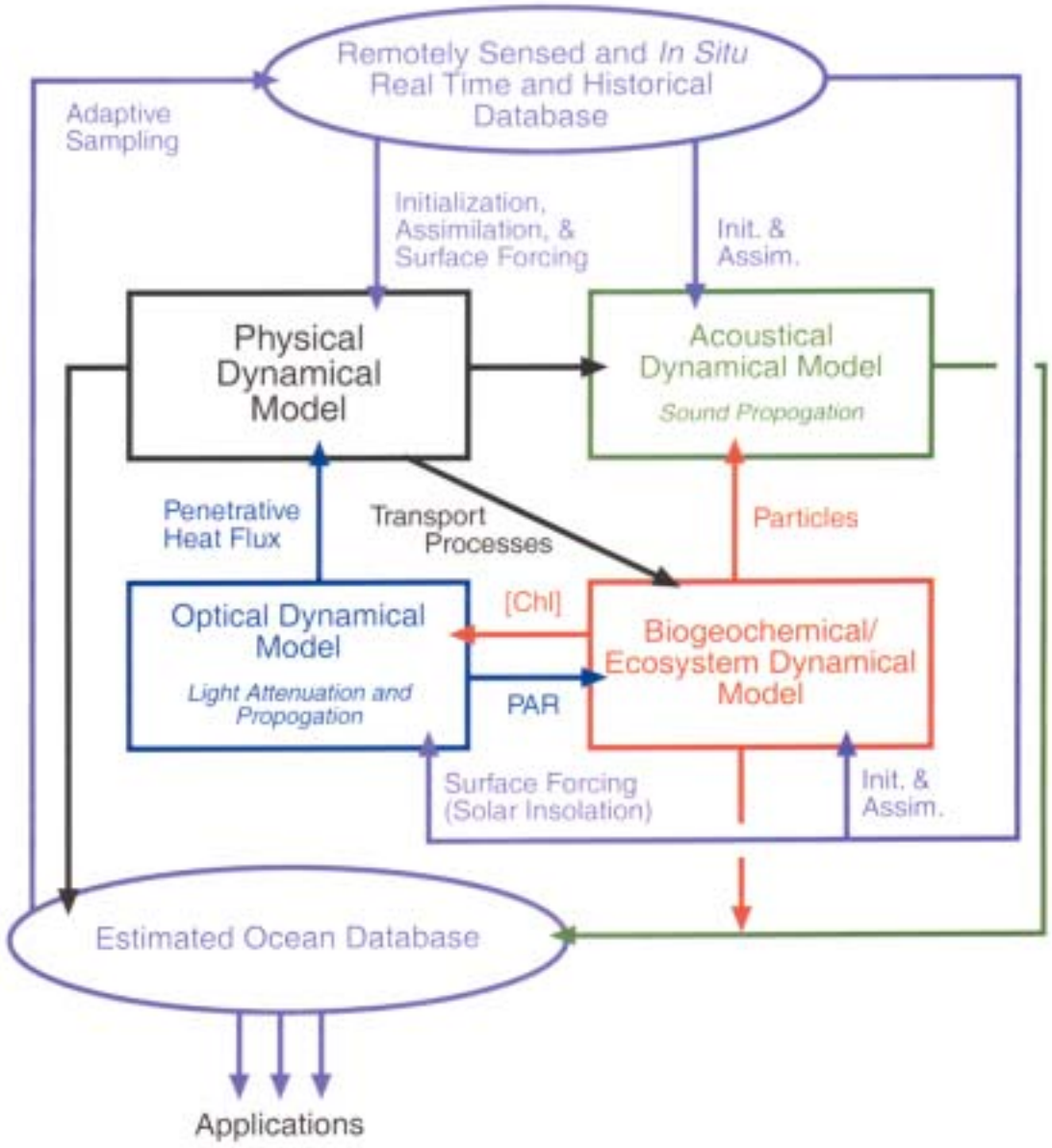
7 May 2002


9 30' E
10 E
10 30' E
11 E
43 24' N
43 12' N
43 N
42 48' N
42 36' N
25 cm/s
18.8
18.1
17.3
16.4
15.7
Min= 1.4155E-01 Max= 1.4155E+01

7 May 2002


9 30' E
10 E
10 30' E
11 E
43 24' N
43 12' N
43 N
42 48' N
42 36' N
25 cm/s
17.3
16.6
15.8
14.9
14.2
Min= 1.3909E-01 Max= 1.3909E+01

Harvard Ocean Prediction System - HOPS



A-POLYMODE

B-Mares Abyssal Plain (*)

C-NDBMP Site

D-California Current (*)

E-Gulfcoast/NOGULFS (*)

F-Iceland Faeroes Front (*)

G-Eastern Mediterranean (*)

H-Northeast Pacific (*)

I-Bermuda (*)

J-AthenA (*)

K-JGOFS (*)

L-Strait of Sicily (*)

M-Haro Straits (*)

N-Black Sea

O-Adriatic

P-Shelf/Slope PRIMER (*)

Q-Drake's Passage

R-Plankton Patchiness (*)

S-Skerki Bank (*)

T-LOOPS/AFMIS (*)

U-Gulf of Cadiz (*)

V-AFMIS/RTDOC (*)

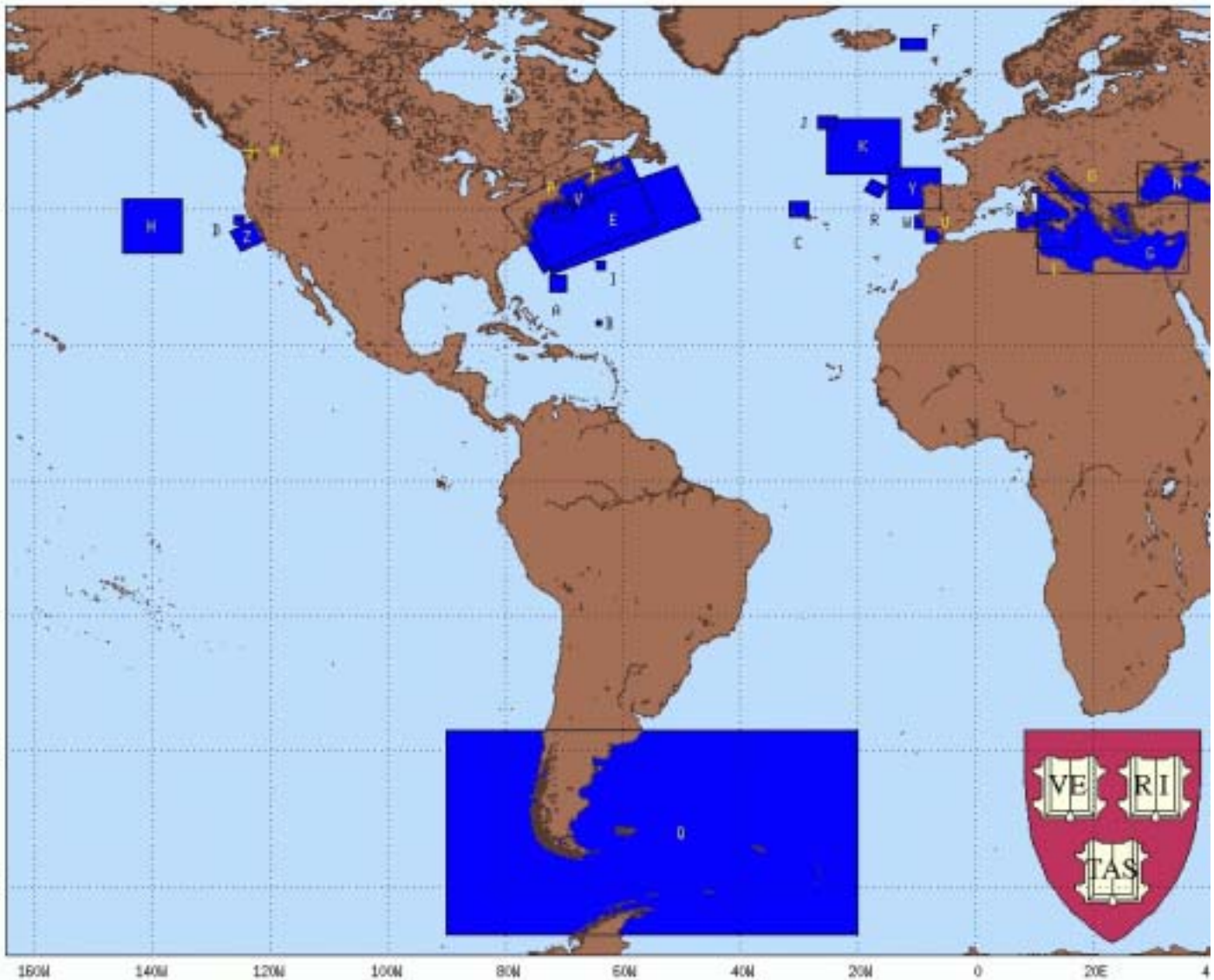
W-Linked Seas (*)

X-GOATS/MEANS (*)

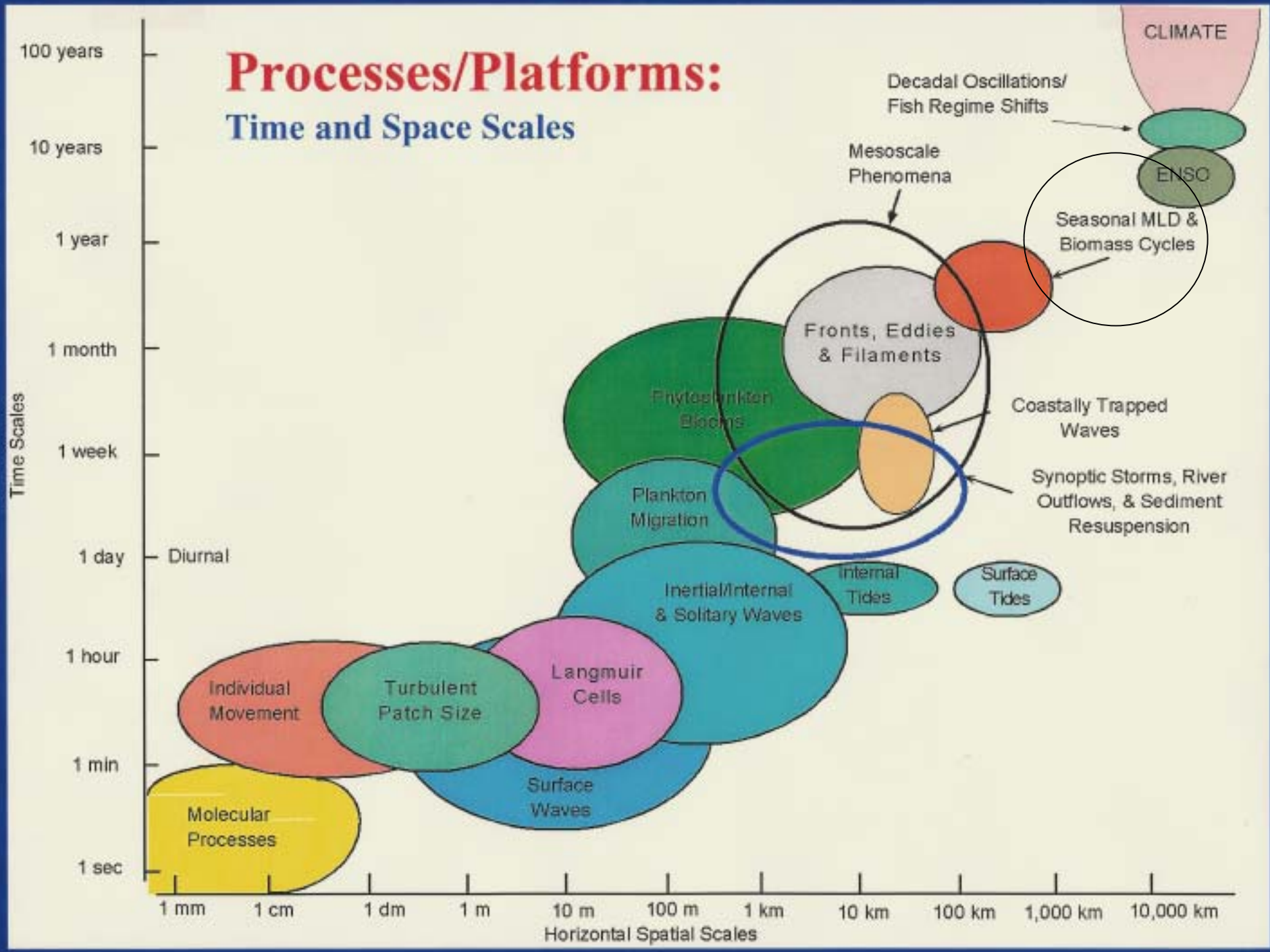
Y-Prestige Oil Spill (*)

Z-AOSN-II (*)

(*) = Realtime/at-Sea



- **Physical Forcing of Coupled Biological/Chemical Dynamical Processes**
- **Primary Productivity and the Food Web**
- **The Biological Pump and its Role in the Changing Global Carbon Cycle**


Processes/Platforms:
Time and Space Scales
CLIMATE
Decadal Oscillations/
Fish Regime Shifts
ENSO
Mesoscale
Phenomena
Seasonal MLD &
Biomass Cycles
Fronts, Eddies
& Filaments
Phytoplankton
Blooms
Coastally Trapped
Waves
Synoptic Storms, River
Outflows, & Sediment
Resuspension
Plankton
Migration
Diurnal
Internal
Tides
Surface
Tides
Inertial/Internal
& Solitary Waves
Langmuir
Cells
Individual
Movement
Turbulent
Patch Size
Surface
Waves
Molecular
Processes
100 years
10 years
1 year
1 month
1 week
1 day
1 hour
1 min
1 sec
Time Scales
1 mm
1 cm
1 dm
1 m
10 m
100 m
1 km
10 km
100 km
1,000 km
10,000 km
Horizontal Spatial Scales

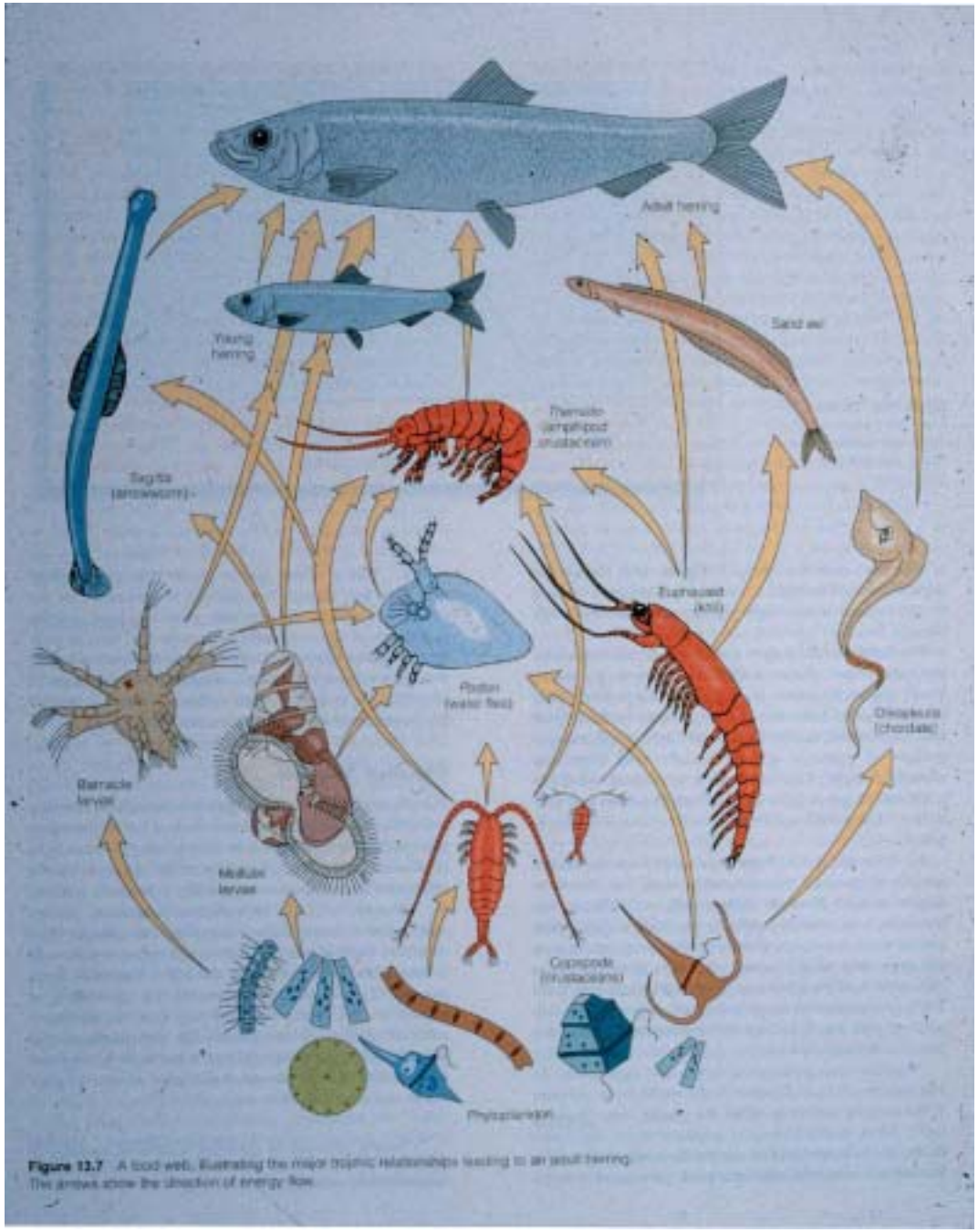
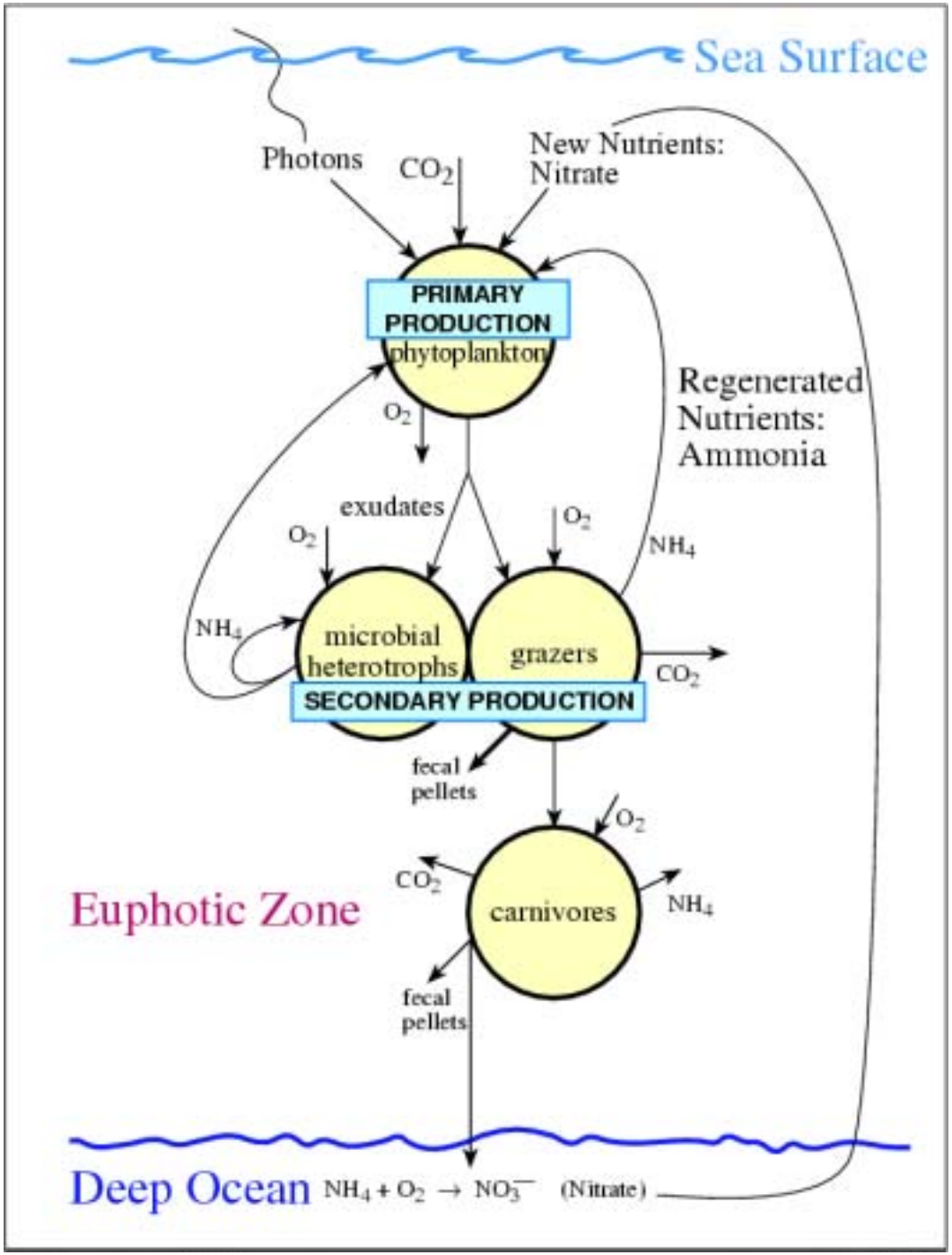
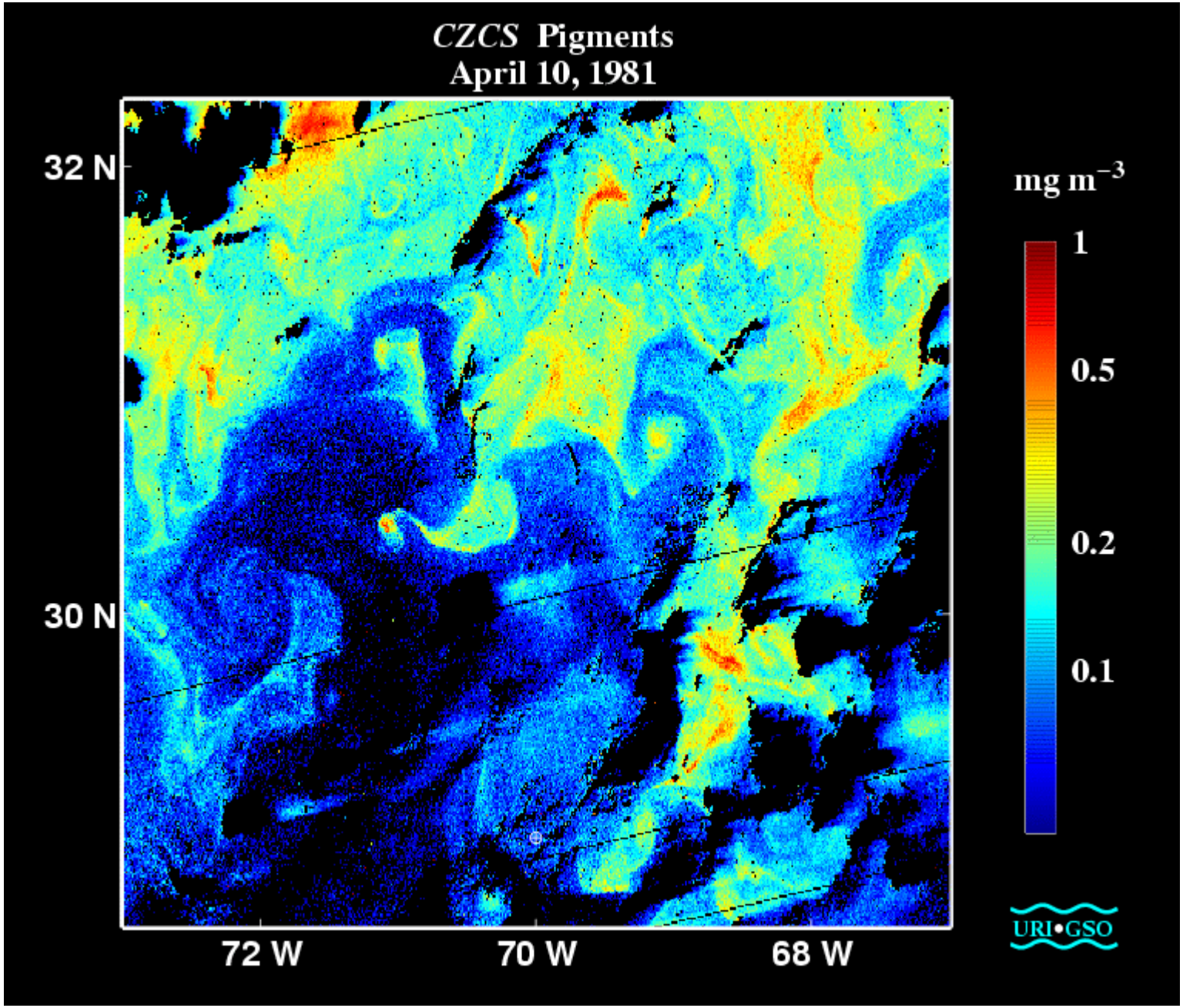
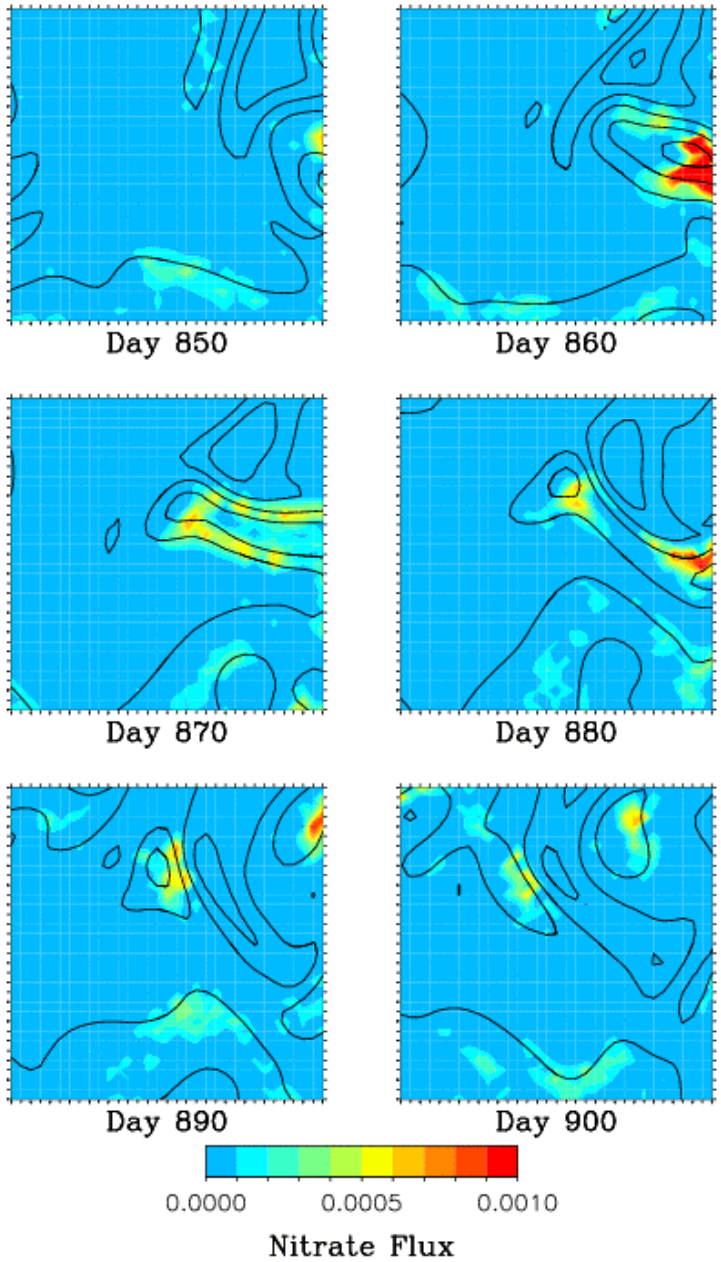


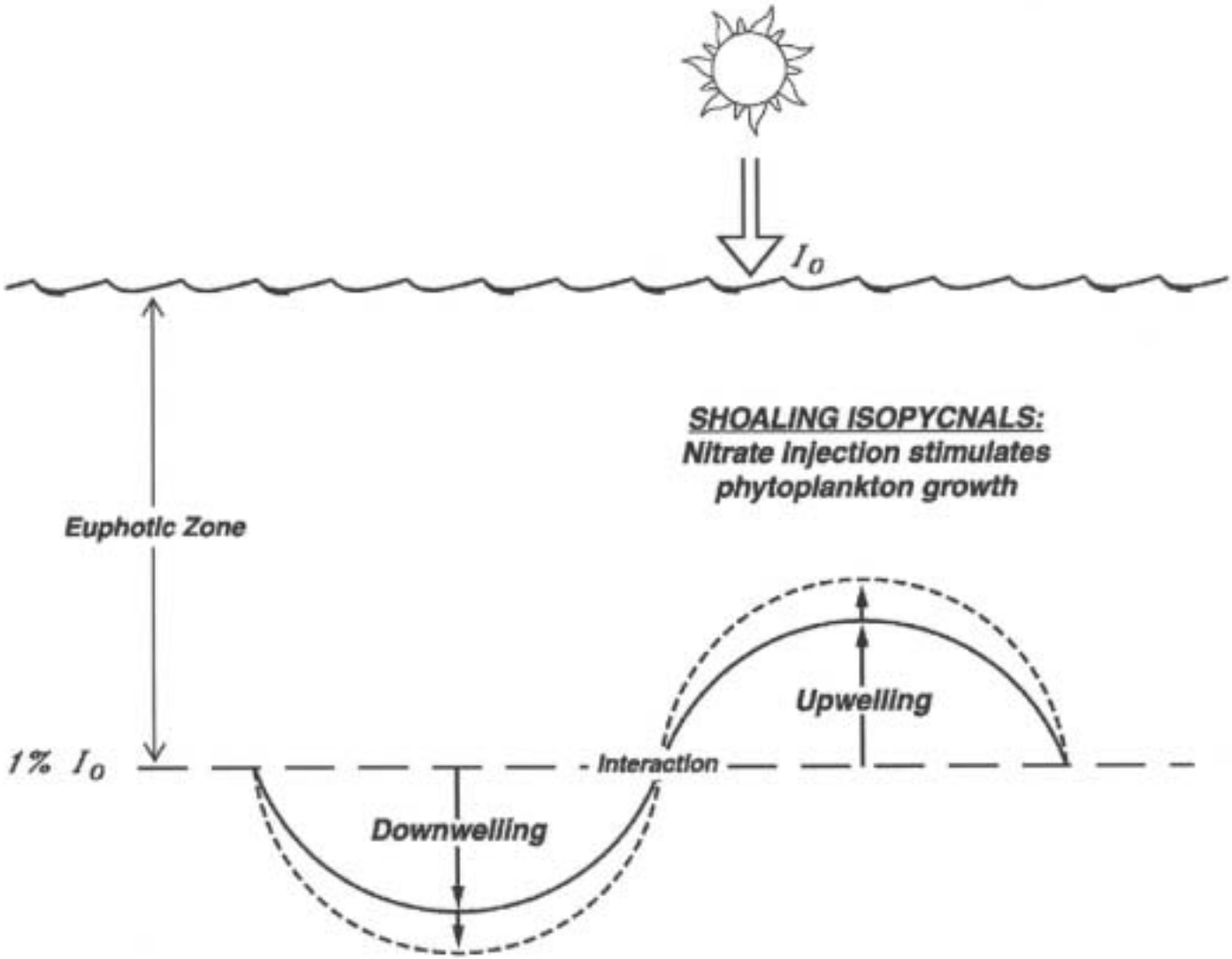
Figure 12.7 A food web, illustrating the major trophic relationships leading to an adult herring. The arrows show the direction of energy flow.

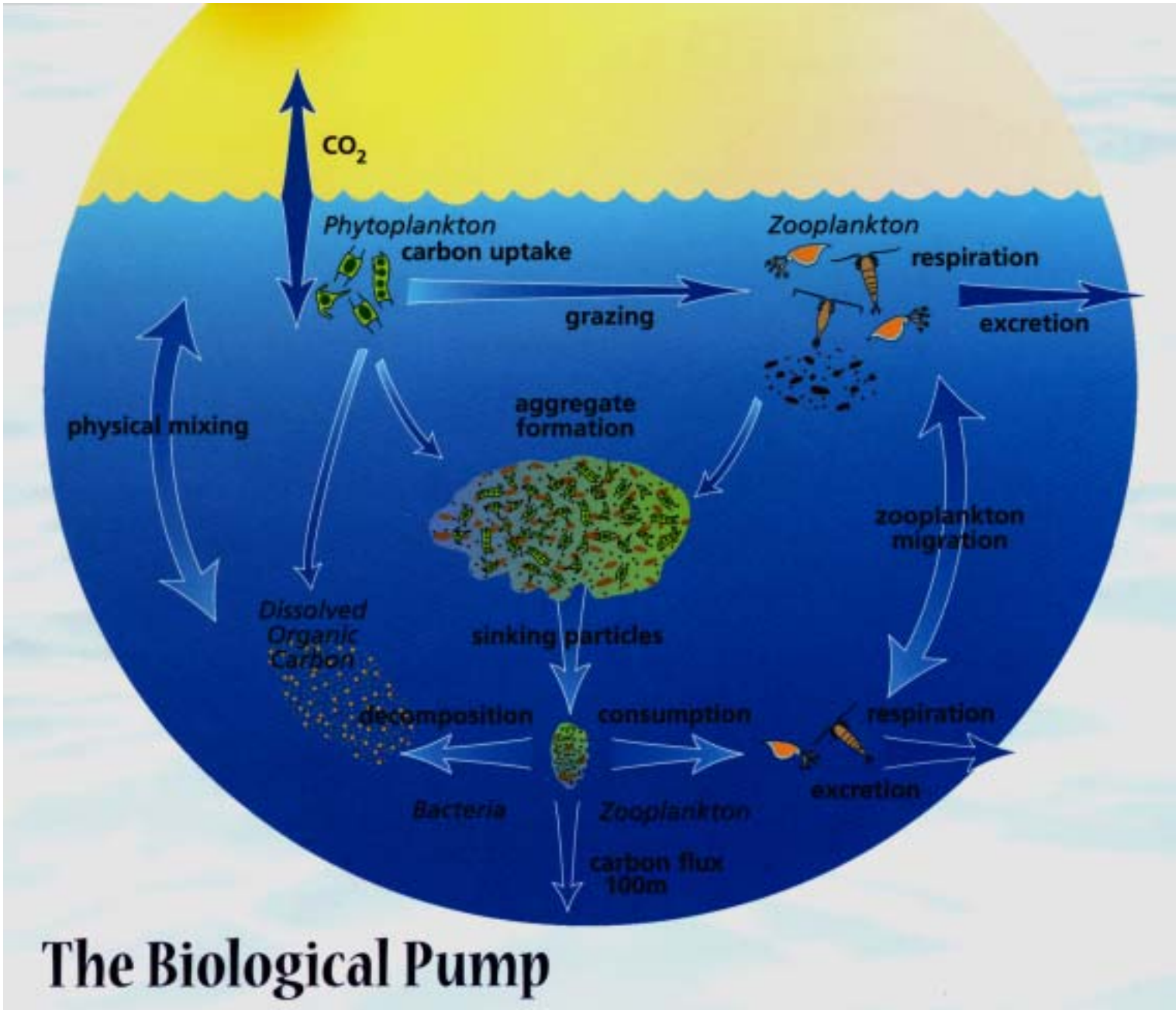

A.C.H.


Sea Surface
Photons
CO_2
New Nutrients:
Nitrate
PRIMARY
PRODUCTION
phytoplankton
O_2
Regenerated
Nutrients:
Ammonia
exudates
O_2
O_2
NH_4
NH_4
microbial
heterotrophs
grazers
CO_2
SECONDARY PRODUCTION
fecal
pellets
O_2
CO_2
carnivores
NH_4
Euphotic Zone
fecal
pellets
Deep Ocean
$NH_4 + O_2 \rightarrow NO_3^-$ (Nitrate)

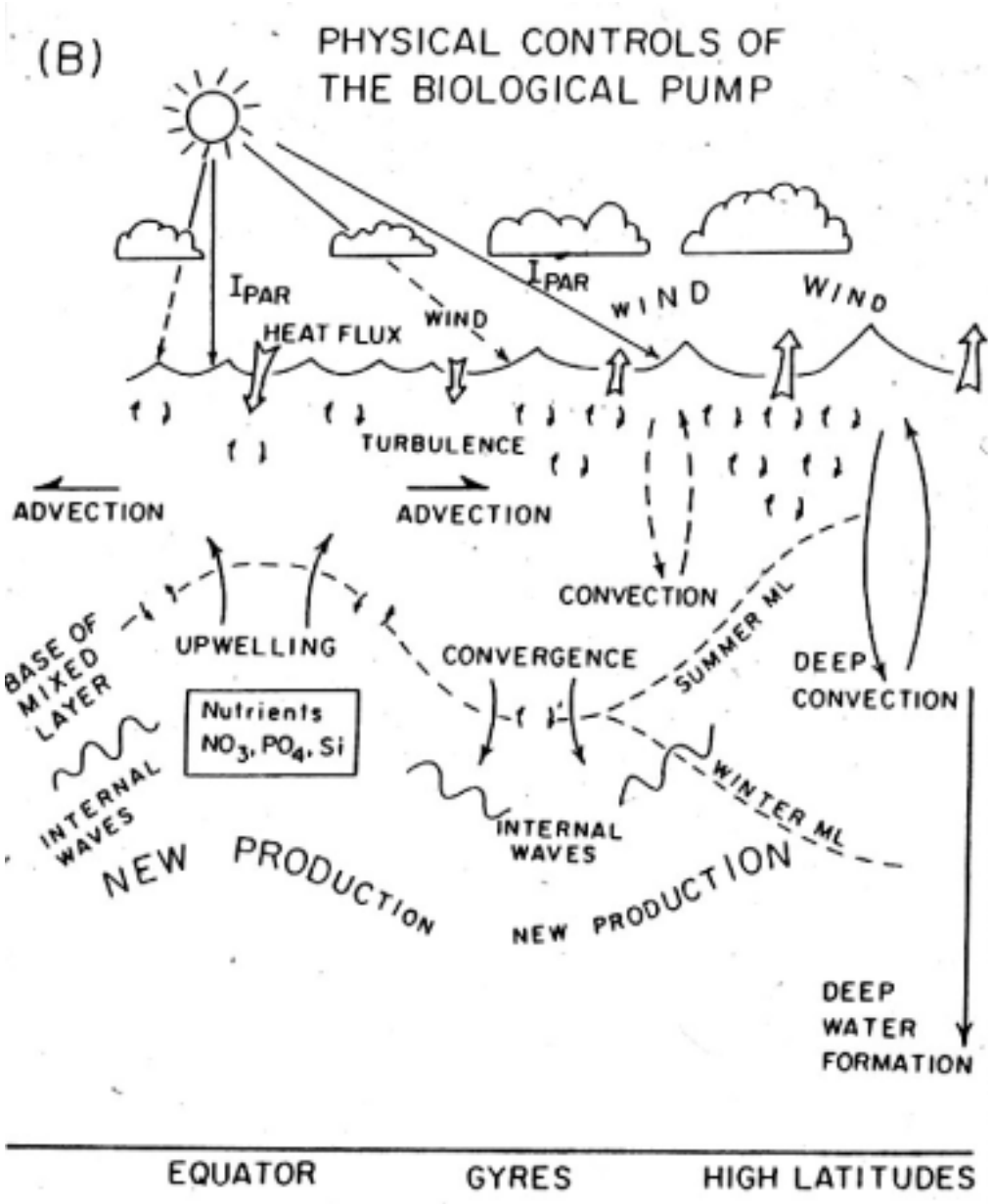

CZCS Pigments
April 10, 1981
32 N
30 N
72 W
70 W
68 W
mg m^{-3}
1
0.5
0.2
0.1
URI•GSO


Day 850
Day 860
Day 870
Day 880
Day 890
Day 900
0.0000
0.0005
0.0010
Nitrate Flux

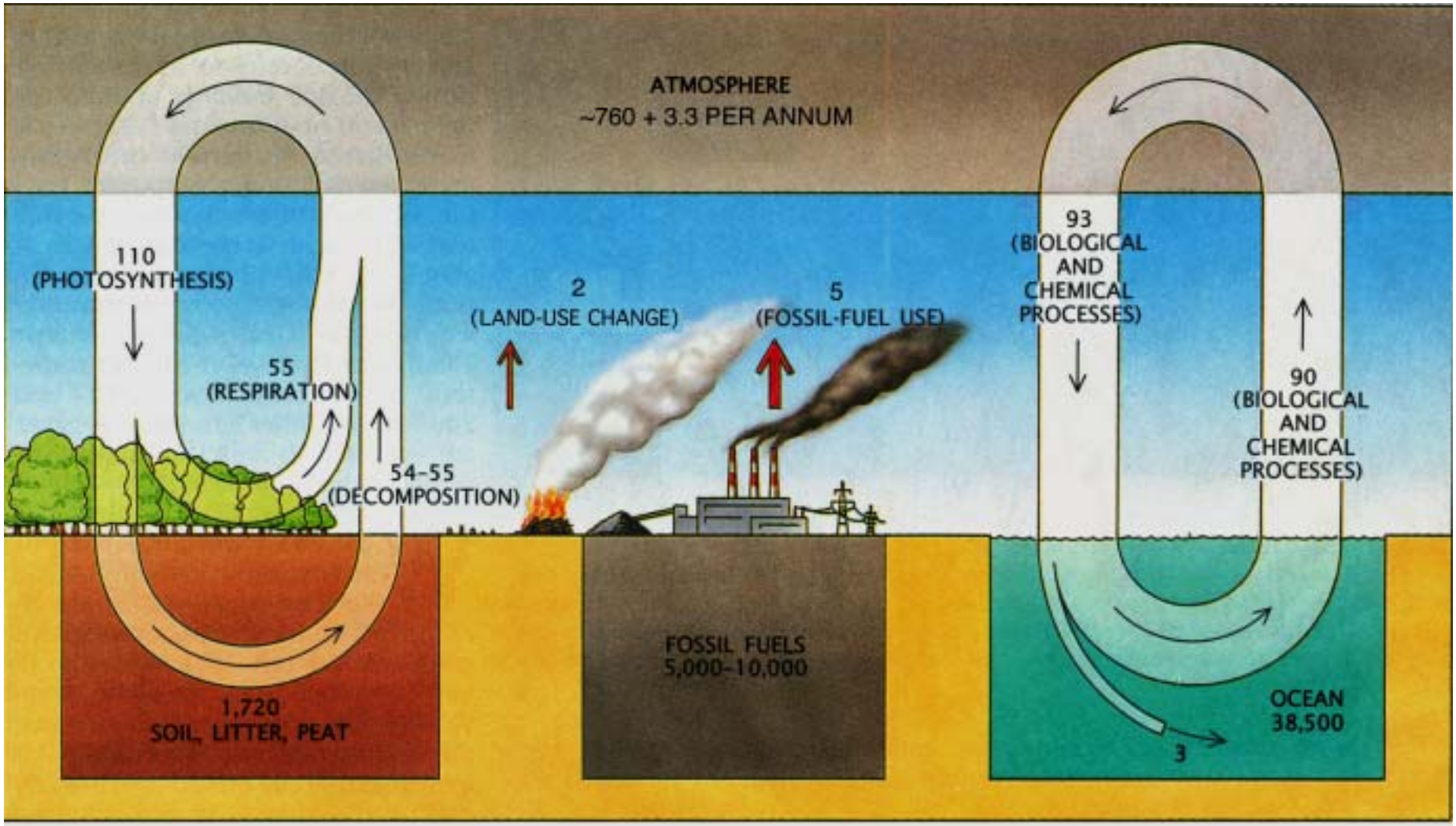

I_0
SHOALING ISOPYCNALS:
Nitrate injection stimulates
phytoplankton growth
Euphotic Zone
Upwelling
1% I_0
Interaction
Downwelling
DEEPENING ISOPYCNALS:
No ecosystem response


CO_2
Phytoplankton
carbon uptake
Zooplankton
respiration
grazing
excretion
physical mixing
aggregate formation
zooplankton migration
Dissolved Organic Carbon
sinking particles
decomposition
consumption
respiration
excretion
Bacteria
Zooplankton
carbon flux 100m
The Biological Pump

JGOFS

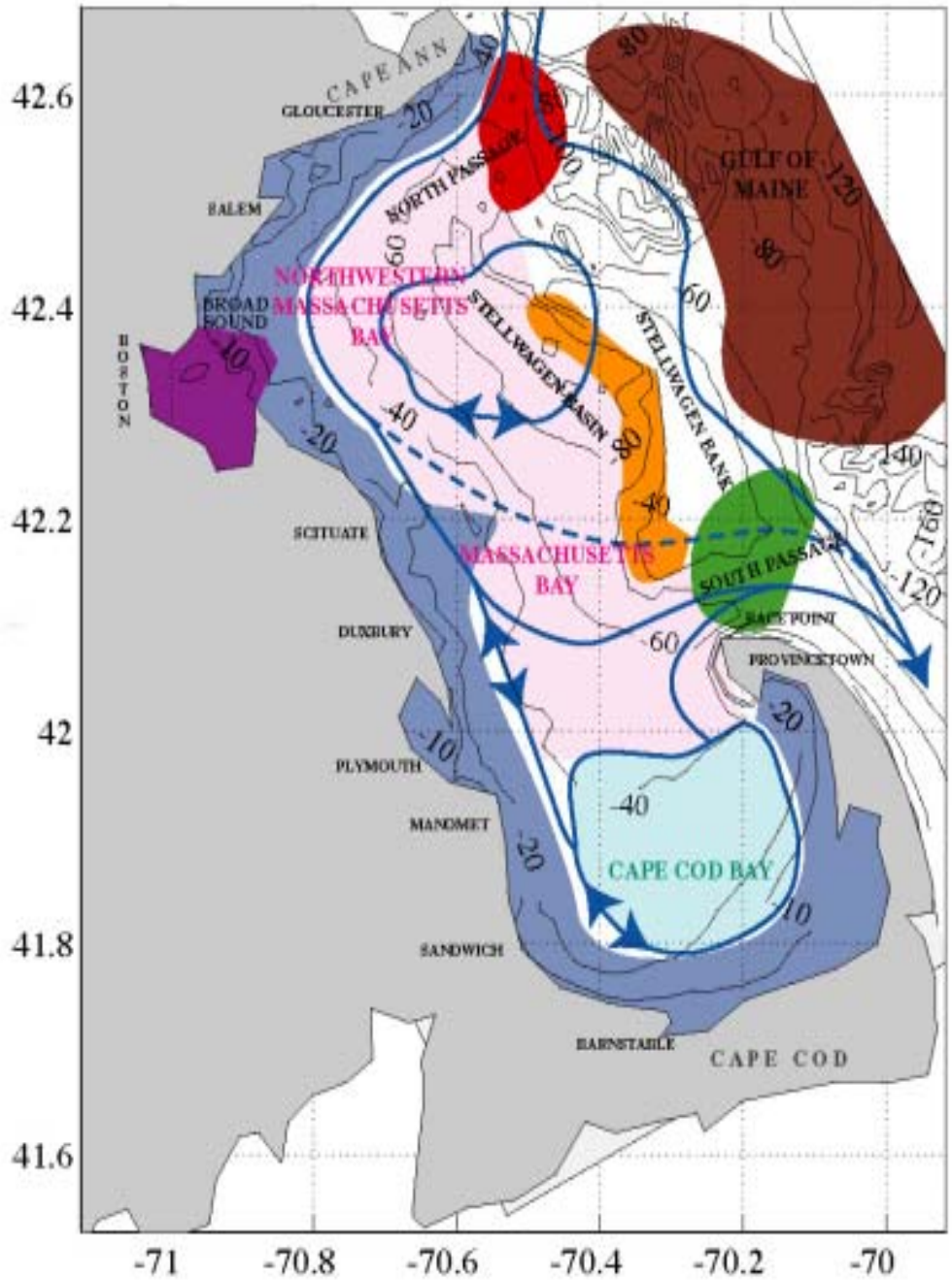

(B)
PHYSICAL CONTROLS OF
THE BIOLOGICAL PUMP
I_{PAR}
HEAT FLUX
WIND
I_{PAR}
WIND
WIND
TURBULENCE
ADVECTION
ADVECTION
CONVECTION
BASE OF MIXED LAYER
UPWELLING
CONVERGENCE
SUMMER ML
DEEP CONVECTION
Nutrients
NO_3, PO_4, Si
INTERNAL WAVES
INTERNAL WAVES
WINTER ML
NEW PRODUCTION
NEW PRODUCTION
DEEP WATER FORMATION
EQUATOR
GYRES
HIGH LATITUDES

Earth's carbon cycle



Average values in carbon reservoirs (Pg C) and carbon flows (Pg C/yr) for the 1990's
(after Schneider 1989; updated values from IPCC 2001)

- **The Advent of Accurate and Efficient Real Time Regional Forecasting -**
- **for Scientific Experimentation with Adaptive Sampling: e.g. Massachusetts Bay and the Gulf of Maine**
- **for Operations in and Management of the Coastal Oceans: e.g. the coasts of Spain and Portugal Today**



Coupled bio-physical sub-regions of Massachusetts Bay in late summer: Dominant dynamics for trophic enrichment and accumulation

Boston Harbor: Charles River, sediments, toxic material, NO_3–NH_4

Along Coast: upwelling/downwelling ⇒ bio ↑/↓

Open Bay: submesoscale/mesoscale eddies. Ageostrophic w ⇒ bio

Cape Cod Bay: Horizontal bio advection and submesoscales

West of Stellwagen Bank: GOM meanders, tides, topographic upwell/downwell

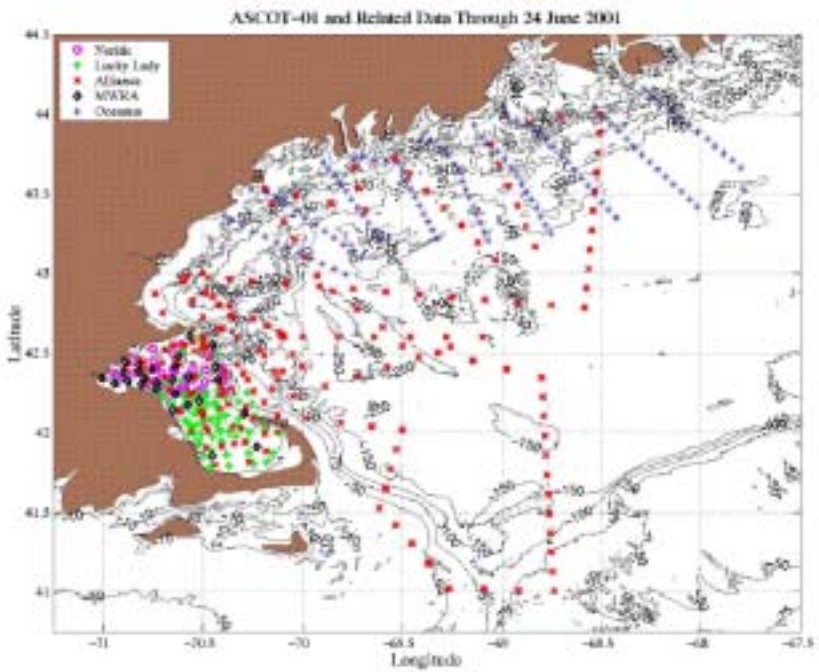
Offshore: GOM meanders

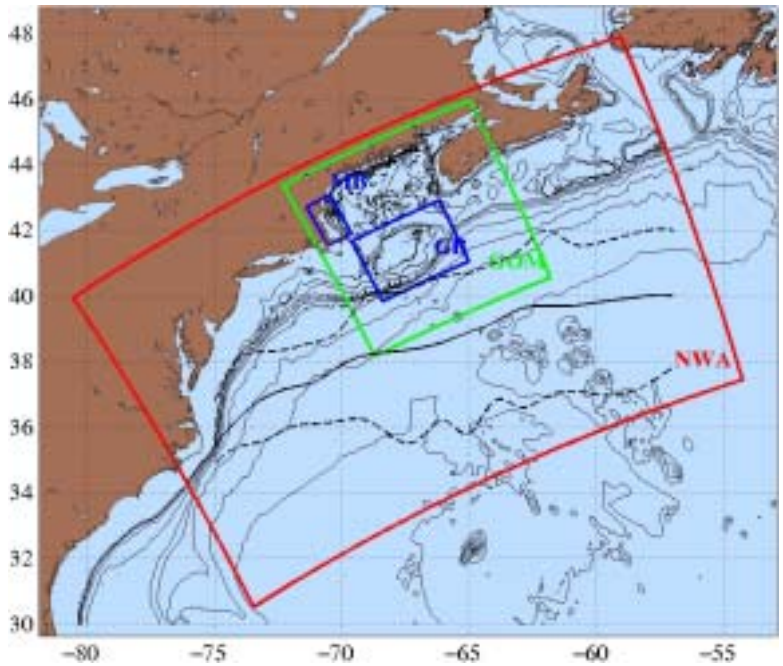
Race Point: Multiple bio advections, accumulation, and tides

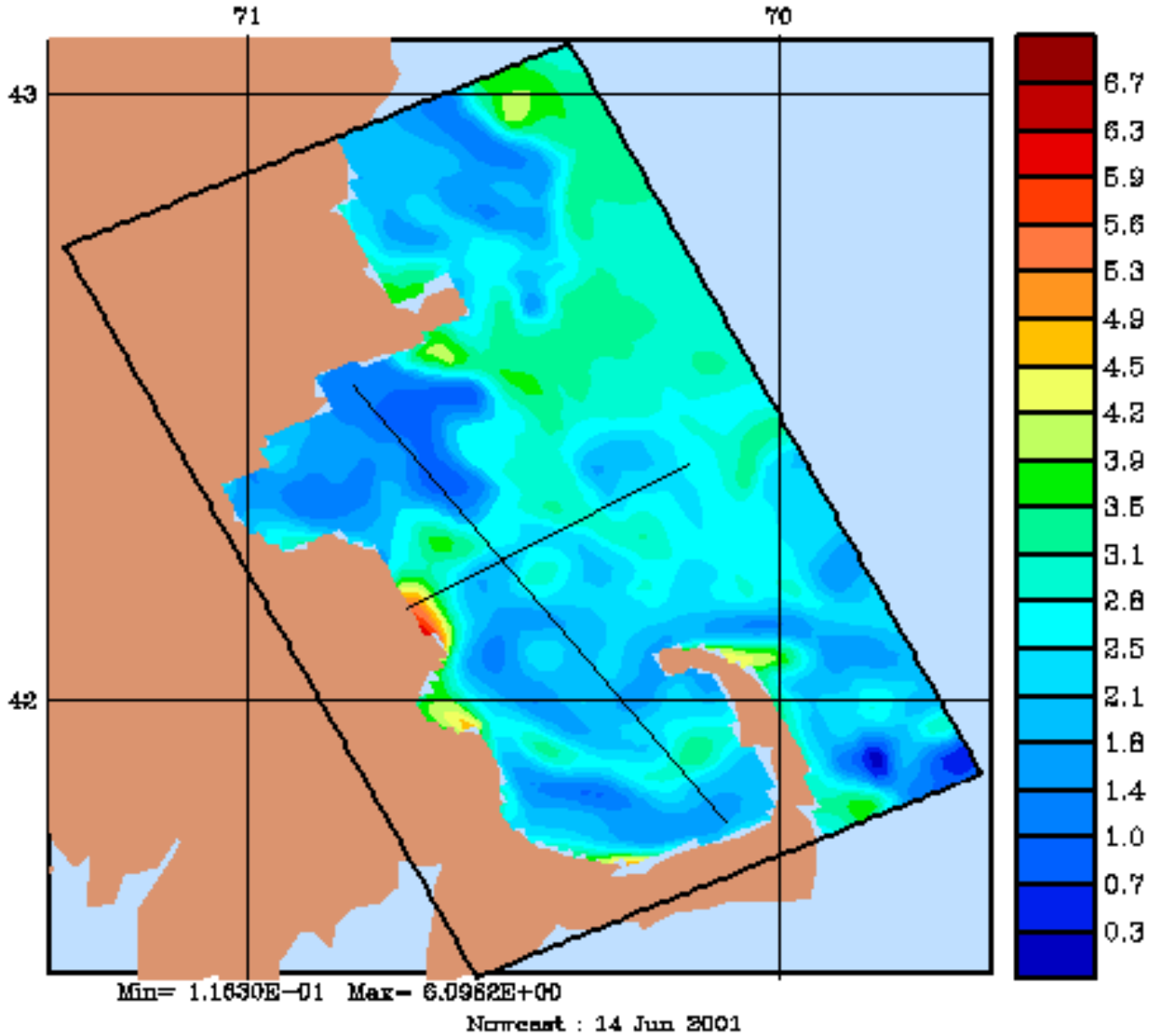
Cape Ann: Physical instabilities at GOM inflow

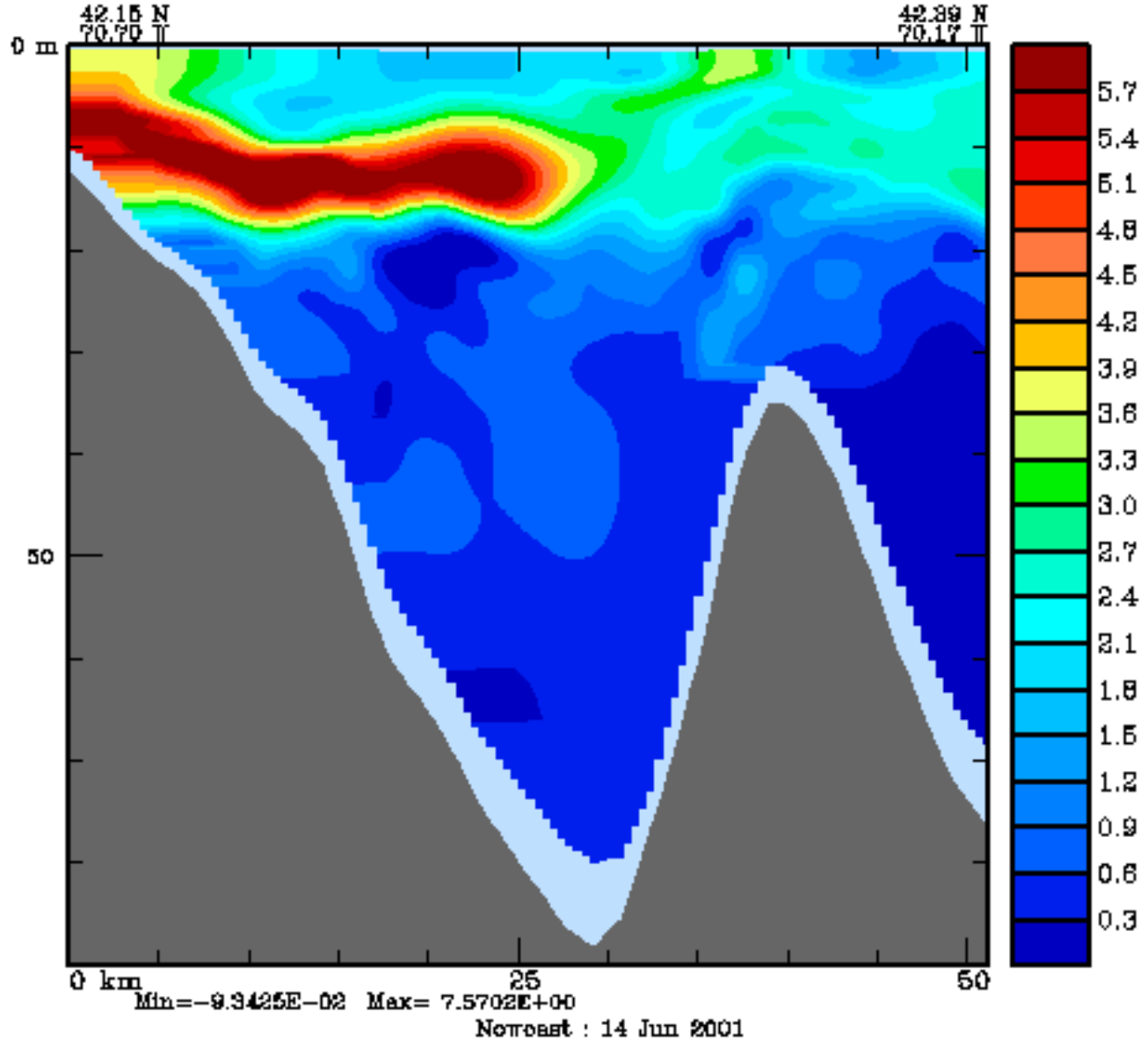
ASCOT-01 Data and Modeling Domains

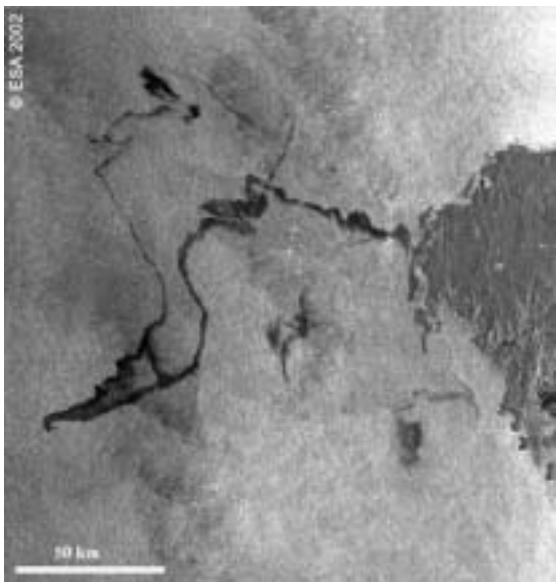
6-26 June 2001

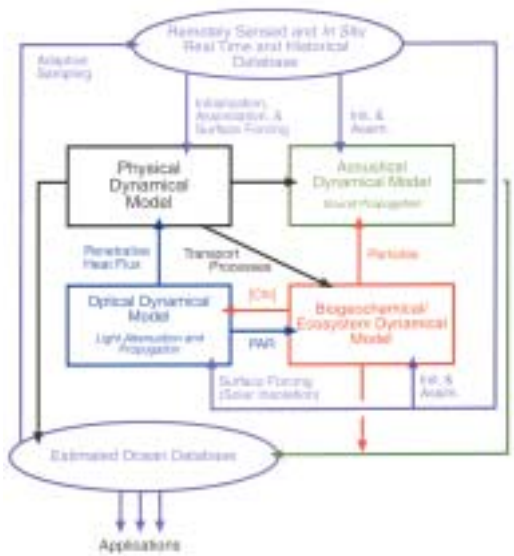




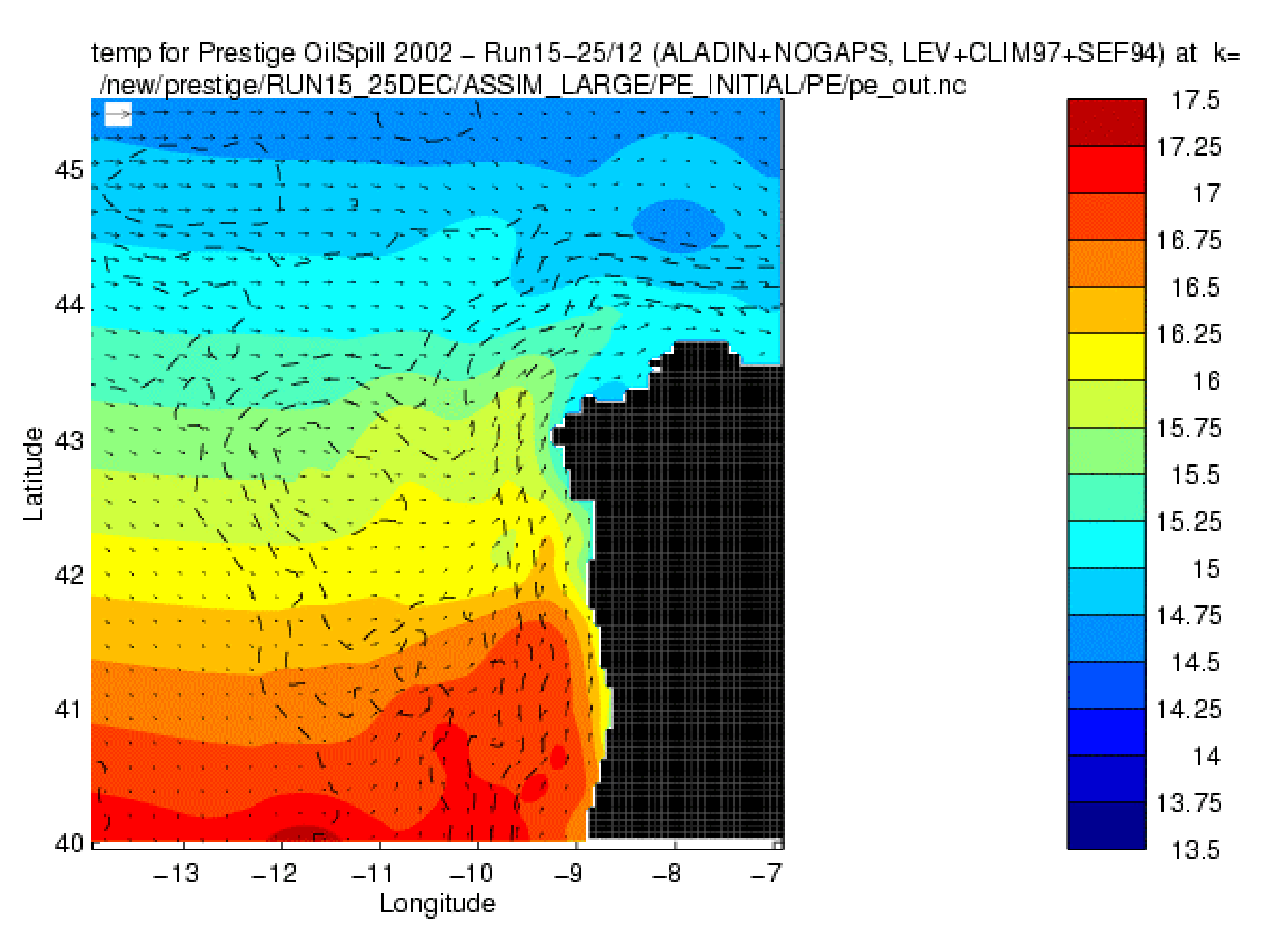

71
70
43
42
6.7
6.3
5.9
5.6
5.3
4.9
4.5
4.2
3.9
3.5
3.1
2.8
2.5
2.1
1.8
1.4
1.0
0.7
0.3
Min= 1.1630E-01 Max= 6.0982E+00
Norcast : 14 Jun 2001


42.15 N
70.70 W
42.39 N
70.17 W
0 m
50
0 km
25
50
5.7
5.4
5.1
4.8
4.5
4.2
3.9
3.6
3.3
3.0
2.7
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
Min=-9.3425E-02 Max= 7.5702E+00
Nowcast : 14 Jun 2001





INSTITUTO ESPAÑOL DE OCEANOGRAFÍA

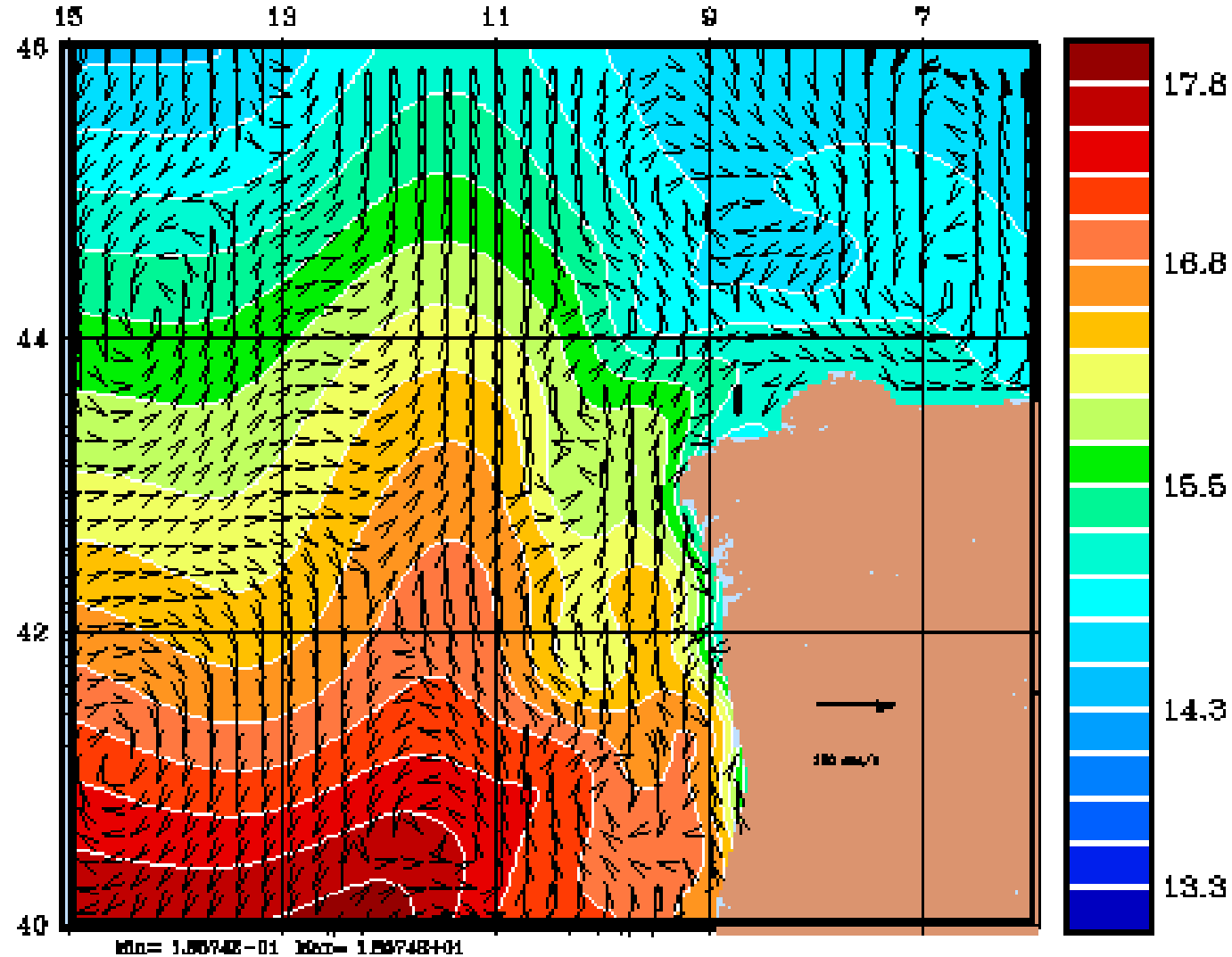

temp for Prestige OilSpill 2002 – Run15–25/12 (ALADIN+NOGAPS, LEV+CLIM97+SEF94) at k=
/new/prestige/RUN15_25DEC/ASSIM_LARGE/PE_INITIAL/PE/pe_out.nc
Latitude
45
44
43
42
41
40
−13
−12
−11
−10
−9
−8
−7
Longitude
17.5
17.25
17
16.75
16.5
16.25
16
15.75
15.5
15.25
15
14.75
14.5
14.25
14
13.75
13.5

Surface Temperature & Velocity

Prestige Oil Spill (Run 87)

SEF0S84,CLIMA27+NovGDEM; CorrideSaavedra02+DecGDEM

ALADIN (10km) + NOGAPS (1°)



Nowcast : 8 Dec 2002

- **Oceanic Dynamical Processes Interactive over Multiple Scales in Space and Time Importantly Influence Both Climate and Life in the Sea.**

- **Internal Ocean Weather Forecasting is Accelerating Progress in Interdisciplinary Ocean Science and Enabling Powerful New Methods for Operations and Management**