Climate and Ecosystem Variability: Forcings and Feedbacks

Antonio J. Busalacchi

2006 Walter Orr Roberts Interdisciplinary Science Lecture

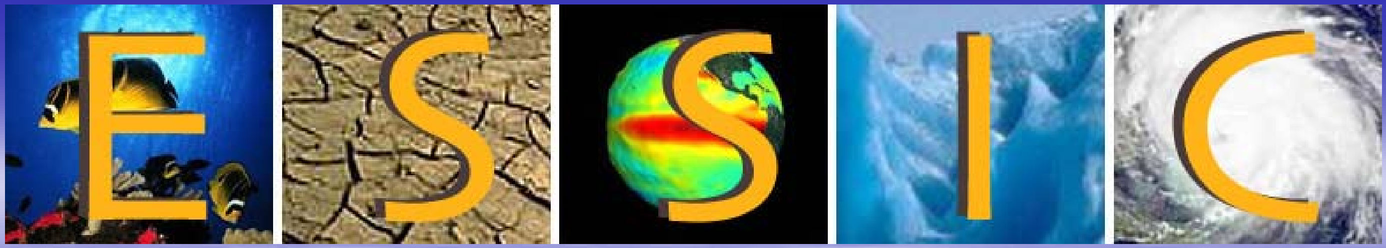
With thanks to

Ragu Murtugudde, Ning Zeng, Joaquim Ballabrera, Annarita Mariotti, Wendy Wang, Rong-Hua Zhang

EARTH SYSTEM SCIENCE INTERDISCIPLINARY CENTER

ESSIC

UNIVERSITY OF MARYLAND



- ESSIC started as a joint center between the University of Maryland Departments of Meteorology, Geology, and Geography together with the Earth Sciences Directorate at the NASA/Goddard Space Flight Center.

- ESSIC now also administers the Cooperative Institute for Climate Studies (CICS) which is joint with NOAA's National Centers for Environmental Prediction (NCEP) and the National Environmental Satellite and Data Information Service (NESDIS).

- The goal of ESSIC is to enhance our understanding of how the atmosphere-ocean-land-biosphere components of the Earth interact as a coupled system and the influence of human activities on this system.

- This is accomplished via studies of the interaction between the physical climate system (e.g., El Nino) and biogeochemical cycles (e.g., greenhouse gases, changes in land use and cover).

- The major research thrusts of the center are studies of Climate Variability and Change, Atmospheric Composition and Processes, and the Global Carbon Cycle (including Terrestrial and Marine Ecosystems/Land Use/Cover Change), and the Global Water Cycle.

- The manner in which this research is accomplished is via analyses of in situ and remotely sensed observations together with component and coupled ocean-atmosphere-land models.

- Together this provides a foundation for understanding and forecasting changes in the global environment and regional implications.

- Data assimilation and regional downscaling provide the means by which the observations and models are linked to study the interactions between the physical climate system and biogeochemical cycles from global to regional scales.

- ESSIC received its first private sector gift in 2006 from a partnership between the University and Mitretek Systems
- The purpose being "to improve and expand climate and environmental change predictions".
- ESSIC has the lead responsibility on the university end and in recognition of this, Mitretek has given ESSIC $75,000 gft and a 1/2 time FTE as a demonstration of their commitment to this partnership.

Cooperative Institute for Climate Studies (CICS)

The purpose of CICS is to:

- Foster collaborative research between NOAA and the University of Maryland in studies of satellite climatology, climate diagnostics, modeling and prediction.
- Serve as a center at which scientists and engineers working on problems of mutual interest may focus on studies contributing to the understanding of the earth-ocean-atmosphere climate system, climate modeling, climate prediction, and satellite climatology.
- Stimulate the training of scientists and engineers in appropriate disciplines

Cooperative Institute for Climate Studies (CICS)

Historical Overview

- CICS research represents a strong and diverse collection of projects conducted jointly between CICS scientists and those from NESDIS ORA/STAR and NWS/NCEP EMC and CPC
- Funding sources include the NOAA Climate Program Office (formerly OGP) and the Joint Center for Satellite Data Assimilation
- NOAA has consistently provided financial support for administrative and infrastructure costs (generally referred to as Base) – however, amounts have varied significantly and have not kept pace with inflation. Currently, Base funding is $150,000/year

For two decades CICS has fostered collaborative research between NOAA and the University that has covered a wide range of problems in radiation budget studies, climate diagnostics and atmospheric chemistry.

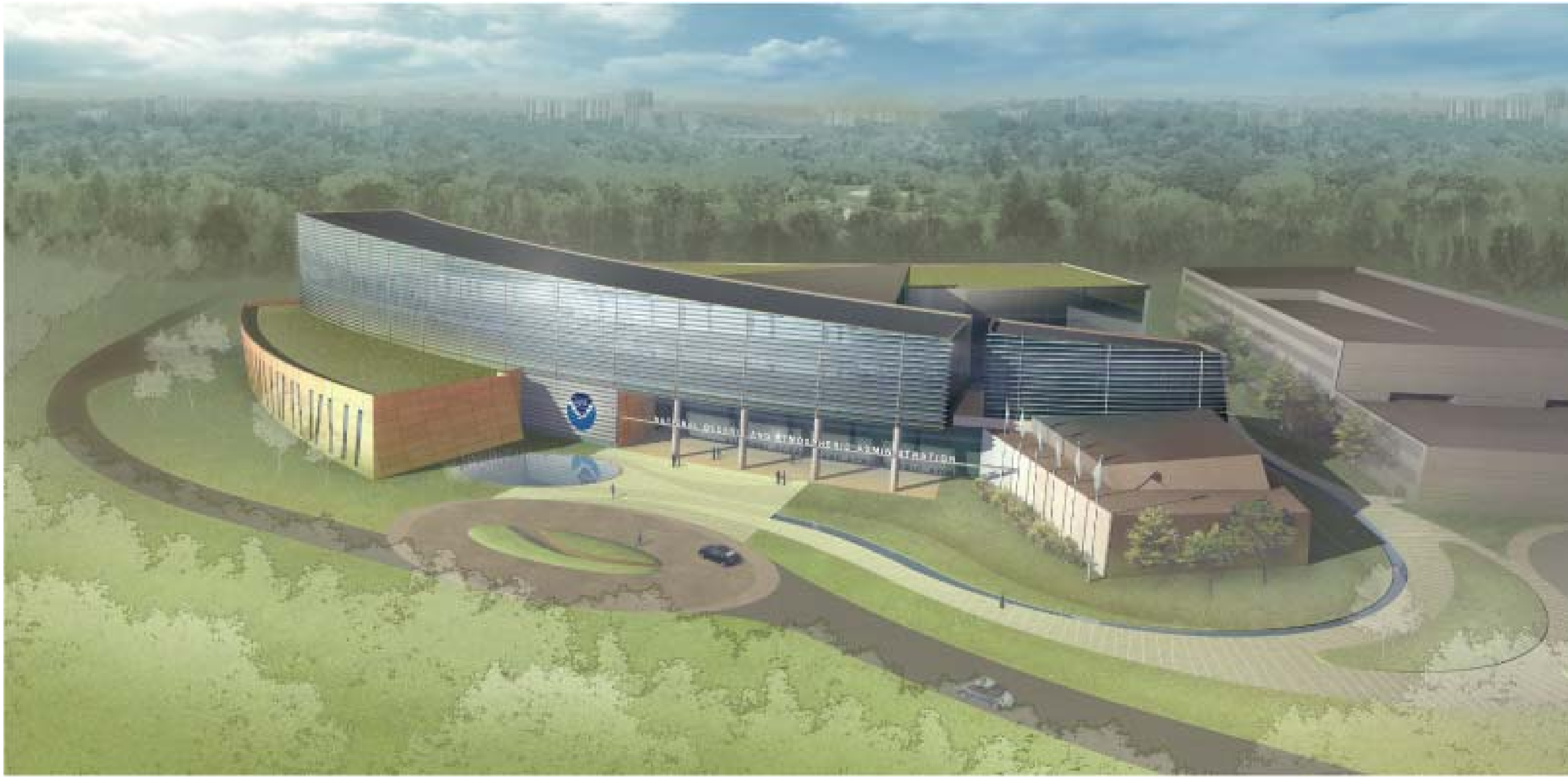
Historically, CICS has consisted of three major research theme areas:

- Global Energy and Water Cycles – Theme 1,
- Climate Diagnostics and Prediction – Theme 2,
- Atmospheric Chemistry – Theme 3

Emerging new themes are:

- Ecosystems
- Observation synthesis and integration

M SQUARE
THE UNIVERSITY OF MARYLAND RESEARCH PARK
COLLEGE PARK, MARYLAND



M Square - 5825 University Research Court
Perspective View

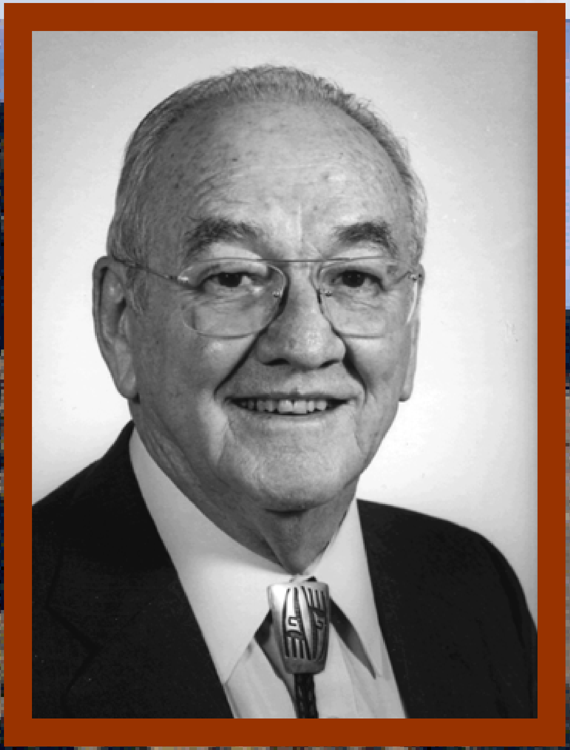
SUMMARY

- Research at the University of Maryland combines in situ and remotely sensed observations together with component and coupled ocean-atmosphere-land models to improve our ability to understand and forecast changes in the Earth System.

- A large portion of our research is joint with NASA Goddard and NOAA

- Together this provides a foundation for understanding and forecasting changes in the global environment and regional implications.

Walter Orr Roberts



"I have a very strong feeling that science exists to serve human welfare. It's wonderful to have the opportunity given us by society to do basic research, but in return, we have a very important moral responsibility to apply that research to benefiting humanity."

Walter Orr Roberts

Courtesy Tim Killeen NCAR

- The theme of the 2005 AMS Meeting was :

"Building the Earth Information System"

GEOSS BENEFITS FOCUS

Natural & Human Induced Disasters

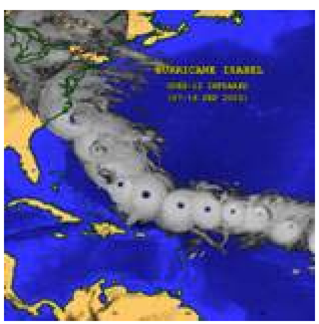
Water Resources

Terrestrial, Coastal & Marine Ecosystems

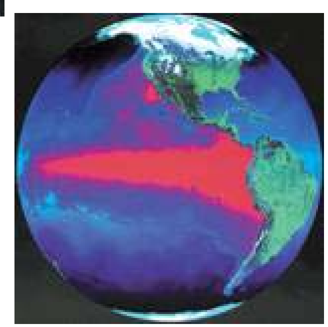
Human Health & Well-Being

Energy Resources

Sustainable Agriculture & Desertification



Weather Information, Forecasting & Warning



Climate Variability & Change

Biodiversity

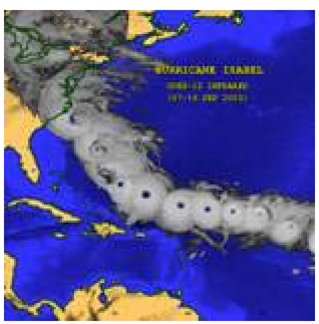
- The theme of last year's 86th Annual AMS Meeting was :

"Applications of Weather and Climate Data"

GEOSS BENEFITS FOCUS

Human Health & Well-Being

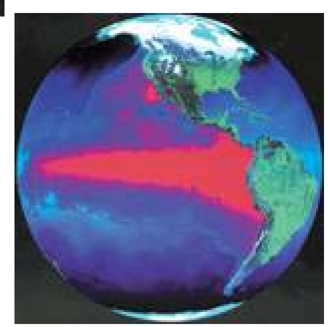
Natural & Human Induced Disasters



Weather Information, Forecasting & Warning

Energy Resources

Water Resources



Climate Variability & Change

Sustainable Agriculture & Desertification

Terrestrial, Coastal & Marine Ecosystems

Biodiversity

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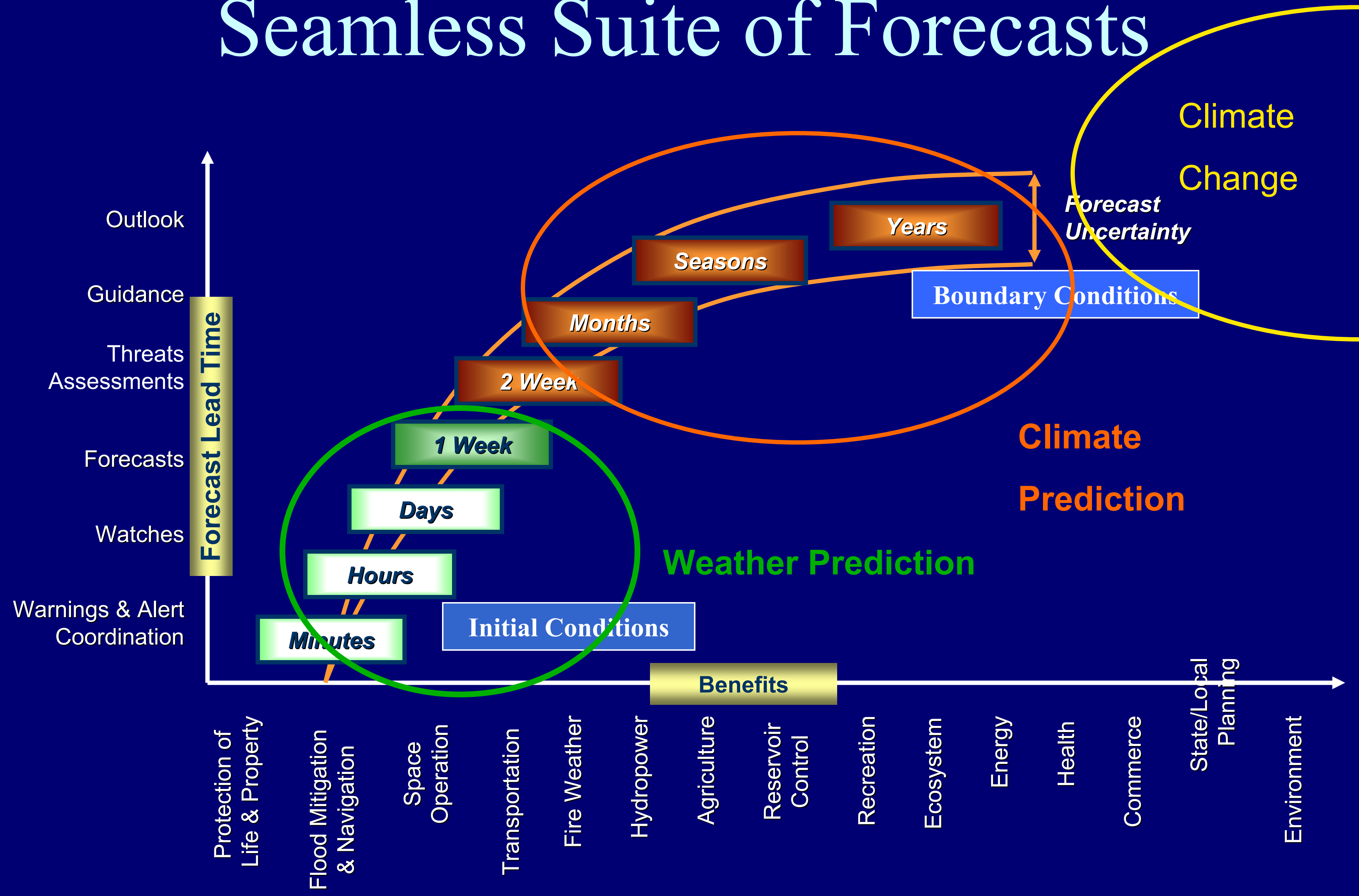
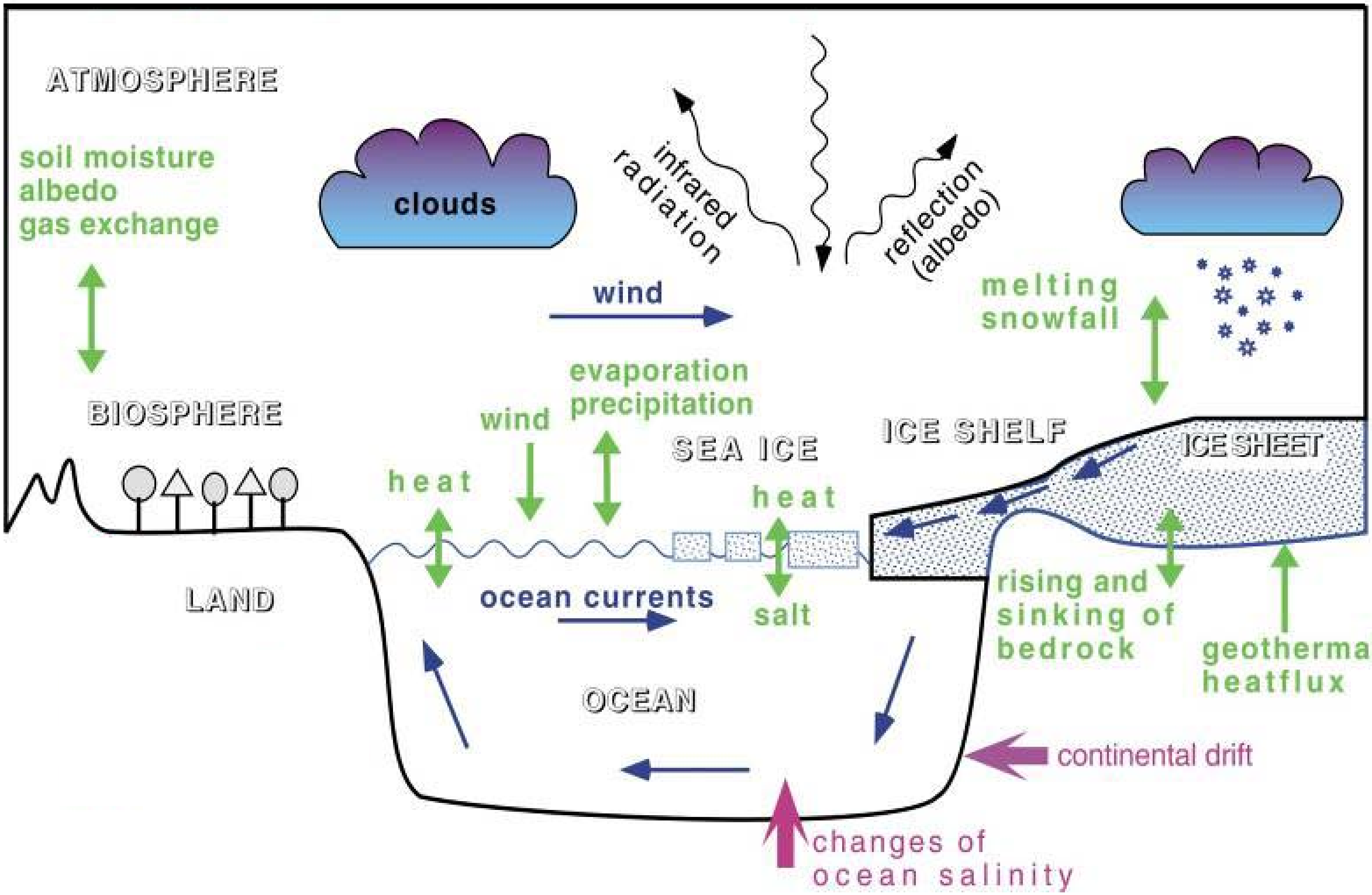
Seamless Suite of Forecasts

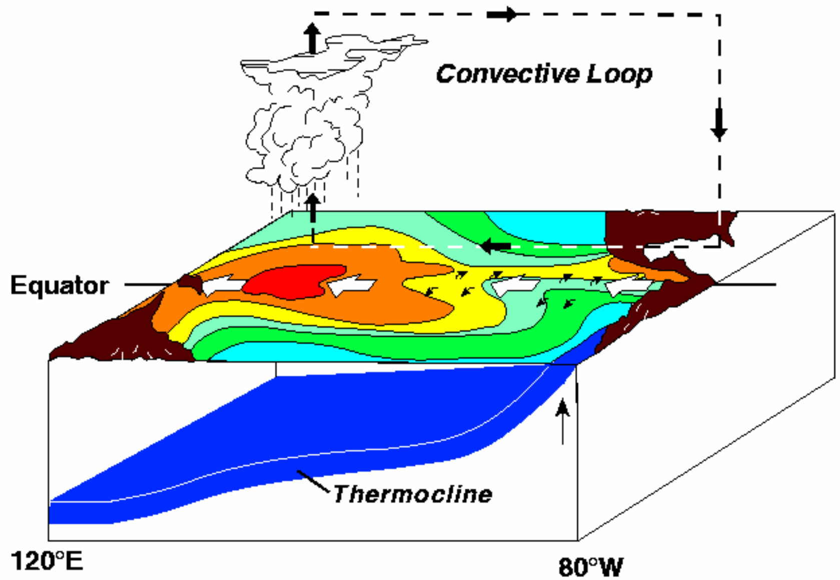


The Physical Climate System

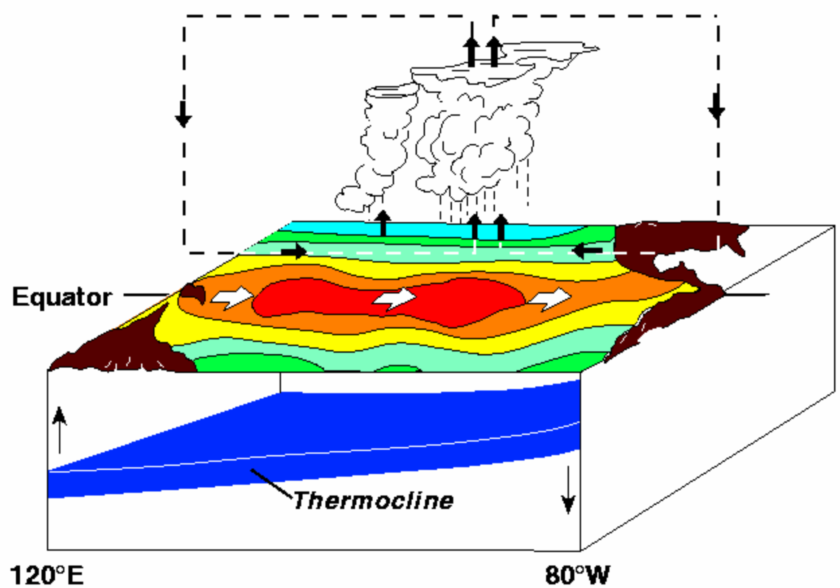


- During the 1980’s the Tropical Ocean Global Atmosphere (TOGA) program brought together meteorologists and oceanographers to advance our understanding of the coupled ENSO problem.
- Both discipline based communities gained an appreciation for each other’s science.
- As a result, a new breed of climate scientist, neither oceanographer nor meteorologist was born.
- An overarching and common goal was seasonal to interannual prediction based on atmosphere-ocean coupling

Normal Conditions



El Niño Conditions



- In the 1990's, in programs such as GEWEX (Global Energy and Water Cycle Experiment) , meteorologists and hydrologists came together to advance our understanding of land-atmosphere coupling.

- Similar to the TOGA experience a new breed of land-atmosphere scientist was born.

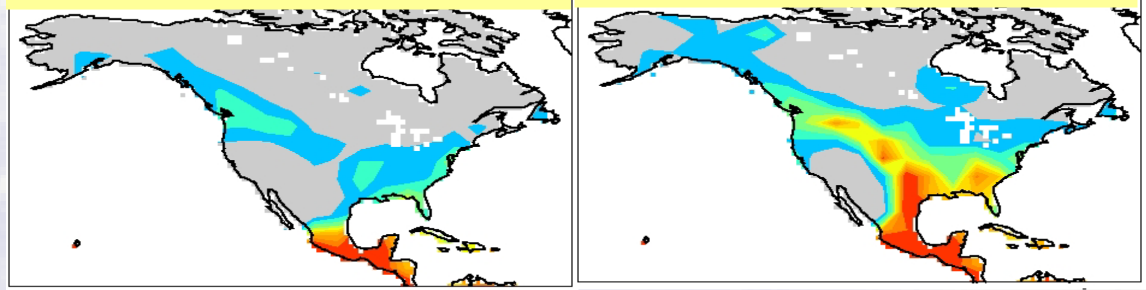
- Once again prediction was a common goal, this time to advance predictions of the global water and energy cycles on time scales from days, weeks, to months.

Land surface models and assimilation

Theoretical estimates of prediction skill

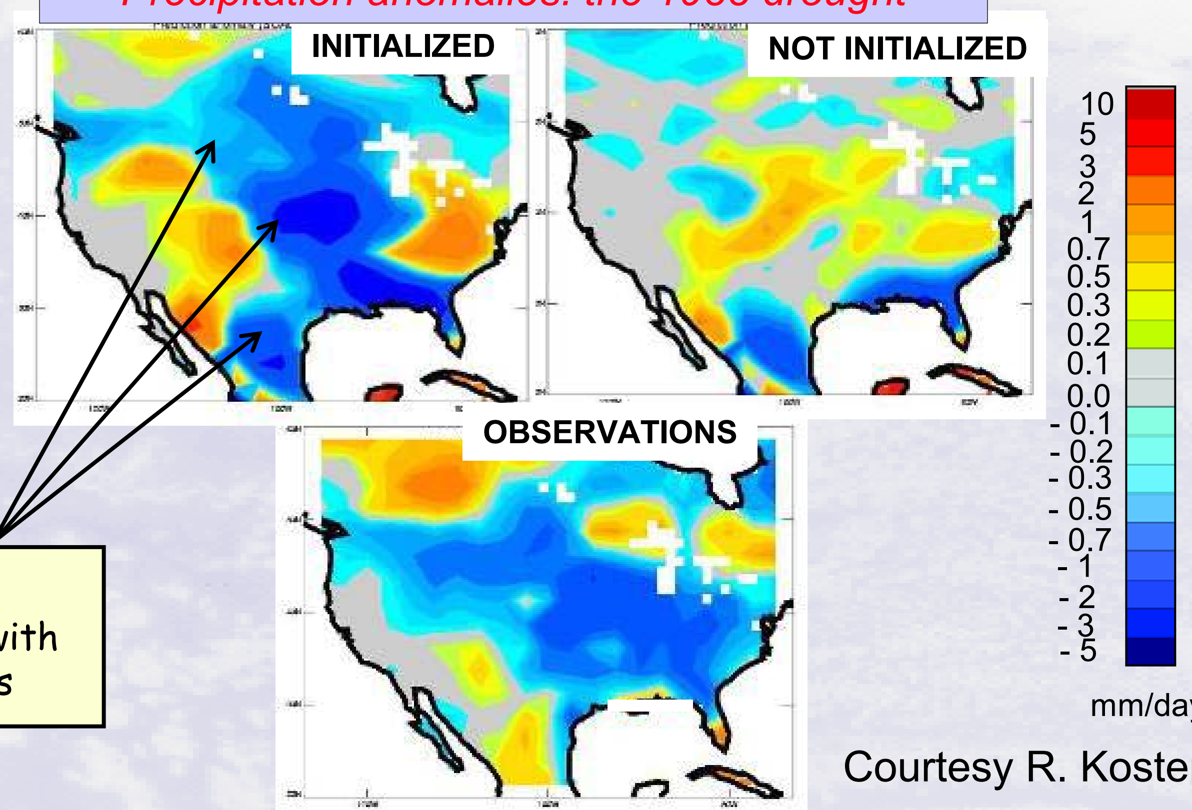
Predictability of JJA precipitation associated with **SST**

Predictability of JJA precipitation associated with **SST & soil wetness**



Large ensembles used to assess potential data impacts

Test of land initialized by observed forcing
Precipitation anomalies: the 1988 drought



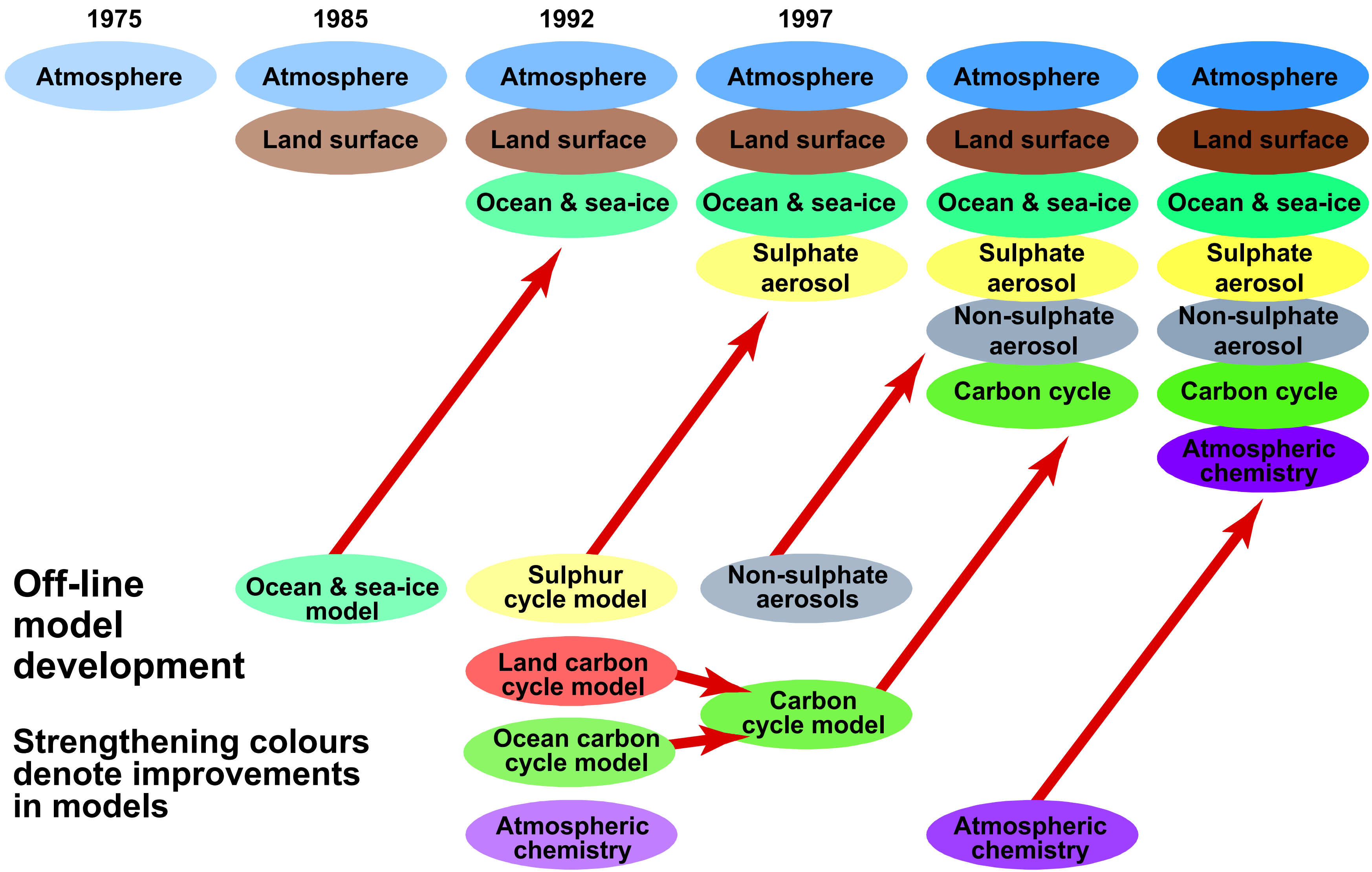
Forecast experiments with simple land initialization to test predictability results

Improvements in areas consistent with theoretical results

Courtesy R. Koster

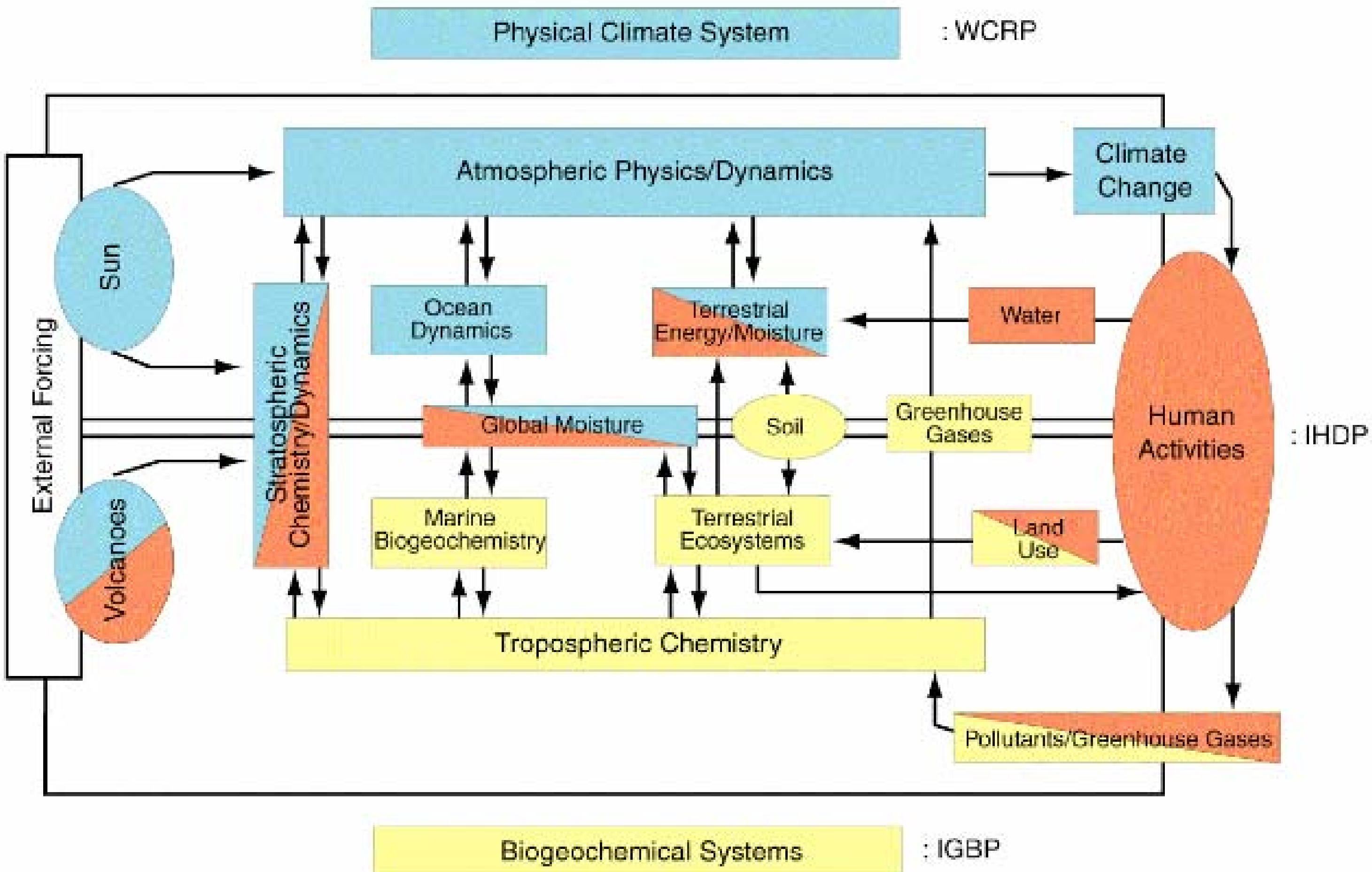
- Has the time come to take the next giant leap toward a predictive capability for the Earth System as a whole?
- The experience of the 1980's and 1990's across the atmosphere, ocean, and land disciplines would suggest that answer is yes!

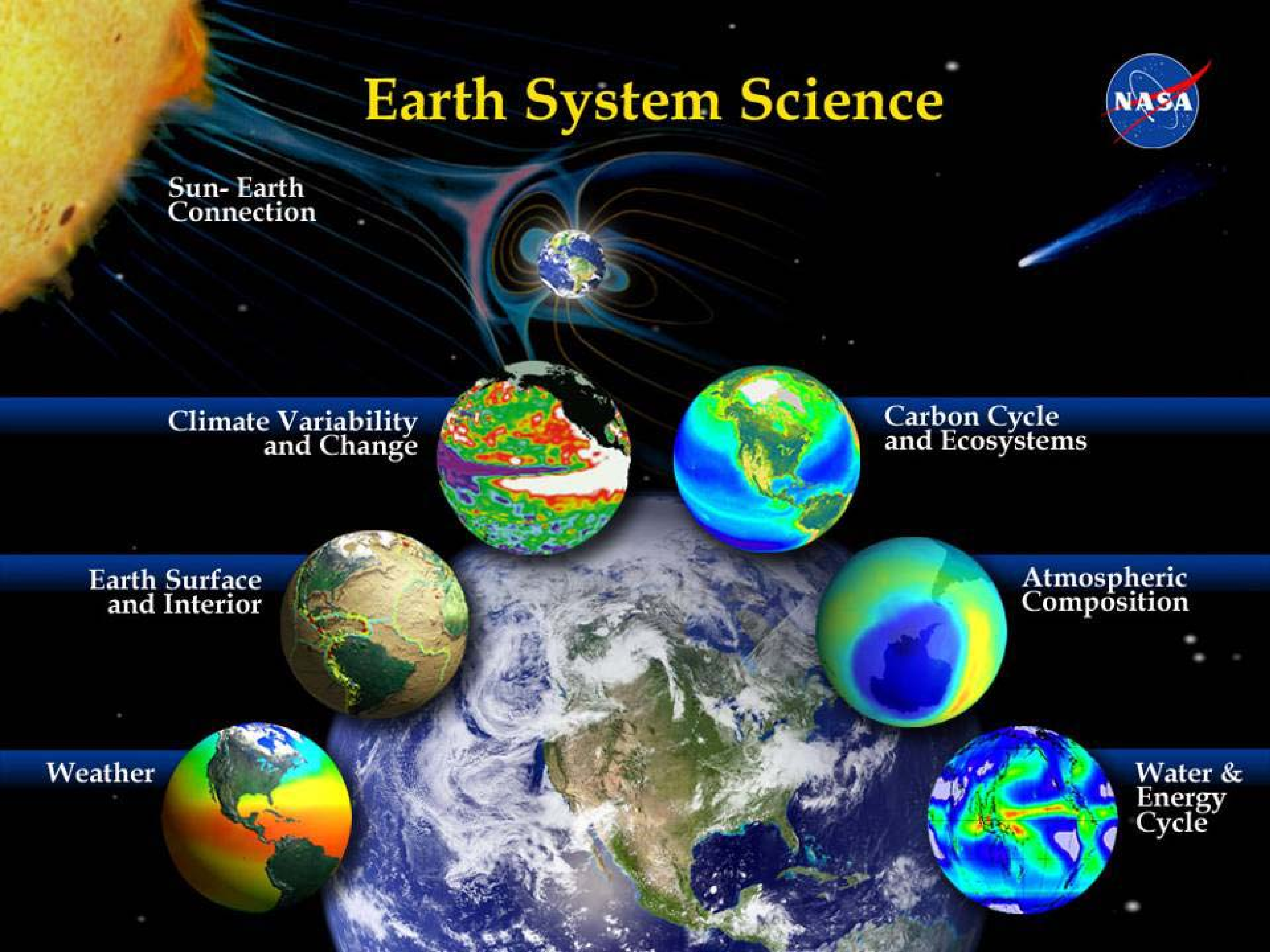
Towards Comprehensive Earth System Models



The Met.Office Hadley Centre

The Earth System: Coupling the Physical, Biogeochemical and Human Components

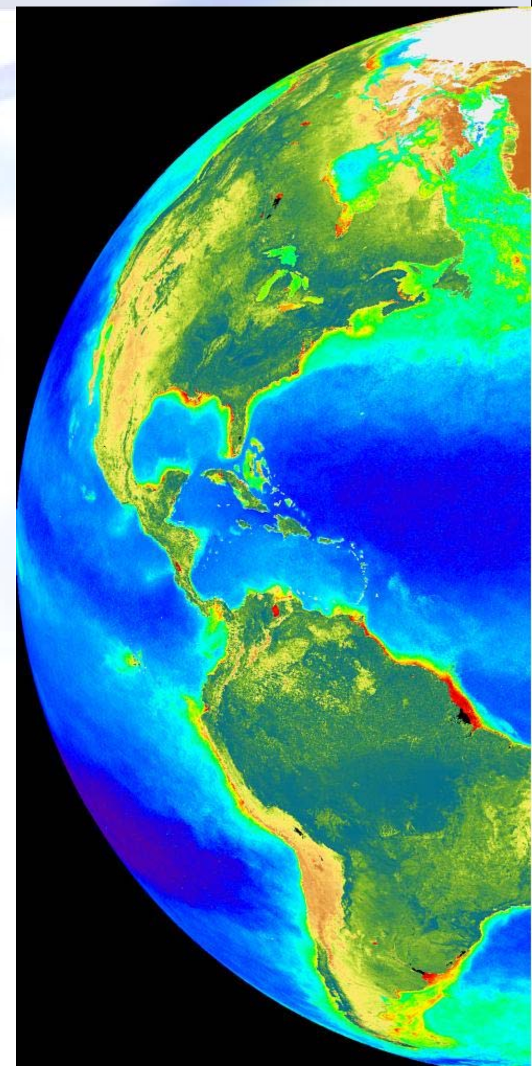



Earth System Science
NASA
Sun- Earth Connection
Climate Variability and Change
Carbon Cycle and Ecosystems
Earth Surface and Interior
Atmospheric Composition
Weather
Water & Energy Cycle

Fundamental Earth Science Questions

How is the Earth changing and what are the consequences of life on Earth?

- How is the global Earth system *changing*?
- What are the primary *forcings* of the Earth system?
- How does the Earth system *respond* to natural and human-induced changes?
- What are the *consequences* of changes in the Earth system for human civilization?
- How well can we *predict* future changes in the Earth system?



NOAA's Five Primary Mission Goals

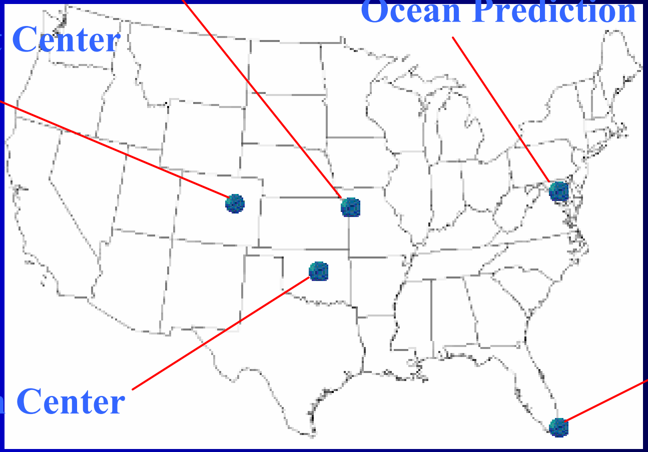
- ECOSYSTEMS: Protect, restore, and manage the use of coastal and ocean resources through ecosystem-based management.
- CLIMATE: Understand climate variability and change to enhance society's ability to plan and respond.
- WEATHER & WATER: Serve society's need for weather and water information.
- TRANSPORTATION: Support the Nation's commerce with information for safe, efficient, and environmentally sound transportation.
- MISSION SUPPORT: Provide critical support for NOAA's mission

NCEP Mission Statement

NCEP delivers analyses, guidance, forecasts and warnings for weather, ocean, climate, water, land surface and space weather to the nation and the world. NCEP provides science-based products and services through collaboration with partners and users to protect life and property, enhance the nation's economy and support the nation's growing need for environmental information.

NCEP Strategic Vision

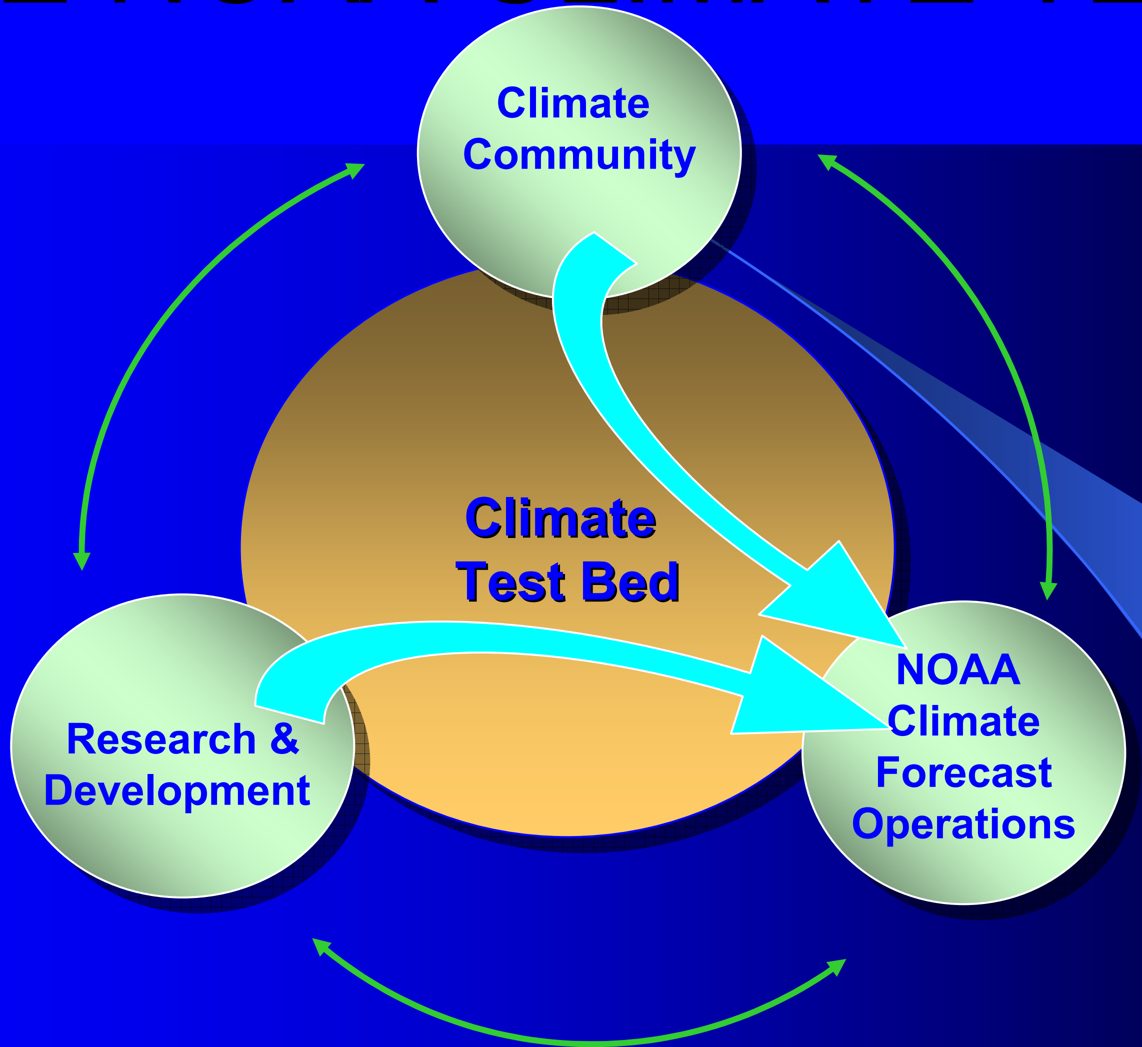
Striving to be America's first choice, first alert and preferred partner for climate, weather and ocean prediction services.



By way of reminder:

- In its former life, NCEP was known as the National Meteorological Center (NMC). The "National Center for Environmental Prediction" was coined in 1995 after Dr. R. McPherson, Director at the time, determined that NOAA required an operational forecast and products unit with a name that was 'extensible' in keeping with its mission.
- NOAA's National Centers for Environmental Prediction as its name and mission statement implies strive to perform truly environmental prediction beyond weather prediction to include water, oceans, and ecosystems.

THE NOAA CLIMATE TEST

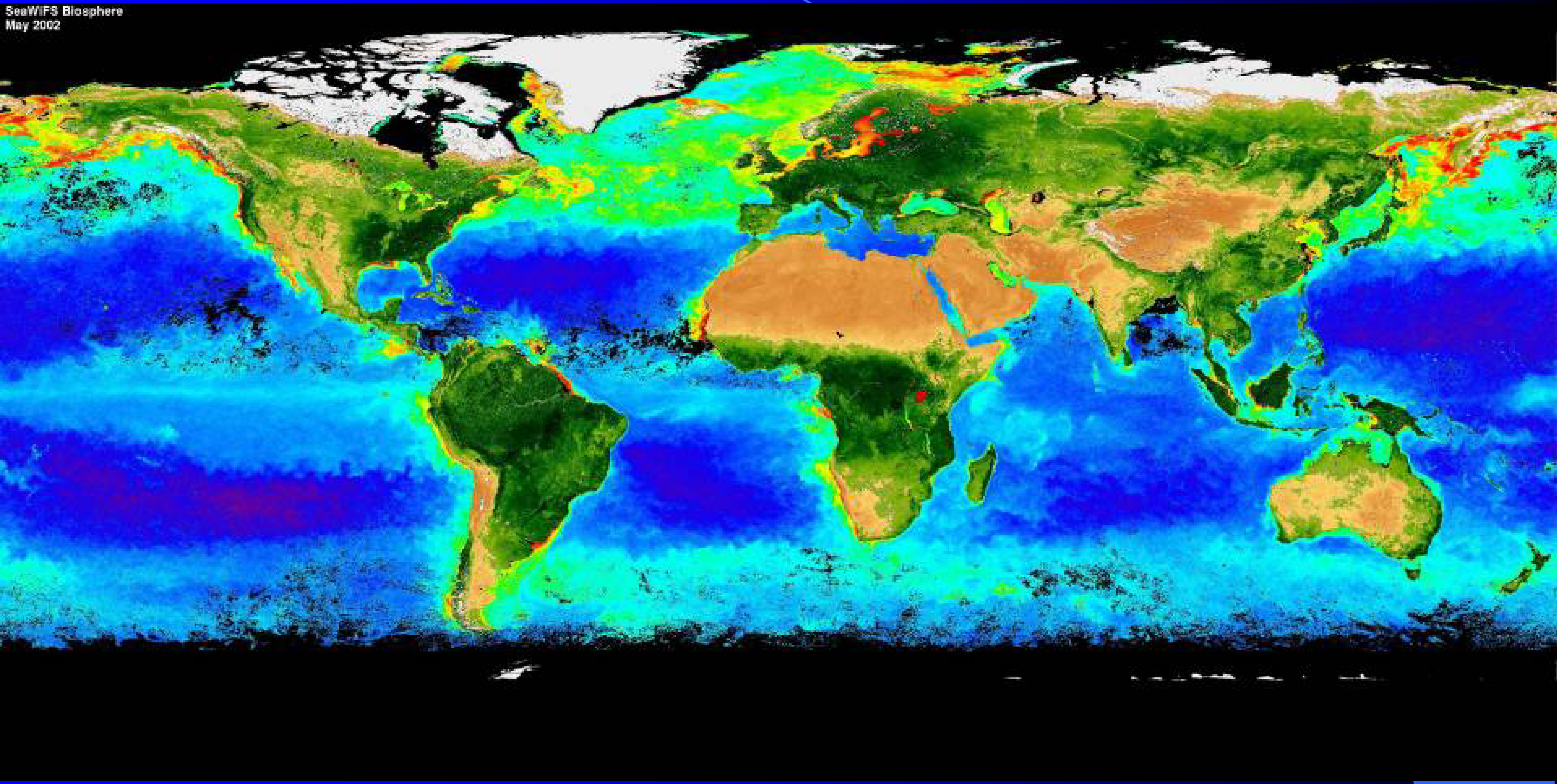


Mission: to accelerate the transition of research and development into improved NOAA operational climate forecasts, products, and applications.

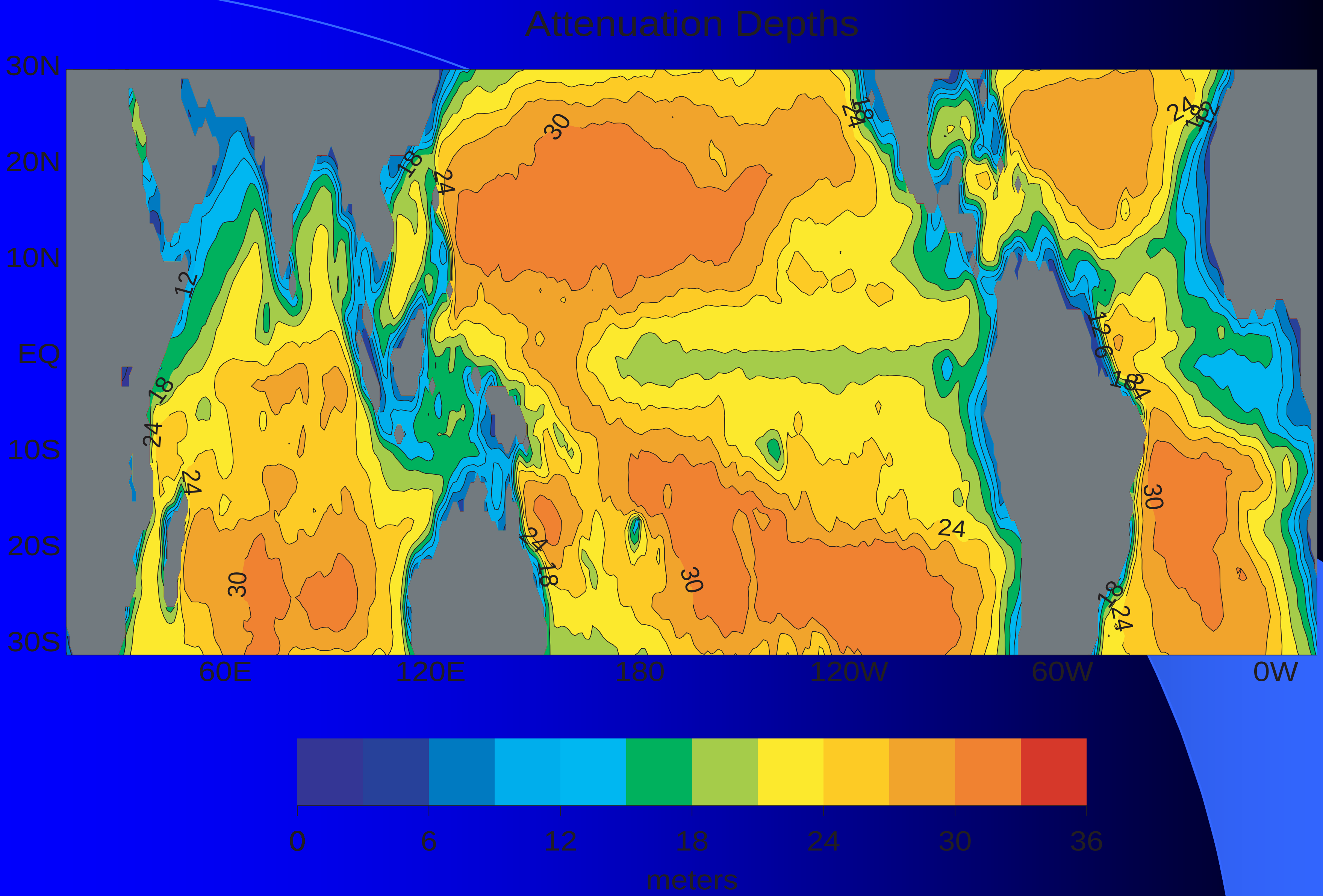
Long-term plans for advanced forecast capabilities (e.g. ecosystems; air chemistry; carbon cycle; fisheries)

- Forcings and feedbacks of marine and terrestrial ecosystems
  - Ocean biology and its impact on the coupled climate system
  - Seasonal to interannual variability of the ocean carbon cycle
  - Terrestrial mechanisms of interannual CO_2 variability

- Opportunities and Challenges


SeaWiFS Biosphere
May 2002

- The impact of turbidity and biological production on the optical properties and radiative heating of the oceans has been of great interest for some time especially since the advent of remote sensing.
- The role of the proper representation of the penetrative solar radiation for accurate SST simulation was first proposed by Denman (1973) and followed by Simpson and Dickey (1981, 1983).
- Most OGCMs and coupled climate models neglected the penetrative part of the solar radiation until such studies as Chen et al. (1994) and Schneider et al. (1996) began to report the significant impact of solar transmission on SSTs, the variable of most interest for seasonal to interannual prediction.

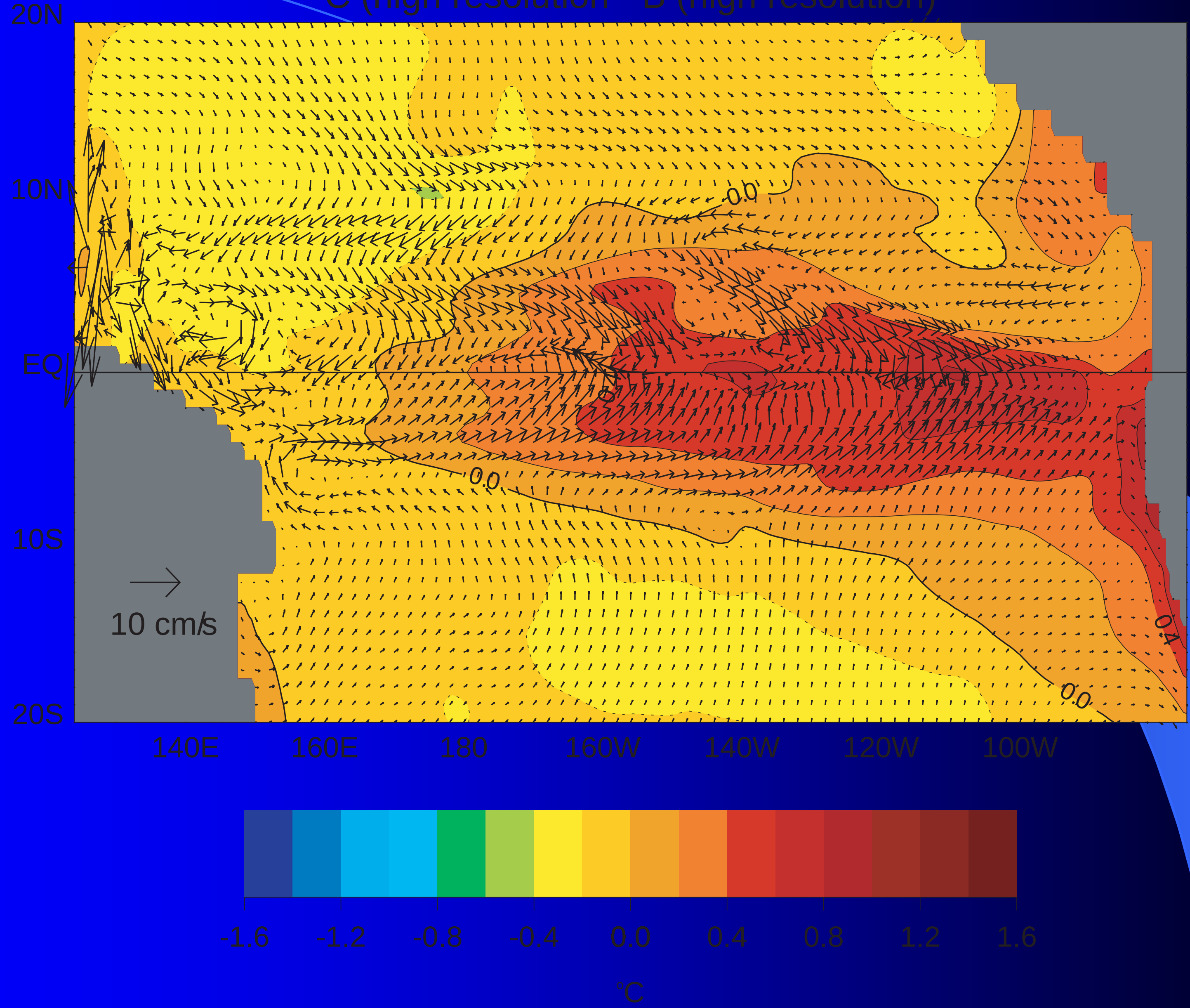


Attenuation depths from CZCS Pigments

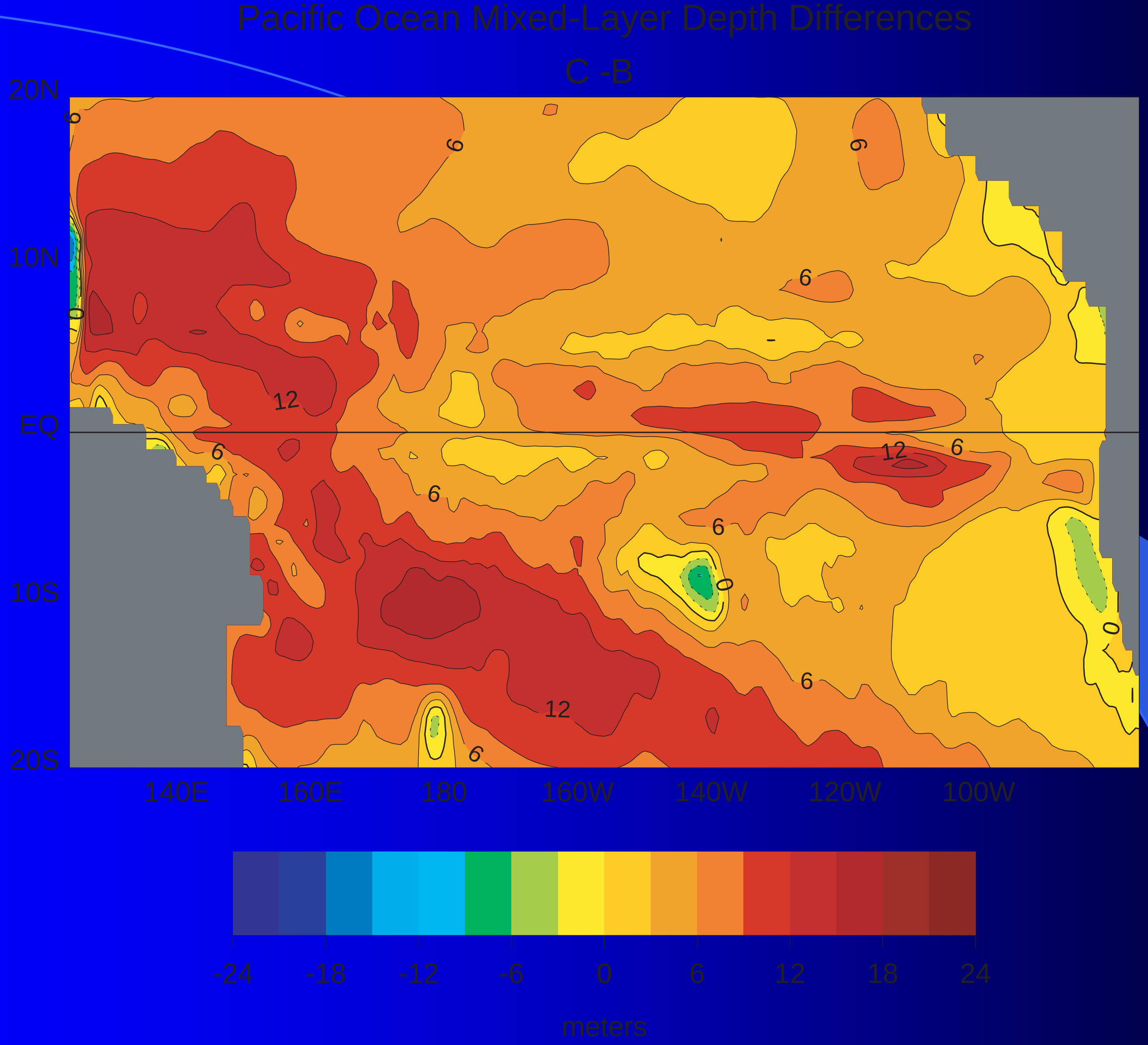
Murtugudde et al., 2002

Pacific Ocean SST and Surface Current Differences

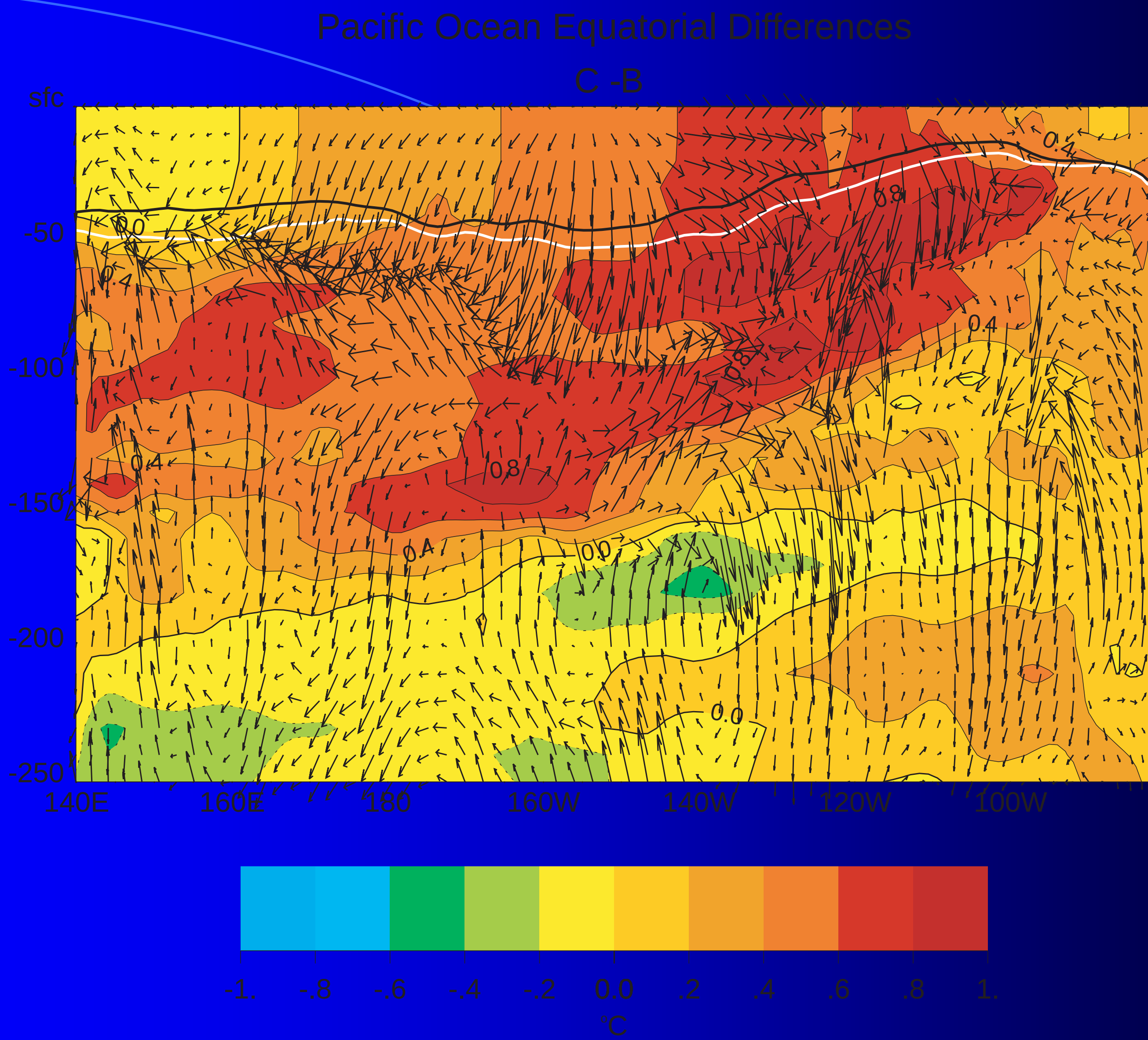
C (high resolution - B (high resolution)



SST and surface current differences between CZCS and 17m att depth simulations.

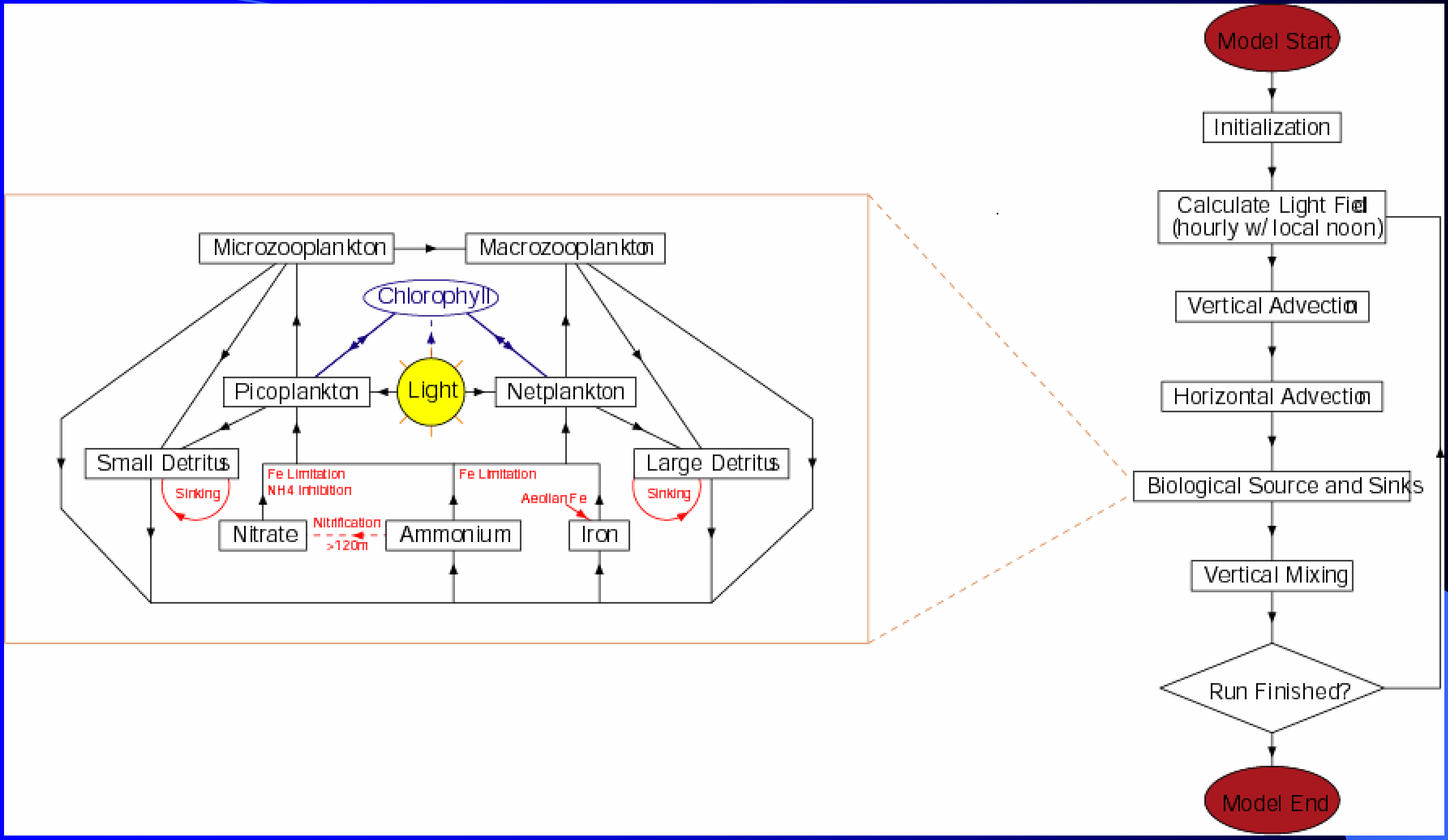


Annual mean mixed layer depth differences between CZCS and 17m att depth simulations.



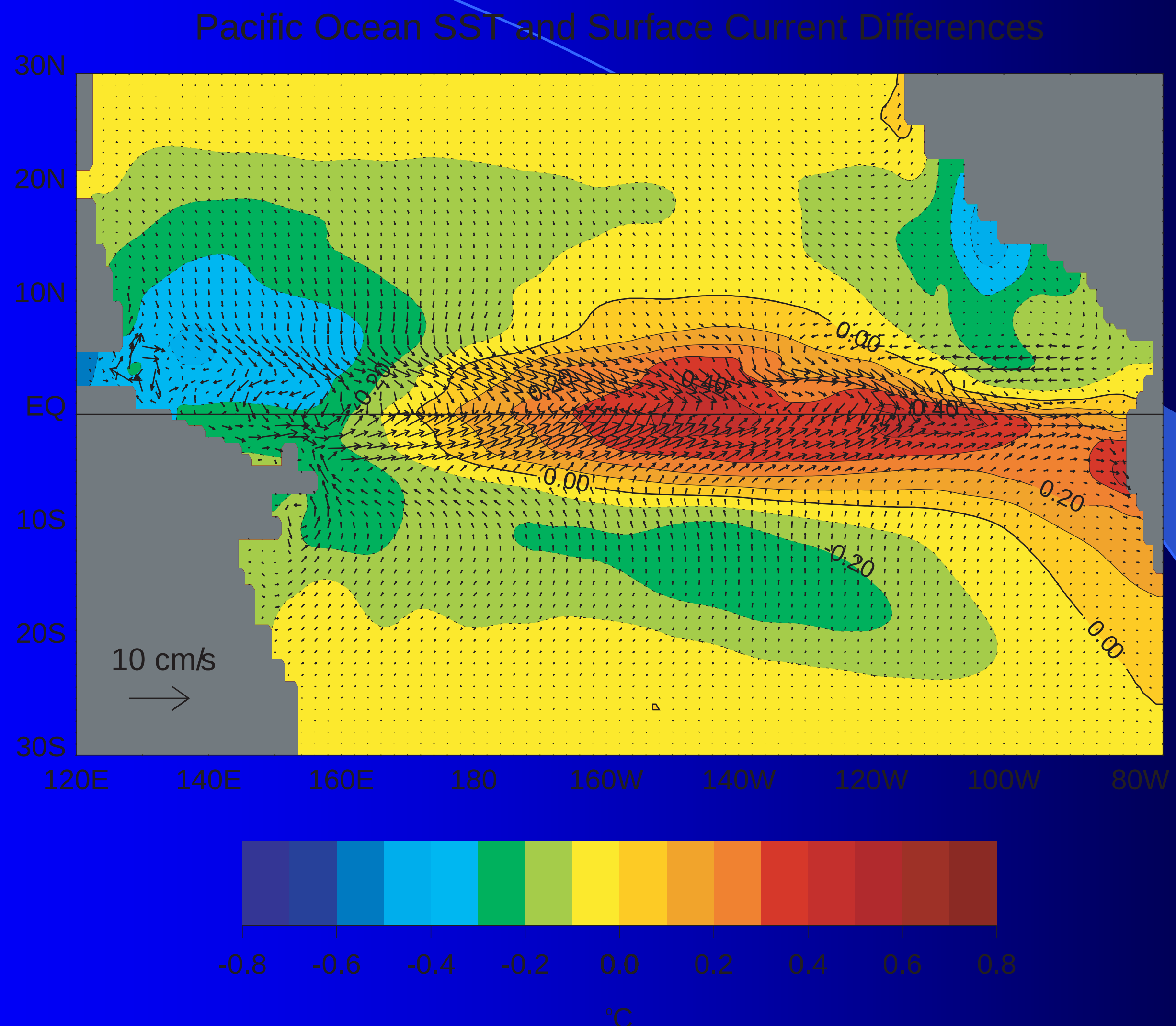
Temperature and current differences along the equator between CZCS and 17m attenuation depths.

Murtugudde et al., 2002

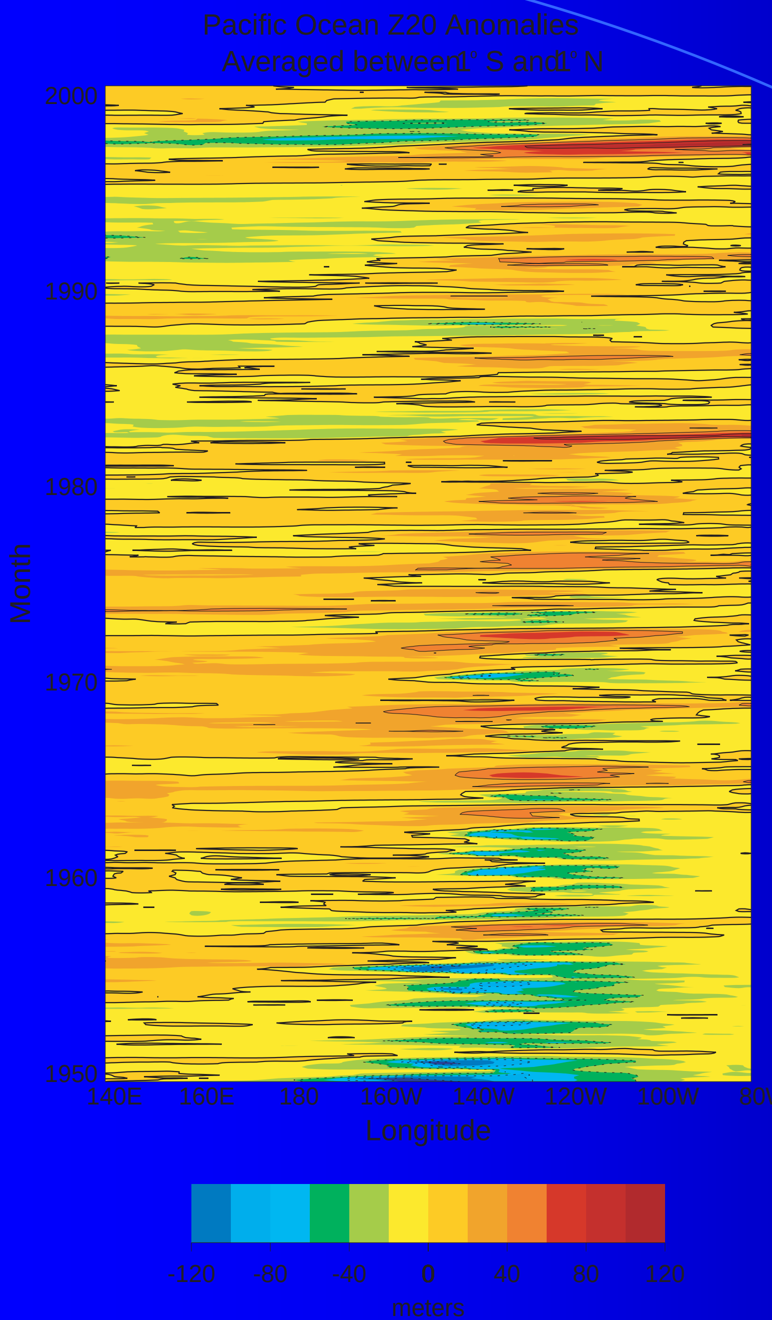


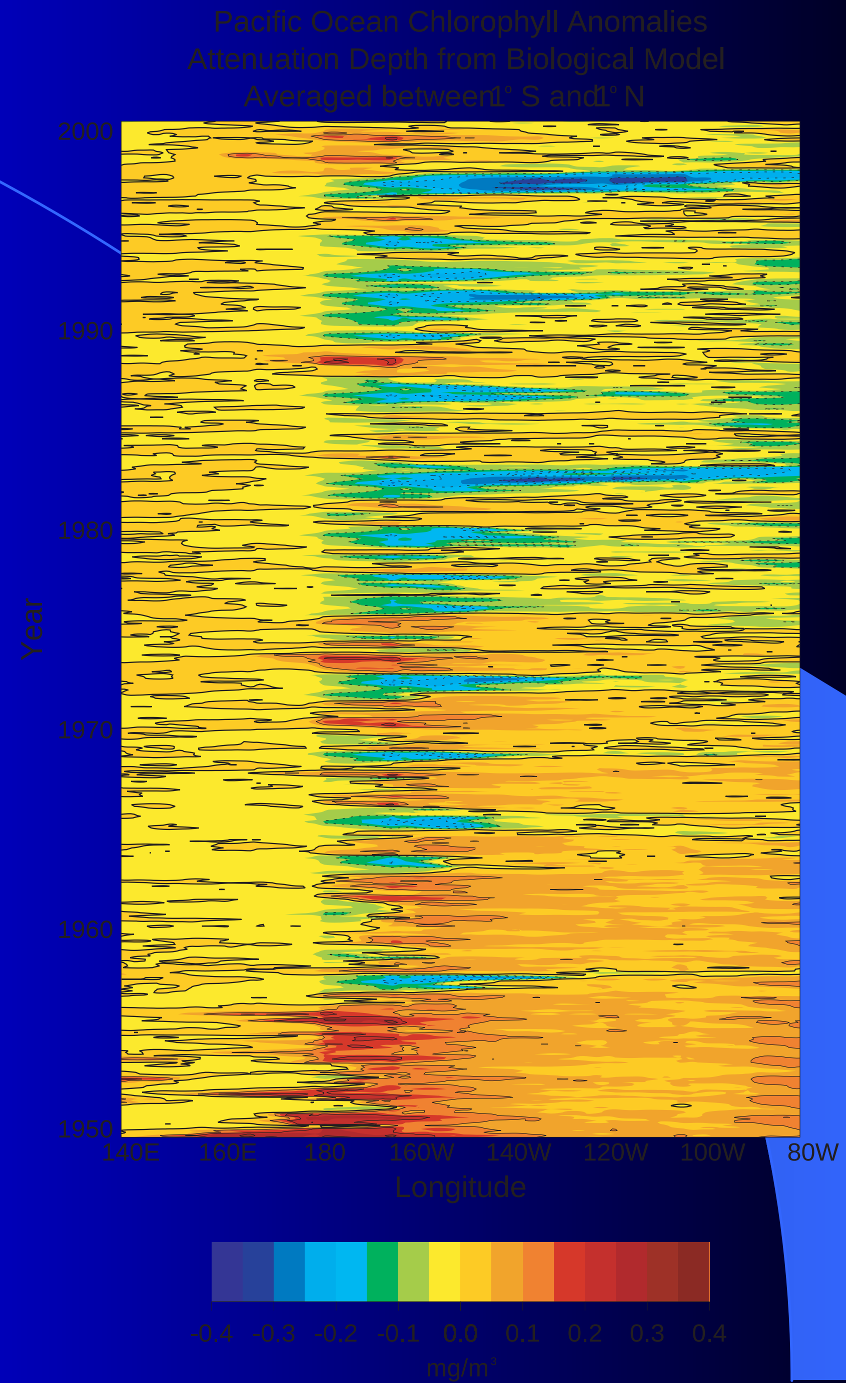
Flow chart for the ecosystem model and its coupling to the OGCM. The three-dimensional coupled physical-biogeochemical model (*Christian et al. 2002*), is based on the one-dimensional ecosystem model of *Leonard et al. (1999*) and the primitive-equation ocean model of *Gent and Cane (1989).*

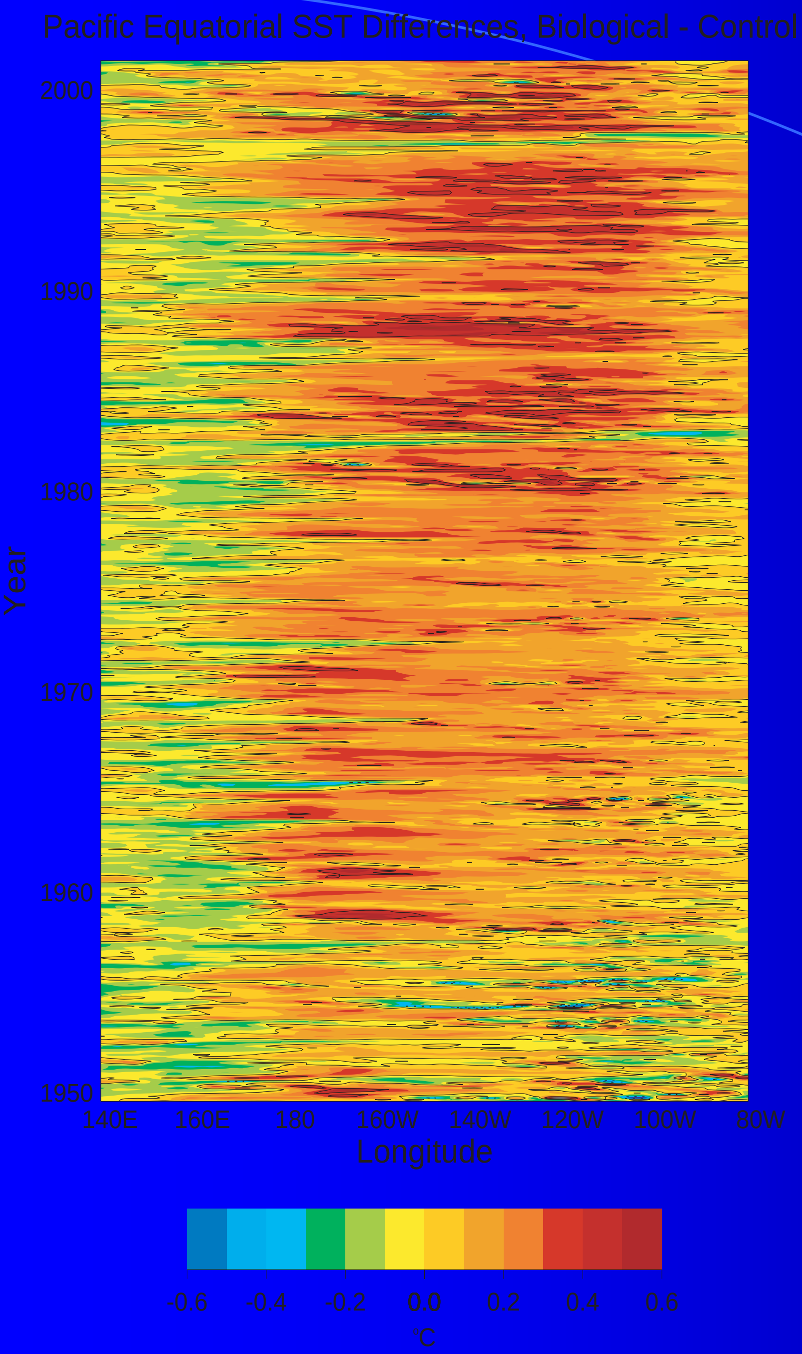
SST and current differences between runs with and without feedbacks between biology and physics



The surface warming produced by the dynamical feedbacks are also reproduced in a forced ocean-biogeochemical model. The SST differences between the control run with Hp=17m and the simulation with biological feedback show a significant reduction in the cold-tongue bias. The trapping of radiation below the surface leads to dynamical feedbacks.


Pacific Ocean Z20 Anomalies
Averaged between 1° S and 1° N
2000
1990
1980
1970
1960
1950
Month
140E
160E
180
160W
140W
120W
100W
80W
Longitude
-120
-80
-40
0
40
80
120
meters


Pacific Ocean Chlorophyll Anomalies
Attenuation Depth from Biological Model
Averaged between 1° S and 1° N
2000
1990
1980
1970
1960
1950
Year
140E
160E
180
160W
140W
120W
100W
80W
Longitude
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
mg/m³



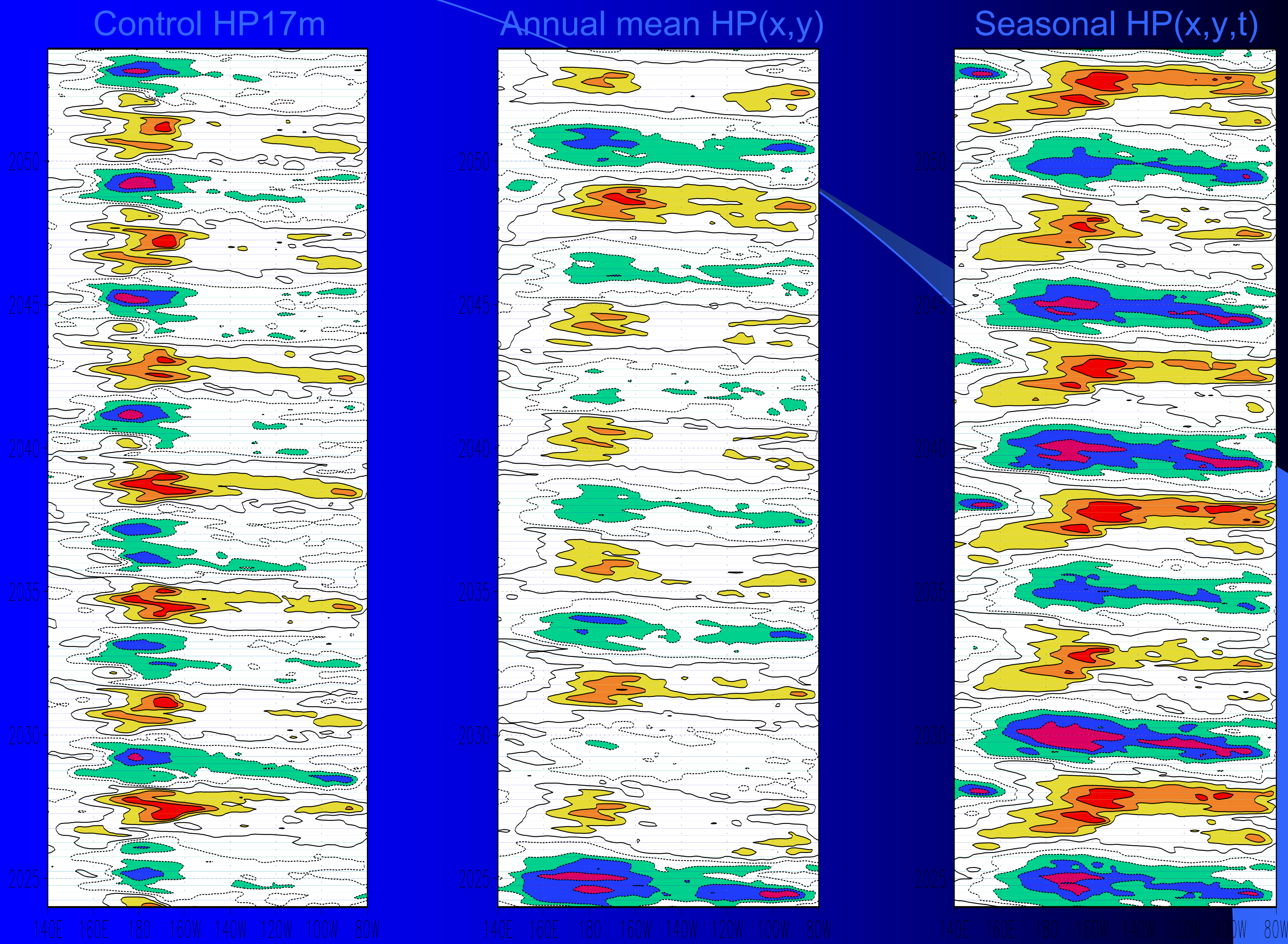
- The SST differences with and without bio-feedbacks have corresponding decadal and ENSO related variability.

- Note that individual ENSO events can produce SST warming/cooling of over 0.5C which can be important in the coupled climate system.

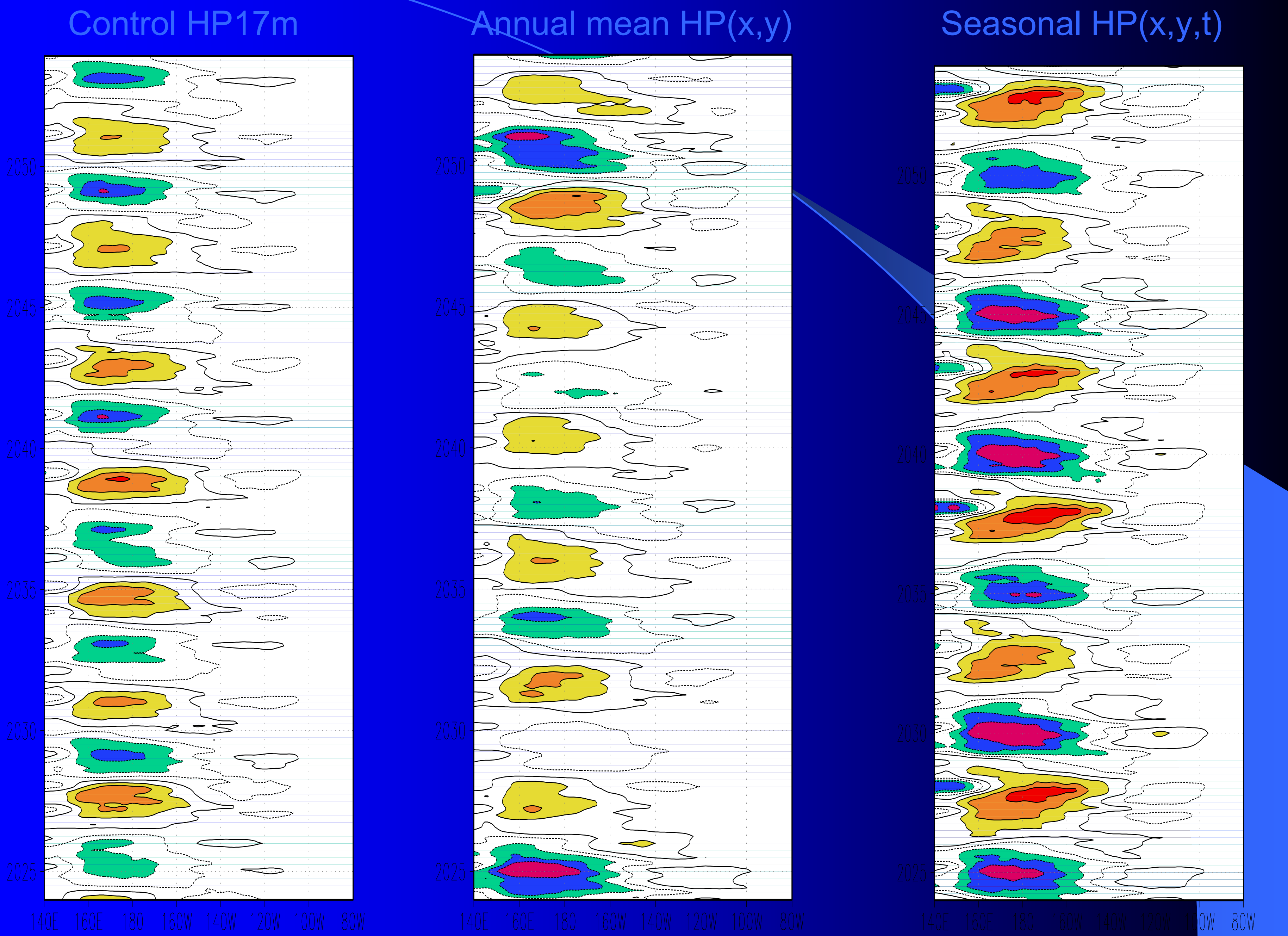
- Ocean biology changes the depth of penetrating radiation
- Such changes influence ocean temperatures and circulation
- Do such changes feed back to the atmosphere in a coupled climate context?
- Next we couple our ocean model to a statistical atmosphere and the depth of penetrating radiation (HP) is determined from SeaWiFS observations:
  - Held fixed (control 17 m)
  - Annual mean (x,y)
  - Seasonally varying (x,y,t)

Ballabrera et al. (2006)

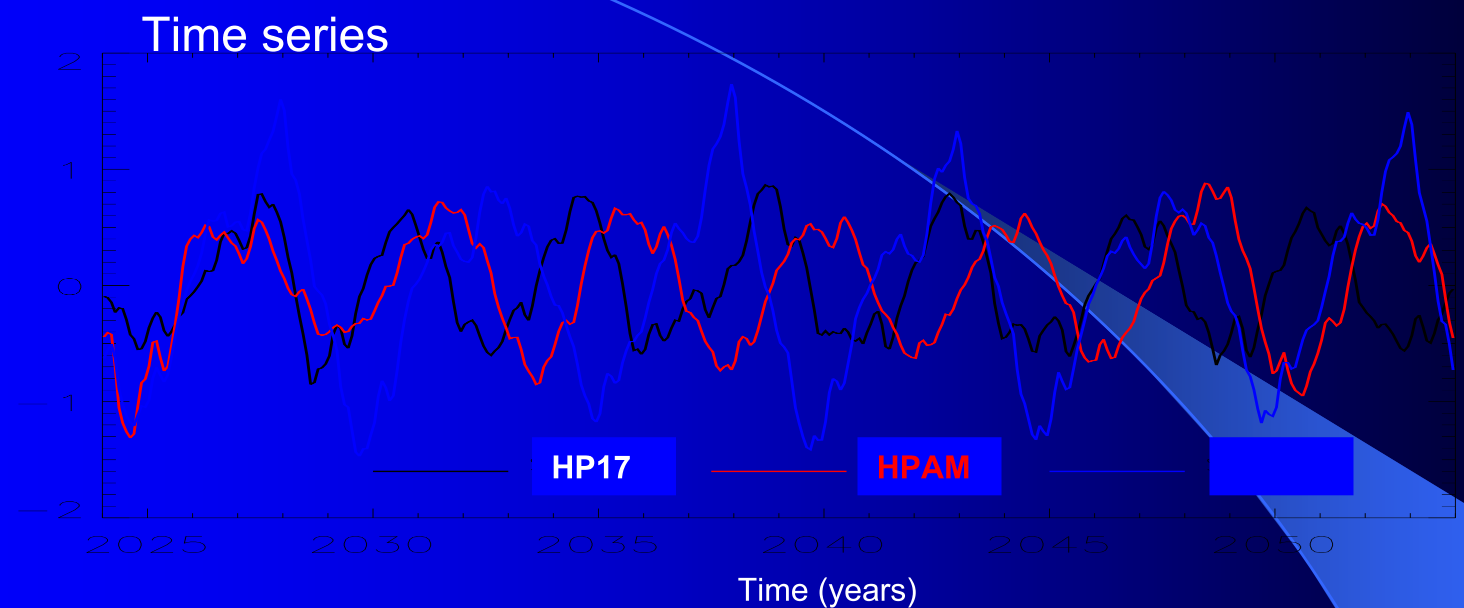
Equatorial Sea Surface Temperature Anomalies

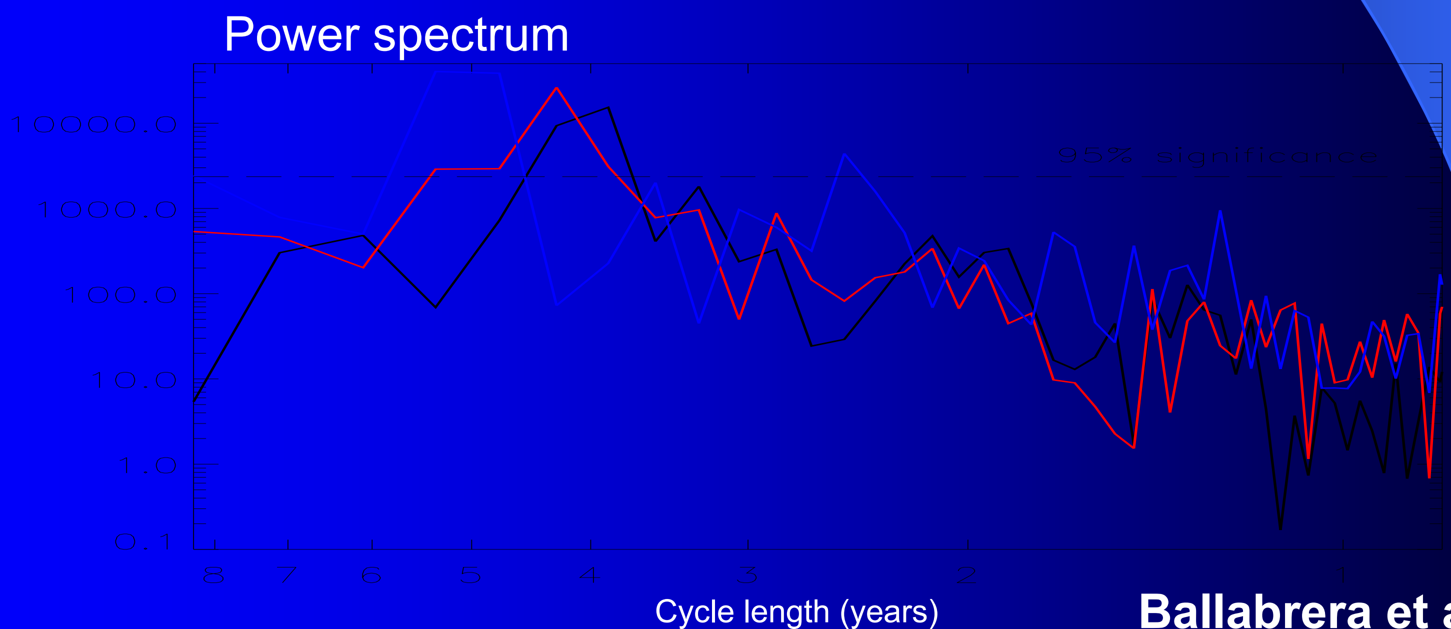


Zonal Winds Stress Anomalies (C.I. 0.1 dyn cm^{-2})



NINO 3 (150ºW-90ºW, 5ºN-5ºS) Sea Surface Temperature Anomalies

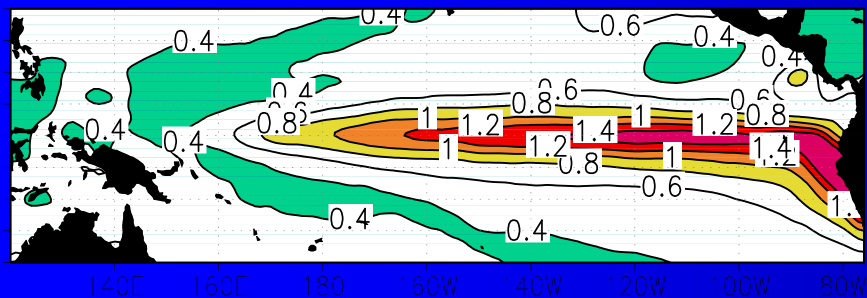




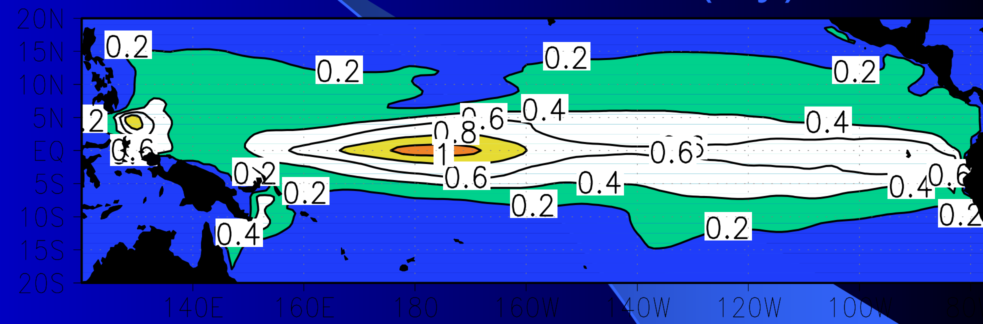
Ballabrera et al., 2006

Standard Deviation of Monthly SST Anomalies

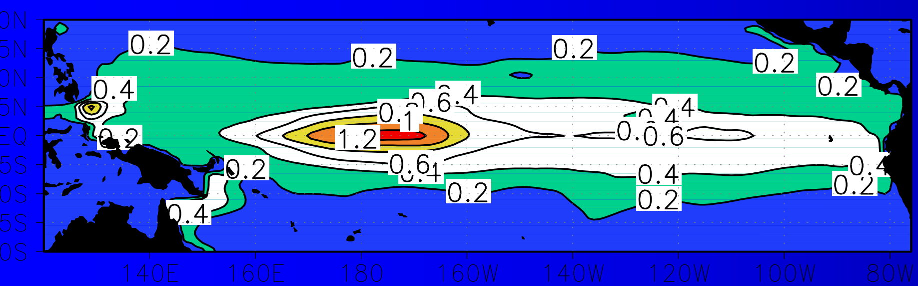
Observed-Reynolds



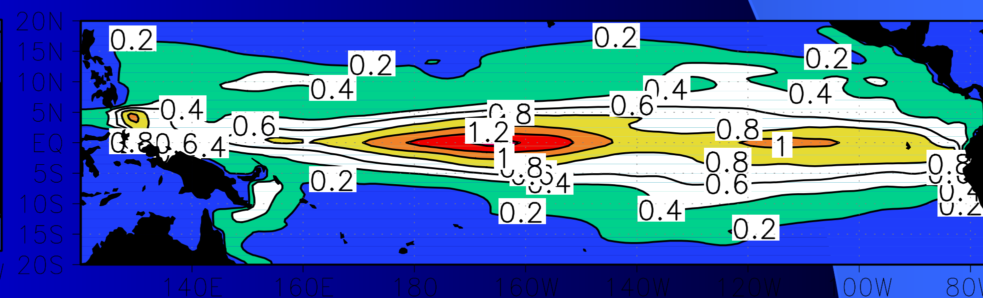
Annual mean HP(x,y)



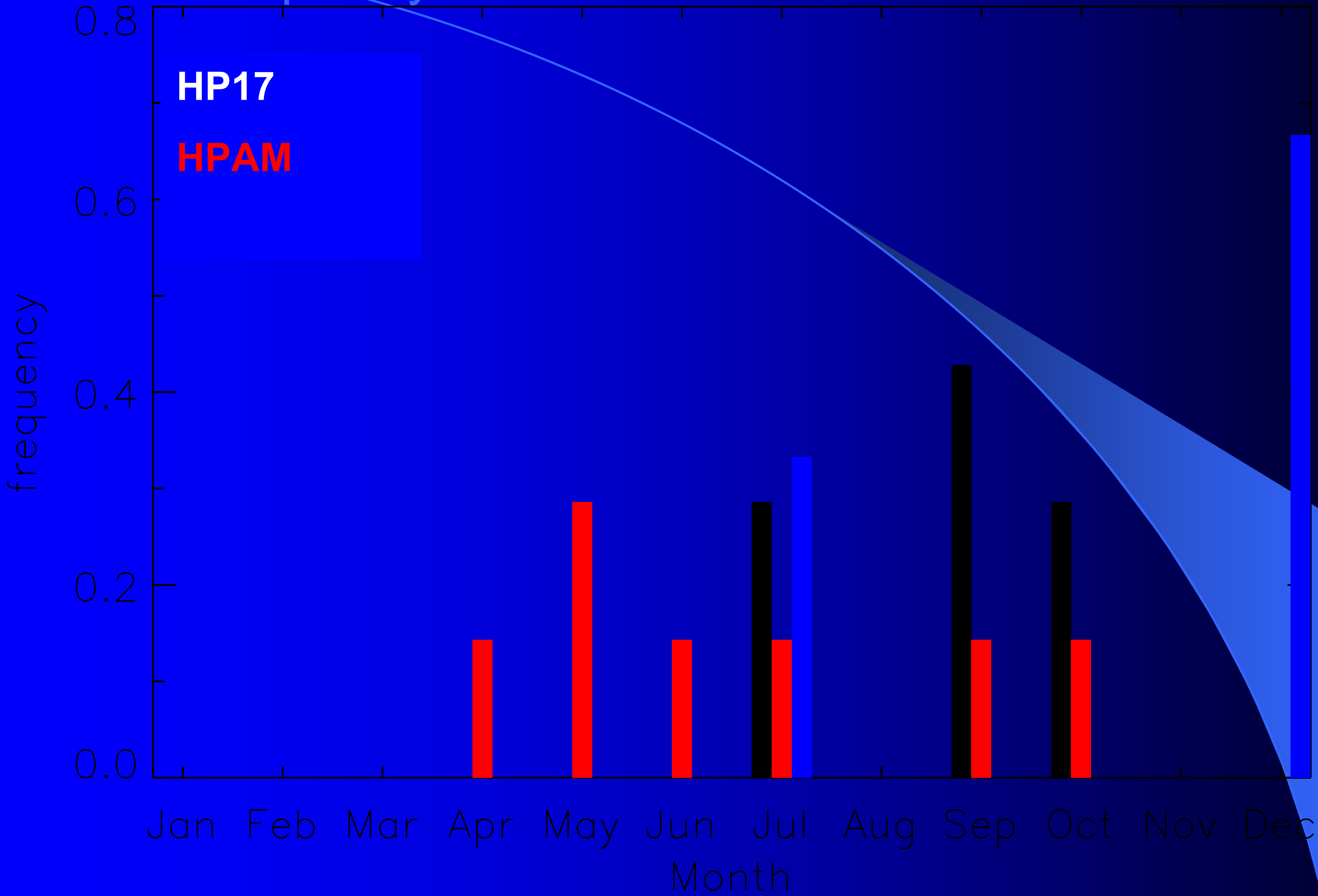
Control HP17m



Seasonal HP(x,y,t)



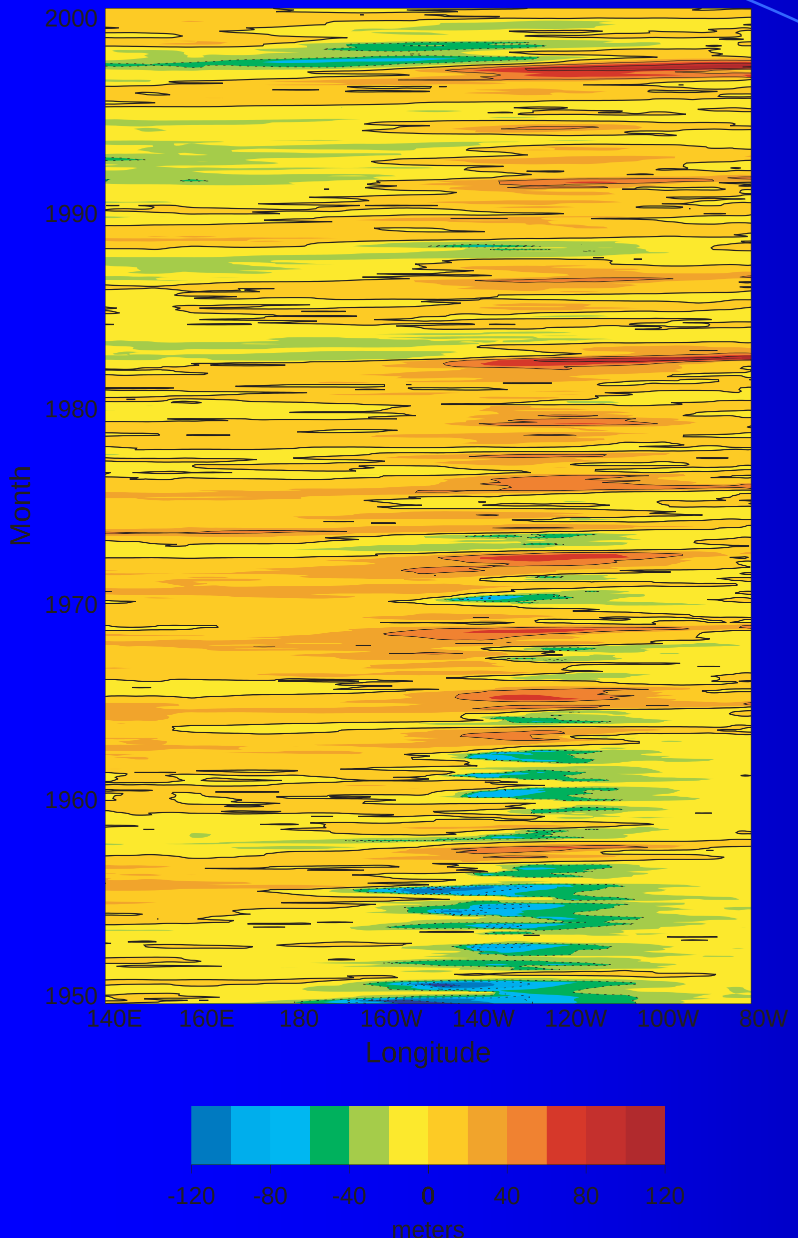
El Nino Frequency Distribution as Function of Time of Year



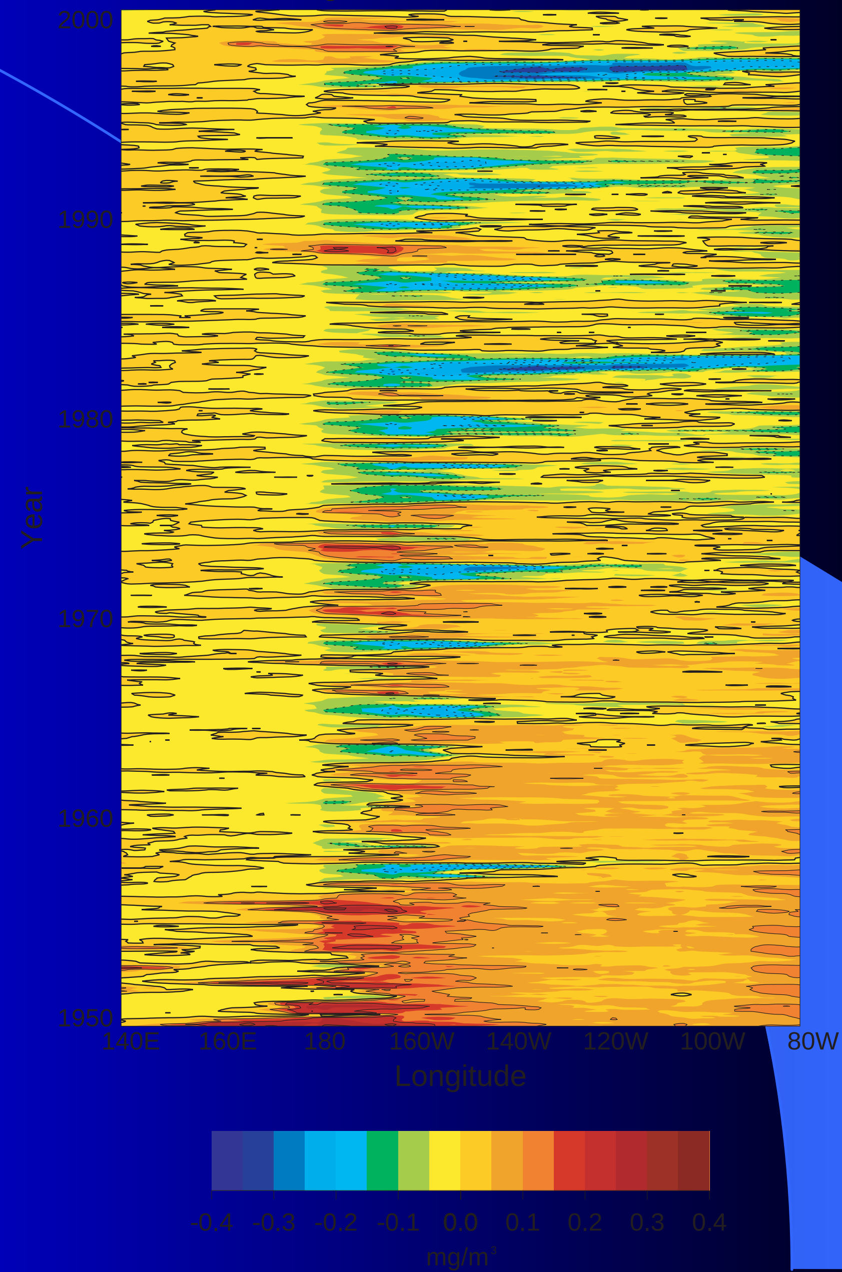
Control simulation with constant attenuation depth of 17m, and simulations with the **annual mean** and **seasonally varying** attenuation depths from satellite ocean color are carried out with an OGCM-Statistical atmosphere model. The annual phase-locking of the ENSO mature phase is accurately reproduced only when the seasonality is included.

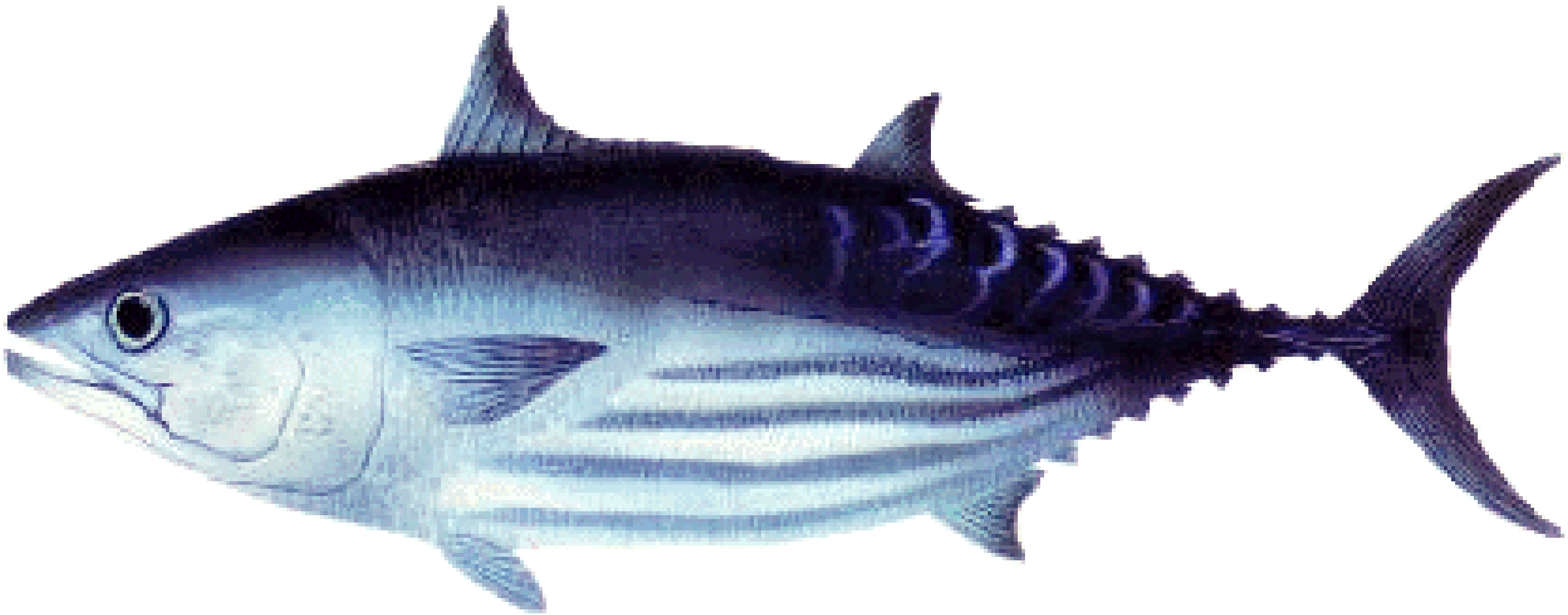
- A uniform attenuation depth in HP17 traps more radiation within the mixed layer during warm events and leads to maximum warming during summer and fall months when climatological upwelling is at its peak.
- The annual mean attenuation depths in HPAM tend to exaggerate the boreal spring warming due to the feedbacks we discussed earlier in Murtugudde et al. (2002).
- The seasonal cycle of attenuation depths best represents the lack of significant biological feedbacks when the thermocline is deep in the latter part of the year.

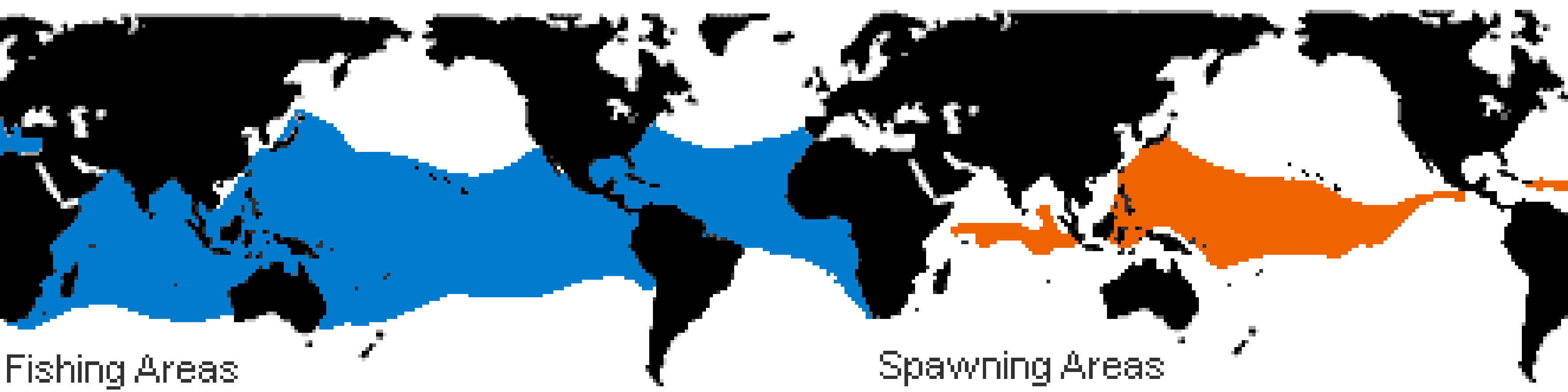
Pacific Ocean Z20 Anomalies
Averaged between 1° S and 1° N



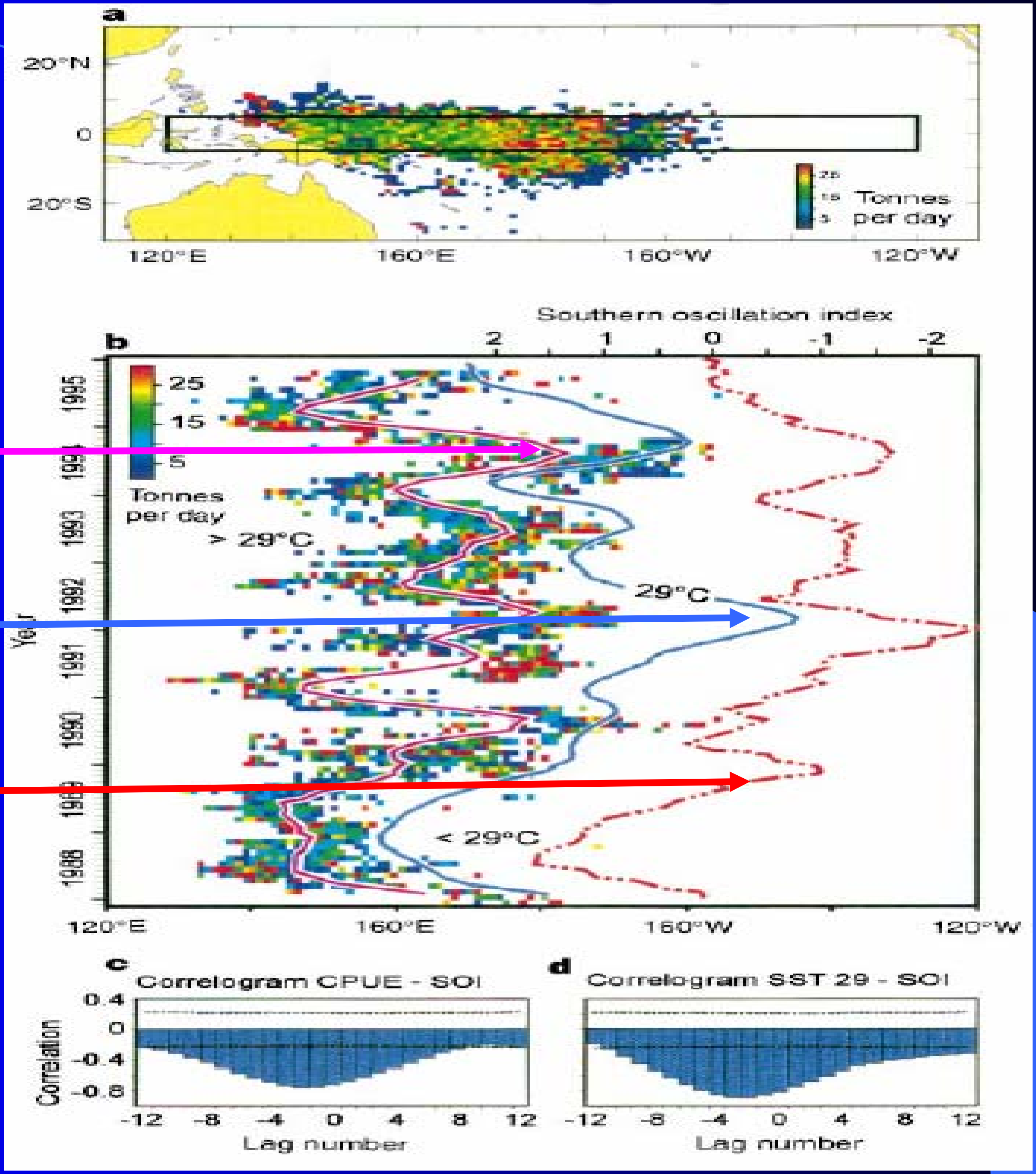
Pacific Ocean Chlorophyll Anomalies
Attenuation Depth from Biological Model
Averaged between 1° S and 1° N






Fishing Areas
Spawning Areas

Skipjack tuna
CPUE 1988-1995

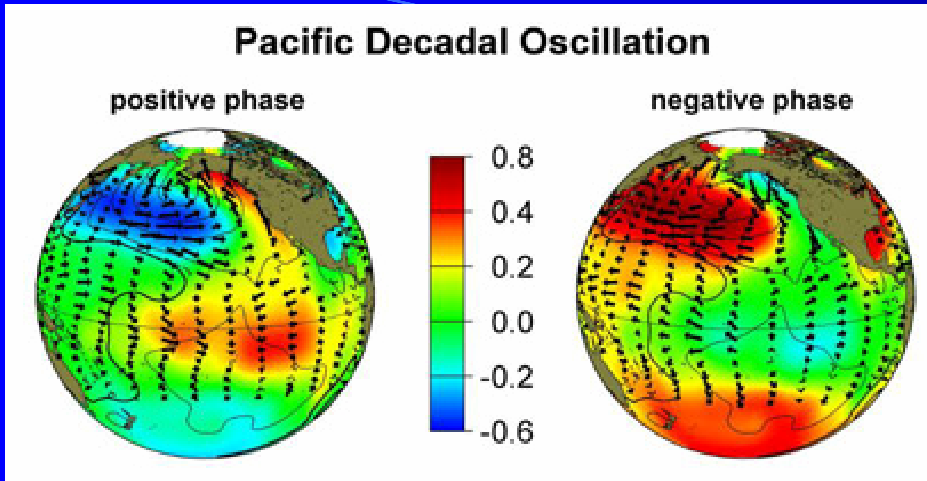


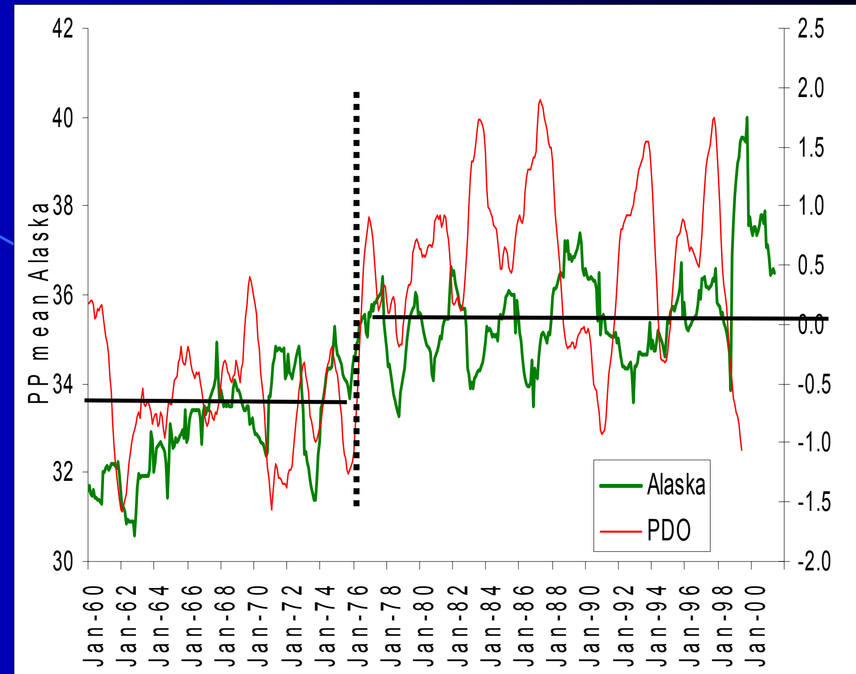
CPUE monthly mean centroid

29°C SST

SOI

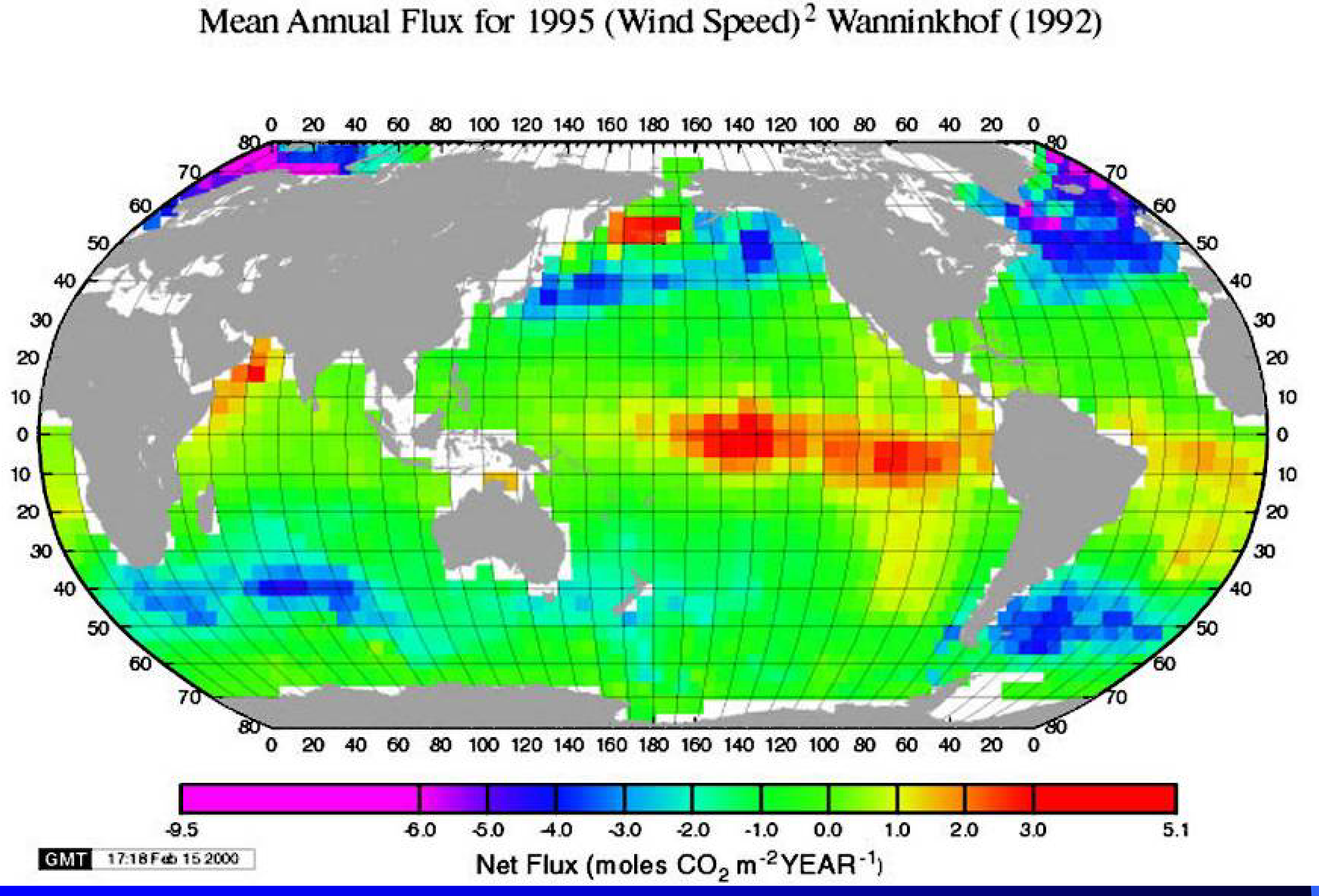
Lehodey et al., 1997



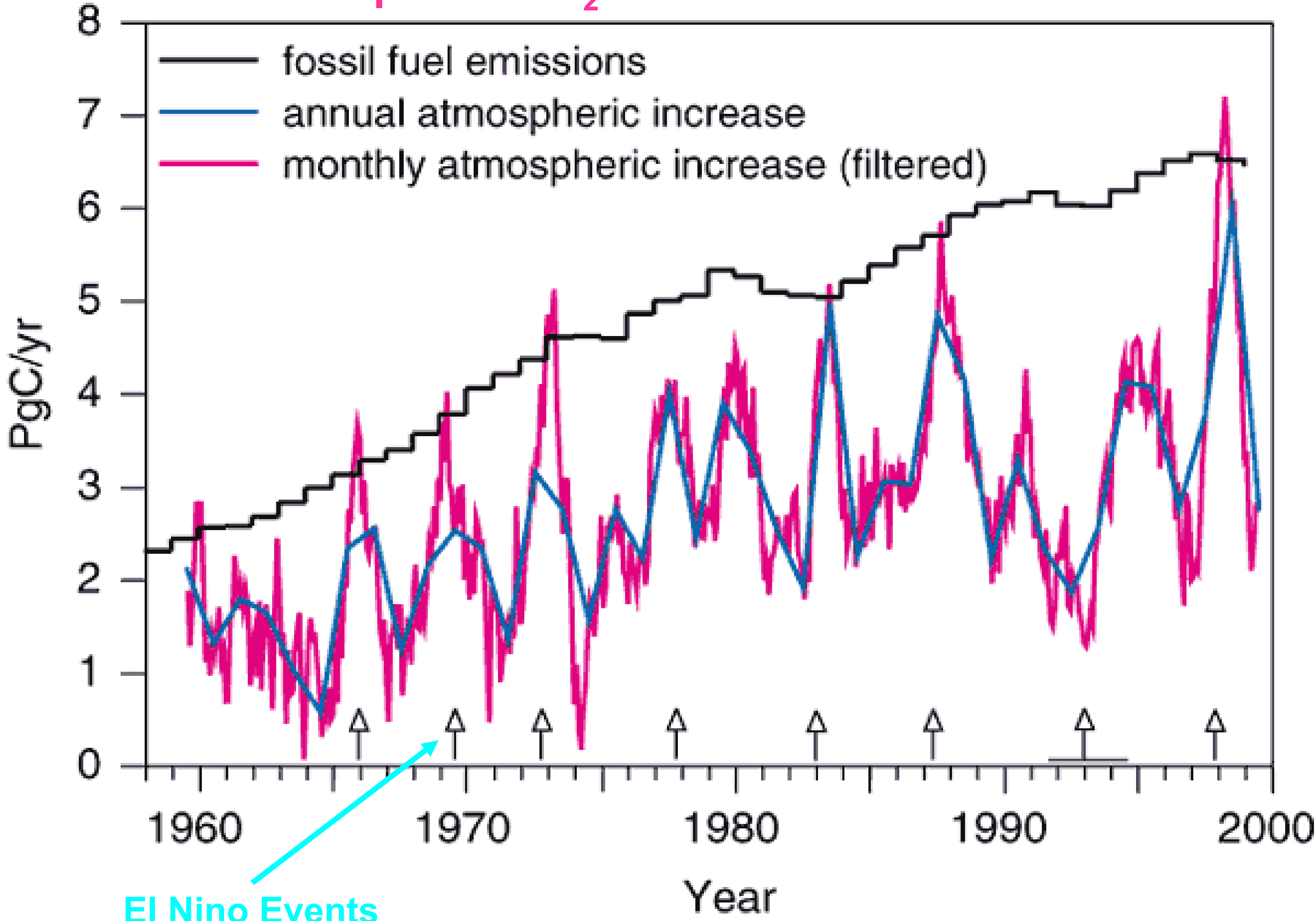


Interannual and the decadal variability in model primary production affects upper trophic levels which is reproduced by an Advection-Diffusion model for the marine foodweb.

CO_2 flux estimate, Takahashi et al., 2002



Atmospheric CO_2 Growth Rate at Mauna Loa



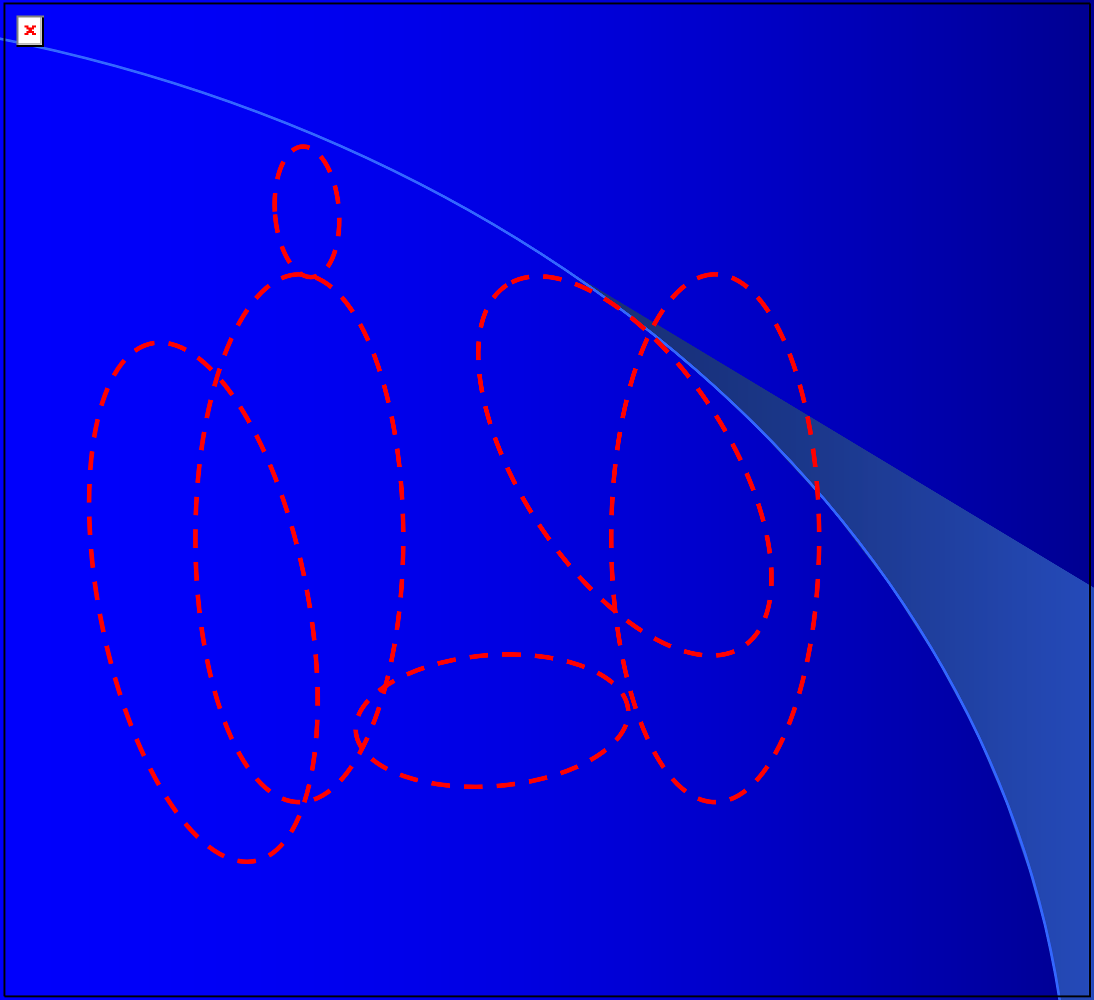
Terminology

- Primary productivity (PP): uptake of NO_3^- +NH_4^+
- New production (NP): uptake of NO_3^-
- Net community production (NCP): the change of dissolved CO_2 (DIC) due to uptake and regeneration of carbon.
- Export production: organic material sunk out of euphotice zone.

In a steady state: NP=NCP=EP

- ΔpCO_2: difference in partial pressure of CO_2 between the ocean and atmosphere.
- Oceanic pCO_2 = f (T, S, alk, DIC)

C cycle in the ocean



A physical-ecosystem-C model

OGCM:

Gent & Cane (1989)

Murtugudde et al.(1996)

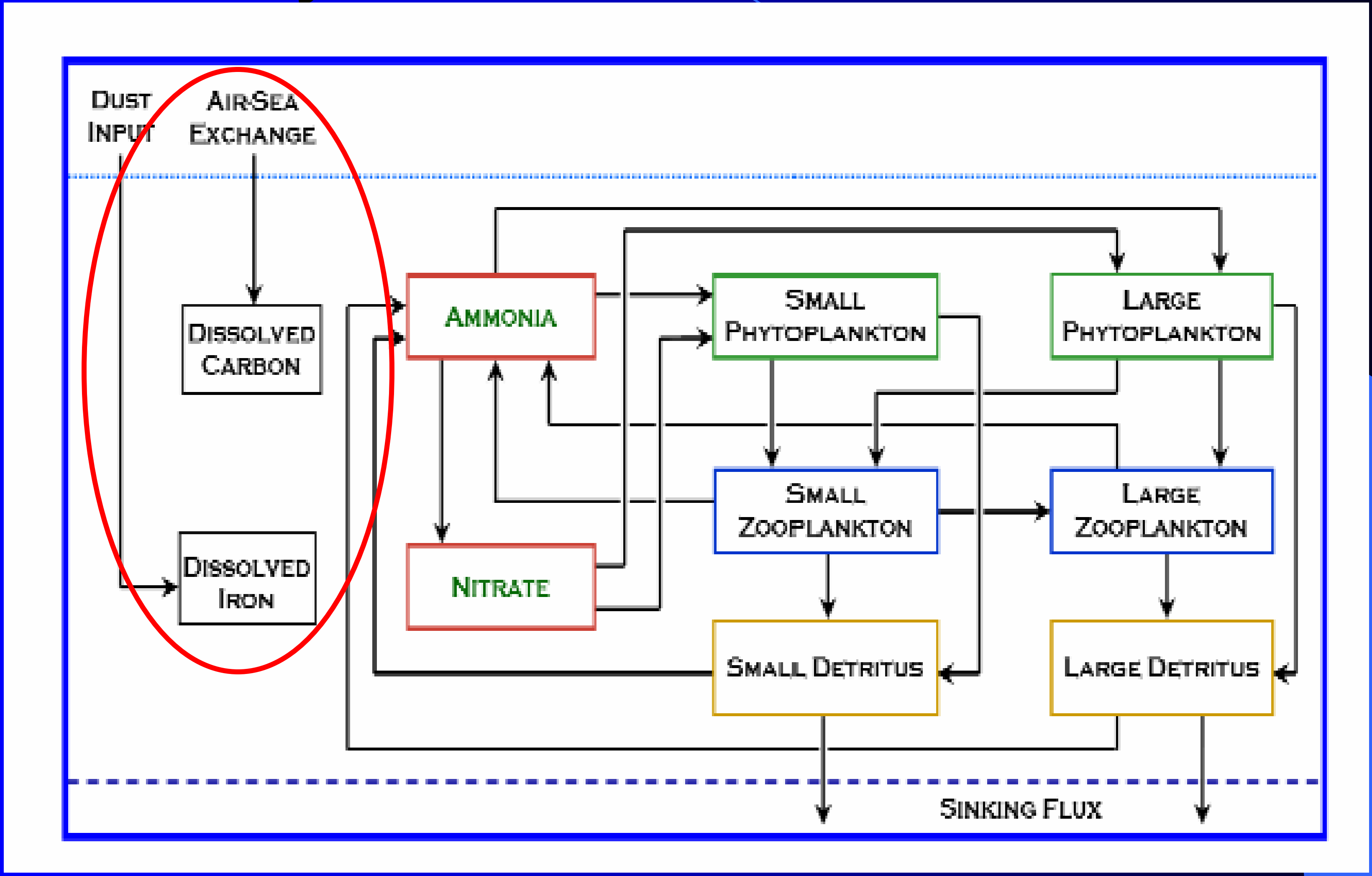
Ecosystem model:

Christian et al.(2001)

Wang et al. (2004)

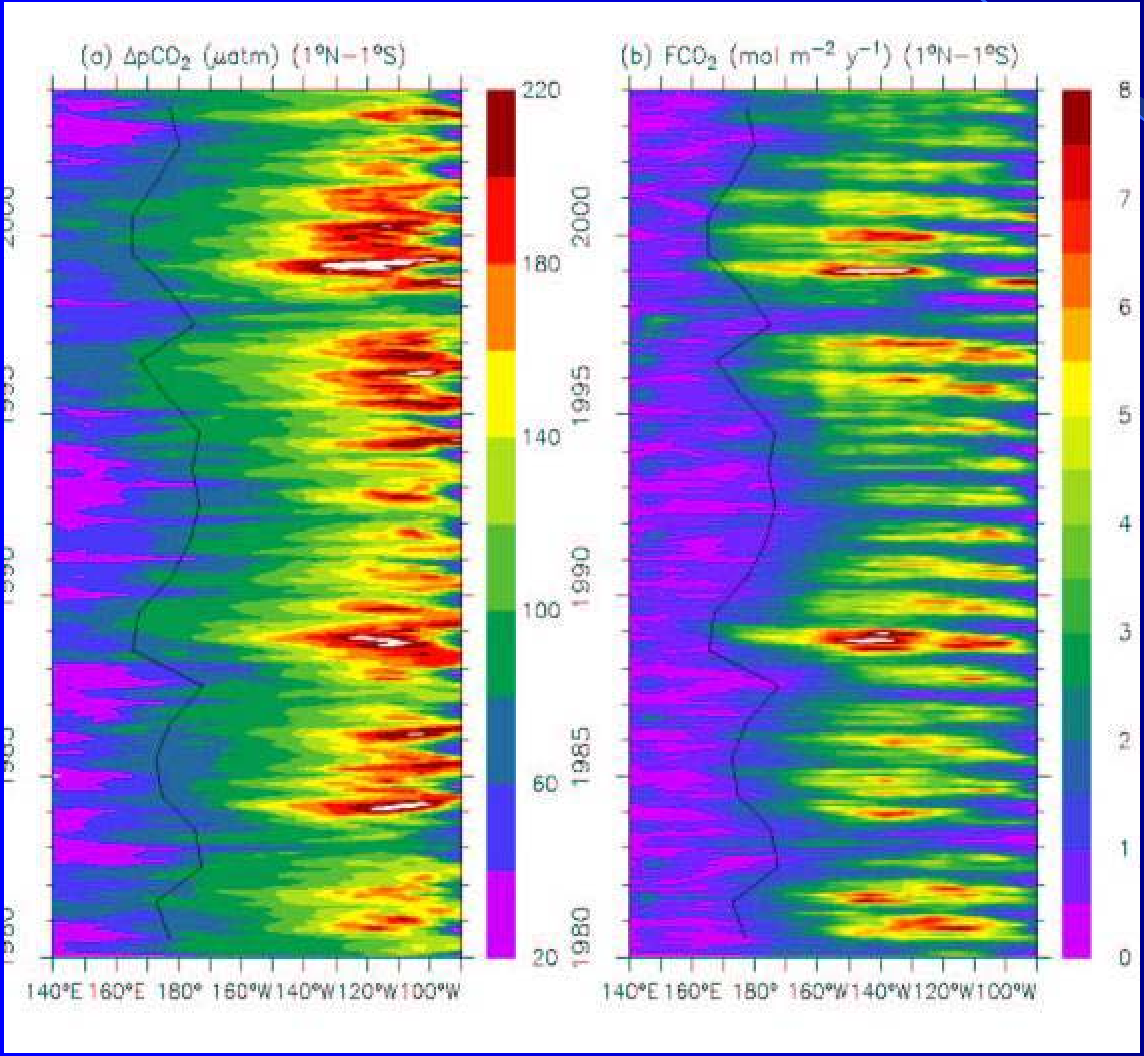
C chemistry model

Ecosystem/Carbon Model



- **Variability**
  - Biogeochemistry & ecosystem
  - Impact of physical forcing
- **New (i.e.** uptake of NO_3)**/Export production** (sinking of organic material out of euphotic zone)
  - Physical & biogeochemical controls
- **ΔpCO_2 and CO_2 flux**
  - Model validation
  - Underlying mechanisms

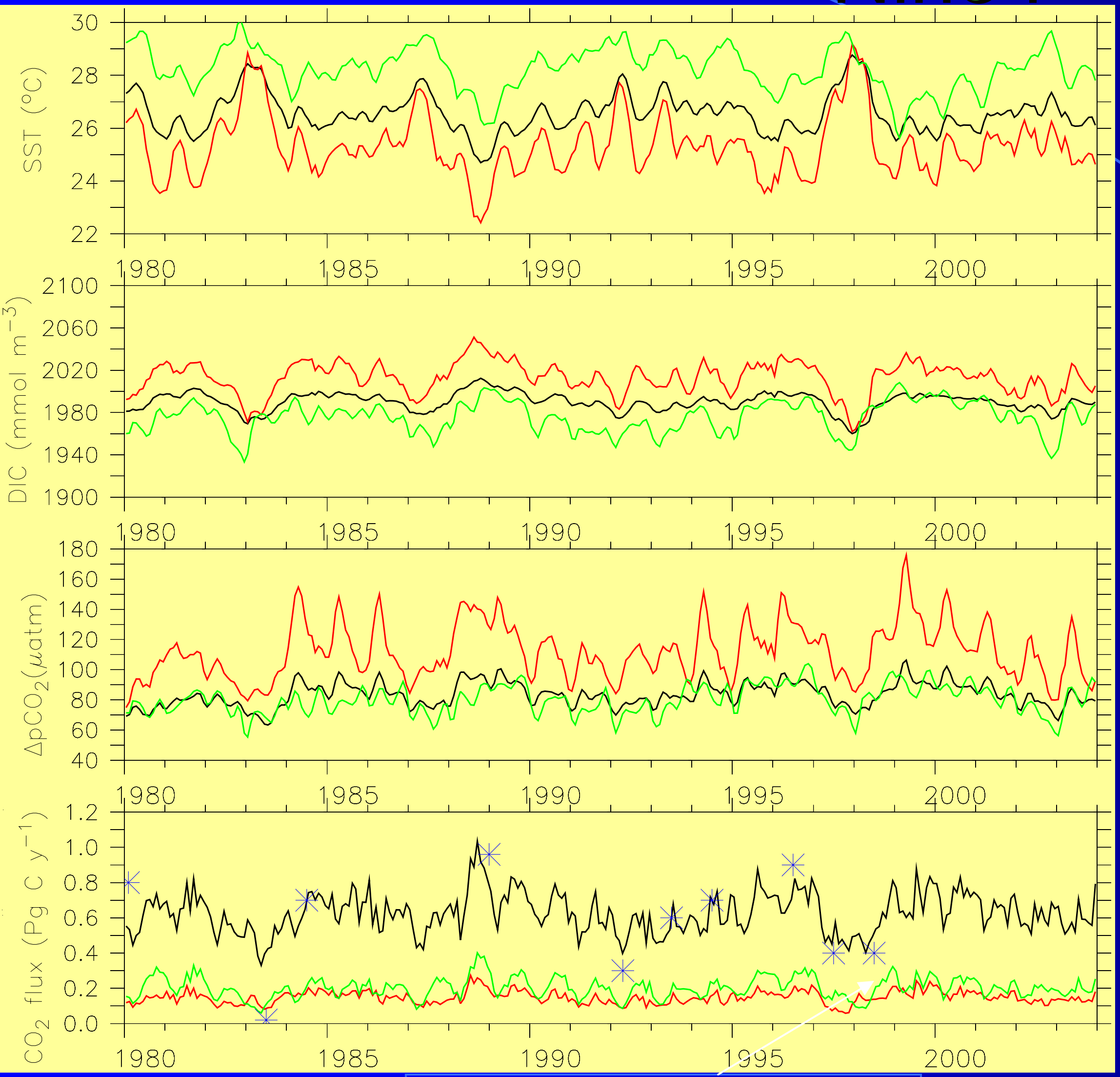
ΔpCO_2 and CO_2 flux (1ºN-1ºS)



- ΔpCO_2 (40-180)
  - Highest in east
  - Strong seasonal & interannual variations
- Outgas 1-6 mol/m^2/y
  - High in central area
  - Strong spatial & temporal variability
- Strong ENSO impact

Wang et al. 2006

SST, DIC, Δ pCO_2 & CO_2 flux for EQ, Nino3, Nino4



- Oceanic pCO2:
  - Seasonal: *SST dominating*
  - Interannual: *DIC dominating SST offsetting*
- Outgas: 0.4-1 Gt C/y, agree with observation

Stars: observations

Wang et al., 2006

- ENSO has significant impact on ecosystem, biogeochemistry, and C cycle.
  - El Nino: **low** Fe & **low** diss. CO_2

    → **low** biomass,Z/P & **low** oceanic pCO_2

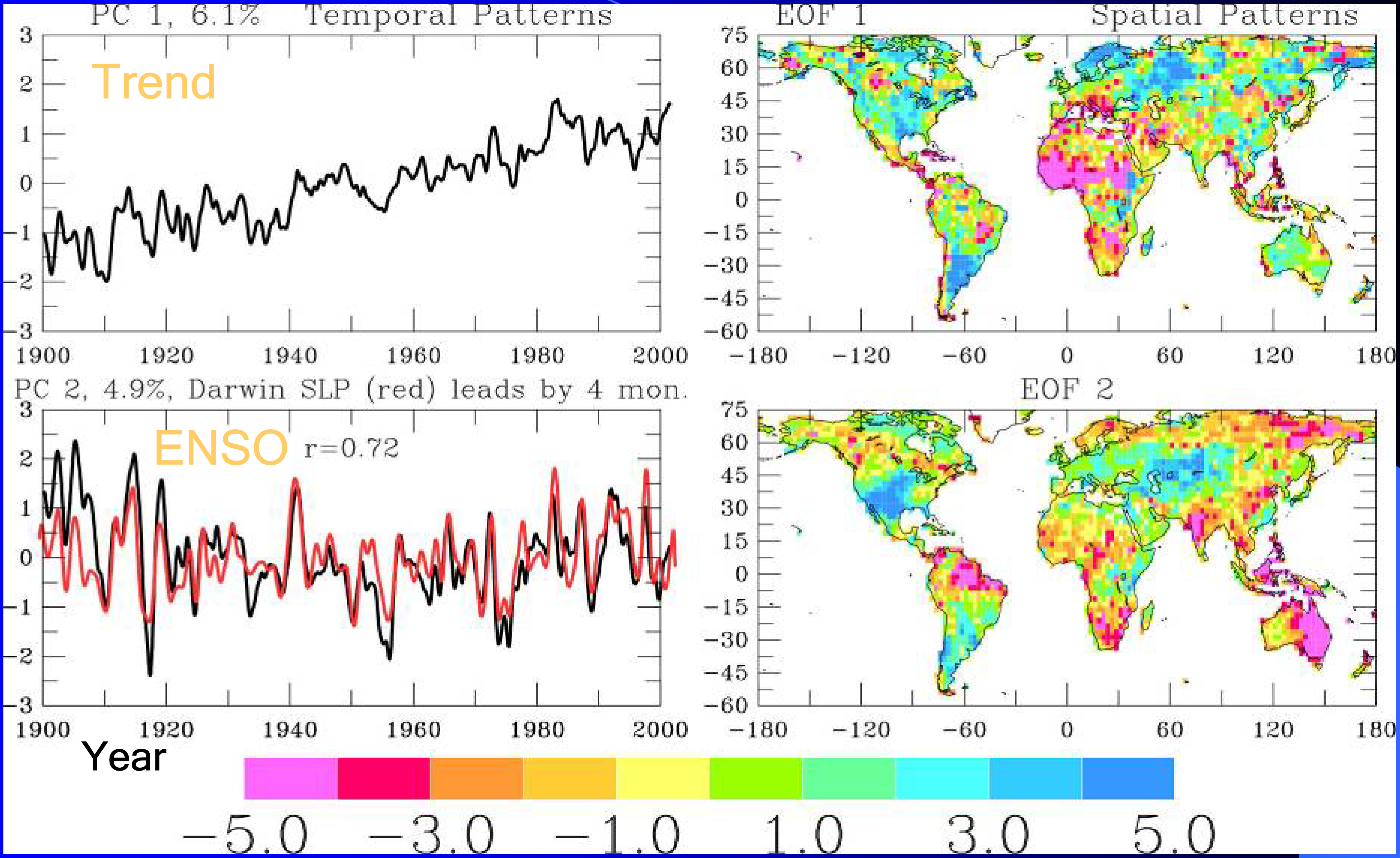
    → **low** PP,NP,EP & **low** outgassing
  - La Nina: **high** Fe & **high** diss. CO_2

    → **high** biomass,Z/P & **high** oceanic pCO_2

    → **high** PP,NP/EP & **high** outgassing

- Outgassing: 0.4-1 Gt C/y, close to observations.
- Oceanic pCO_2 is dominated by DIC at interannual time scale, but by SST at seasonal time scale.
- SST also plays a role in weakening the interannual variability.

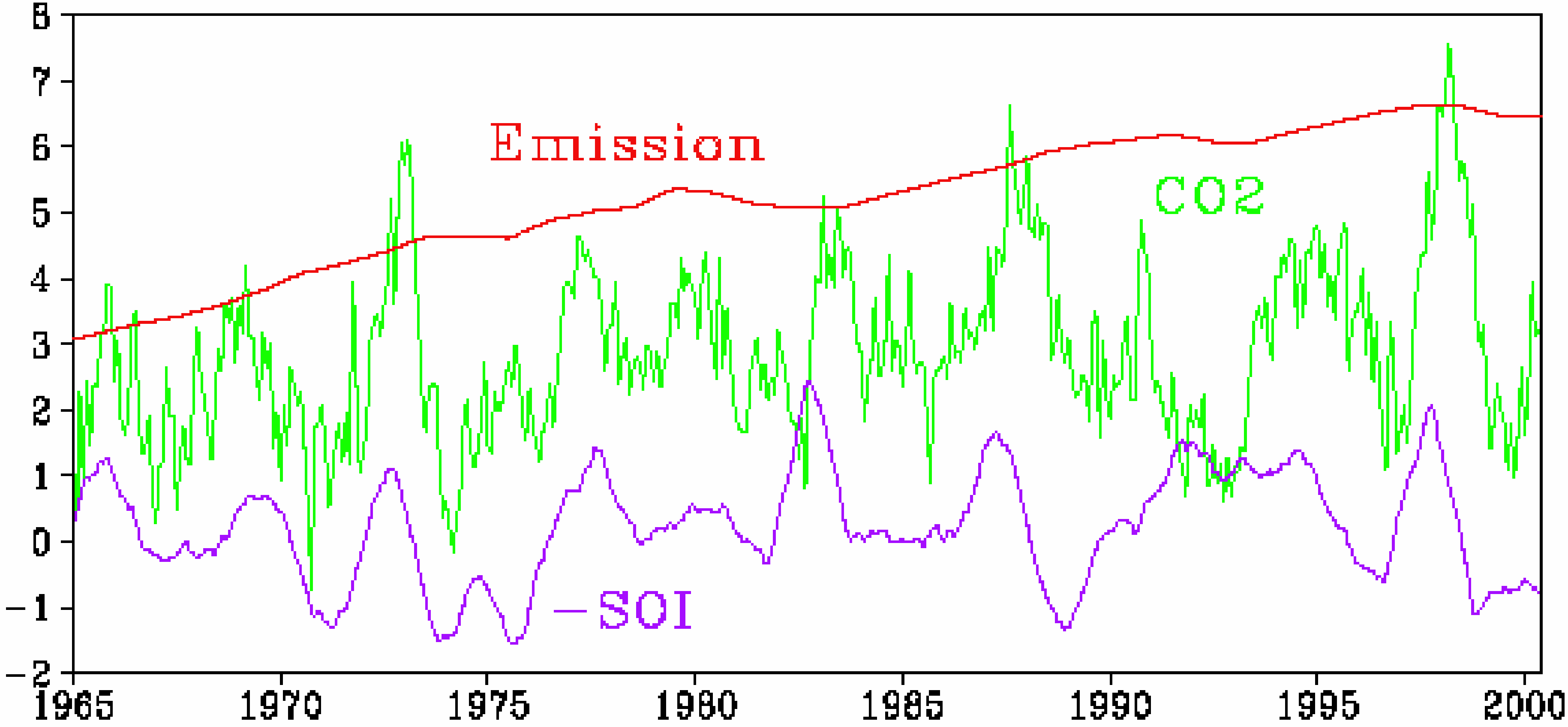
Leading Modes of PDSI Variations



Precipitation is dominant contributor

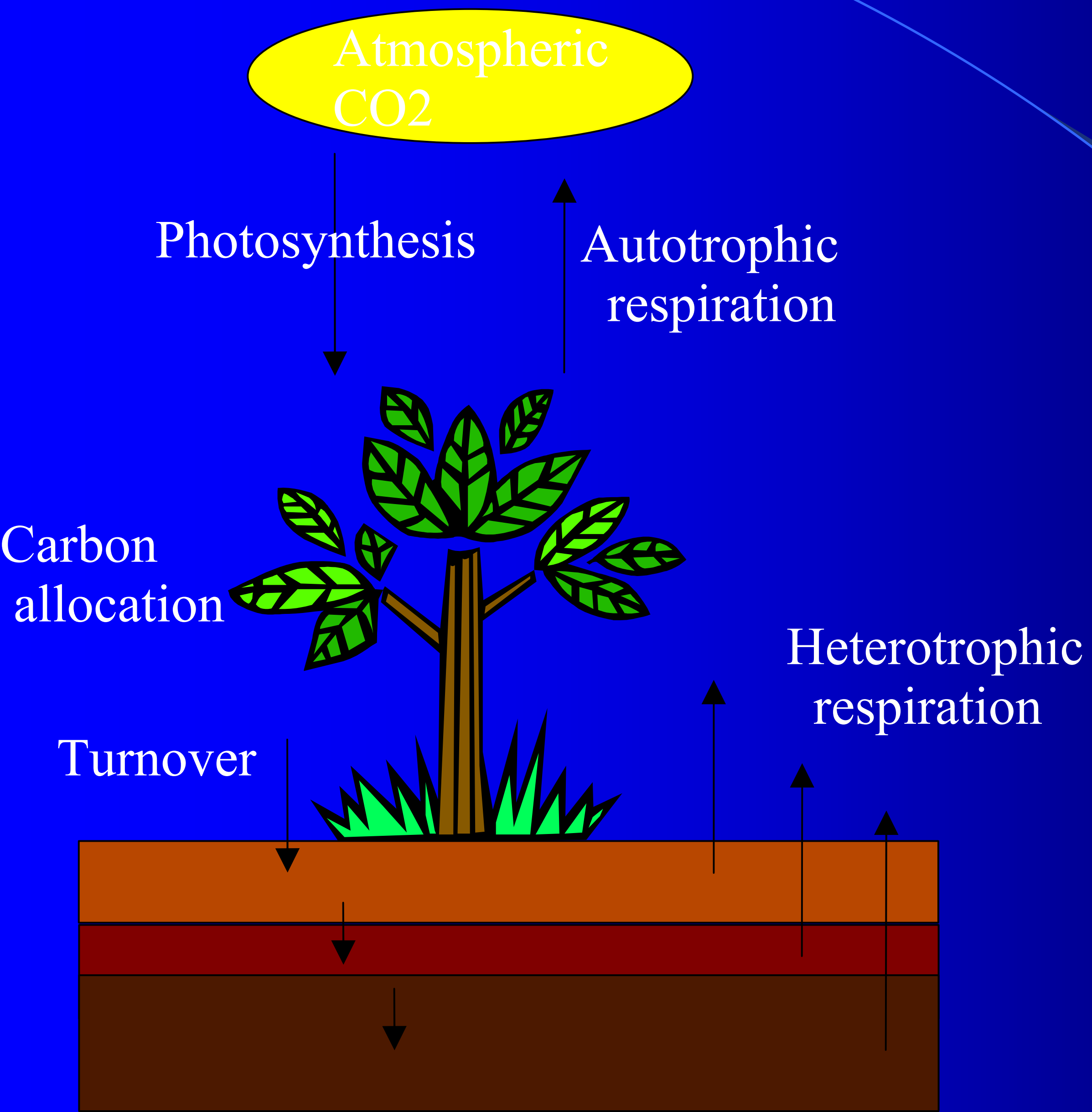
Courtesy A. Dai

Anthropogenic CO_2 Emission and Atmospheric CO_2 Growth Rate at Mauna Loa ($PgC\ yr^{-1}$)



Zeng et al. 2005

The VEgetation-Global Atmosphere-Soil Model (VEGAS)



4 **Plant Functional Types**:
- Broadleaf tree
- Needleleaf tree
- C3 Grass (cold)
- C4 Grass (warm)

3 Vegetation carbon pools:
- Leaf
- Root
- Wood

3 Soil carbon pools:
- Fast
- Intermediate
- Slow

VEGAS II

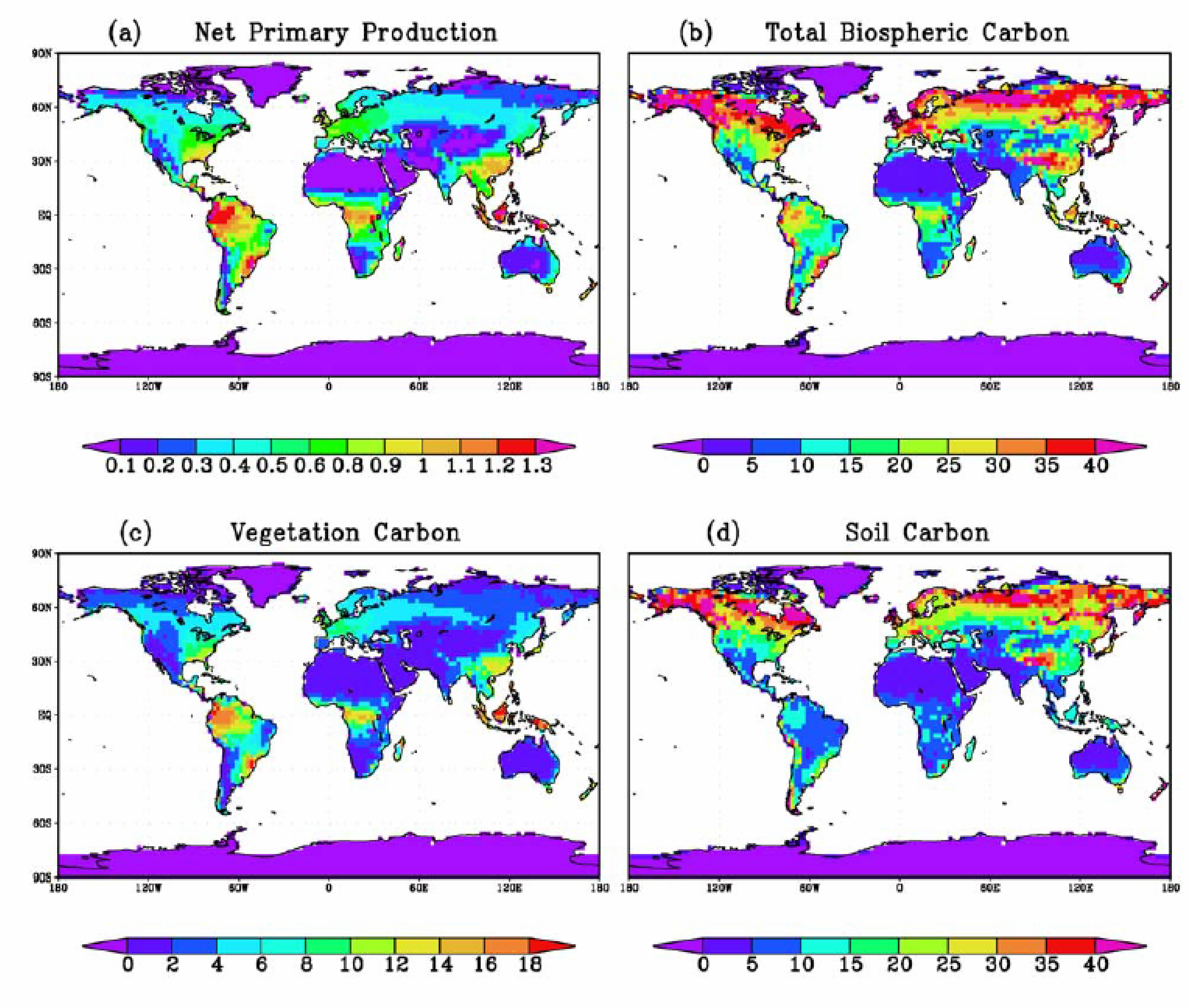
Light (PAR, LAI, Height), soil moisture, temperature, CO_2

temperature, soil moisture, lower soil pools slower decay

Net growth, shading => fractional cover

moisture, fuel load, PFT dependent resistance

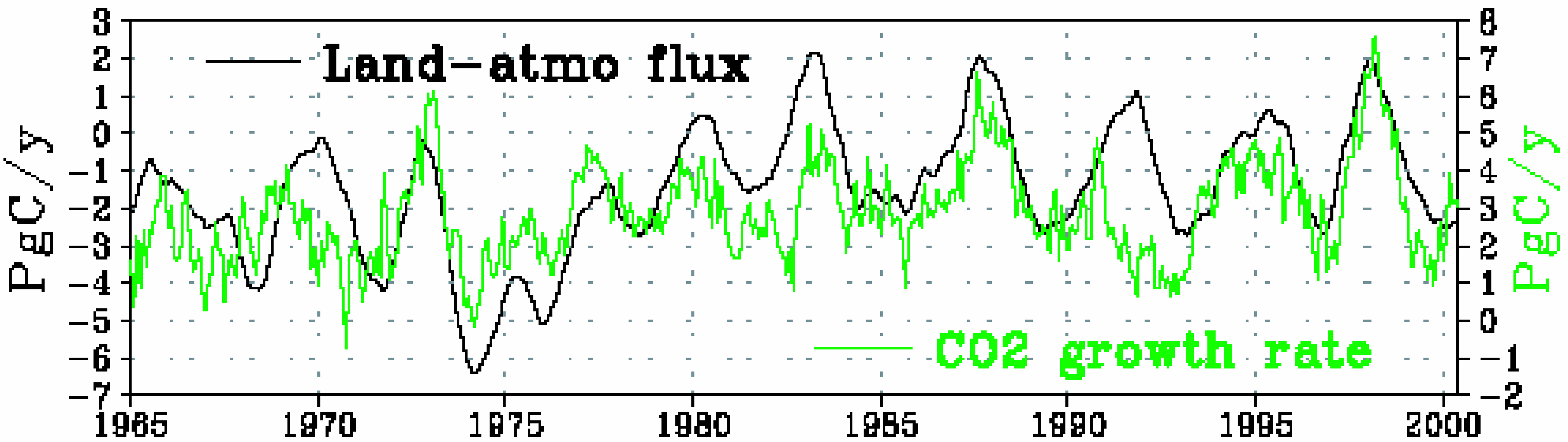
Spatial Distribution of VEGAS Model Simulated Annual Mean NPP Averaged for 1965-2000 ($kg\ m^{-2}\ yr^{-1}$) and C ($kg\ m^{-2}$)



Modeled Monthly Carbon Flux From Land to Atmosphere

and

Observed CO_2 Growth Rate

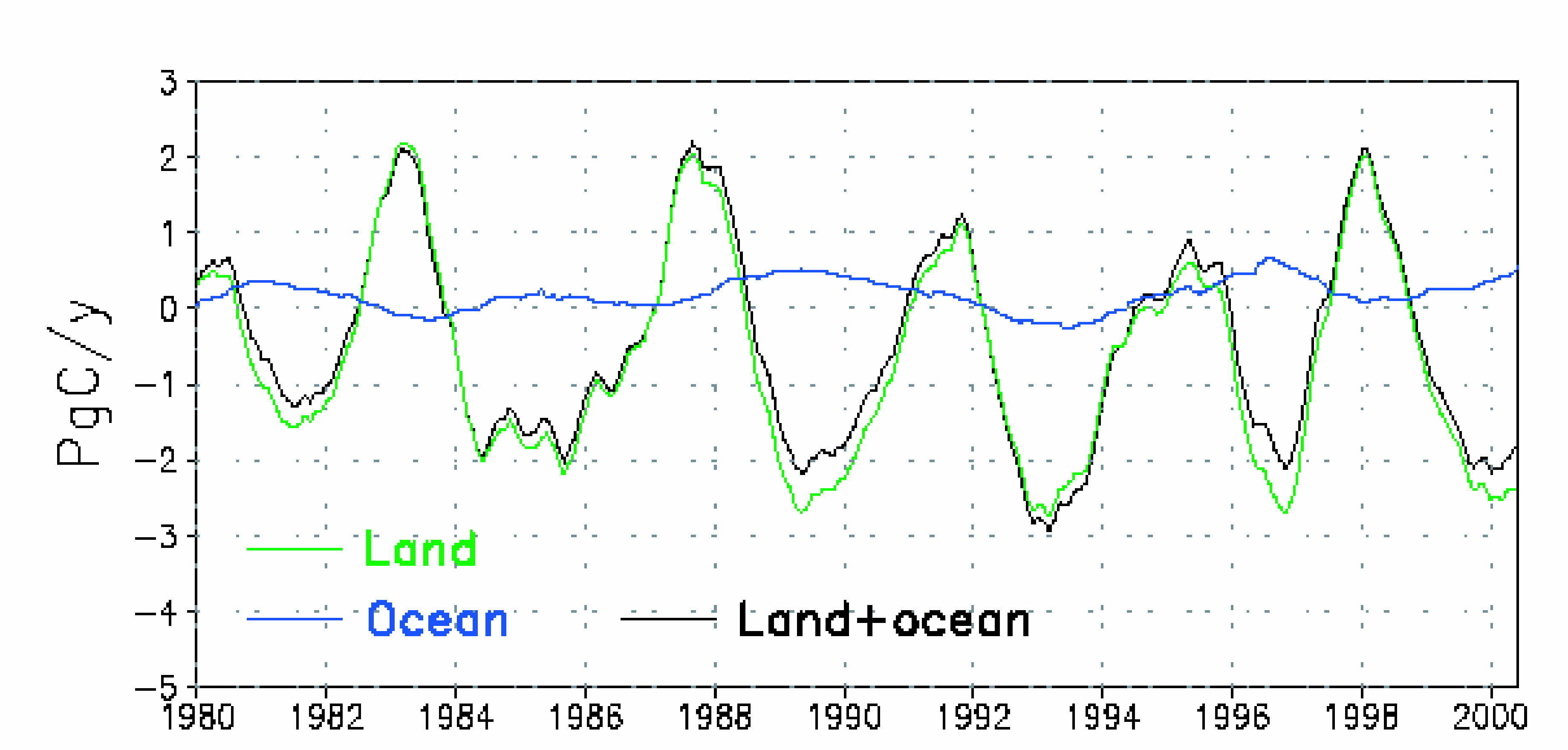


Zeng et al. 2005

Land-Atmosphere Carbon Flux Modeled by VEGAS

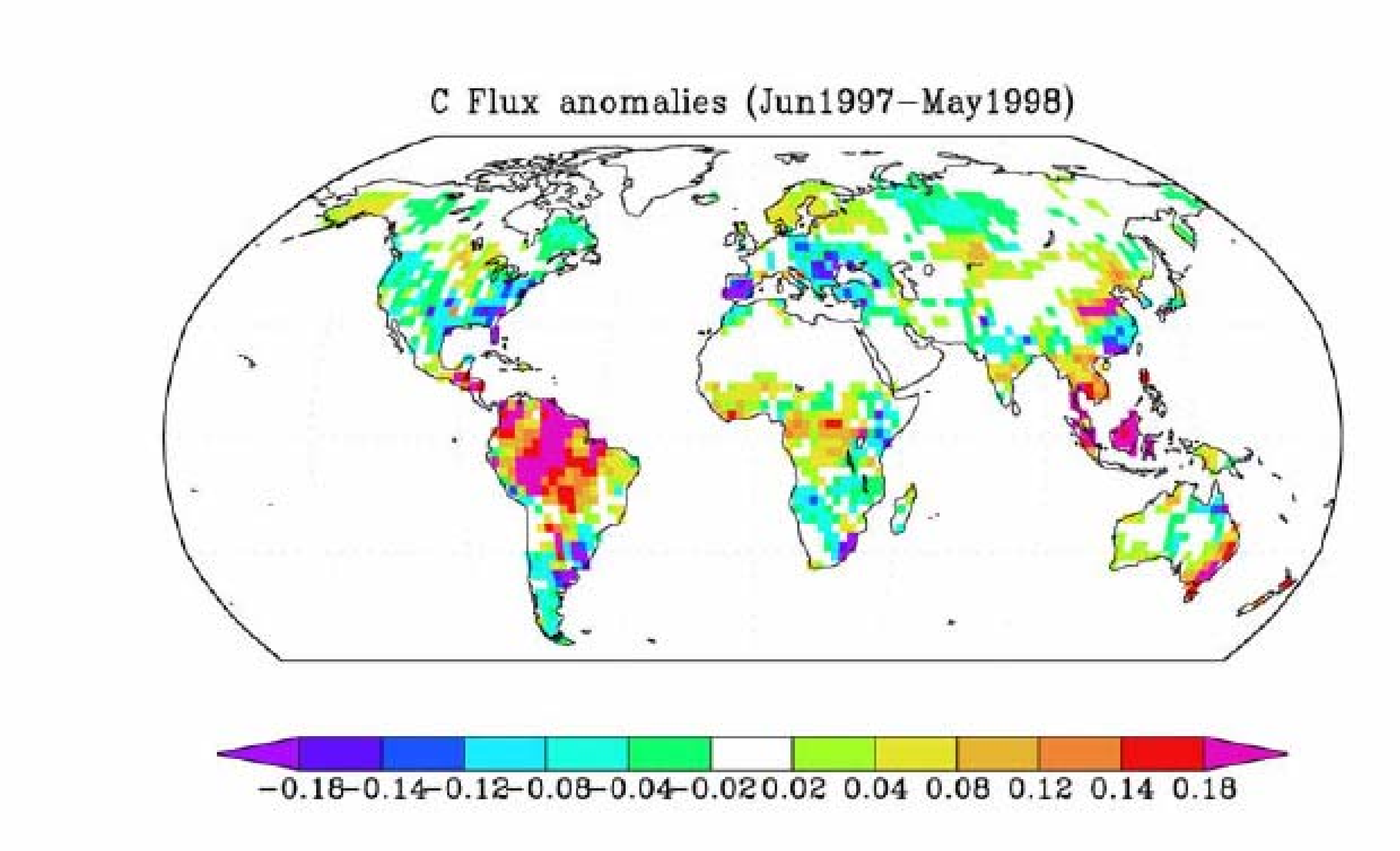
And

Ocean-Atmosphere Carbon Flux Modeled by HAMOCC



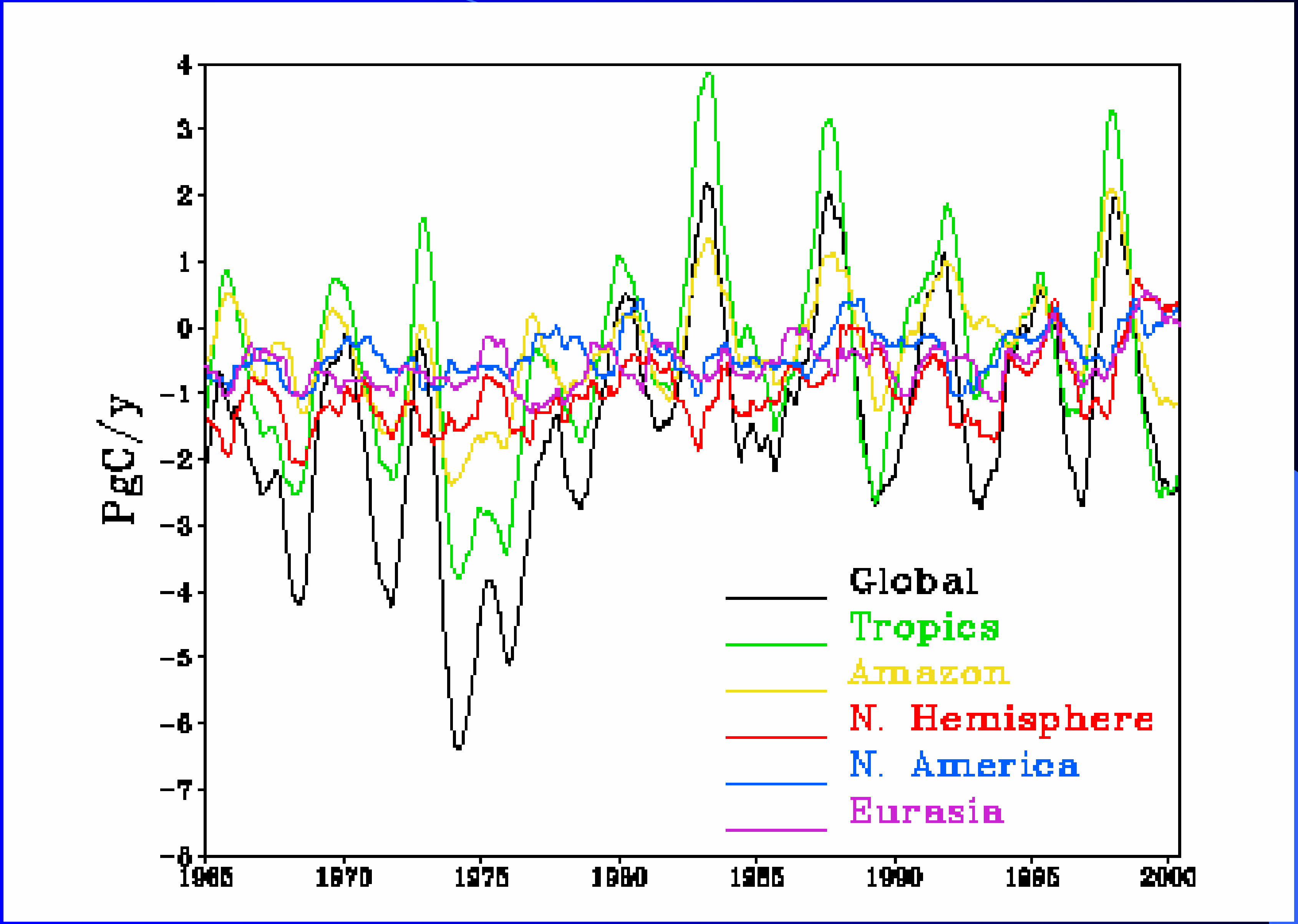
Zeng et al., 2005

Modeled Carbon Flux Anomalies during the 1997-1998 El Nino (kg m^{-2} yr^{-1})

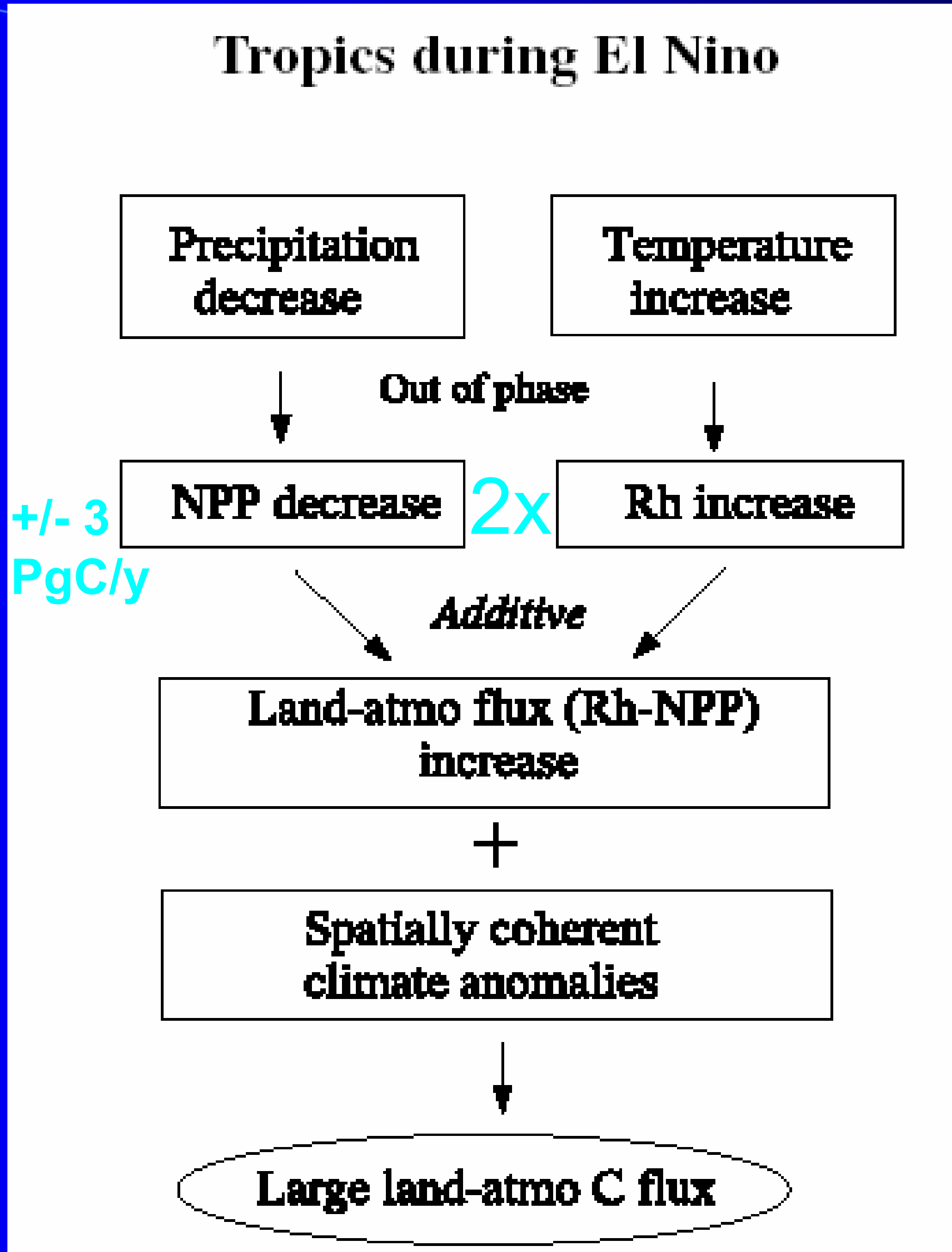


Zeng et al., 2005

Interannual Variability of Regional Land-Atmosphere Carbon Fluxes

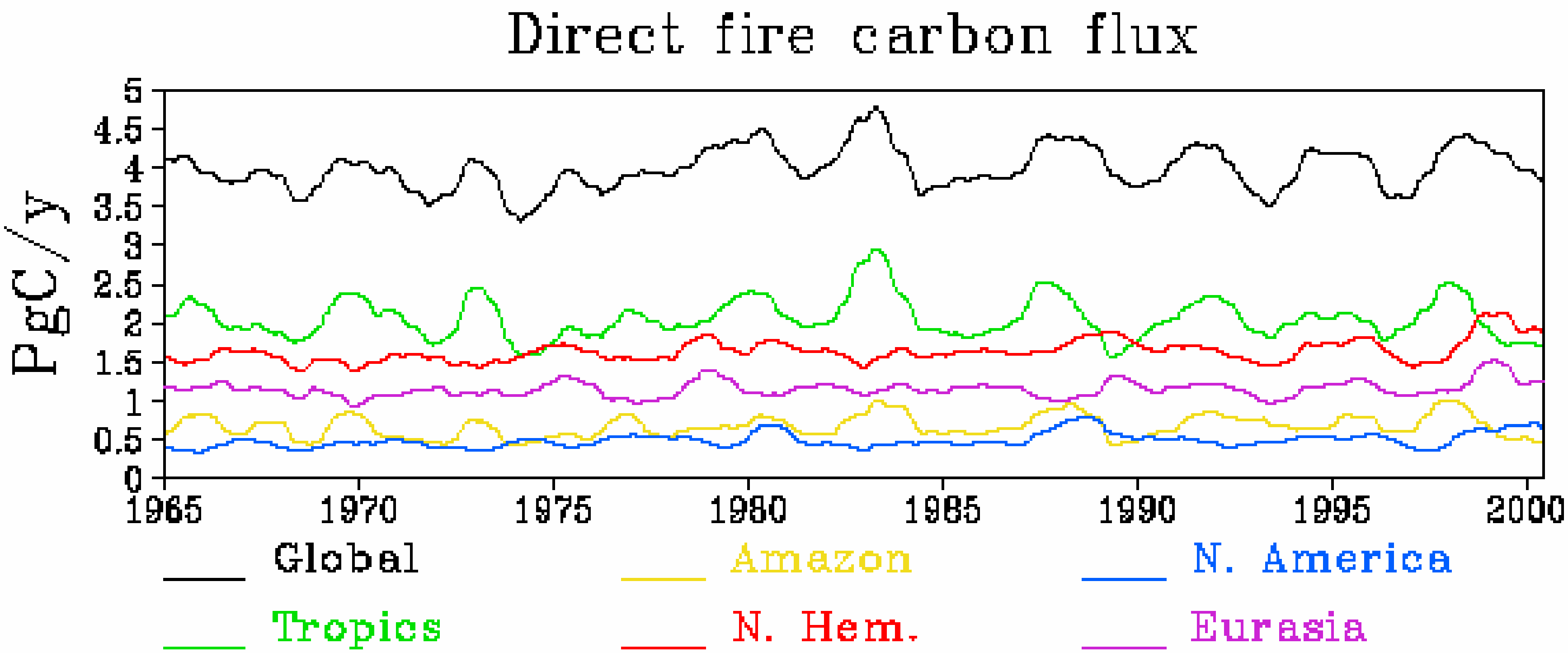


Zeng et al., 2005



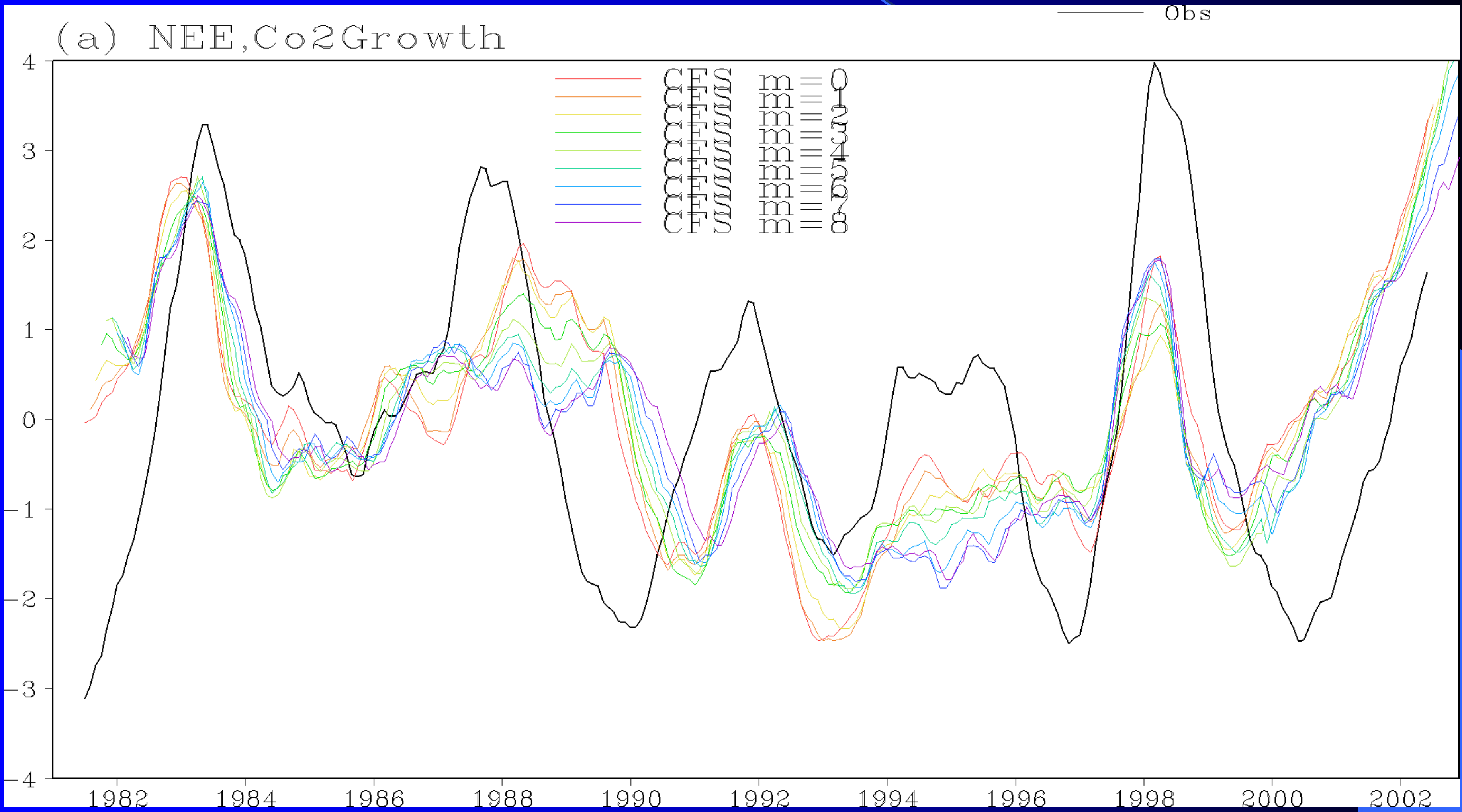
Zeng et al., 2005

Modeled Carbon Fluxes due to Fires in Various Regions



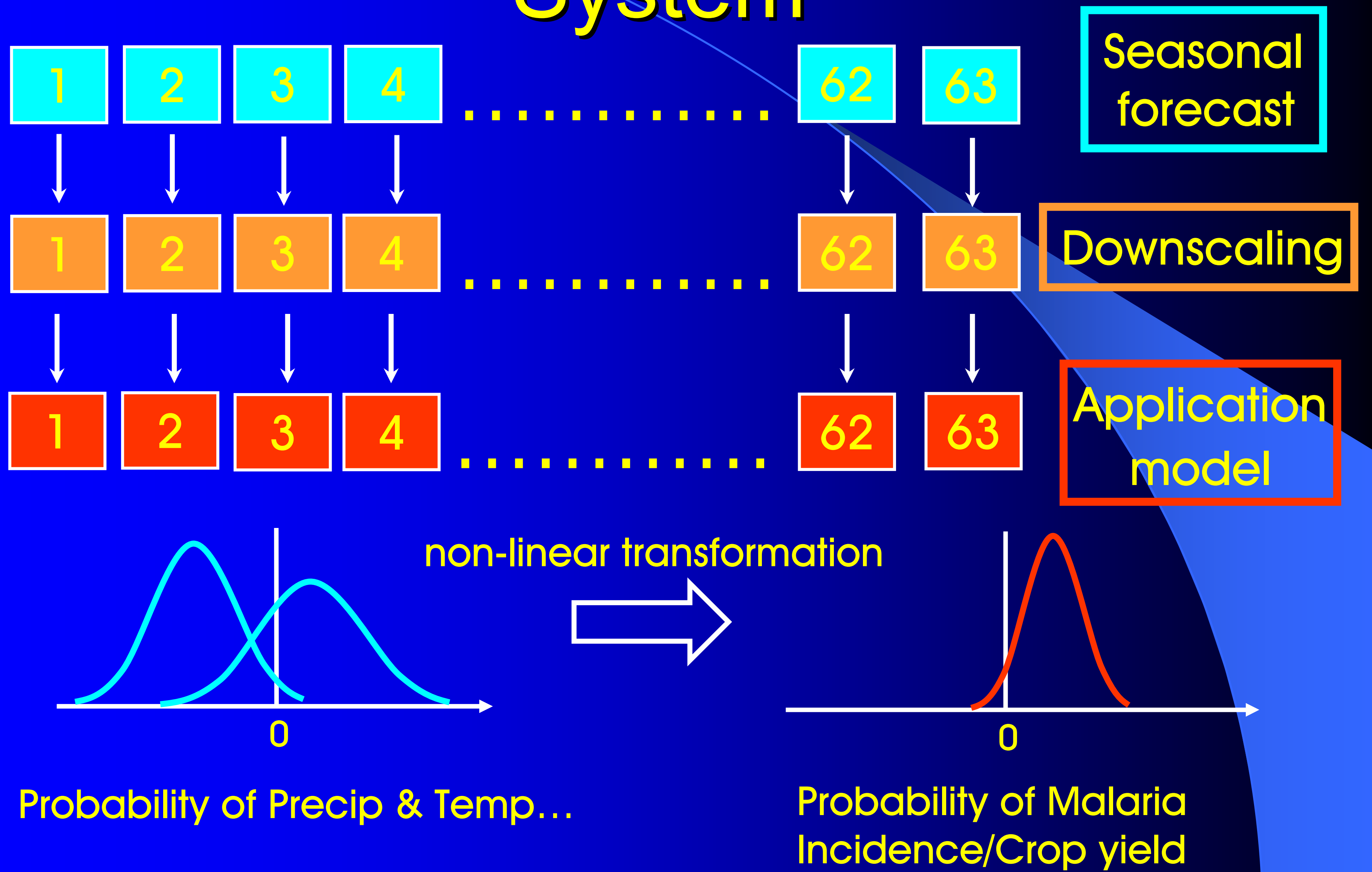
Zeng et al., 2005

Predicted global cabon flux



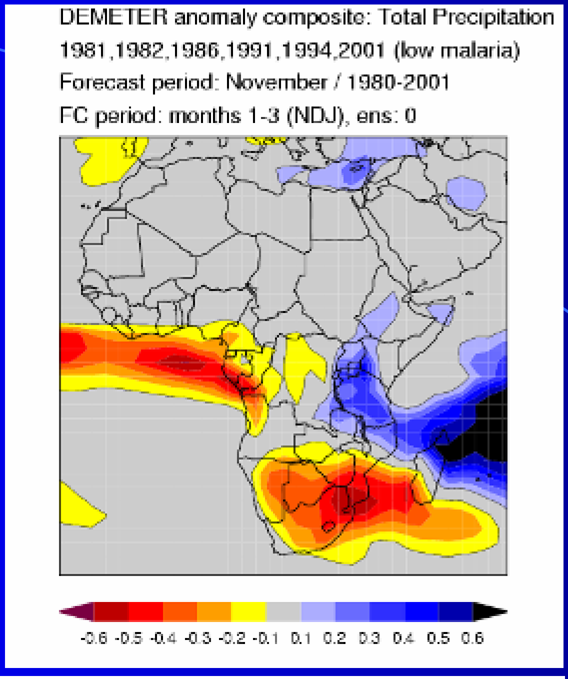
- The European Centre for Medium Range Weather Forecasting (ECMWF) has moved beyond the bounds of traditional weather prediction toward Earth system prediction that includes assimilation of the global carbon cycle, prediction of infectious disease outbreaks such as malaria, and seasonal forecasts for a range of agricultural crops.

DEMETER End-to-end Forecast System

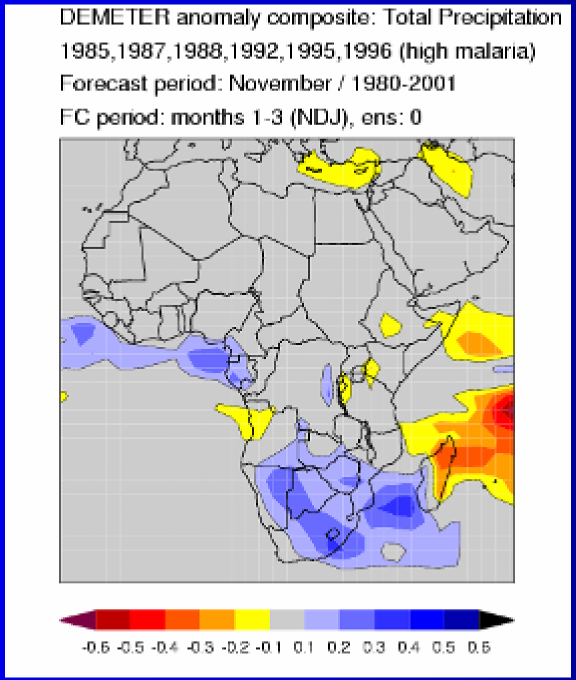


DEMETER Multi-model ensemble-mean precipitation

Thomson et al (2005)

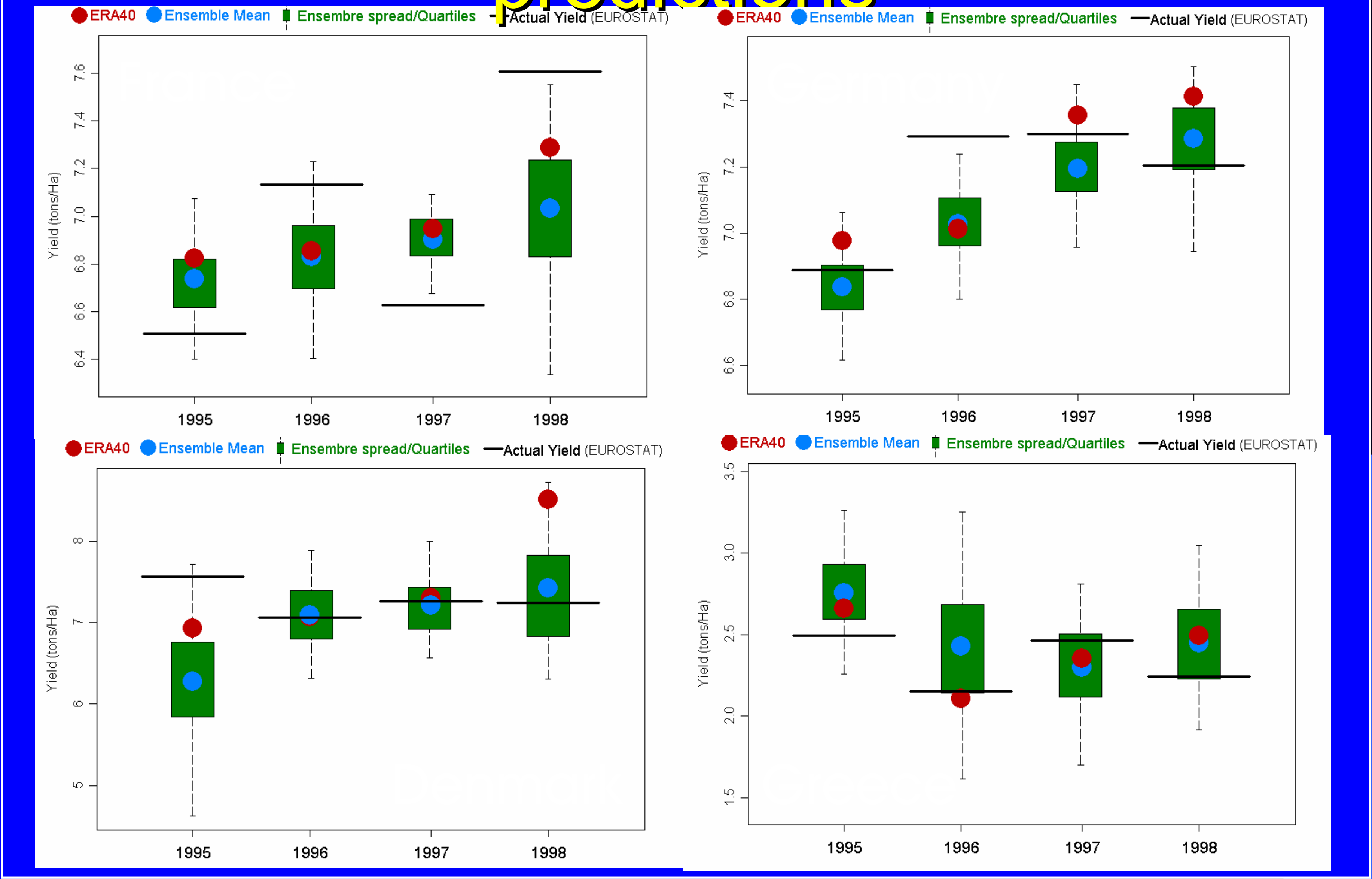


a) Low malaria incidence years in Botswana



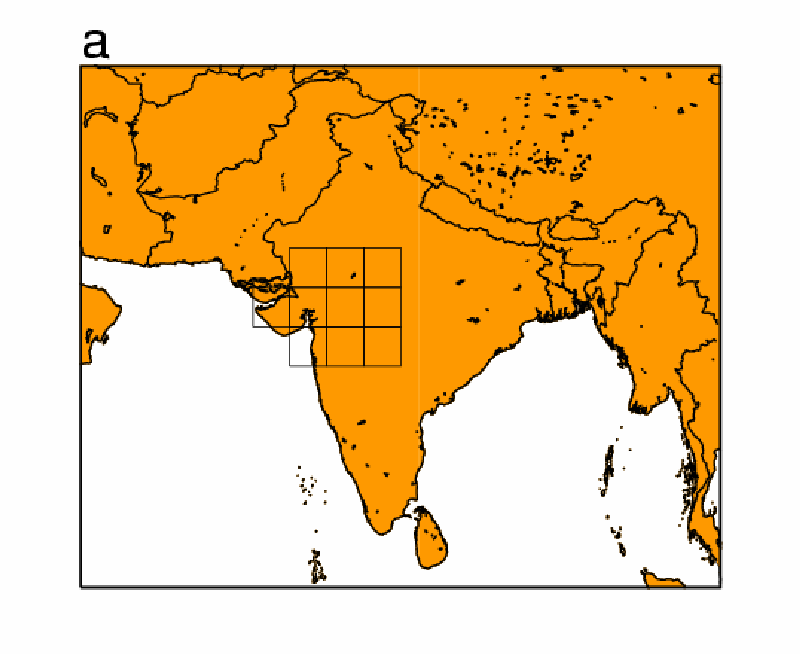
b) High malaria incidence years in Botswana

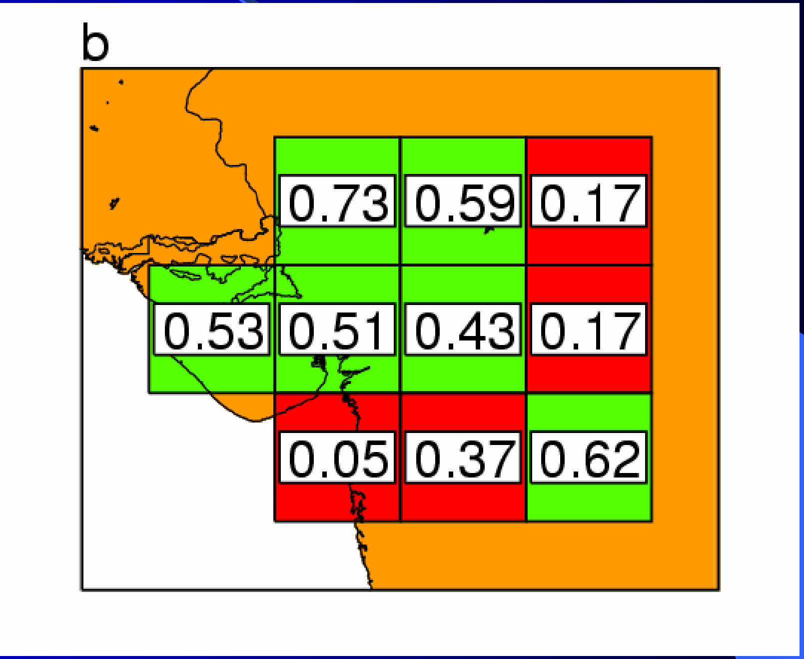
DEMETER: wheat yield predictions



Cantelaube et al, 2005

DEMETER Prediction of Groundnut Yield in India





Correlation between predicted and observed yields (Challinor et al, 2005)

- The European Centre for Medium Range Weather Forecasting (ECMWF) has moved beyond the bounds of traditional weather prediction toward a program for Earth system prediction that includes assimilation of the global carbon cycle, prediction of infectious disease outbreaks such as malaria, and seasonal forecasts for a range of agricultural crops.

- Similarly, in Japan the Earth Simulator supercomputer has served as a national focus for the development of a comprehensive Earth System model.

- The United States government, in particular NOAA, has demonstrated international leadership with the concept of a Global Earth Observation System of Systems (GEOSS).
- A key to the success of GEOSS in the long-term will be the sustained use and demand for such observations of the Earth System in support of operational prediction across the atmosphere, ocean, land and ecosystem sectors.
- The development of a predictive capability for the Earth System has unique policy implications at both the national and international levels with respect to agriculture, energy, transportation, commerce, health and homeland security.

- The modeling component of the US Climate Change Science Program (CCSP) is based primarily upon global change projections.
- The National Research Council has indicated that a national strategy is lacking and needs to be developed for comprehensive climate prediction on times scales from seasons to decades.
- What is our national strategy for prediction of the Earth System?

What are the prospects for the future?

New **environmental** forecast products will be feasible

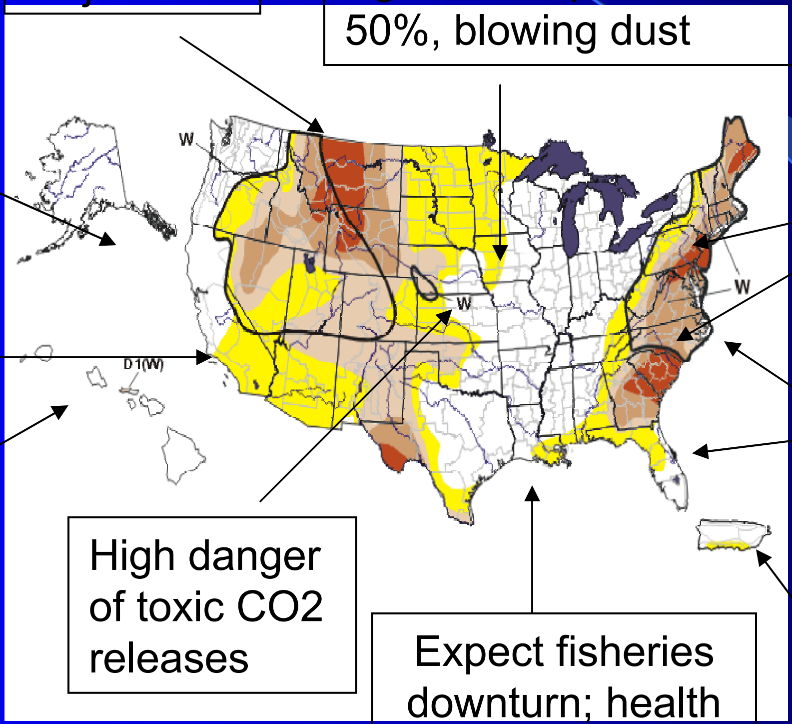
Major fires

Agricultural production at 50%, blowing dust

major fisheries regime change likely

Health warning: Limit outdoor activities; expect brownouts

Air quality alerts – 75% of days



Swimming and Fishing prohibited

Frequent floodings and Asian dust threats continue

High danger of toxic CO_2 releases

Expect fisheries downturn; health threats

African bacteria alerts

Possible Threats-Summer 2020: hot, dry and unhealthy

In summary, I would submit the time is right to begin developing a system that would:

- Provide a predictive capability for the Earth System on time scales from seasons to decades
- Go beyond the physical climate system to include a predictive capability for marine and terrestrial ecosystems
- Require development of an assimilative approach to the coupled Earth System. Note this extends beyond the physical climate system and includes assimilation of/for carbon, chemistry, and ecosystems both marine and terrestrial.
- Include an assessment of today's suite of Earth System observations within a predictive context and those observations needed to be sustained routinely
- Identify new observations and algorithms needed to advance prediction skill.
- Include a predictive capability for disease vectors such as malaria, dengue, cholera, Rift Valley fever, encephalitis
- Include agricultural forecasts
- Education and training in the development and use of such components
- Have implications for homeland security as a result of an advanced forecasting capability indicating aspects of the Earth system particularly vulnerable and prone to disruption on lead times of seasons to decades
- Provide policy neutral information on the implications and ramifications of environmental prediction.