# THE GLOBAL COASTAL OCEAN: INTERDISCIPLINARY MULTISCALE PROCESSES, REGIONAL DYNAMICS AND SYNTHESES

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Harvard University

## THE GLOBAL COASTAL OCEAN

- **Interesting and important interdisciplinary marine system**
- **Natural laboratory for fundamental coupled physical-biological-chemical sedimentation processes**
- **Contribution to global ocean dynamics generally?**

## COASTAL OCEAN INTERACTIONS

- **Link together the land, the open sea, the atmosphere and the underlying sediments**
- **Impact global processes disproportionately to relative volume**

## COASTAL ZONE CHANGES

- **Local and global forcings**
- **Natural and anthropogenic origins**
- **Sensitive to climate change**
- **Increasing human coastal populations and impact**

## COASTAL OCEAN MANAGEMENT

- **Scientific understanding essential input to advanced methods**

The effective management and protection of coastal ecosystems must be science-based. With this general purpose in mind, the **COASTS** Programme, sponsored by the Intergovernmental Oceanographic Commission of UNESCO and the Scientific Committee on Oceanic Research, was established ***to promote and facilitate research and applications in interdisciplinary coastal and shelf ocean sciences and technology on a global basis to increase scientific understanding of coastal ocean processes***.

# THE SEA
# Ideas and Observations on Progress in the Study of the Seas

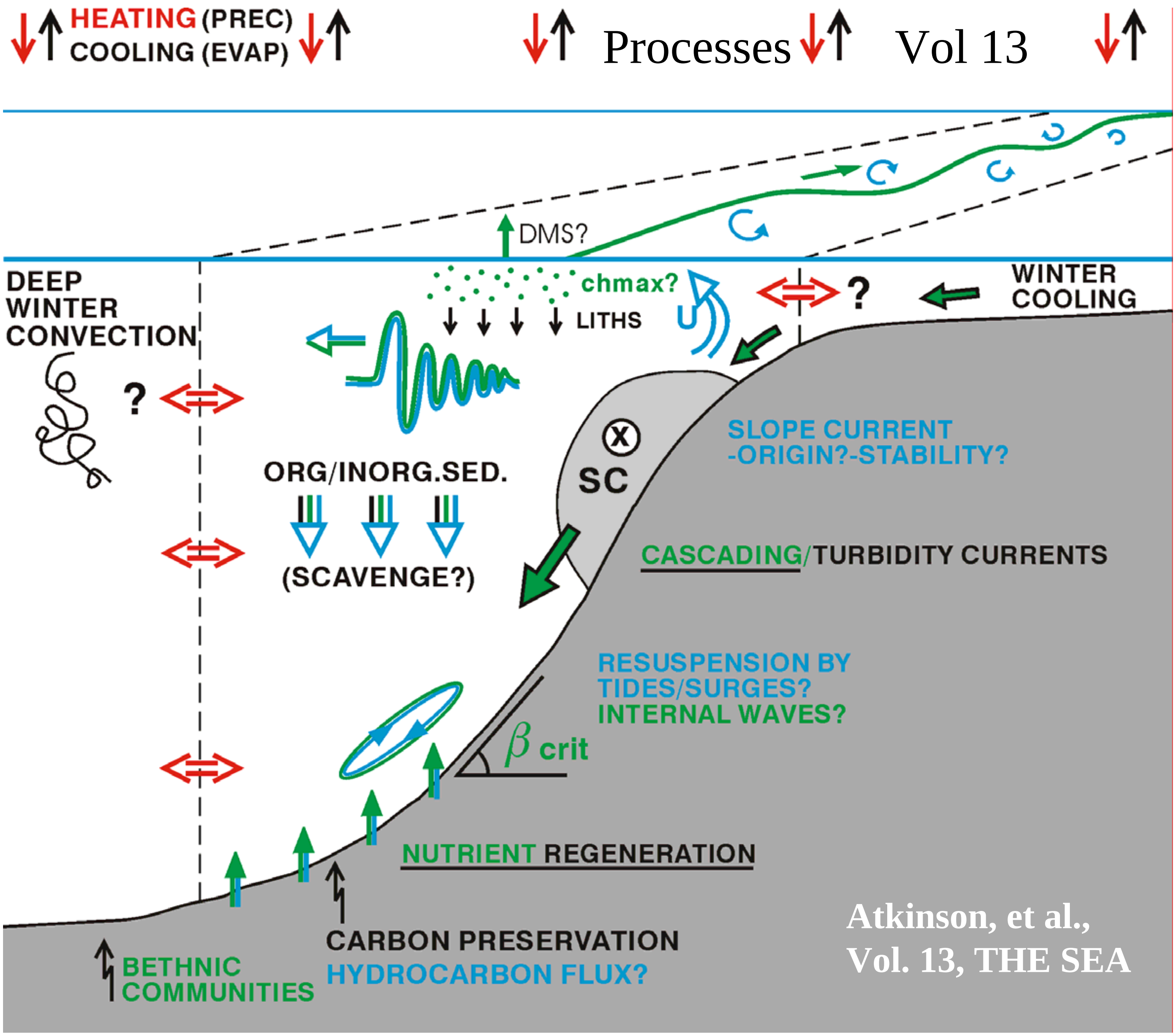
***Volume 13***: THE GLOBAL COASTAL OCEAN: MULTISCALE INTERDISCIPLINARY PROCESSES

***Volume 14***: THE GLOBAL COASTAL OCEAN: INTERDISCIPLINARY REGIONAL STUDIES AND SYNTHESES

Part A – Pan-regional Syntheses and the Coasts of North America and South America and Asia
Part B – The Coasts of Africa, Europe, Middle East, Oceania and Polar Regions.

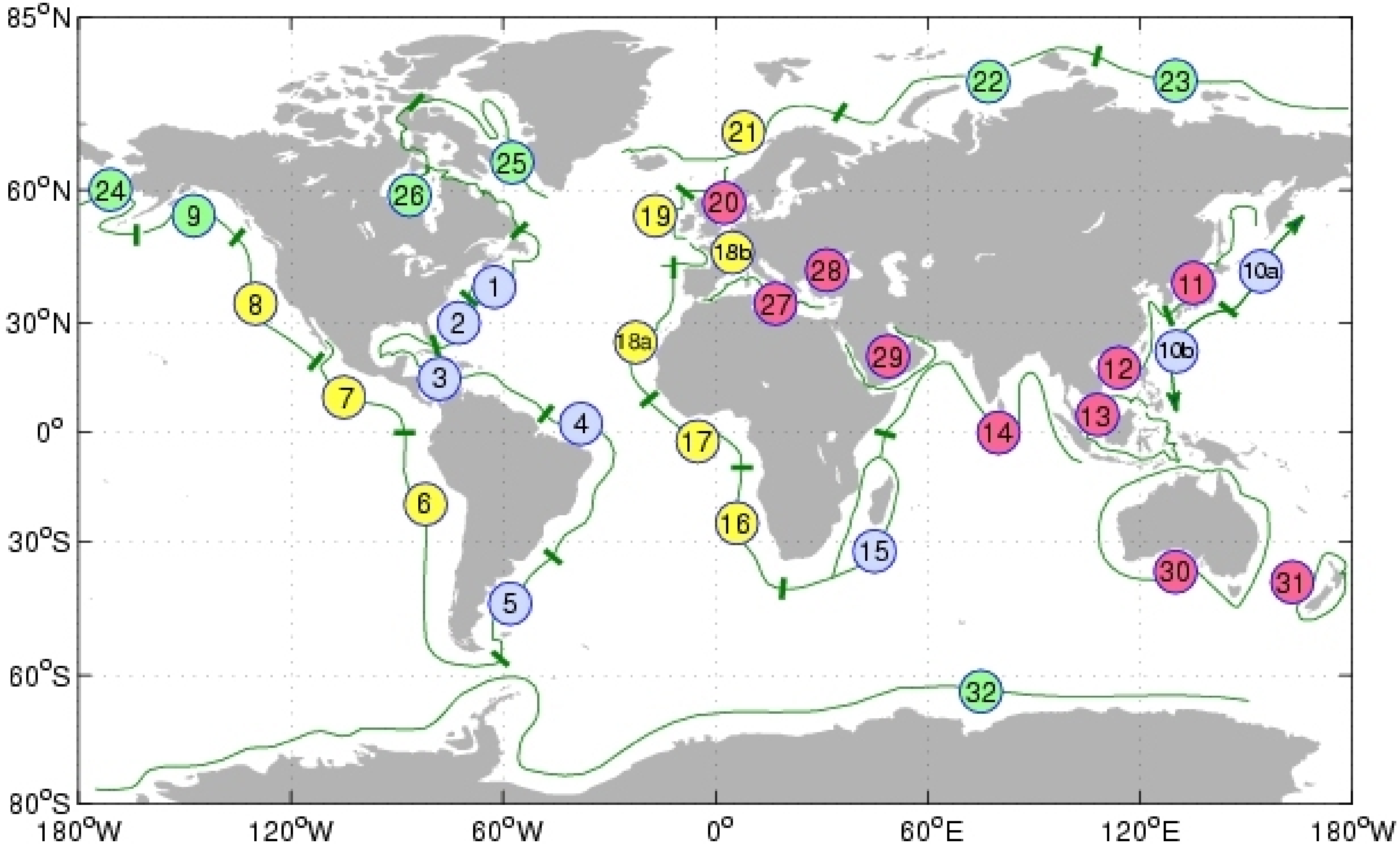
***Allan R. Robinson and Kenneth H. Brink, Editors***

**THE VOLUMES COMPRISE 60 CHAPTERS, 2550 PAGES, AUTHORED BY 170 INTERNATIONAL SCIENTISTS.**



HEATING (PREC)
COOLING (EVAP)
DMS?
chmax?
LITHS
DEEP WINTER CONVECTION
?
WINTER COOLING
?
U
SC
SLOPE CURRENT -ORIGIN?-STABILITY?
ORG/INORG.SED.
(SCAVENGE?)
CASCADING/TURBIDITY CURRENTS
RESUSPENSION BY TIDES/SURGES? INTERNAL WAVES?
β crit
NUTRIENT REGENERATION
CARBON PRESERVATION
HYDROCARBON FLUX?
BETHNIC COMMUNITIES
Atkinson, et al., Vol. 13, THE SEA

# Regions and Syntheses – Vol. 14A, B



# Global Coastal Ocean and its Subregions - 1

PRESENTLY NON-UNIFORM TERMINOLOGY

- the coastal ocean, coastal zone, coastal margin, continental shelf, continental margin, shelf sea
- terms used (often without definition) interchangeably by different scientists
- Obfuscates the inter-comparison of quantitative estimates of processes

PROPOSED DEFINITION: the coastal ocean - that area, extending offshore from the surf zone and from estuarine mouths, that includes at least the continental shelf and slope, and that also includes waters extending uninterruptedly farther offshore that are (based on temperature or salinity properties only) of shelf or inshore origin

# Global Coastal Ocean and its Subregions - 2

## THE CLASSIFICATION OF SUBREGIONS VIA GEOGRAPHY, GEOMORPHOLOGY AND DYNAMICAL PROCESSES

- 4 panregions - eastern and western boundaries, polar, semi-enclosed seas/islands;
- 5 physical processes - boundary layers, tides, wind and buoyancy forcing, boundary currents;
- 6 offshore zones - near shore, freshwater influence, well mixed, tidal fronts, thermally stratified, shelf-edge;
- 7 biogeochemical processes - subtropical shelf pumps, temperate shelf: biology or physics dominant, upwelling: biology or physics dominant, coral reefs, polar ice pump;
- 7 ecosystem types (permanent and intermittent polar ice, mid-latitude and topographically forced coastal, upwelling, wet and dry tropical.

**COMMON SCIENTIFIC VERNACULAR NECESSARY FOR COLLABORATIVE INTERDISCIPLINARY RESEARCH AND INTERNATIONAL COOPERATION**

# Status of Knowledge

## *The coastal ocean's role in the global carbon cycle*

- Is coastal ocean net source or sink of $CO_2$ to atmosphere?
- Conclusions controversial at this time
  - Varying definitions
  - Balances difficult to work out

## *High coastal ocean biological production*

- Most biologically productive part of world's oceans
- Processes which drive productivity not globally well known

## *Natural ecosystem variability*

- Shifts pre-date significant human influences
- Physical-biological couplings under investigation

## *The role of the bottom*

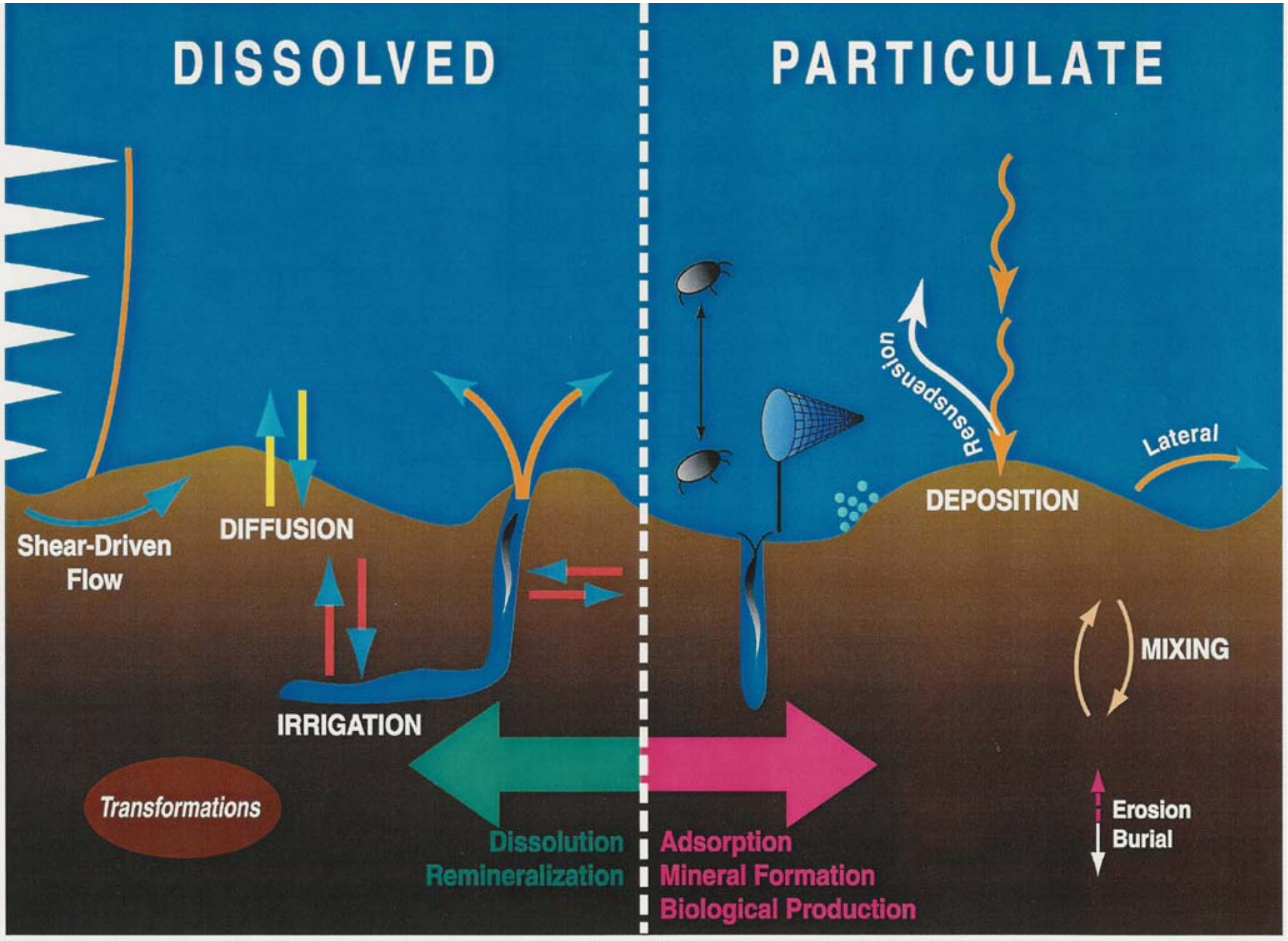
- Coupling of bottom to water column generally poorly quantified on a global basis

## *Understanding human impacts on the coastal ocean*

- Anthropogenic influences increasingly obvious and diverse
  - Nutrient release can cause harmful algal blooms
  - Fishing practices can change ecosystems

## *Need for more data*

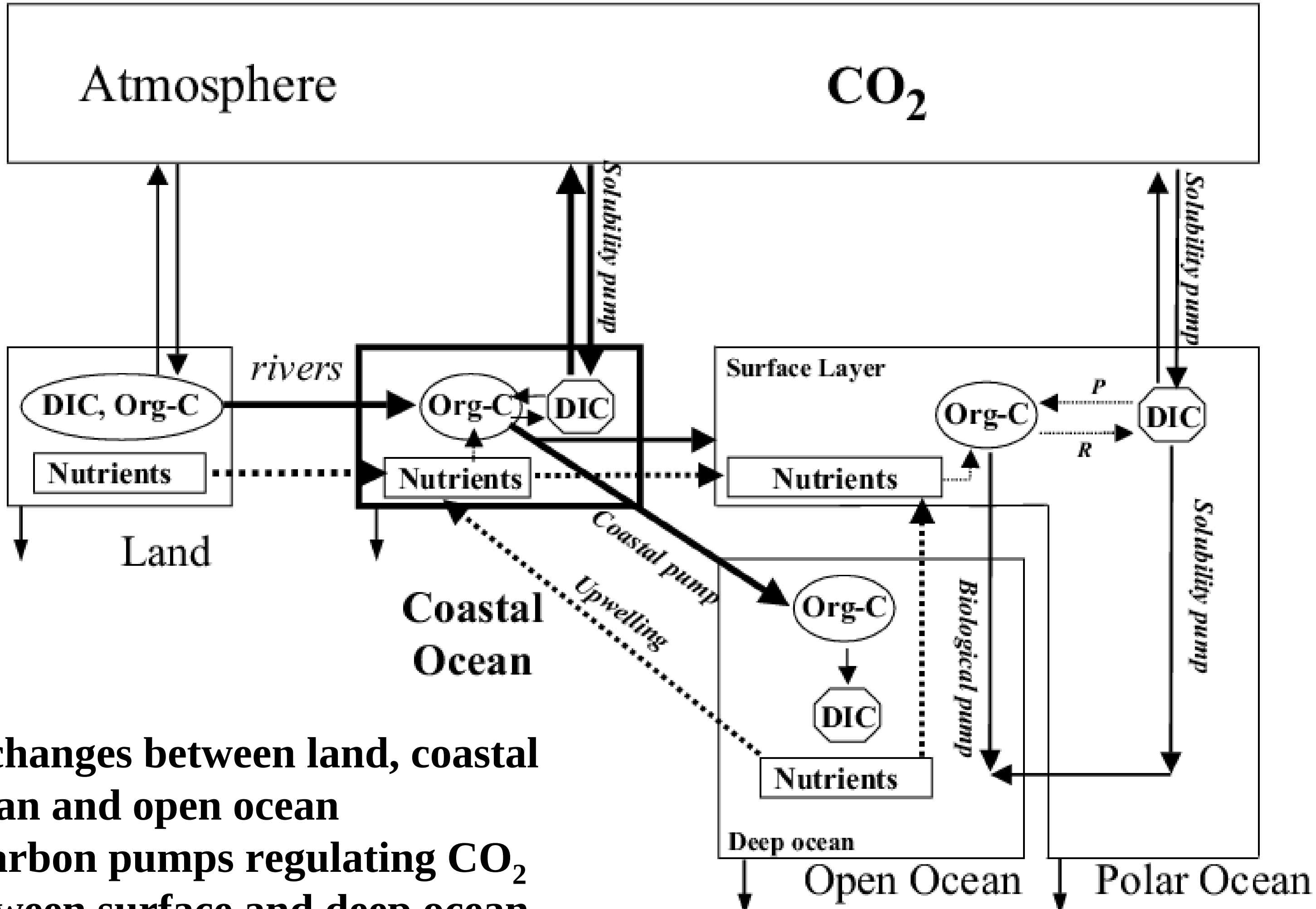
# Sediment Dynamics – Transport and Reaction Processes




- Particulates converted through dissolution and remineralization
- Adsorption, precipitation and biological production creates particulates

**Jahnke, Vol. 13, THE SEA**

# Biogeochemical Dynamics – Carbon and Nutrient Exchanges

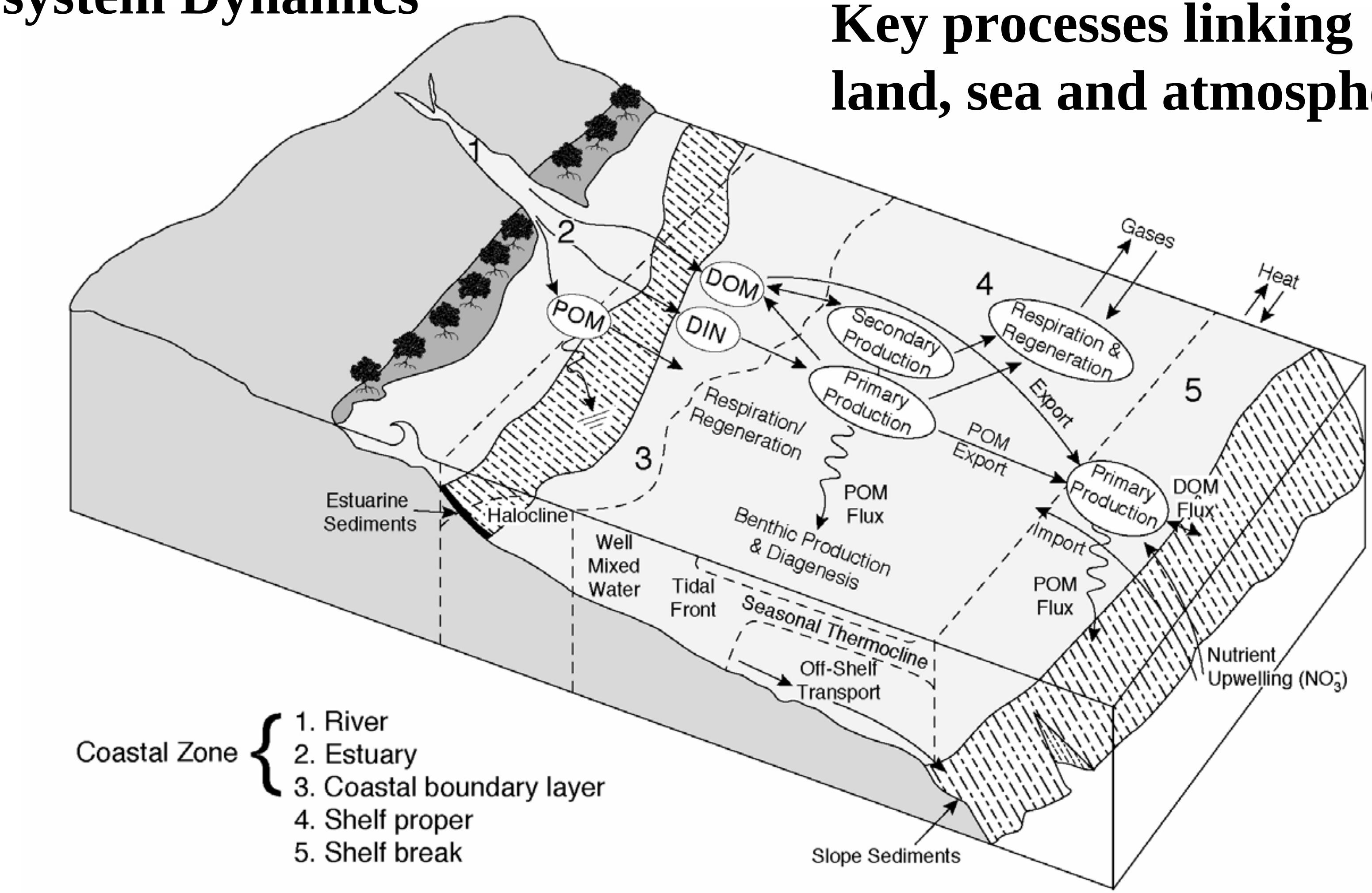



- **Exchanges between land, coastal ocean and open ocean**
- **3 carbon pumps regulating $CO_2$ between surface and deep ocean**
- **Biologically mediated exchanges between inorganic and organic carbon pools**

**Ducklow and McCallister, *et al.*, Vol. 13, THE SEA**

# Ecosystem Dynamics

## Key processes linking land, sea and atmosphere




- Intermingling of estuarine and oceanic boundaries and food webs
- High fertility of coastal ocean ecosystem driven by nutrient inputs from rivers and groundwater, upwelling, exchanges at shelf edge and atmospheric inputs

**Alongi, Vol. 13, THE SEA**

# Measurements and Observations

***Critical reasons for coastal measurements*:**

- Establishing a global baseline of coastal information,
- Discovering ocean processes, understanding how they work, and developing parameterizations,
- Testing hypotheses,
- Driving and evaluating numerical models,
- Observing change, either secular (as in the atmospheric increase of CO2), or low frequency (such as ENSO phenomenology), and
- Essential for monitoring and input to management

***Ability to measure improved radically***

- New sensors (optical techniques, Video Plankton Recorders, etc.)

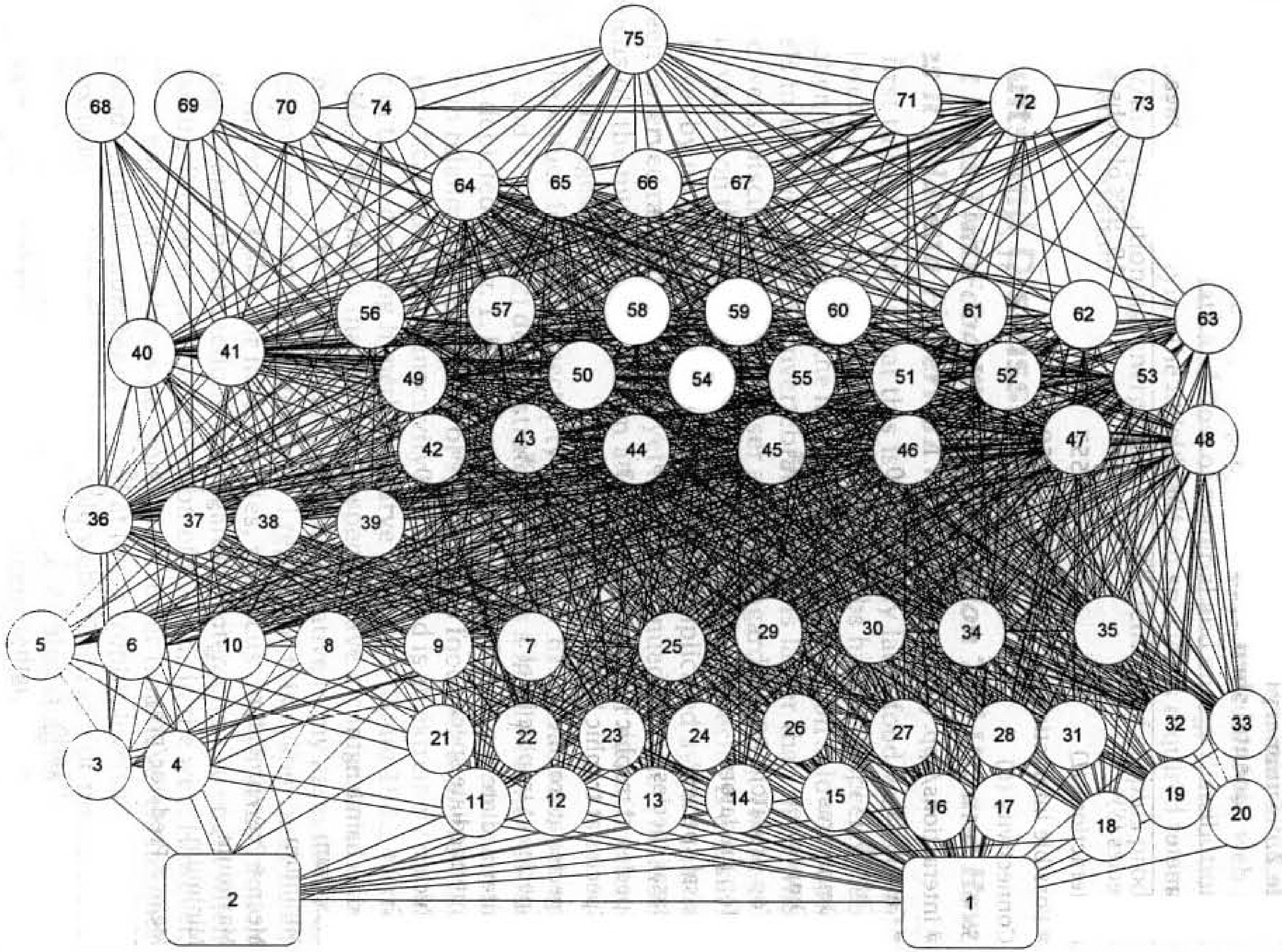
***How to deploy sensors evolving***

- Remote sensing, AUVs, Ocean Observatories

***Knowledge of space/time scales is critical***

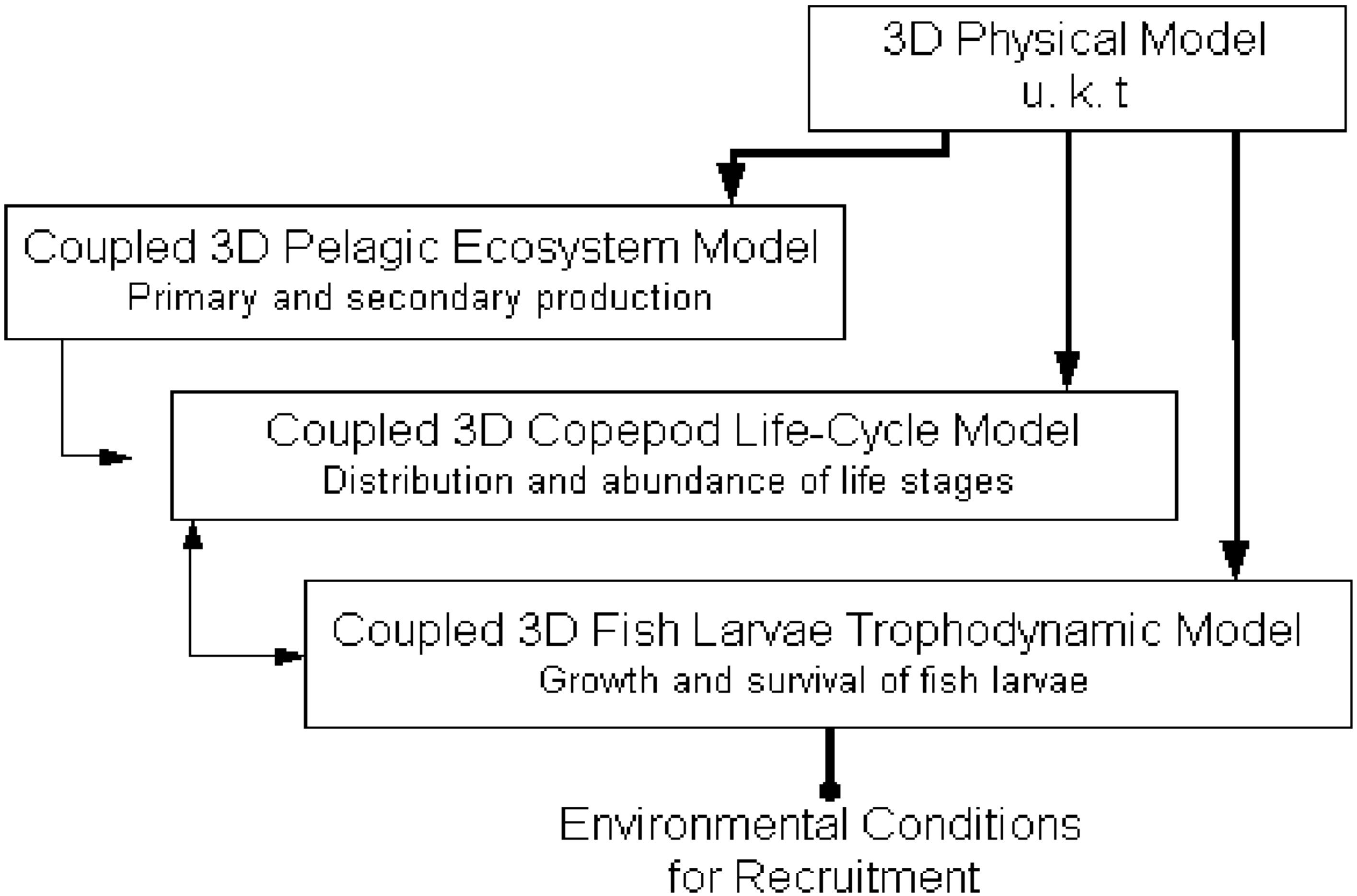
- Frequency, repetition, resolution

# Models




Cury, *et al*., Vol. 13, THE SEA

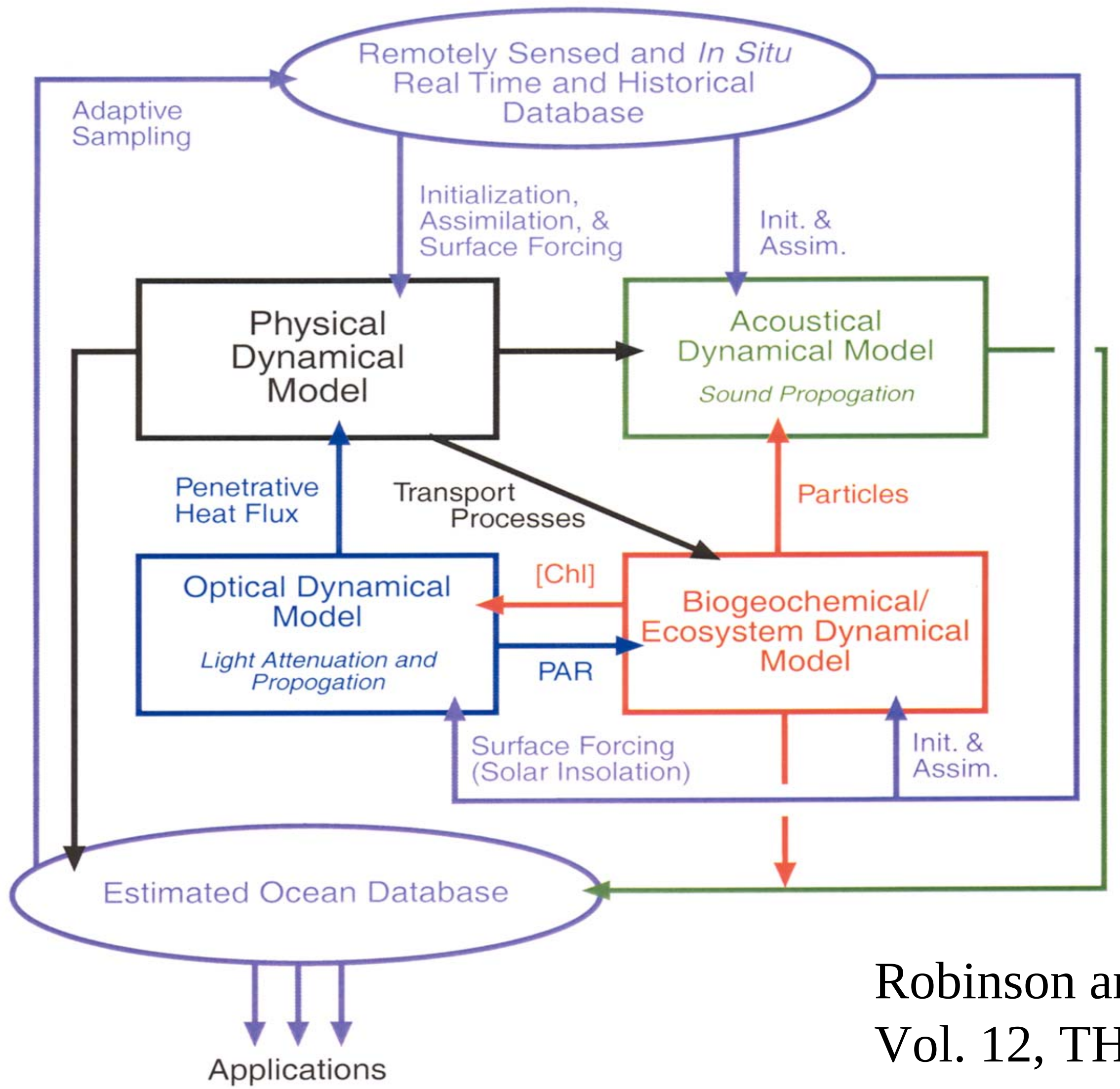
# Linked, Coupled Models




**Runge, *et al.*, Vol. 13, THE SEA**

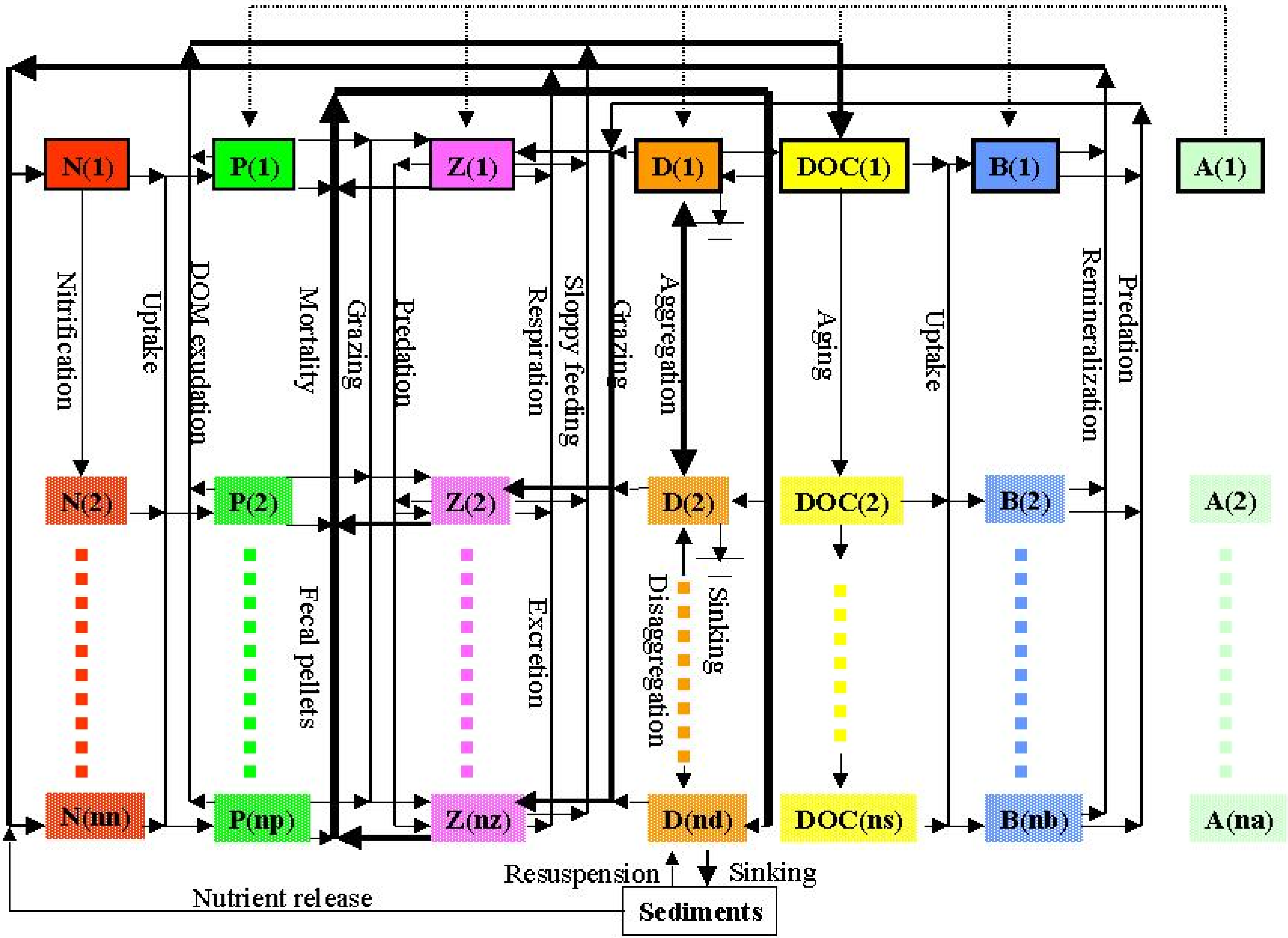
# Linked Coupled Models and Adaptive Modeling

## Harvard Ocean Prediction System - HOPS




Robinson and Lermusiaux,
Vol. 12, THE SEA

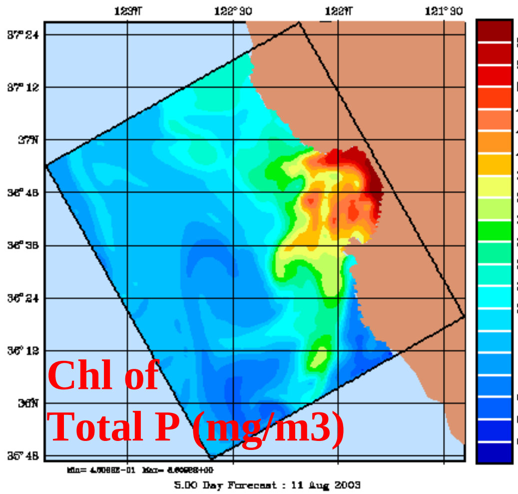
# Harvard Generalized Adaptable Biological Model

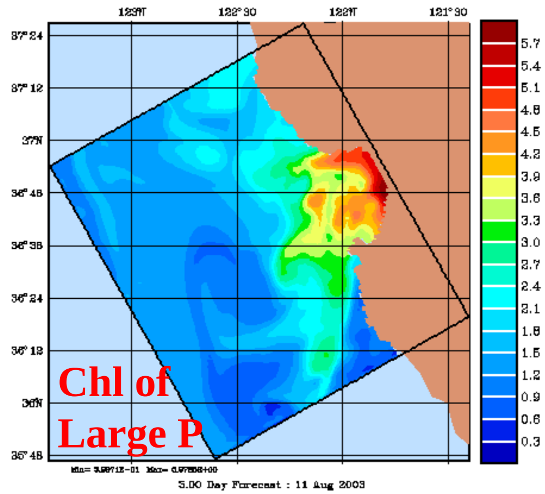


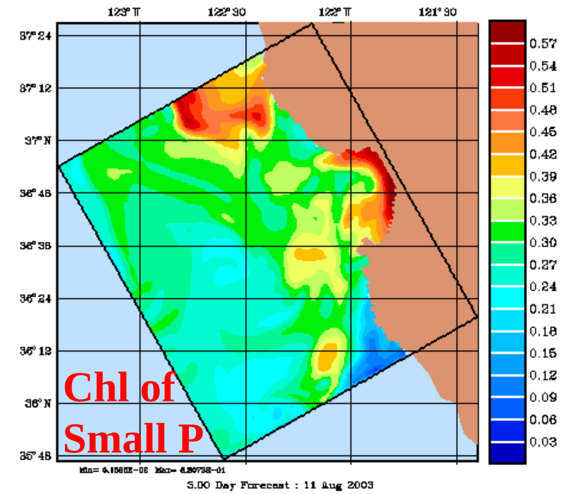

R.C. Tian, P.F.J. Lermusiaux, J.J. McCarthy and A.R. Robinson, HU, 2004

# Towards automated quantitative model aggregation and simplification

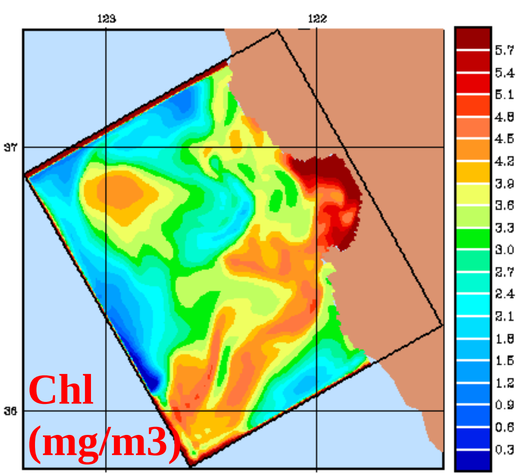
***A priori*** **configuration of generalized model on Aug 11 during an upwelling event**

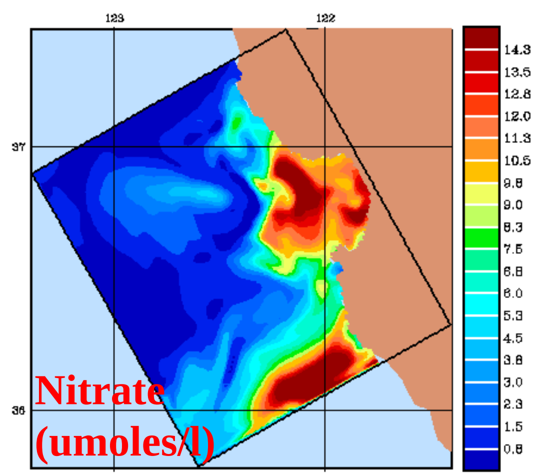


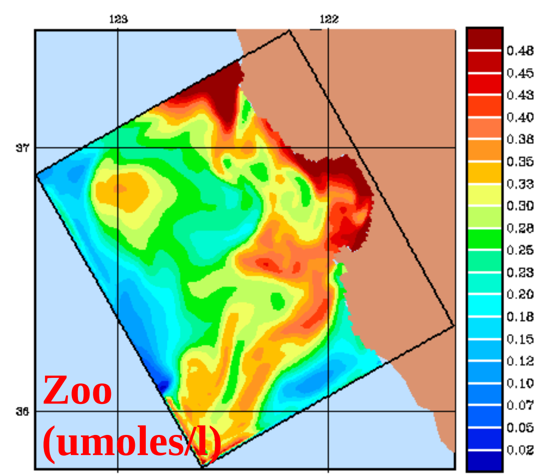




**Simple NPZ configuration of generalized model on Aug 11 during same upwelling event**

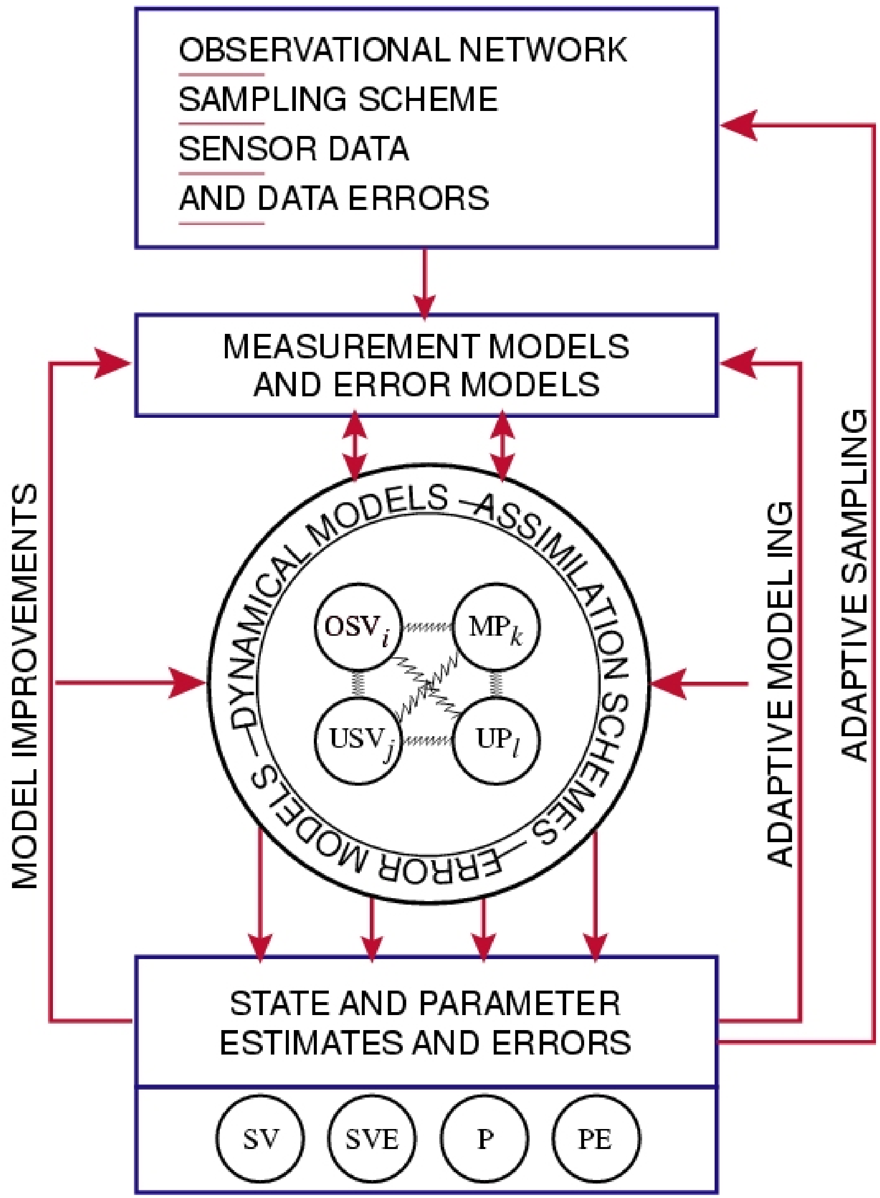



Dr. Rucheng Tian

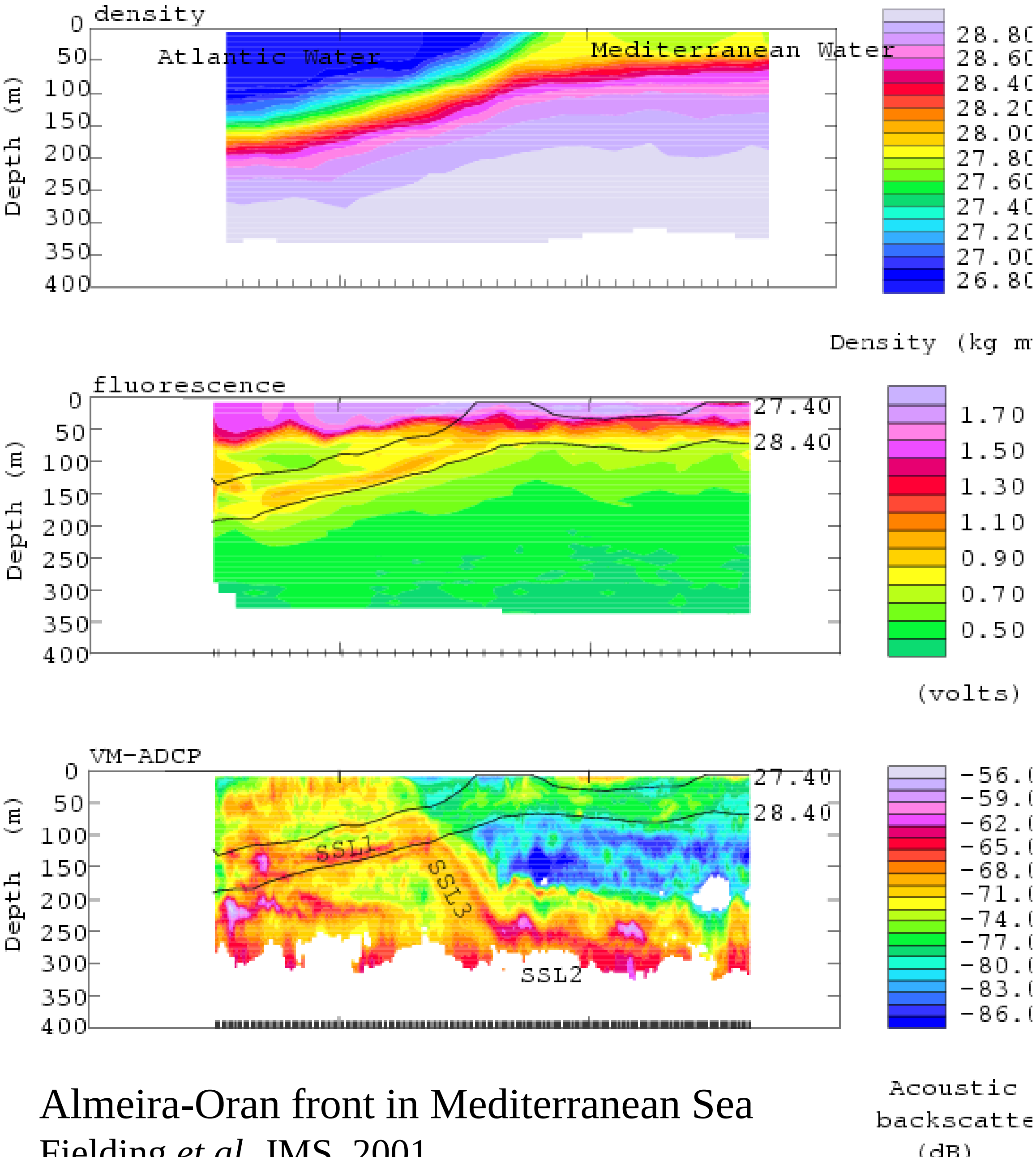
# Measurements and Models: Data Assimilation in Advanced Interdisciplinary Ocean Prediction Systems




SV: STATE VARIABLE
P: PARAMETER
O: OBSERVED
M: MEASURED
U: UNOBSERVED OR UNMEASURED
E: ERROR
: DYNAMICAL LINKAGES

Robinson and Lermusiaux,
Vol. 12, THE SEA

# Interdisciplinary Processes - Biological-Physical-Acoustical Interactions




Physics - Density

Biology – Fluorescence (Phytoplankton)

Acoustics – Backscatter (Zooplankton)

Almeira-Oran front in Mediterranean Sea
Fielding *et al*, JMS, 2001

Griffiths *et al*.,
Vol. 12, THE SEA

# Coupled Interdisciplinary Data Assimilation

$\boldsymbol{x} = [\boldsymbol{x}_A \;\; \boldsymbol{x}_O \;\; \boldsymbol{x}_B]$ **Unified interdisciplinary state vector**

Physics: $\boldsymbol{x}_O = [T, S, U, V, W]$

Biology: $\boldsymbol{x}_B = [N_i, P_i, Z_i, B_i, D_i, C_i]$

Acoustics: $\boldsymbol{x}_A = [\text{Pressure } (p), \text{Phase } (\varphi)]$

$$\boldsymbol{P} = \varepsilon \left\{ (\hat{\boldsymbol{x}} - \boldsymbol{x}^t)(\hat{\boldsymbol{x}} - \boldsymbol{x}^t)^T \right\}$$

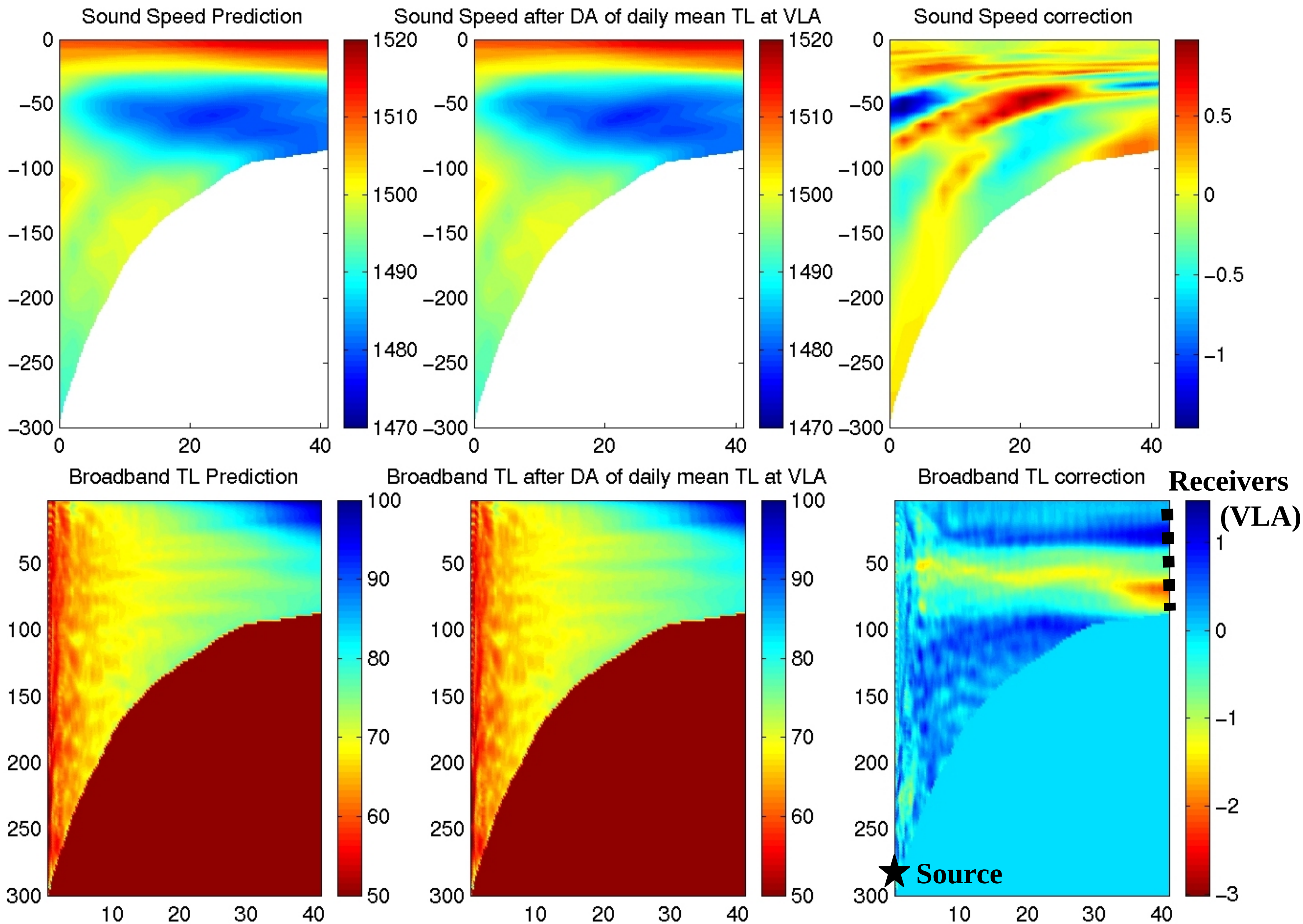
**Coupled error covariance with off-diagonal terms**

$$\boldsymbol{P} = \begin{pmatrix} P_{AA} & P_{AO} & P_{AB} \\ P_{OA} & P_{OO} & P_{OB} \\ P_{BA} & P_{BO} & P_{BB} \end{pmatrix}$$

**Lermusiaux and Chiu,**
***Acoustic Variability, 2002***
**Robinson and Lermusiaux,**
***Theoretical and Computational Acoustics, 2003***

# Coupled Physical-Acoustical Data Assimilation of real TL-CTD data:

TL measurements affect TL and C everywhere.



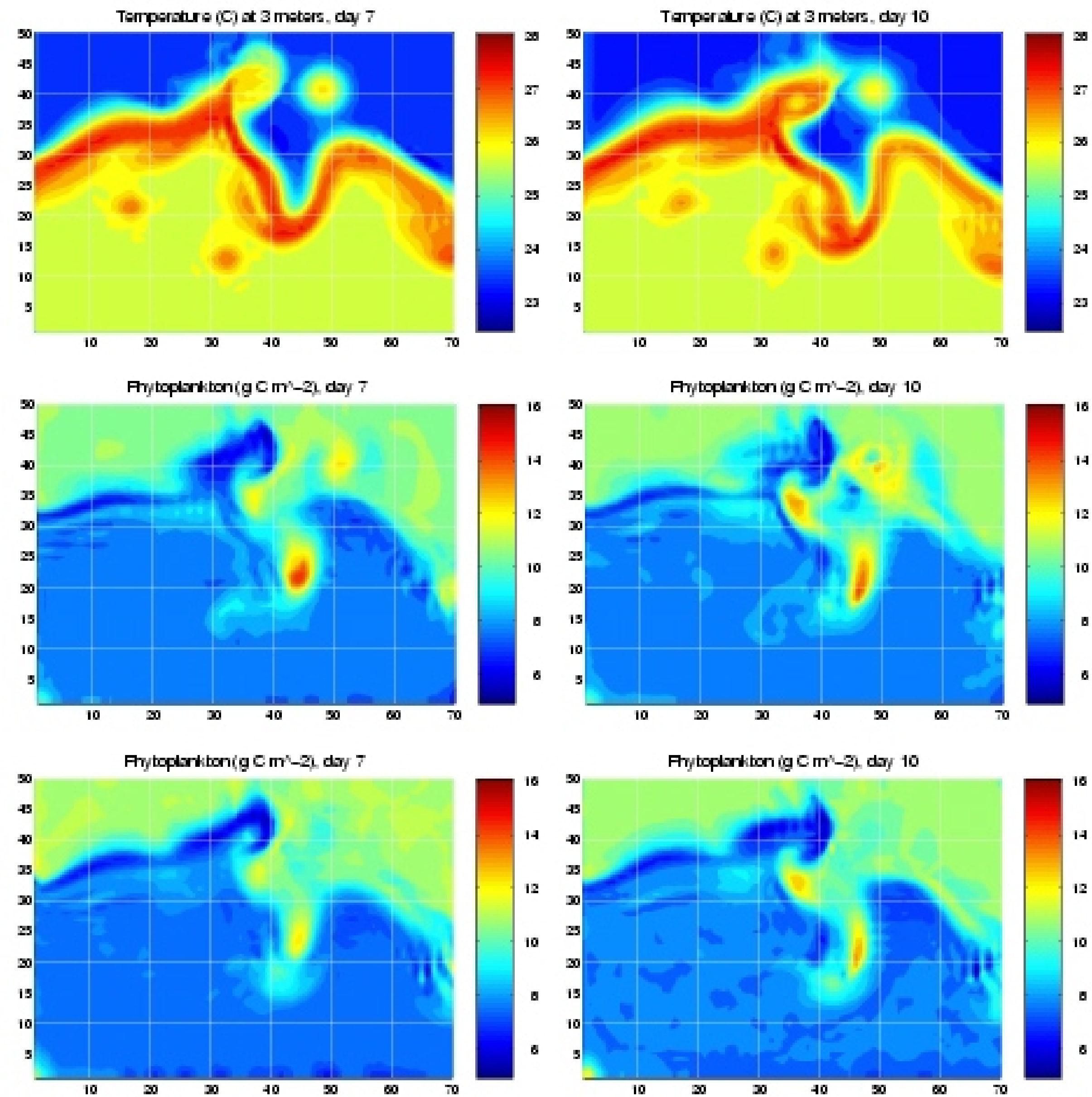
# Coupled Physical-Biological Data Assimilation – Compatibility Issues

**Day 7** **Day 10**

Temperature

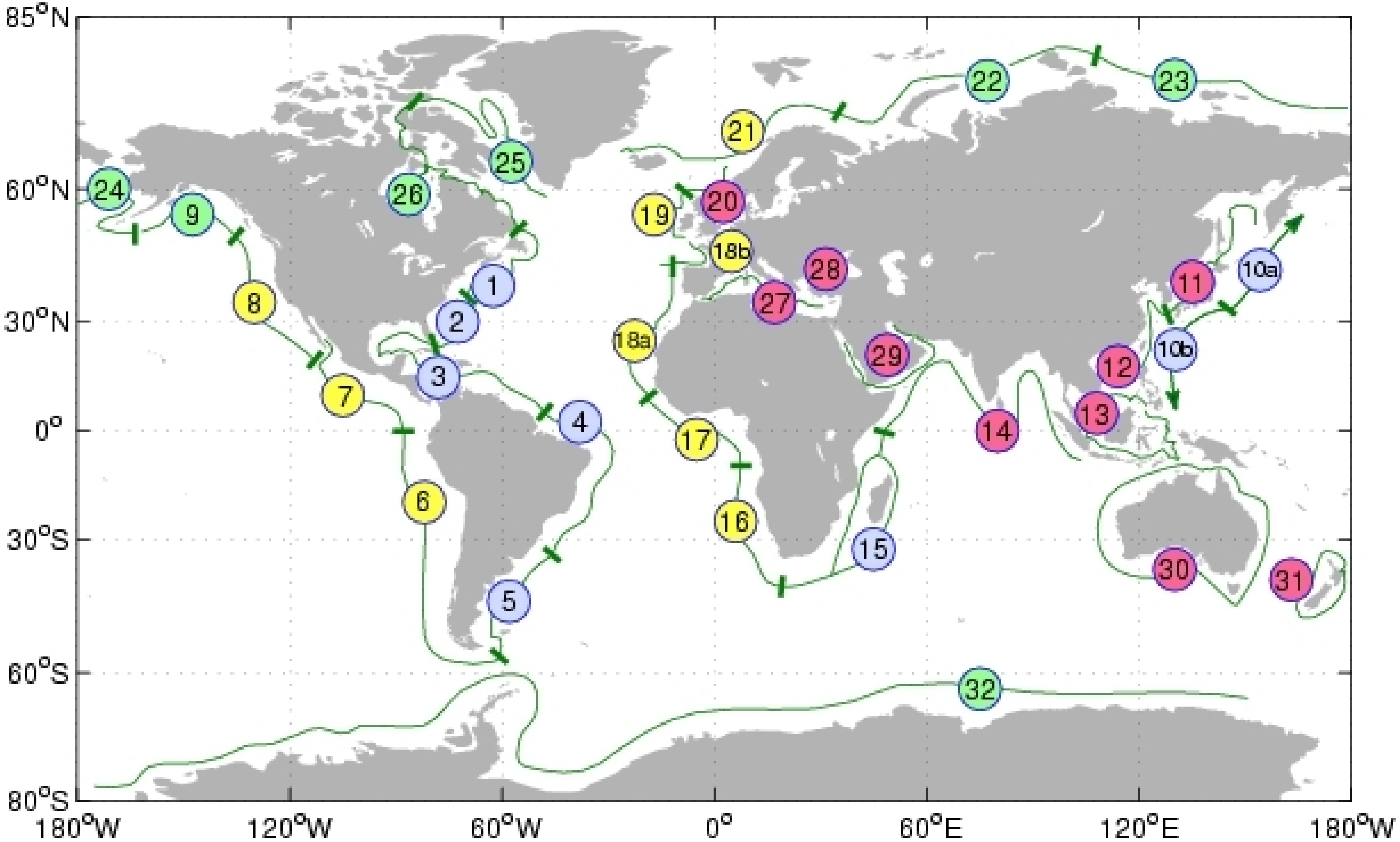
Phytoplankton
Physical Assim.

Phytoplankton
Coupled Assim.




**Anderson and Robinson,**
**DSR I, 48, 1139-1168**.

# Regions and Syntheses



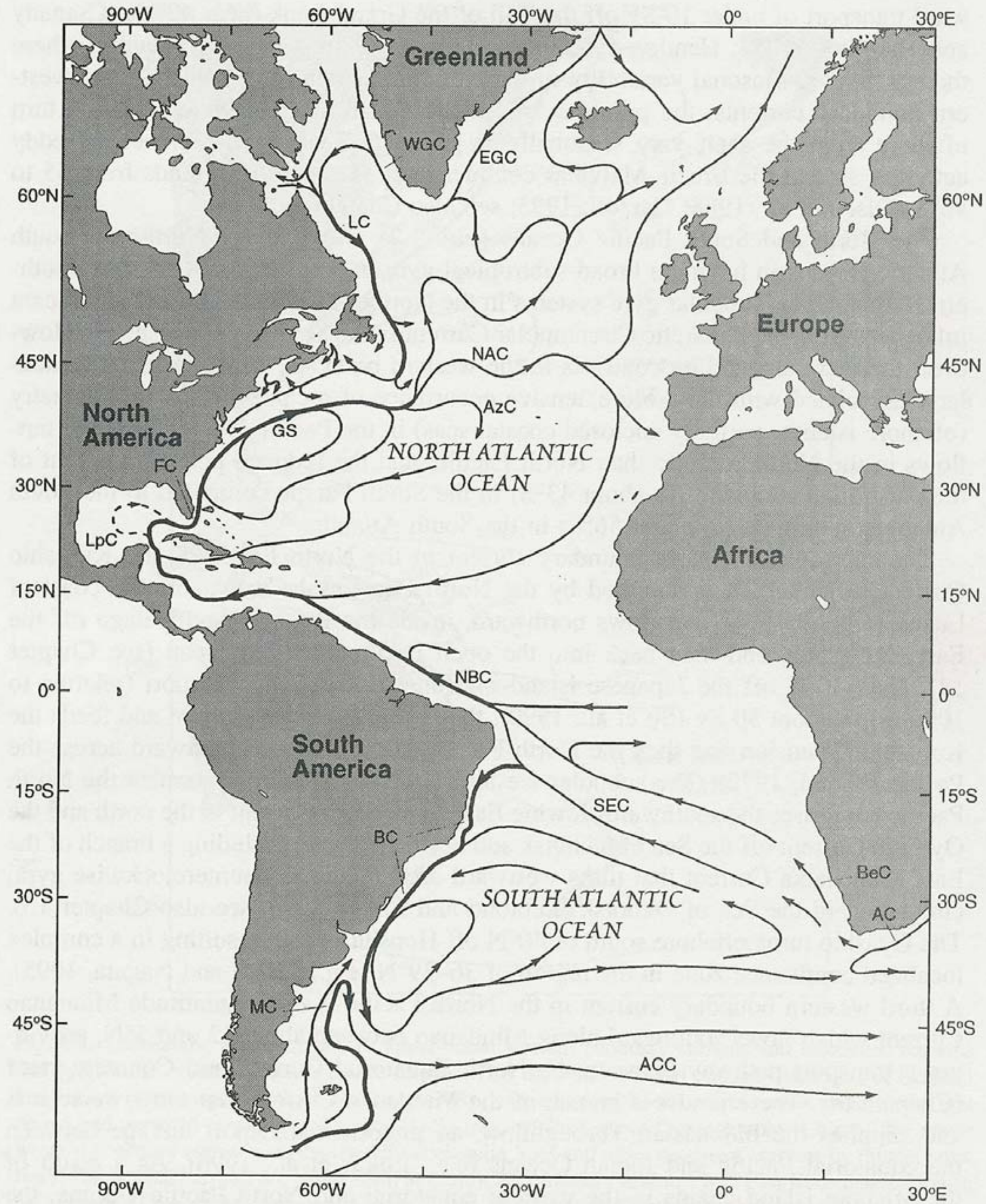

Western boundary – blue

Polar boundary – green

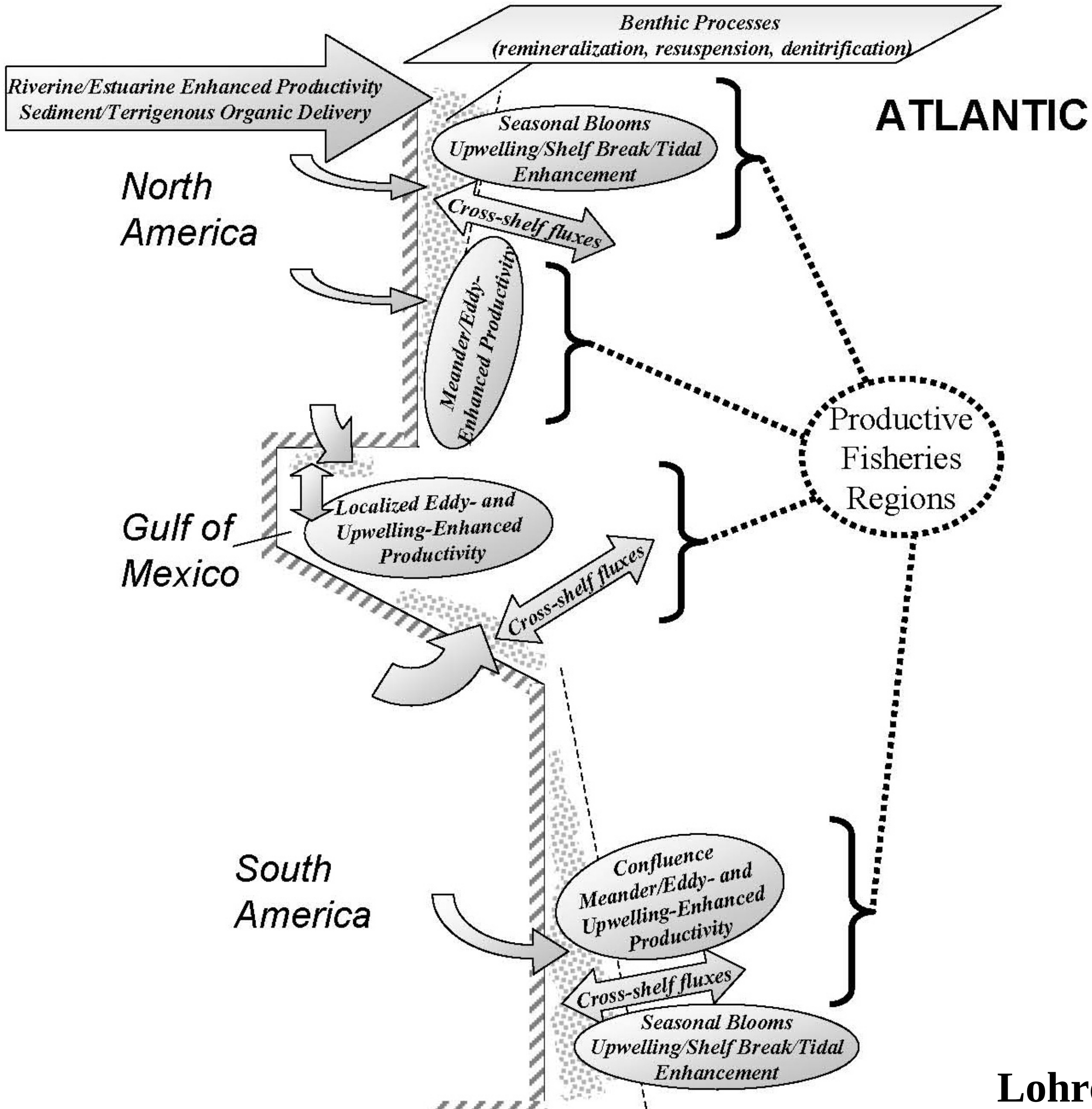
Eastern boundary – yellow

Semi-enclosed seas - red

# Western Boundaries




**Loder, Boicourt and Simpson,**
**Vol. 11, THE SEA**

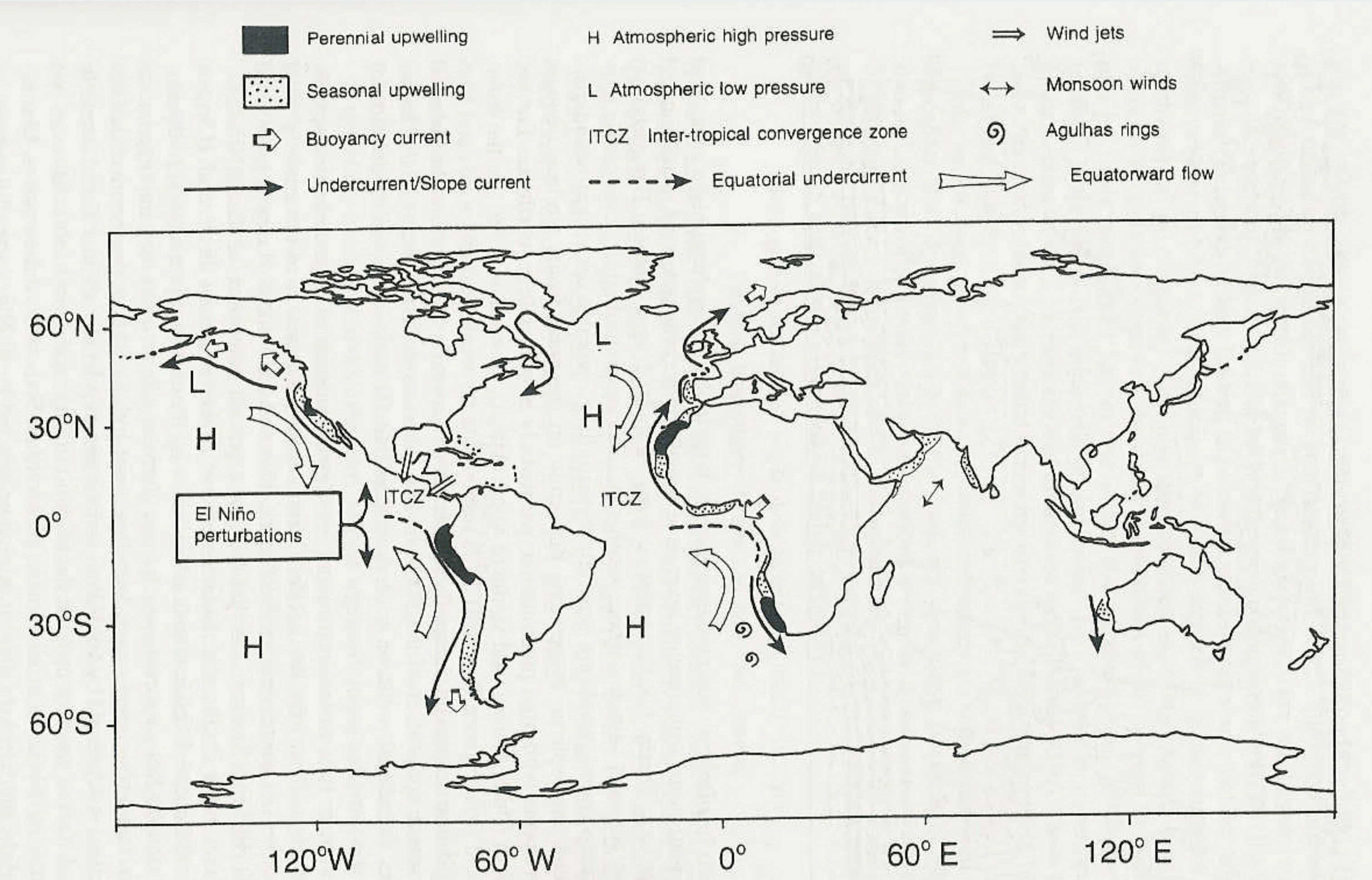



**Lohrenz and Castro**
**Vol. 14A, THE SEA**

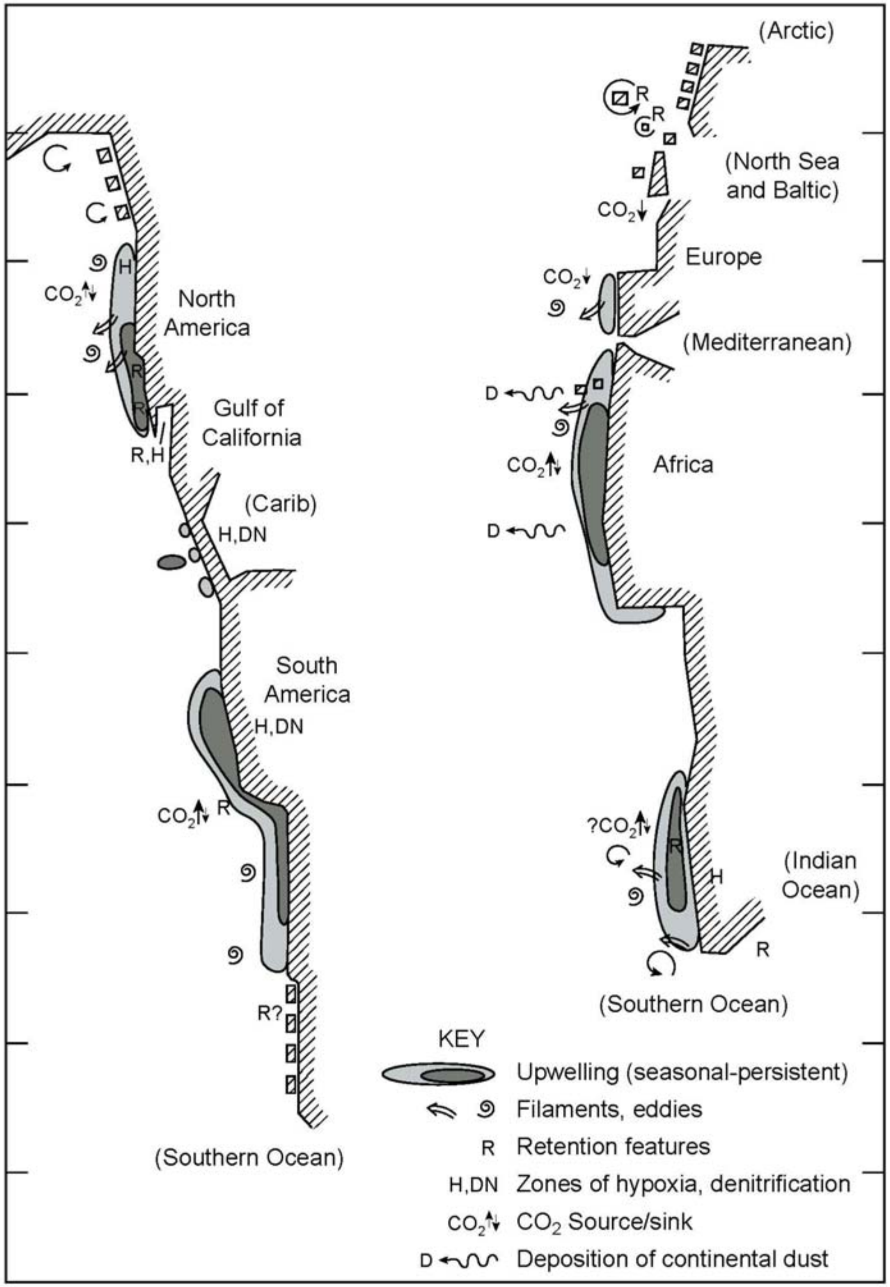
# Western Ocean Boundaries

- **Complex circulation patterns, typified by eddies and current instabilities, are key to enhanced nutrient entrainment and high biological productivity.**
- **Exchanges between offshore and coastal waters create a dynamic environment, in many cases stimulating high primary productivity.**
- **Role of intrusions of subsurface waters in enhancing nutrient supply is important for extensive areas of continental shelves.**
- **Linkages are evident within regions, and important linkages exist between western boundary current systems and other regions. Consequences and importance for ecosystem processes have only begun to be explored.**
- **Lack of observations limits understanding of physics and associated ecosystem processes. Examples: linkages between primary production and higher trophic levels, and impact on recruitment of key fisheries species; biogeochemical rates critical for carbon and nitrogen budgets; microbial processing of terrigeneous organic matter; denitrification; and, nitrogen fixation.**

# Eastern Boundaries




**Hill, Hickey, Shillington, Strub, Brink, Barton, Thomas, Vol. 11, THE SEA**




**Mackas, Strub, Thomas, Montecino, Vol. 14A, THE SEA**

# Eastern Ocean Boundaries

- ***Eastern Boundary Current mid & low latitude upwelling zones*. Includes four of the world's five major boundary current upwelling systems. Characteristics: wind-driven upwelling and high productivity of plankton and pelagic fish; strong alongshore advection; poleward undercurrent; seaward extension of the boundary current and biological system beyond the continental shelf; physical forcing by local winds and by larger scale teleconnections, and very low to moderate precipitation and coastal freshwater inputs.**

- ***Equatorial*. Characterized by wet and warm climates. Include or adjoin the Inter-tropical Convergence Zone (ITCZ), and strongly affected by the ITCZ throughout the year. Alongshore advection is strong. Physical forcing by local winds is intense but probably of less overall importance than external forcing caused by variation in the strength and location of zonal winds and currents.**

- ***High latitude, poleward surface flow and downwelling*. Regions include southern Chile in the southern hemisphere and in the northern hemisphere the Pacific coast of Alaska and Canada north of ~52°N, the Bay of Biscay, the "Celtic Seas" and the Norwegian Sea/Faeroe/Iceland regions off European coasts of the Atlantic. All have relatively large inputs of freshwater from precipitation and coastal discharge, large seasonal ranges of temperature, wind mixing, and productivity, and stormy winter conditions.**

# Eastern Ocean Boundaries

Important research issues and oceanographic mechanisms are important in all or most regions, including:

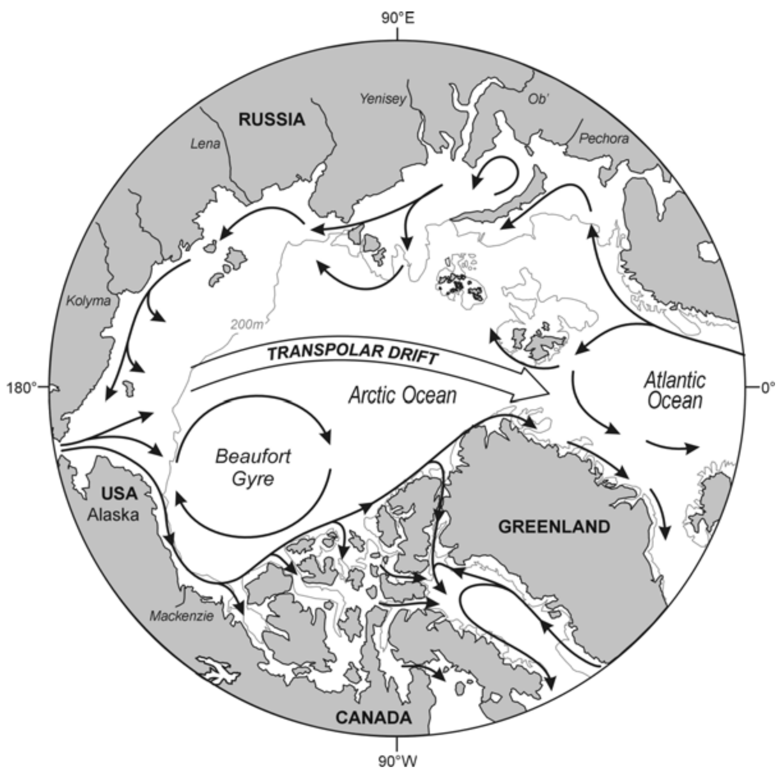
- **Mechanisms and rates of nutrient supply, and differences in these between macronutrients (N, P, Si) vs. micronutrients (Fe, Cu, . . .)**

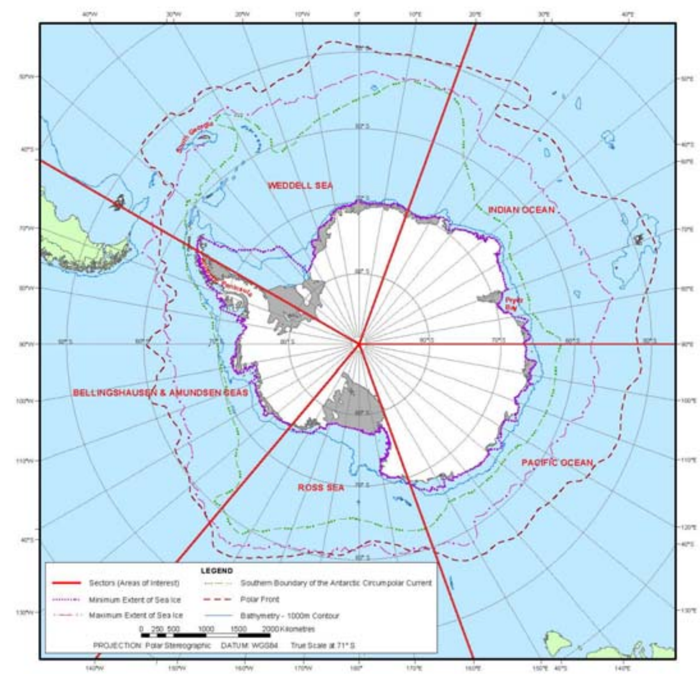
- **Within-region zonation of habitat utilization – 'hotspots' of high productivity and abundance, spawning centers, nursery grounds.**

- **Strong variability at interannual to decadal time scales. Important between- and within-region contrasts in seasonal and event-scale timing and sequencing of key processes, especially relative phasing of nutrient supply, advection, mixing, and somatic and reproductive growth of biota.**

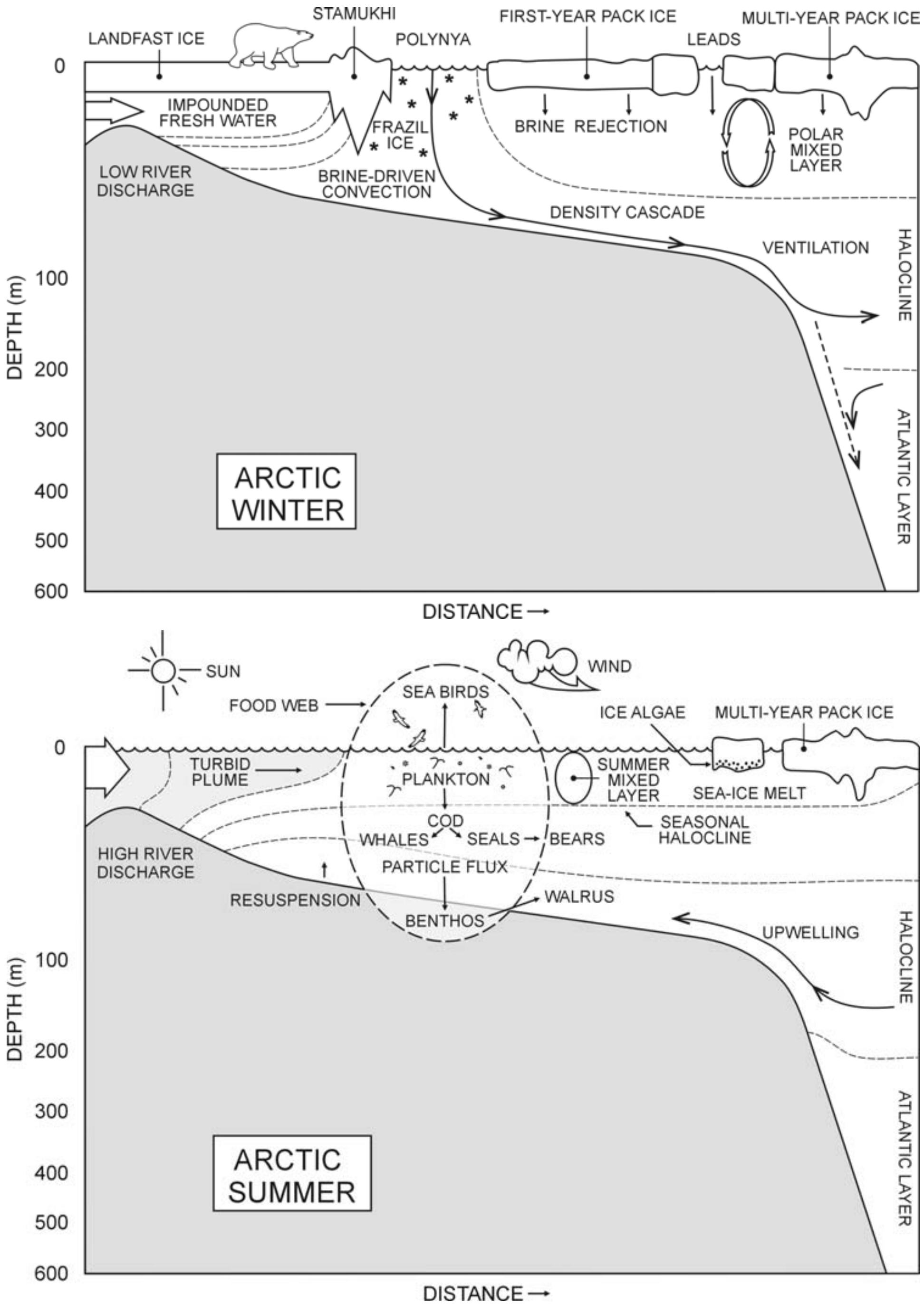
- **Role of topographic complexity: islands, capes, canyons and shelf-edge irregularities produce important and recurrent perturbations of distribution fields.**

# Polar Boundaries

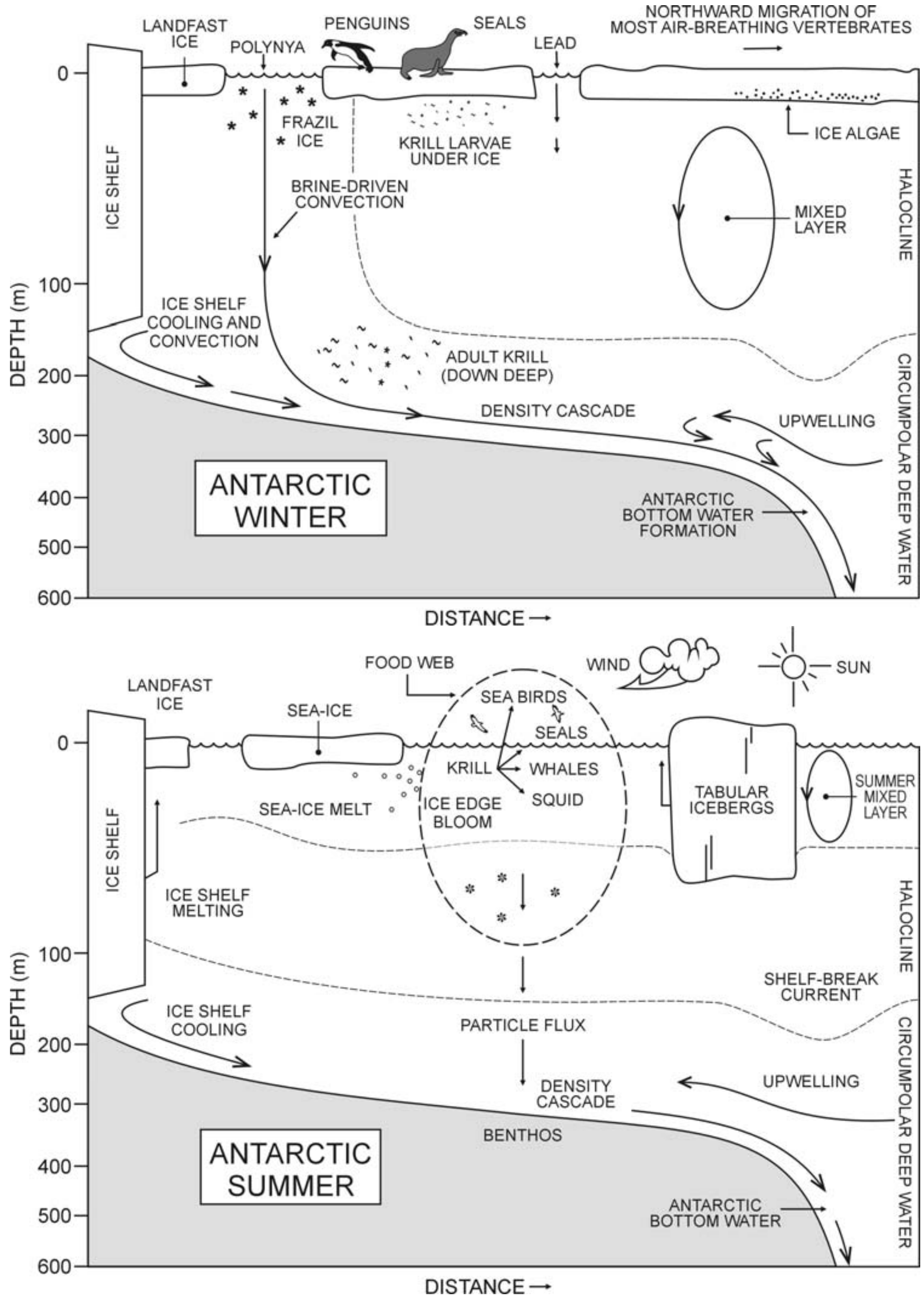



**Ingram, Carmack, McLaughlin, Nicol**
**Vol. 14A, THE SEA**




**Ingram, Carmack, McLaughlin, Nicol**
**Vol. 14A, THE SEA**



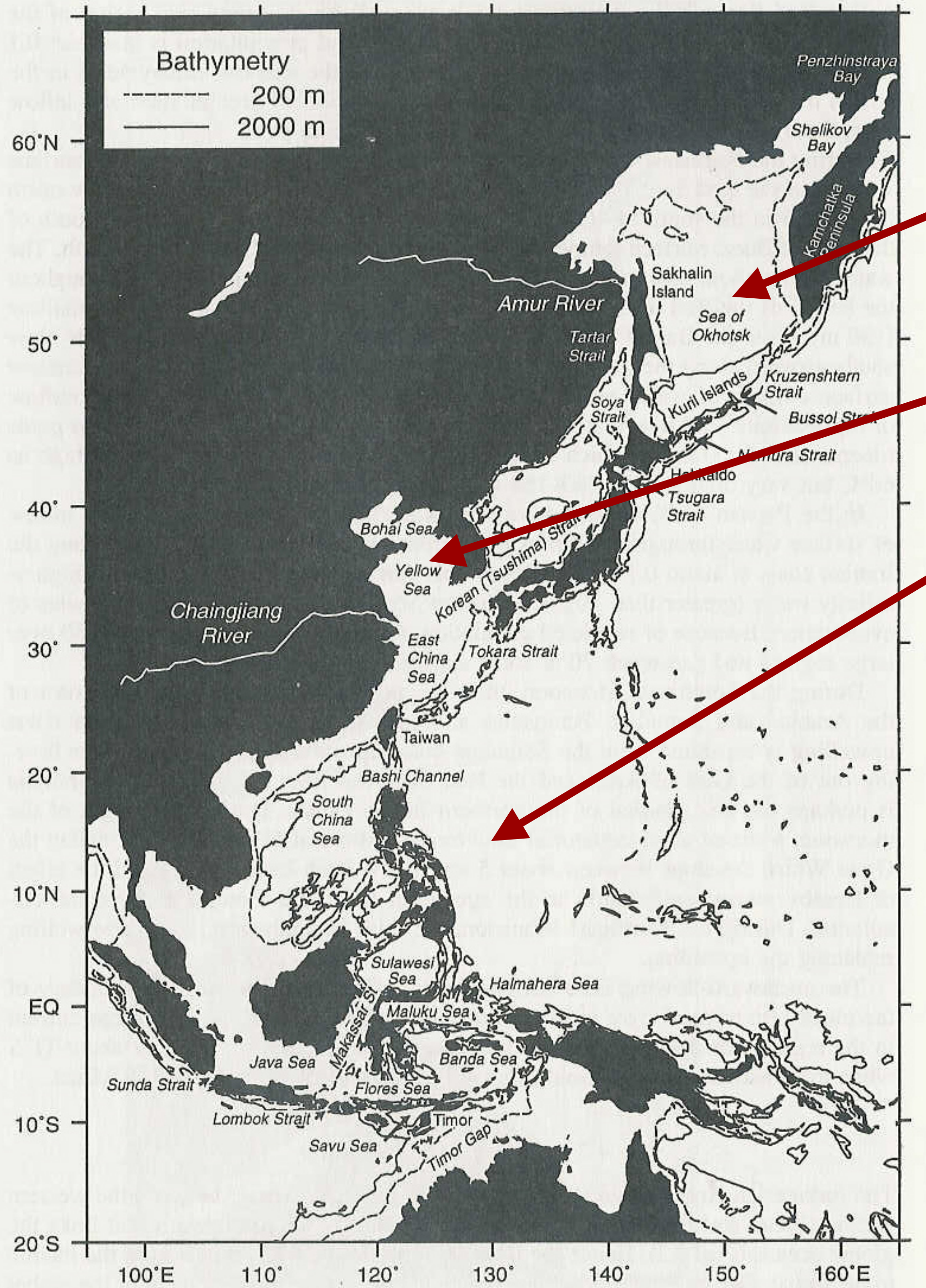

**Ingram, Carmack, McLaughlin, Nicol Vol. 14A, THE SEA**

# Polar Ocean Boundaries

- Arctic Ocean is centered on North Pole and entirely contained within Arctic circle. The Southern Ocean rings the Antarctic continent and extends poleward south of 80°S under the ice shelves of the Weddell and Ross Seas.
- Arctic Ocean receives considerable inputs from surrounding continents, and both Pacific and Atlantic oceans. The Southern Ocean tends to be an export system; Antarctic continent supplies mainly ice but processes at the Antarctic margins lead to circulation patterns that spread throughout the globe.
- Surface circulation of Southern Ocean is essentially self-contained, with the Antarctic Circumpolar Current (ACC) flowing eastwards, south of the Polar Front, and the Coastal Current flowing westwards and inshore of the ACC. In the Arctic, surface currents communicate with major ocean basins, through Bering and Fram Straits and the straits in the Canadian Arctic Archipelago.
- Pack ice system in the Antarctic is highly mobile and can reach extreme thickness where rafting occurs and where multi-year ice accumulates. In the Arctic, multi-year ice is either exported via the Transpolar Drift or has longer residence time and recirculates in the Canadian Basin in the Beaufort Gyre.

# Polar Ocean Boundaries

- Nutrients present in upper layers of Arctic due to Pacific Ocean and riverine inputs and upwelling but in Antarctic almost entirely due to upwelling and mixing. Biological productivity is driven by similar processes in spring but in Arctic ice-melt driven productivity spreads northward from the shelf toward the basin interior; in Antarctic it is the opposite, as productivity begins in the open ocean then moves southward toward the continent.
- Food webs of Arctic are relatively short and generally relatively unproductive. In Southern Ocean the biomass of fish is reduced and intermediate trophic levels are occupied by species of krill. Both systems support large and transient populations of air breathing vertebrates – whales, seabirds and seals.
- Species remain during winter using ice as a habitat: Emperor penguins and pack ice seals in Antarctic and harp seals and polar bears in Arctic. Penguins and polar bears are unique to southern and northern poles, respectively.
- Recent changes in Arctic Ocean and dramatic reductions in the sea ice cover demonstrate that climate and marine ecosystems changes are occurring. Climate change models predict further reductions of sea ice. Earlier ice melt and delayed freeze-up will lead to modified atmosphere-Ocean fluxes and complex modifications to all levels of the food chain.



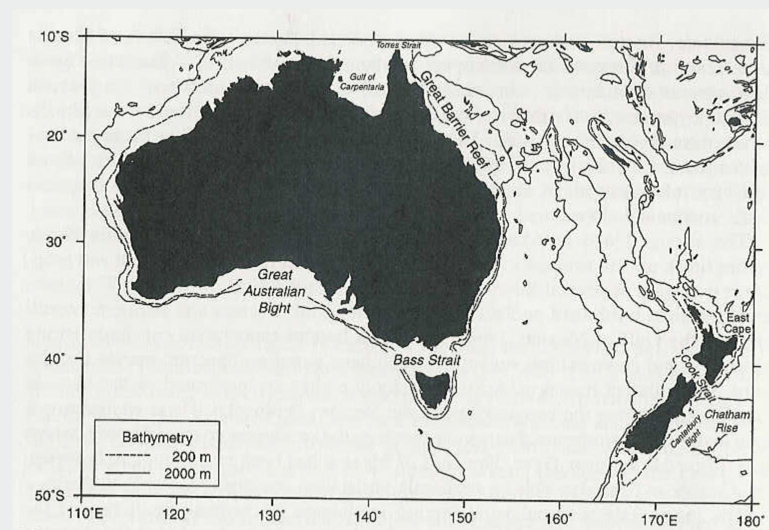

# Semi-Enclosed Seas and Islands

**Three types:**

**i) nearly-enclosed with limited exchanges with the open ocean (e.g. Sea of Okhotsk, Bohai Sea, Japan Sea)**

**ii) Partially-enclosed with moderate exchanges along 1 or 2 boundaries (e.g. Yellow Sea)**

**iii) Peripheral seas extending along continental margins and having strong interactions (e.g. Outer SE China Sea, shelf seas around Australia)**




**Church, Bethoux, Theocharis, Vol. 11, THE SEA; Oguz and Su, Vol. 14, THE SEA**

# Semi-Enclosed Seas, Islands and Australia

- Overview on 4 regions: (1) European semi-enclosed seas, (2) Arabian Peninsula and Northern Indian Ocean marginal seas, (3) East Asian (or Western North Pacific) marginal seas, (4) Australia-New Zealand shelf seas
- Contain complex and diverse ecosystems involving rich natural resources and concentrated human activities – provide vital habitat for many commercial and endangered species
- Food web structures, affected by internal and external factors associated with natural and anthropogenic changes, may undergo strong nonlinear changes within existing state or abruptly switch to another state with almost no warning of impending changes
- Must assess types of structural changes possibly introduced by human-induced interventions in the next decades, to what extent they might be controlled, and implementation of possible strategies for sustainable use of their resources through process-oriented model explorations and data assimilation

# Progress in interdisciplinary research on the multi-scale dynamics of the global coastal ocean

**Three emerging concepts**

- coupled pelagic-benthic dynamical processes interactive between the water column and the sediments
- significant contribution arising from coastal ocean biogeochemical cycles to global cycles and budgets
- large variety of dominant structures, trophic interactions and variabilities (robust-rapid change-robust) that occur in the highly productive coastal ocean ecosystems

**These three concepts and their linkages provide now a powerful potential framework for research directions**

- specific research issues and next step problems essential

***Challenging from intellectual, scientific, technical and methodological viewpoints***

# Progress 2: Critical Processes

To advance understanding of the dynamics of the complex global coastal ocean, ***critical processes*** must be identified and quantified by critical experiments and concomitant advanced theoretical/numerical models.

- coastal deep sea exchanges, benthic productivity, CO2 uptake/release, recruitment, etc.
- issues of measurability and modelability

Efficient progress can be made by using processes to identify ***dynamically analogous regions*** of the global coastal ocean and sharing scientific information, technologies and methodologies among them

- Many types of interactions among relatively well studied and less well understood regions can be fruitful

## From a technical and methodological viewpoint we are at the threshold of a new management era.

The material presented indicates the great complexity of the requisite scientific input *and* the unique opportunity for advanced management now provided by ongoing scientific and methodological progress, including advanced interdisciplinary ocean prediction systems.

Efficient and holistic management of the global coastal ocean and its interconnected natural and national subregions is essential to ensure the health of the coastal seas and their ecosystems, and the well being of the ever increasing human coastal populations.

Achievable only via effective and well-motivated collaboration and cooperation among the scientific, technical, governmental, commercial, economic and environmental communities.