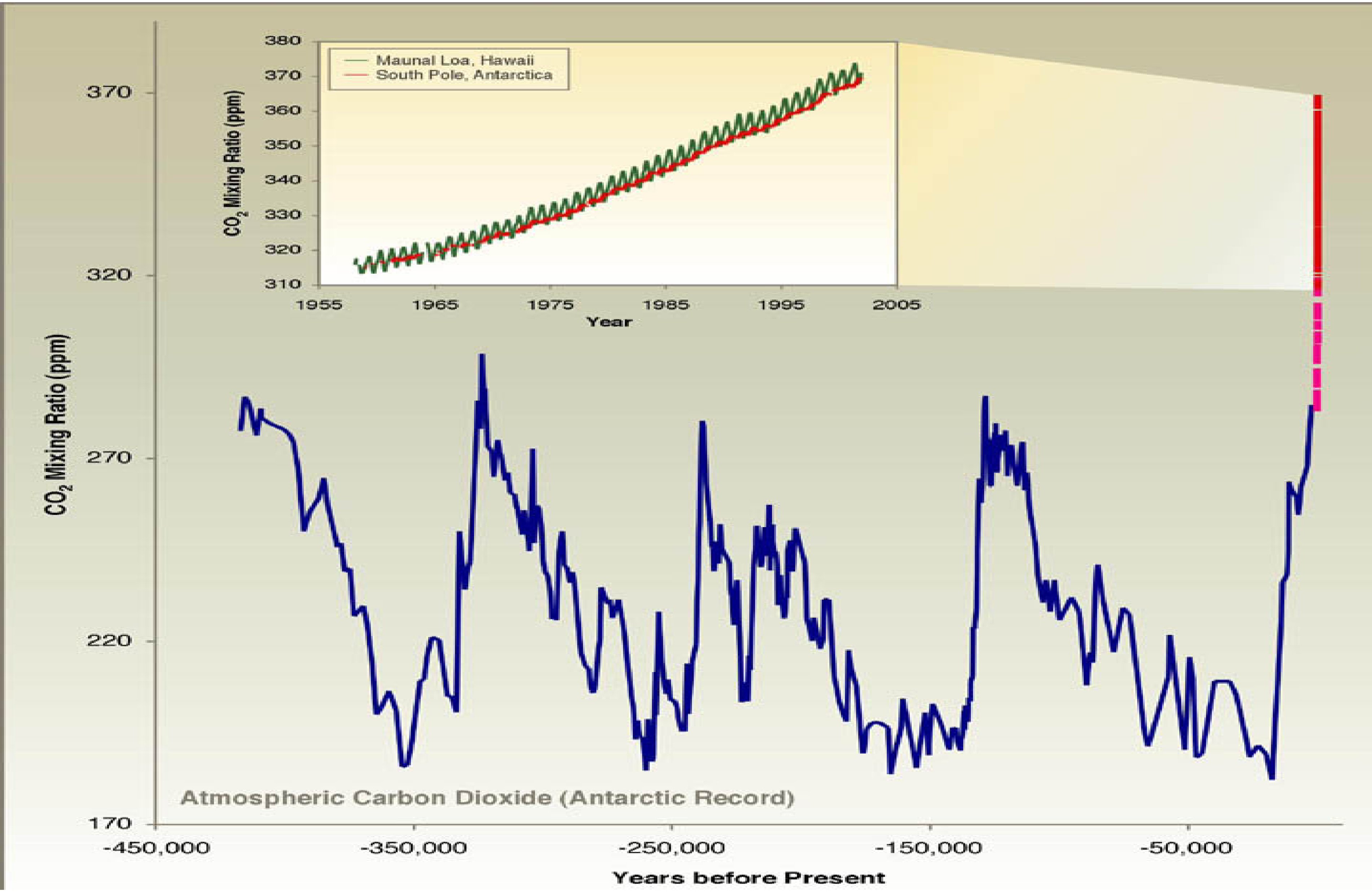
Carbon System Prediction: Approaches, Challenges and Opportunities for Earth System Modeling

John Dunne
NOAA/GFDL

Importance of Carbon in Climate

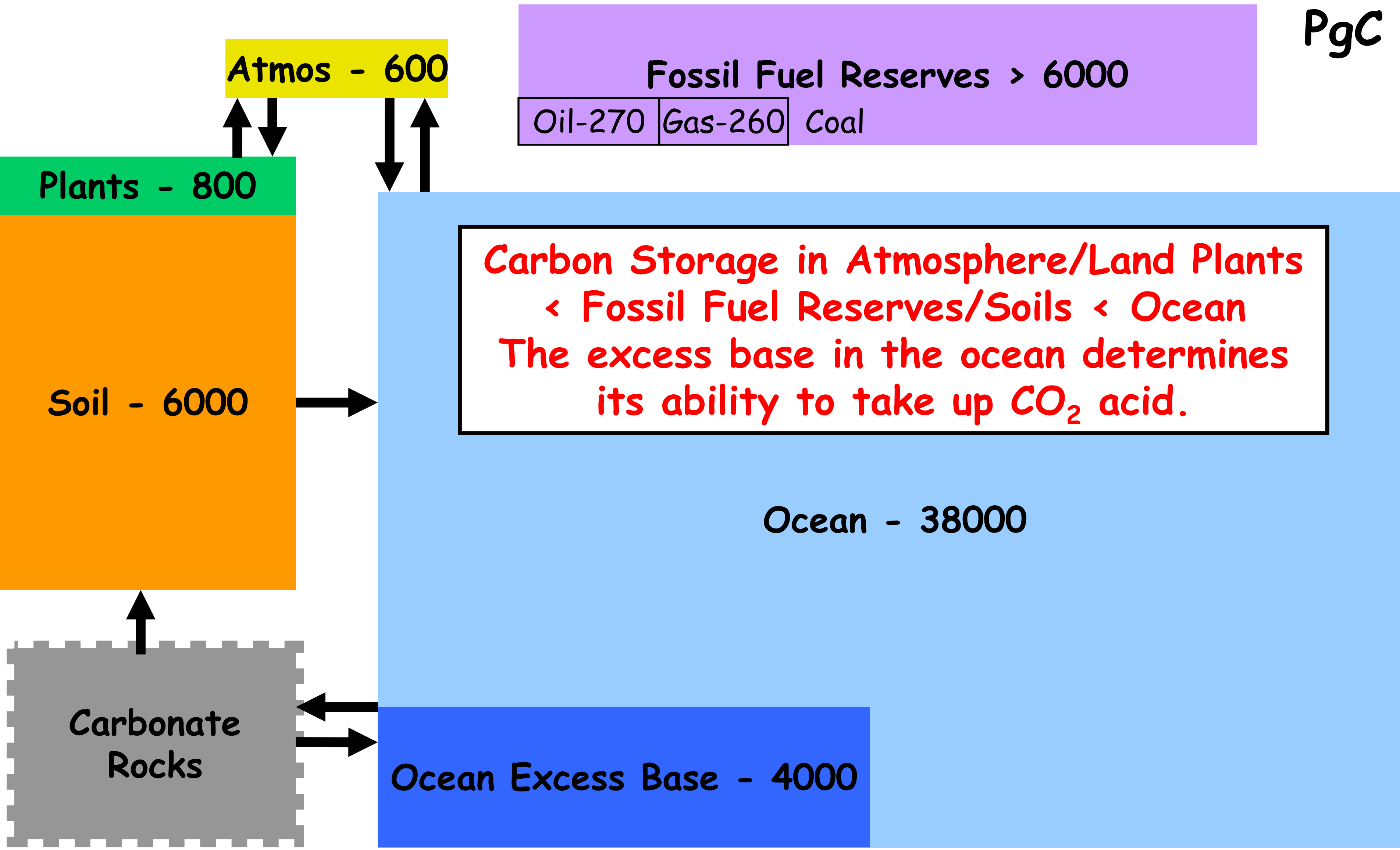
- The carbon budget is undergoing large changes
- Current climate models predict large climate changes in response to atmospheric CO_2 changes.
- These models simplify the global cycling of carbon.
- This simplification makes these predictions highly uncertain.
- Models that would purport to simulate carbon in realistic manner have many additional potential applications

Atmospheric CO_2 Over Time

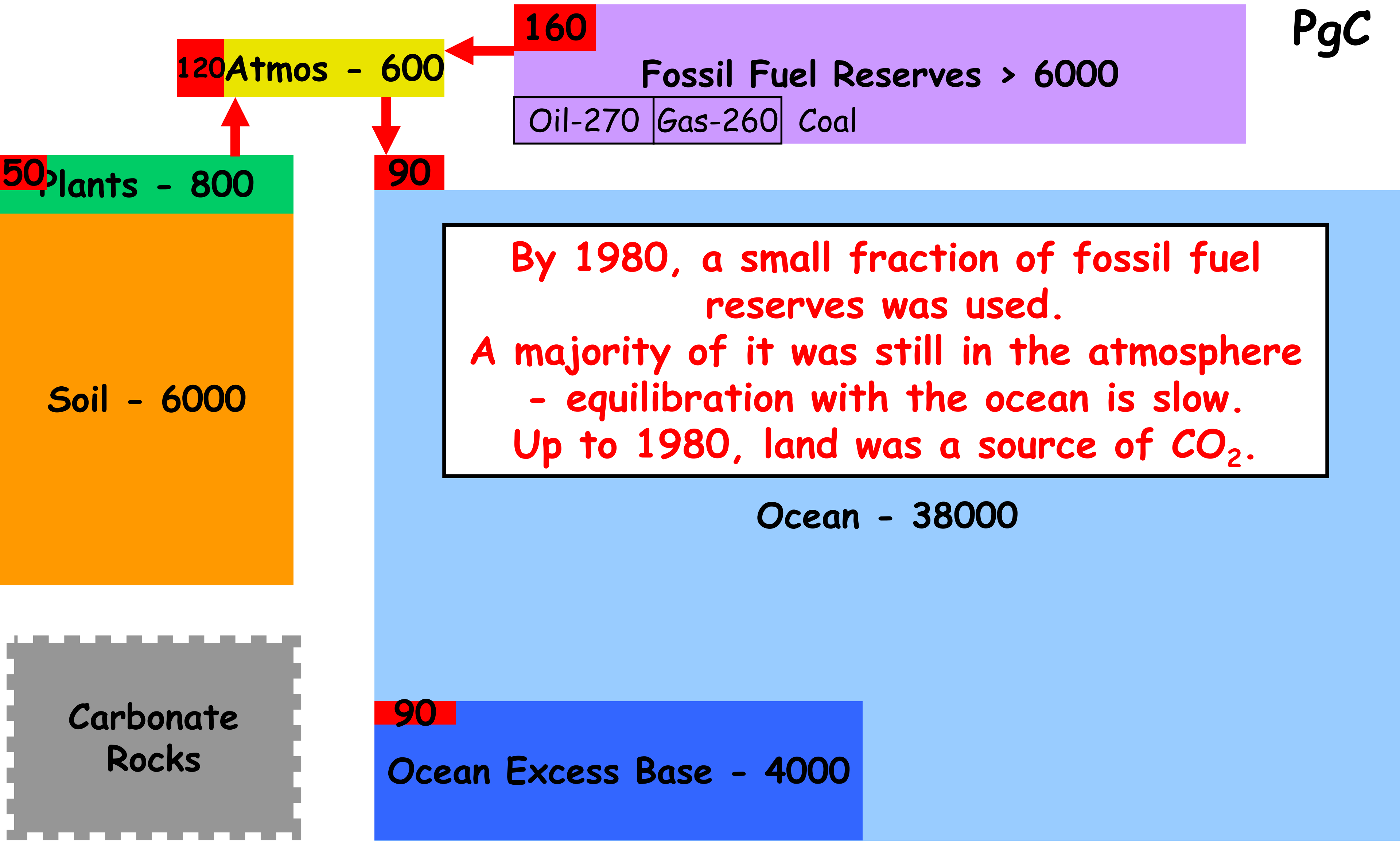


US Climate Change Science Program Strategic Plan, 2003

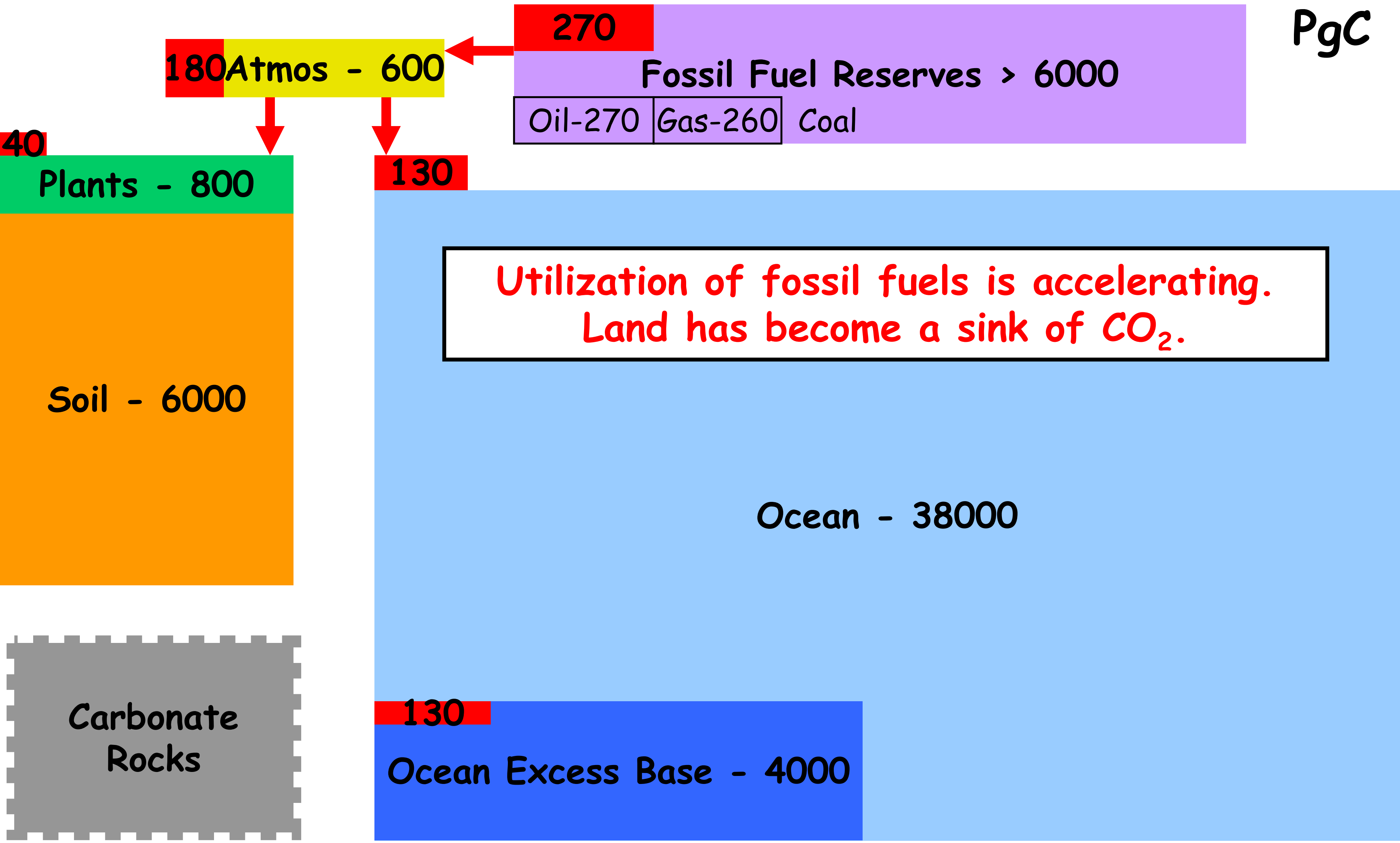
Preindustrial Carbon Budget



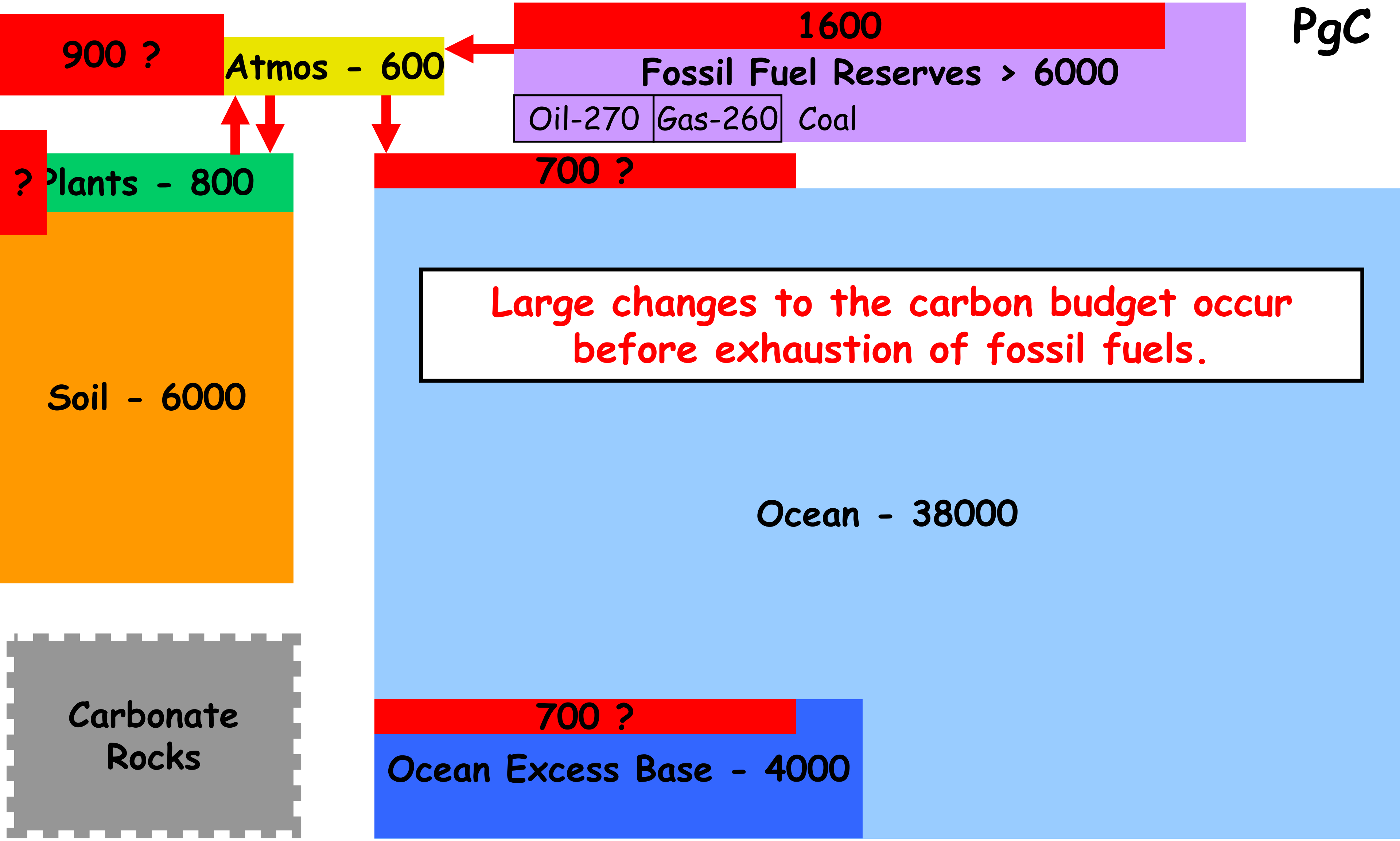
1980 Carbon Budget (Sabine and Feely, 2005)



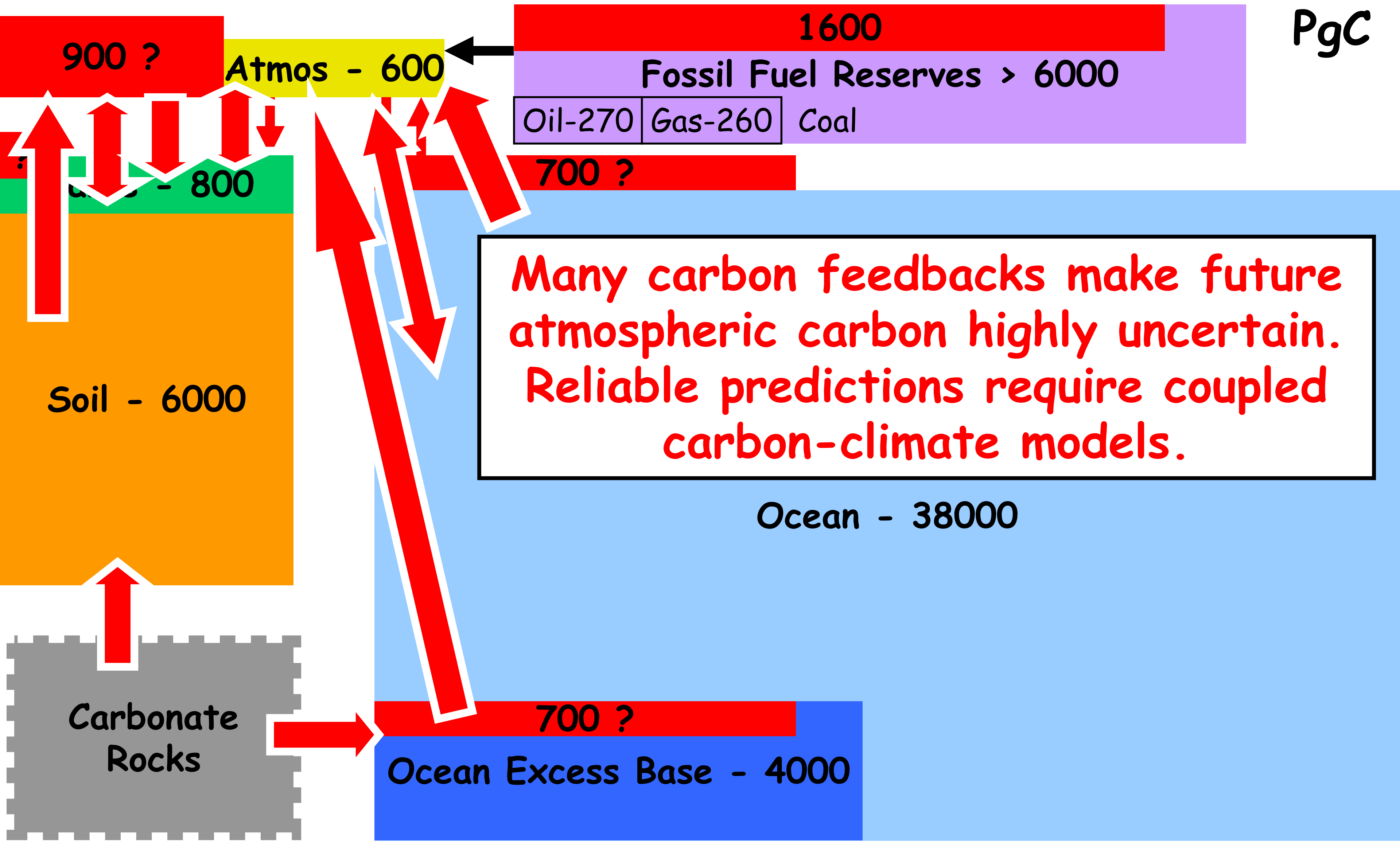
2000 Carbon Budget (Sabine and Feely, 2005)



2100 Carbon Budget (IPCC A1B scenario)



Carbon Feedbacks



Many carbon feedbacks make future atmospheric carbon highly uncertain. Reliable predictions require coupled carbon-climate models.

Sensitivity in Land and Ocean Carbon Cycles to Climate Change

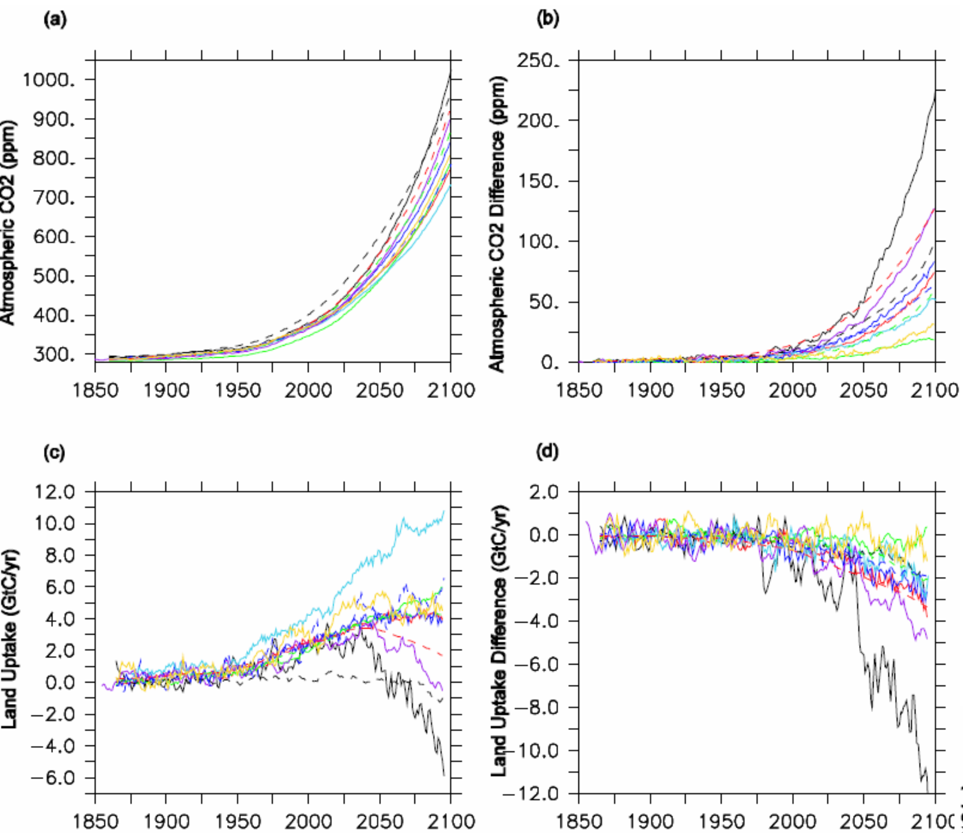
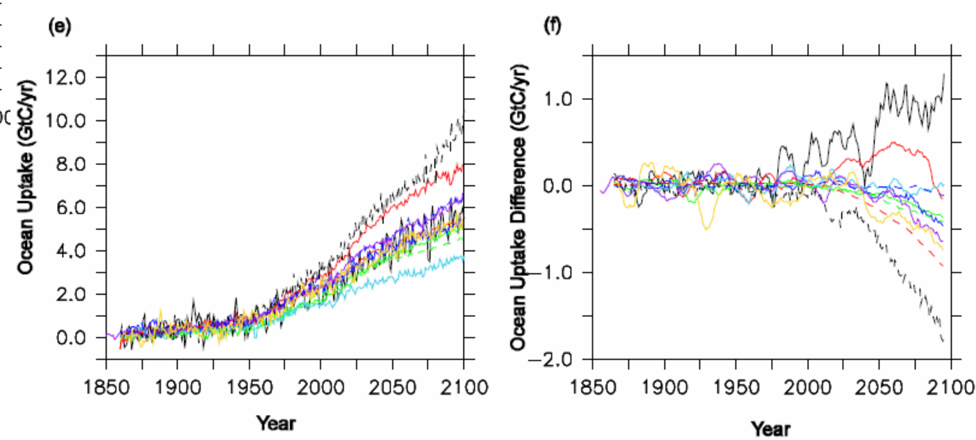


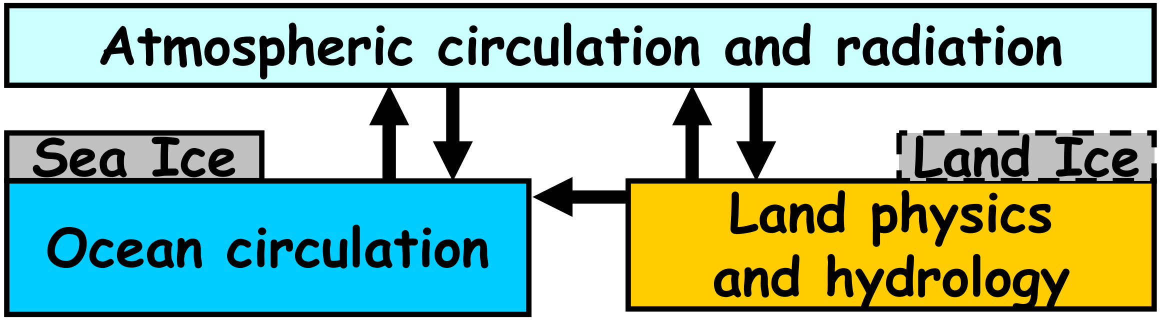
Figure 1. (a) Atmospheric CO_2 for the coupled simulations (ppm) as simulated by the HadCM3LC (solid black), IPSL-CM2C (solid red), IPSL-CM4-LOOP (solid yellow), CSM-1 (solid green), MPI (solid dark blue), LLNL (solid light blue), FRCGC (solid purple), UMD (dash black), UVic-2.7 (dash red) and CLIMBER (dash green), BERN-CC (dash blue). (b) Atmospheric CO_2 difference between the coupled and uncoupled simulations (ppm). (c) Land carbon fluxes for the coupled runs (GtC/yr). (d) Differences between coupled and uncoupled land carbon fluxes (GtC/yr). (e) and (f) same as (c) and (d) respectively for the ocean carbon fluxes.

Friedlingstein et al (2005; J, Climate)

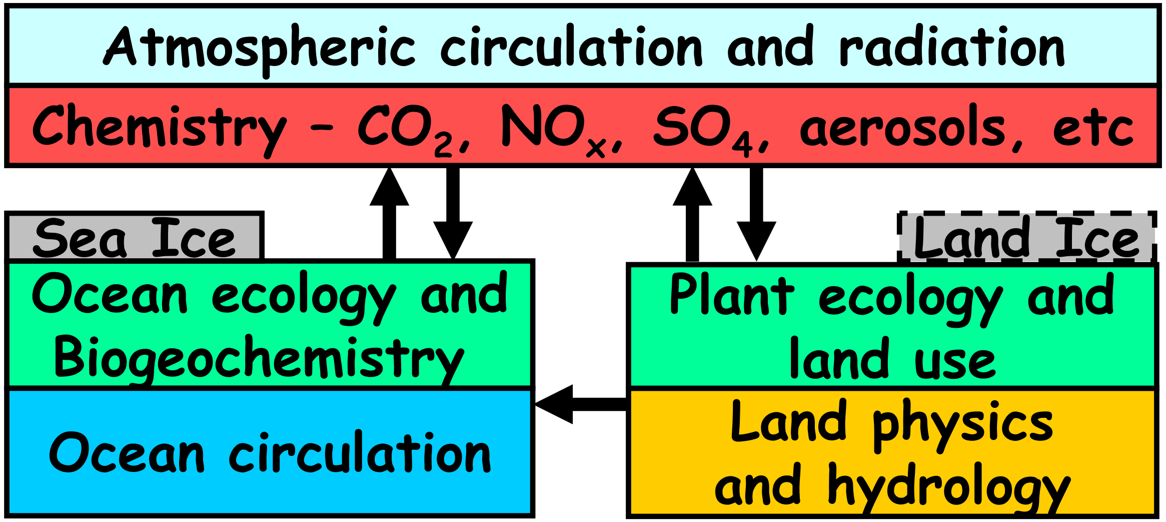


Earth System Model for coupled carbon-climate

Climate Model



Earth System Model



Earth System Model example applications

- What proportion of Fossil Fuel CO_2 emissions will stay in the atmosphere? For how long?
- What are the ecological impacts of increased CO_2?
- What are the ecological impacts of climate change?
- What is the role of land use on carbon cycling?
- How effective would proposed CO_2 sequestration studies be? (e.g. iron fertilization, deep ocean CO_2 injection forest preservation)

General scope of science questions requiring Earth System Modeling

- Earth System component functioning
  - What negative feedback mechanisms control the overall state?
  - Are there positive feedback mechanisms involved?
  - How non-linearly does the system respond to perturbation?
- Global scale hindcasts/forecasts
  - How can field observations be put in a theoretical context?
  - How sensitive is the Earth System to its forcing?
  - How sensitive is the Earth System to its boundary conditions?
- Local downscaling for hindcasts/forecasts on long timescales
  - How do boundary conditions evolve over long time scales?
- Feedbacks between components
  - How do components in the full Earth System interact?

What Earth System processes must be simulated?

- Climate goals require biogeochemical radiative feedbacks:
  - Land - albedo, transpiration, heat capacity, gas exchange
  - Ocean - gas exchange, solubility, surface nutrients (and chl. for SW?)
  - Atmosphere - CH_4, NO_x, O_3, aerosol cycles
- Biogeochemical goals require ecosystems:
  - Terrestrial ecology (and land-use)
  - Atmospheric processing and transport
  - Ocean productivity and trophic interactions
  - Rivers, sediments, estuaries, sea ice?
- Human impact goals require socioeconomic factors:
  - Population/economic dynamics
  - Human health, susceptibility to catastrophe
  - Water supplies, water quality
  - Agriculture and fisheries

Considerations for scoping out an earth system modeling effort

- Limitations of physical models
  - Unresolved processes
  - Sub-gridscale parameterizations
  - Errors in forcing
- Limitations of biogeochemical and ecological models
  - Understanding of physiology and stoichiometry controls
  - Diversity of ecosystems
- Practical issues
  - Calibration: observation sparseness and difficulty in interpretation
  - Execution: resolution requirements for speed, storage and analysis are paramount
  - Complexity: intellectual resources for interpretation

Challenges to succeeding in an Earth system modeling effort

- How to describe all the important feedbacks?
  - How many degrees of freedom are there?
  - Are any positive feedbacks involved?
- How to assure the model is globally robust and regionally applicable?
  - Calibrate locally and apply globally?
  - Calibrate globally and apply locally?
- When do we know the system is stable?
  - Can models be run to steady state?
- When do we stop developing?
  - Practical - Need to publish? Run out of funding?
  - Theoretical - Run out of ideas?
  - Functional - Meet previously derived metrics for success?

Connections between ocean and land carbon cycle predictions

- CO_2 fluxes between land and ocean through atmosphere and rivers
- Fe, N and P and mineral fluxes from land to ocean through the atmosphere and rivers.
- Ocean sea salt, sulfate and organic carbon emissions and light penetration scaling (Chl, cDOM, mineral) that may impact land climate.
- Land albedo, heat capacity and emissions that may impact ocean circulation

Range of Earth System Modeling Approaches to these problems

- **Intuition of Earth System Sages/Seers (e.g. quoted for 'The Day After Tomorrow')**
  - Inspire discussion, theory and experiments, but lack mathematical basis; prone to human passion
- **Box models (e.g. Garrels, Broecker)**
  - Allow assessment of scales, can be fully understood, but prone to vast oversimplification
- **Algorithmic or statistical models (e.g. Joos carbon sensitivity)**
  - Can be tuned to get a particular answer, but have no mechanistic foundation
- **Atmospheric and ocean stream function models (e.g. Pandora)**
  - Allow exploration of mechanisms, but represent only a simplified interpretation of a single process
- **Land and ocean site models (e.g. testbeds and other groups of regional studies)**
  - Allow detailed comparison of models with observations, but do not represent the global scale
- **Component general circulation models**
  - Allow sophisticated sensitivity studies of component response to perturbation, but not investigation of the Earth as a coupled system; too complex to be completely understood
- **Earth system models of Intermediate Complexity (EMICs, energy balance models)**
  - Capable of running on small computer clusters for millennial simulations, but require intensive 2-10 person teams and - with flux adjustments for credible climate - are only partially prognostic
- **IPCC-class Earth System Models**
  - Simulate the fully coupled climate, biogeochemical, ecological system. When run without flux adjustment, are fully prognostic, but require a dedicated supercomputer
- **Earth System Models for ecological prediction**
  - Simulate regional climate within the global system and can be used for ecological prediction but are currently beyond any laboratory's computational capabilities

Needs for Ocean Biogeochemical and Ecological Prediction

- Variability as it impacts the things we care about
  - Fisheries, charismatic species, ecological richness
  - water quality issues: harmful algal blooms, anoxia, clarity
- Role of the ocean in taking up anthropogenic CO_2 – How much and how fast?
- Response to physical climate change
  - Changes in frequency, intensity and location of productivity regimes
  - Shifts in ecological structure due to temperature and circulation
- Response of ocean ecology to the biogeochemical changes
- Assessment of climate feedbacks

Some of the ecological decisions involved

- What regulates phytoplankton blooms?
  - Critical depth - Sverdrup
  - Grazing – Frost/Banse
  - Resting stages - Dugdale
  - Iron hypothesis - Martin
- Why are there so many species? (Paradox of the plankton – Hutchinson)
  - Continuum of light and nutrient niches?
  - Grazing? Do single predator - single prey interactions exist?
  - Variability? Eternal disequilibrium?
  - Chaos of niche competition?
- When are bacteria governed by kinetics rather than chemical potential?
  - What keeps chemistry out of thermodynamic equilibrium?
  - What controls microbial metabolic rates? Do light and organic stoichiometry play a role?
  - What controls the depth scale of sinking?
- Is plankton motility important?
  - Zooplankton migration on grazing, carbon flux and fisheries
  - Phytoplankton flotation and sinking

Some of the biogeochemical decisions involved

- What are the negative feedbacks regulating the system?
  - Marine ecological functioning
    - Primary productivity
    - Grazing (and higher trophic level control?)
    - Recycling, sinking and remineralization
  - Biogeochemical controls
    - Elemental stoichiometry
    - Hypoxia and denitrification
    - Carbonate chemistry
  - Climate feedbacks
    - Primary producers, major nutrients and Fe and CO_2 cycling through the organic pump
    - $CaCO_3$ producers and CO_2 cycling through the inorganic pump
    - CH_4 and N_2O cycling
    - Sulfur cycling (e.g. Charlson et al., 1987)
    - Chlorophyll and shortwave penetration (e.g. Morel, 1988)
    - Organic aerosols (e.g. O'Dowd et al., 2004)
- How will climate change impact this system?
  - Are there positive feedbacks?

An example timelime of these simulation challenges

Bulk biogeochemistry

- Export out of the surface
- Enhancement of nutrients in subsurface waters
- Winter overturning
- Large scale upwelling
- Resupply of surface nutrients from mode waters
- Enhancement of nutrients in deep waters

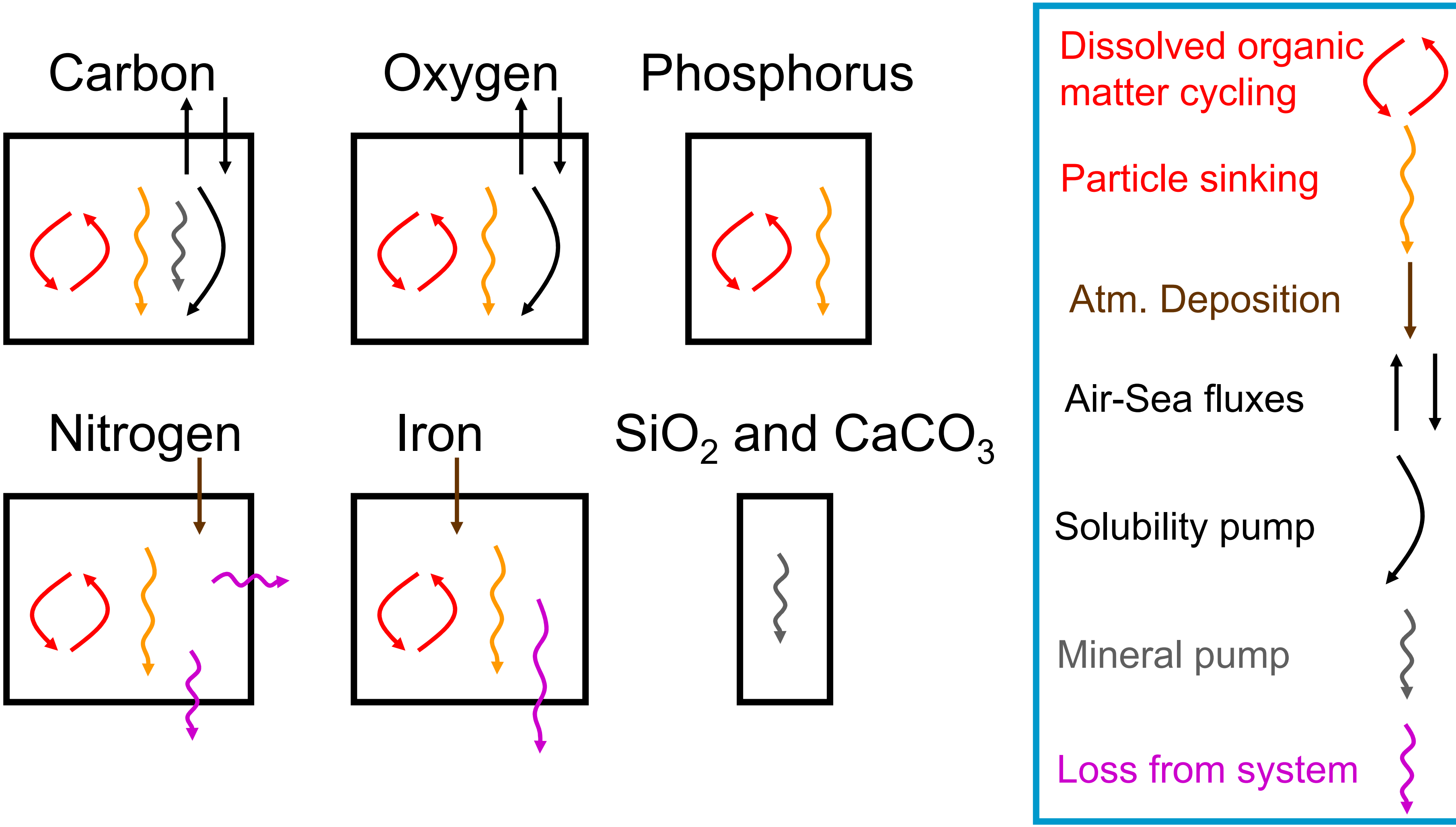
Time

Interactions

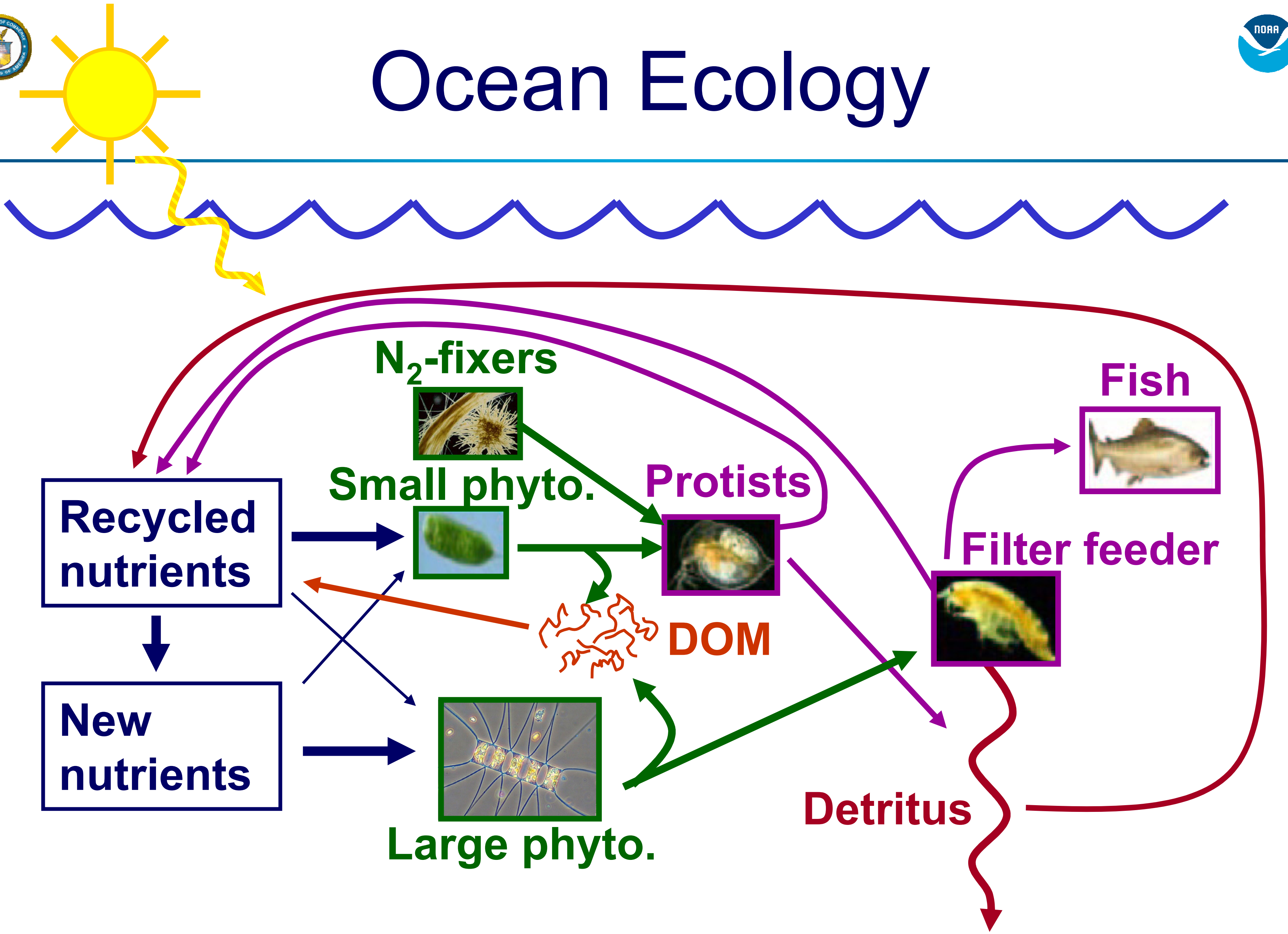
Processes involved

- Control of phytoplankton blooms
  - Relationship between light, nutrients and production
  - Metazoan grazing and higher trophic level controls
- High amount of recycling (~80%) in surface ocean
  - Microbial food web
- Extent of high nitrate-low chlorophyll
  - Multiple size classes of phytoplankton
  - Role of iron
- Subsurface remineralization and dissolution scales
  - Mineral protection of organic matter
  - Temperature and food web effects
- Physical-biological coupling
  - Mixed layer light-temperature and nutrient dynamics
  - Maintenance of subsurface properties
- Achieving stability in the Carbon budget
  - Intensity of organic, inorganic and solubility pumps
  - Role of rivers and sediments
- Role of climate change (next slide)
- Achieving stability in the Nitrogen budget
  - Balance between surface NO_3 and PO_4
  - Nitrogen fixation
  - Water column and sediment denitrification
  - River and atmospheric fluxes
- Tailoring the model for societal applications, e.g.
  - Hypoxia
  - Harmful algal blooms
  - Fisheries

Ocean Biogeochemistry



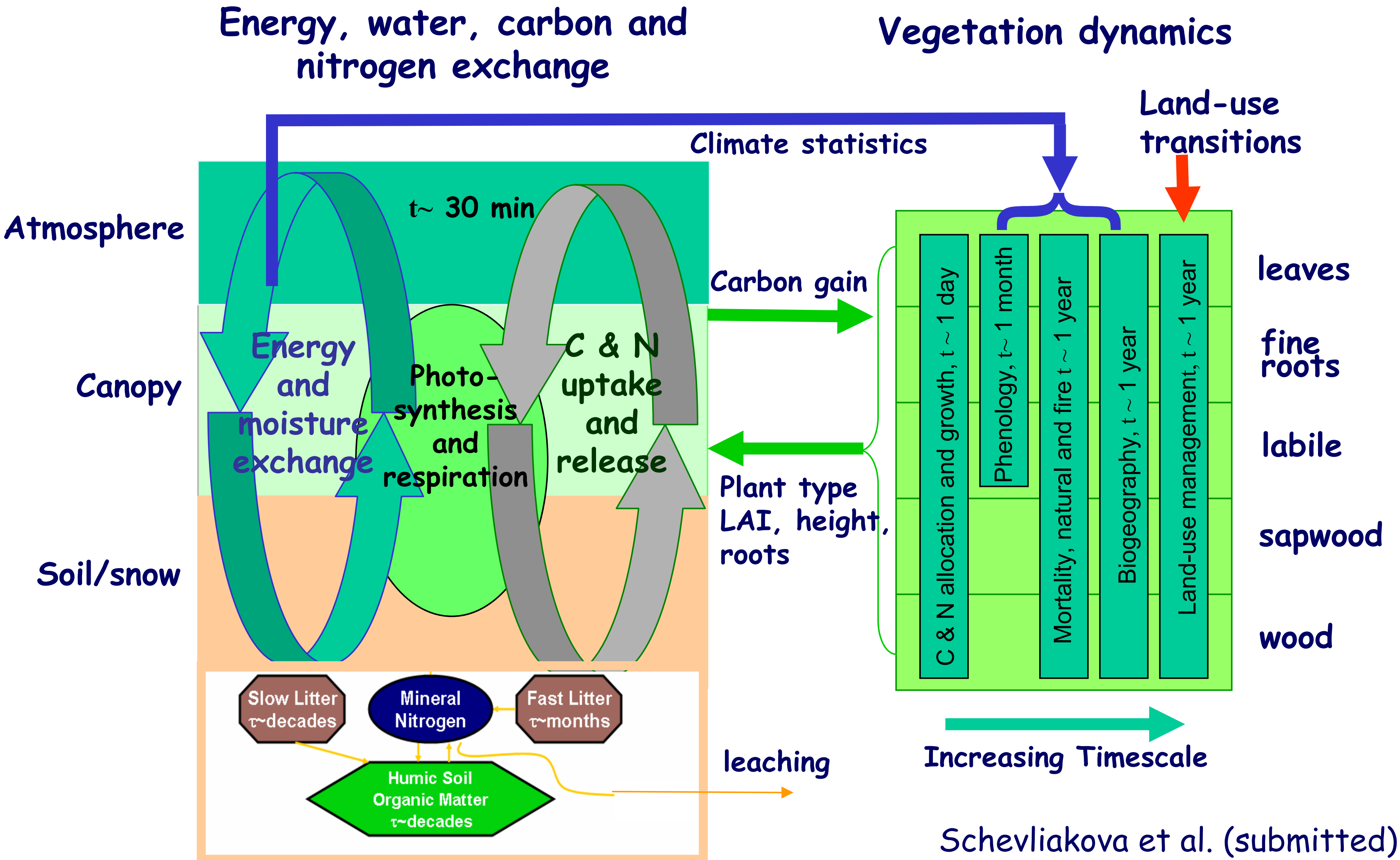
Ocean Ecology



Ocean processes currently represented

- Phytoplankton function types
  - Microbial loop
  - Open ocean diatom bloom
  - Calcification
  - Nitrogen fixation
- Zooplankton
  - Microbial loop – single microzooplankton
  - Single (or perhaps double) Mesozooplankton
- Simple variable Chl:C:N:P:Si:Fe stoichiometry
- Carbon chemistry
- Atmospheric and river fluxes
- Sediment removal and Fe fluxes

Dynamic Land Model LM3V

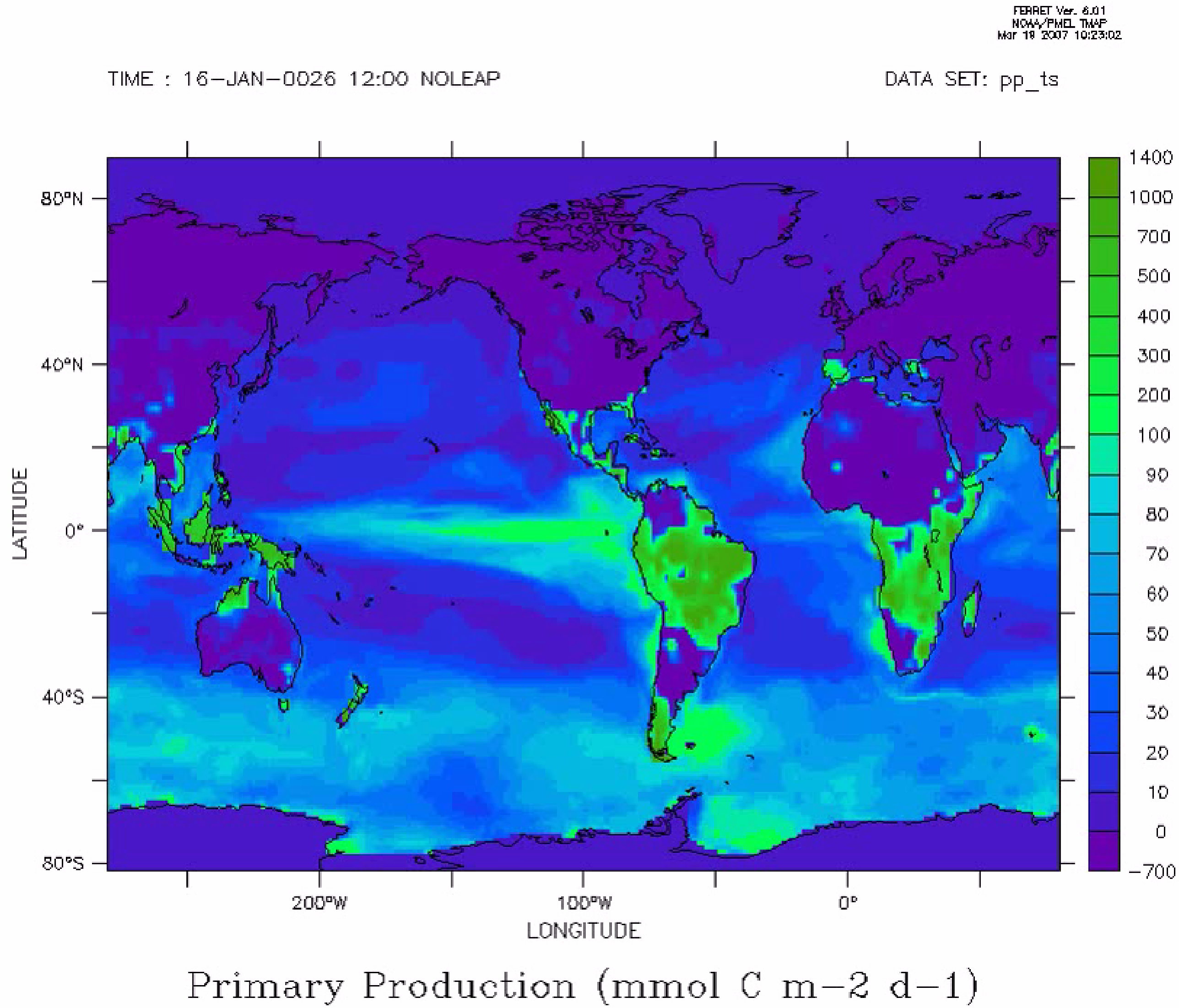


Schevliakova et al. (submitted)

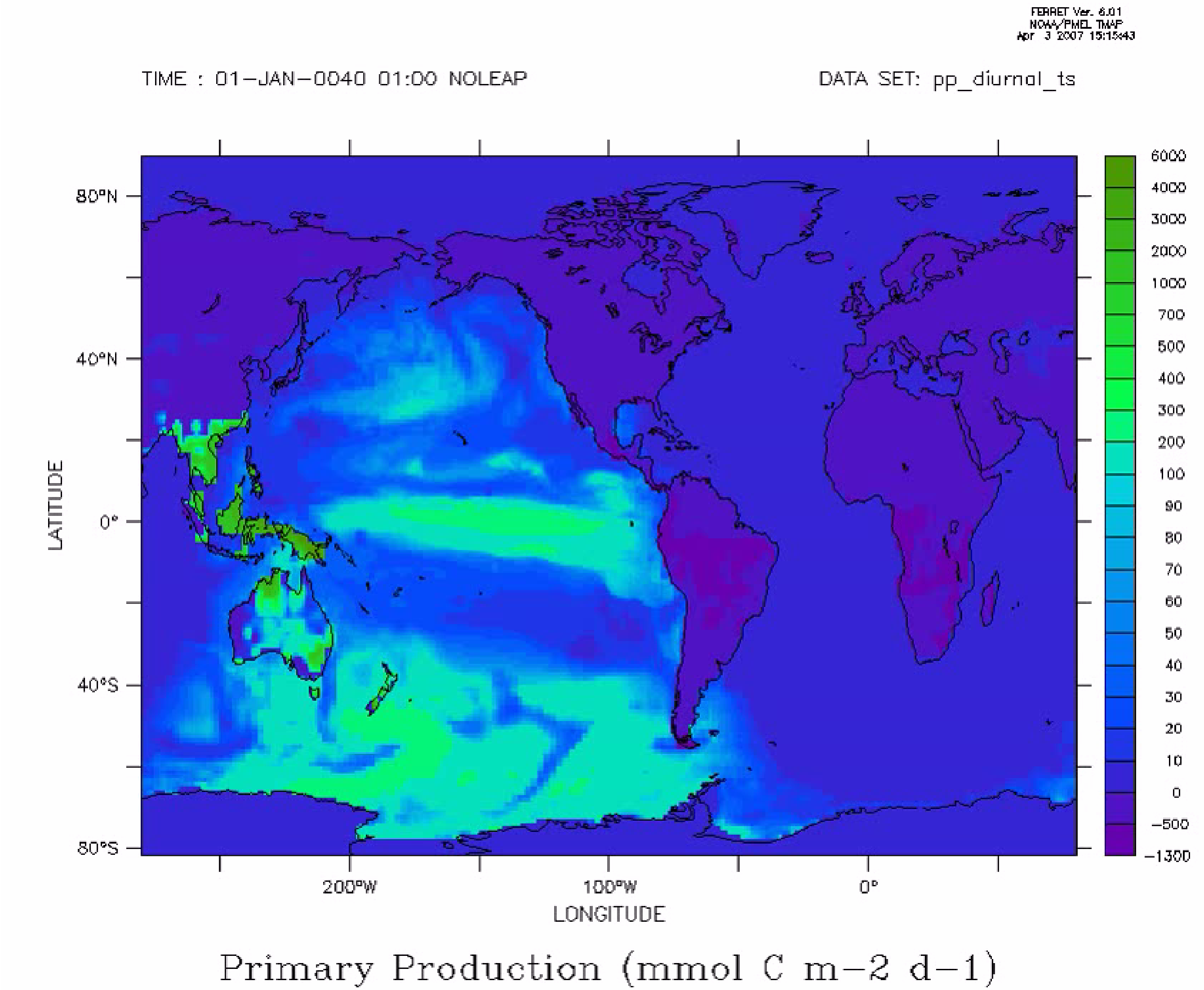
Land processes currently represented

- Plant physiology
  - Water, light, temperature, humidity, CO_2
  - Carbon in leaves, wood, and roots
  - Efforts in N and P limitation
- Forest biodiversity
  - Tropical evergreen, coniferous, deciduous, warm grasses, dry grasses
- Forest succession
  - Competition between forest types
- Land use
  - Deforestation, denudation and abandonment
- Fire
  - Annual losses as a function of drought and biomass
  - Efforts on subannual anthropogenic losses

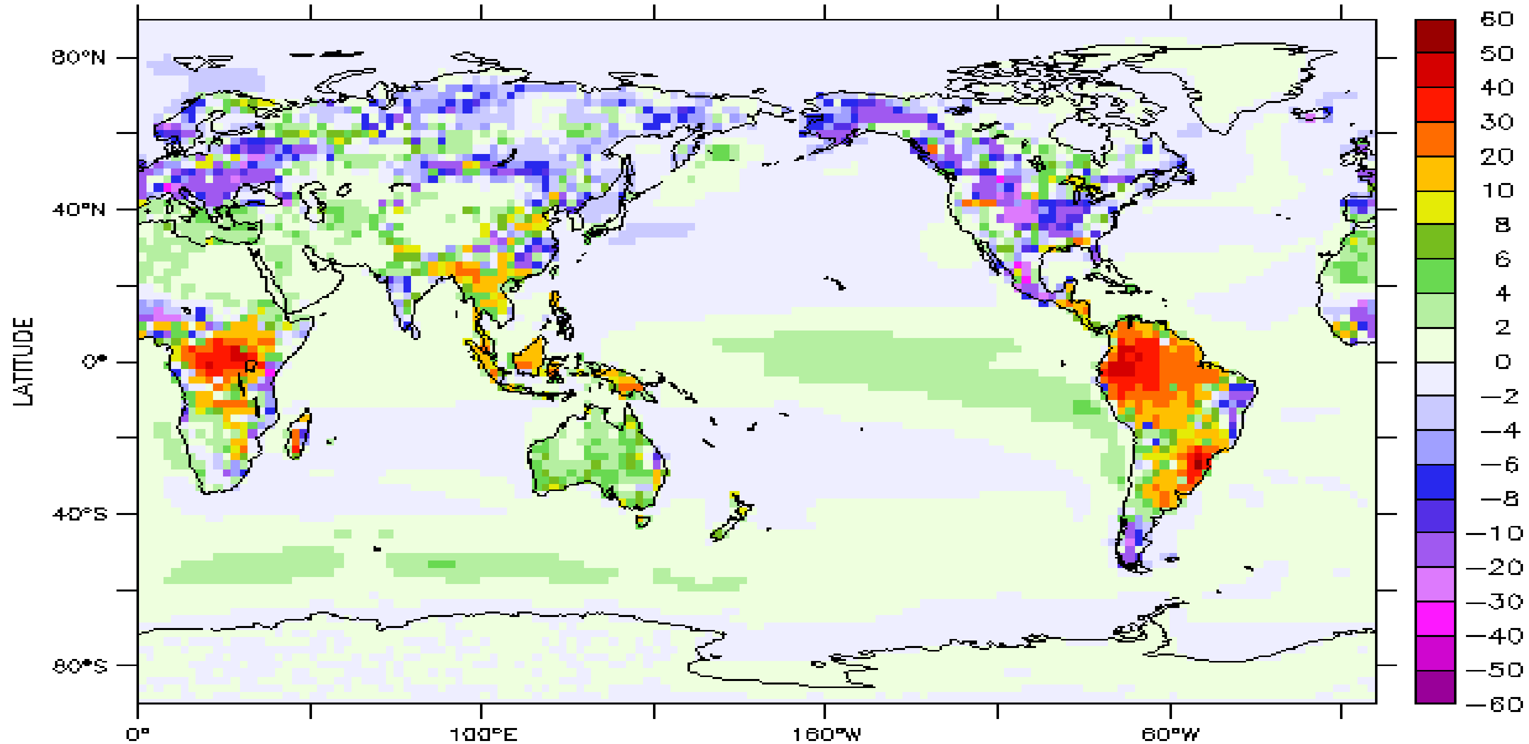
Plant Growth in the GFDL Earth System Model - seasonal cycle



Plant Growth in the GFDL Earth System Model - diurnal cycle



Model atmosphere CO_2 Fluxes



CO_2 flux (mol m^{-2} y^{-1})

On the short term – years to decades - almost all interesting stuff is on land
Ocean eventually - decades to centuries - overwhelms the atmosphere

Coupled Carbon-Climate-Ecology interactions in current models

- Higher temperature
  - Longer growing season in high latitude
  - More temperature stress at low latitude
  - Increased metabolism in animals
  - More nutrient stress in ocean through stratification
- Higher CO_2
  - Less CO_2 stress on land
  - Acidification in ocean – strongly at surface
- Intensified water cycle
  - More water stress on land
  - More nutrient stress in ocean through stratification
  - Less nutrient stress in ocean through winds

Ocean processes currently demonstrating critical uncertainty

- Lack of nutrient exhaustion in tropics and subtropics
- Mode water formation rates and composition
- Southern Ocean CO_2 uptake (e.g. Friedlingstein et al 2005)
- Boundary current productivity and CO_2 cycling
- Non-Redfield stoichiometry
- Role of iron
- Controls on oxygen
- Ecological controls

Land processes currently demonstrating critical uncertainty

- Climate model biases generating ecological biases and sensitivites (e.g the 'great amazonian desert')
- CO_2 fertilization – productivity limitation by CO_2, H_2O and light versus N, P and others
- Natural (and perturbed) land emissions of radiatively important atmospheric species.

Ocean processes currently missing

- Coastal processes
  - Shelf, coastal and estuarine interactions
  - diatoms and dinoflagellates that bloom, senesce and germinate
  - Coral, sea grass, mangrove and wetland ecosystems
- Open ocean processes
  - The biodiversity of calcification and ecological role of acidification
- Zooplankton and upper trophic level realism
  - Vertical migration
  - Diversity of species
  - Links to fish and charismatic megafauna
- Sea floor processes
  - Seafloor ecology
  - Sediment biogeochemistry
- Explicit heterotrophic bacterial controls beyond a rate constant and reservoir of biomass
  - Heterotrophic nutrient uptake
  - Modulation of stoichiometry
  - Modulation of remineralization

Land processes currently missing

- Biogeochemical and anthropogenic N cycling
  - E.g. fertilizer application, denitrification, industrial and agricultural emissions
- Weathering of P, $CaCO_3$, SiO_2 and organic C
- Individual crops
- Role of human alterations to land surface
- River biogeochemistry and ecology
- Groundwater biogeochemistry
- Terrestrial microbial and heterotrophic community
- Permafrost

Some current ideas for ocean model improvement

- Allometric (size-based) and environmentally-based parameter functions
- Optimal allocation strategies for flexible parameter values and stoichiometry
- Stochastic modeling (e.g. Follows et al. 2007)
- Vertical migration for large phytoplankton and zooplankton
- Reformulation of model components to better compare with observation data types

Earth System Modeling Research and Collaboration Needs

- Laboratory and field observations in areas most uncertain and critical in the models
- Synthesis of these observations into consensus paradigms within idealized models
- Integration of biogeochemistry and ecology into physically realistic models
- Coordination between academic and government research for:
  - High risk, high potential research for future development
  - Development, implementation and experimental configuration of deliverables
  - Analysis, assessment and interpretation of output

Example collaborations

- The general "What's wrong with the model and what should we do about it"
- Community consensus efforts to develop paradigms to guide model development and improvement
- Satellite comparisons
- Data synthesis needs
  - River fluxes of NO_3, NH_4, DON, DOC, SiO_4, Fe, lithogenic mineral
  - Global maps of new data types akin to Levitus (e.g. Iron, HPLC pigments, zooplankton, deep sediment traps, sediment fluxes)
- Intensive comparisons of field observations of complex and extensive data types with models (e.g. Optical plankton counter, pigments and particle size, isotopes)
- Field testing of model predictions

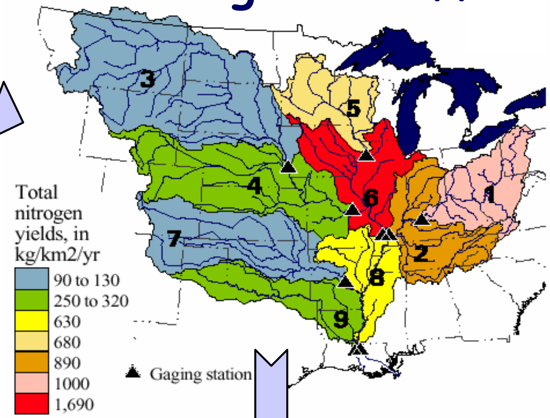
Long term plans for Earth System Modeling – beyond Carbon

- Coupled atmospheric chemistry
  - Pollution (e.g. smog, acid rain, mercury)
  - Other greenhouse gas and aerosol cycling
- Earth System Cycling of N, P, CH_4, Hg, SO_4,
- River and near shore water quality
  - Oxygen stress
  - Water clarity
  - Harmful algal blooms
- Fish habitat and productivity assessment
  - global krill productivity
  - Small pelagics
  - Bottom fisheries

Future Model Applications:
Nitrogen cycle ecological prediction

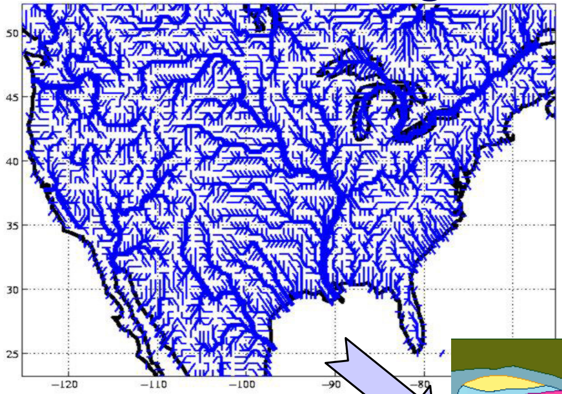
Land-use and ecology

Nitrogen runoff

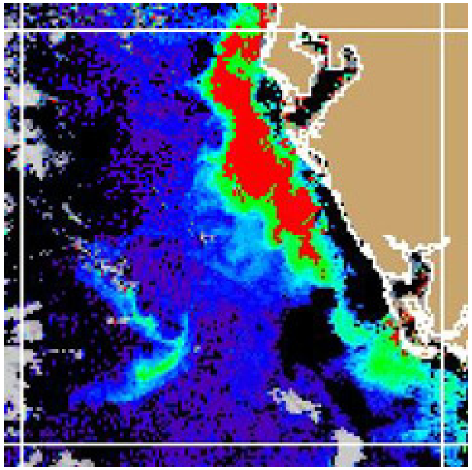


Atmospheric chemistry

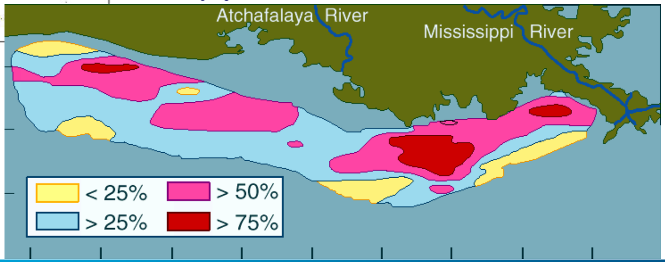
River Routing



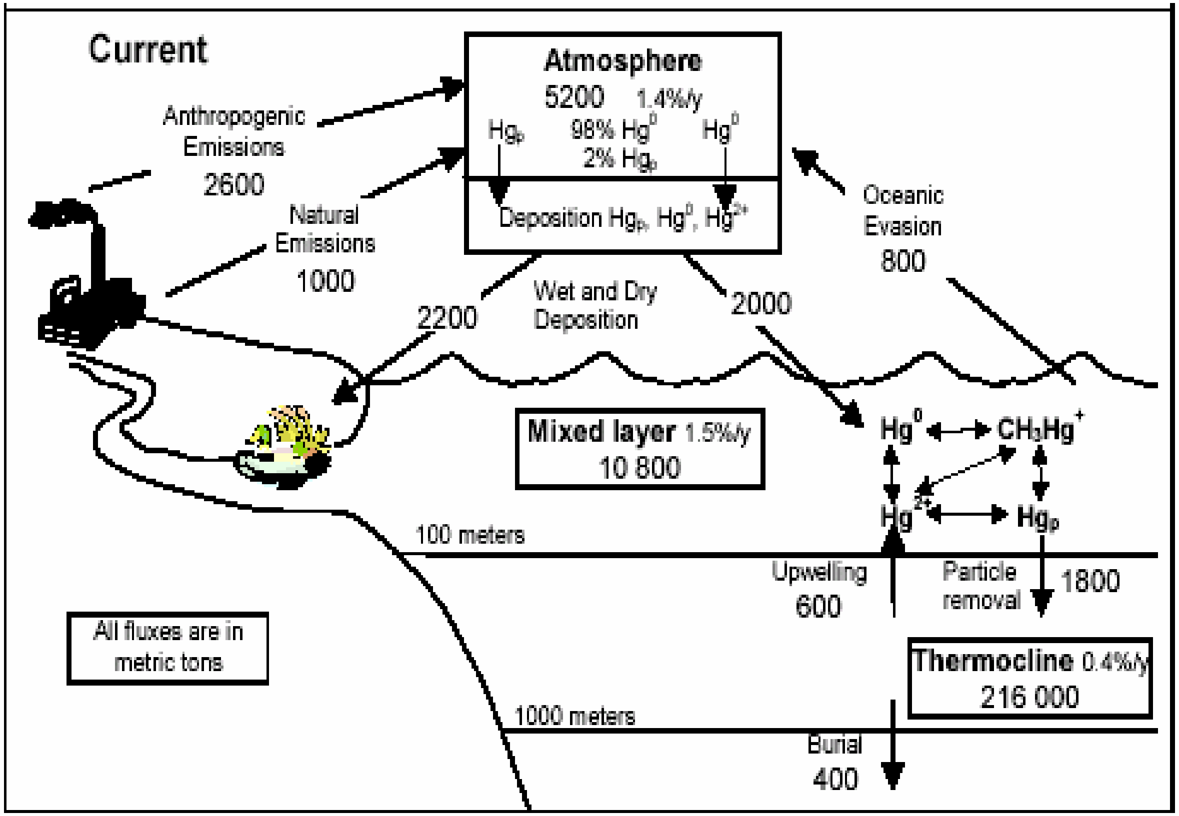
Harmful algal blooms



Hypoxia events



Application: Mercury cycling



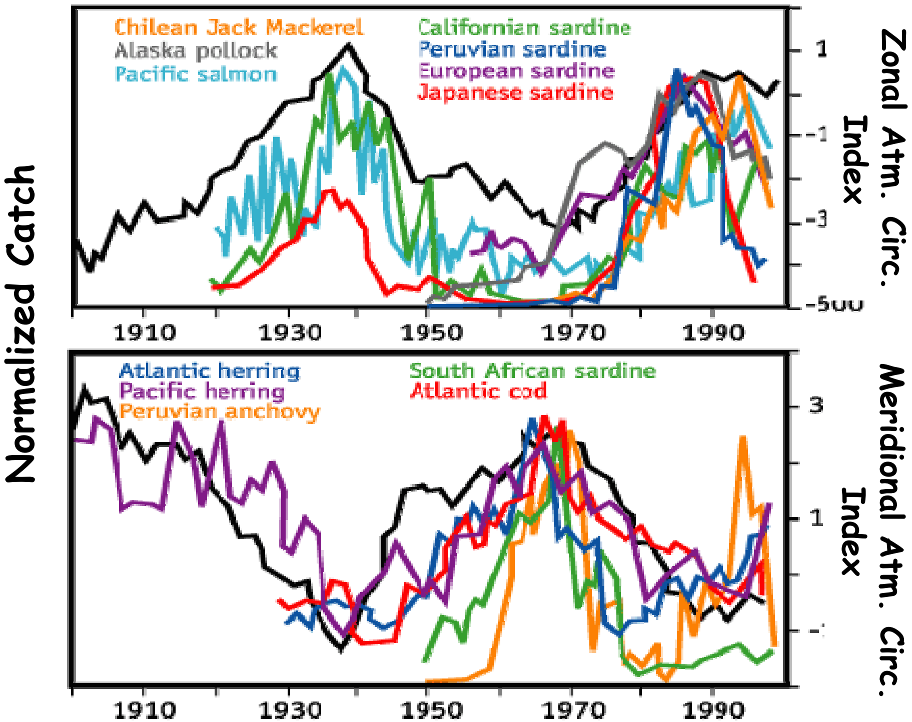
Source: UNEP Global Mercury Assessment

- Mercury is a global environmental pollutant
- Atmospheric concentrations have increased 3x from pre-industrial times
- Health risks from accumulation of methyl mercury in fish
- Rapid activation in Arctic (?)

Application: Fisheries retrospective and prediction

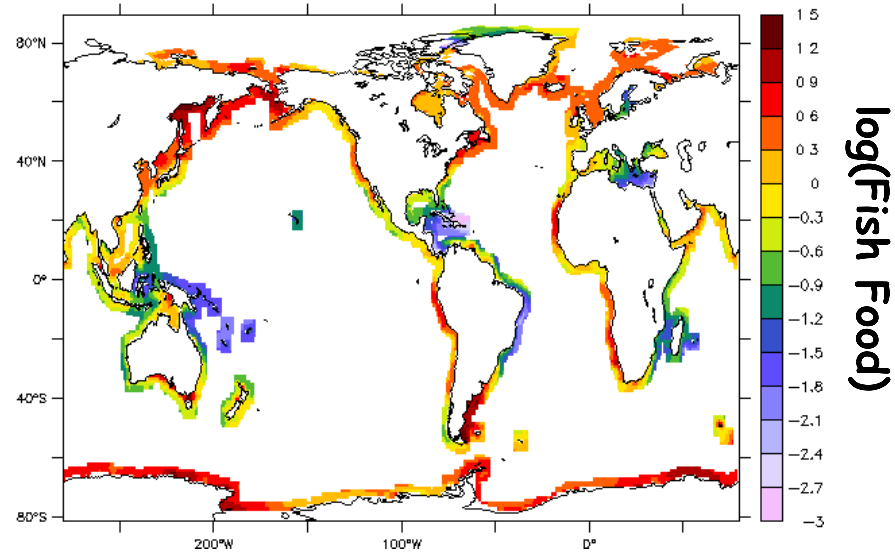
Climate-fisheries connection

12 Species account for 40-50% of global fisheries catch



Adapted from Klyashtorin (2001) FAO Fish. Tech. Pap. 410, 86 pp.

Exclusive Economic Zones

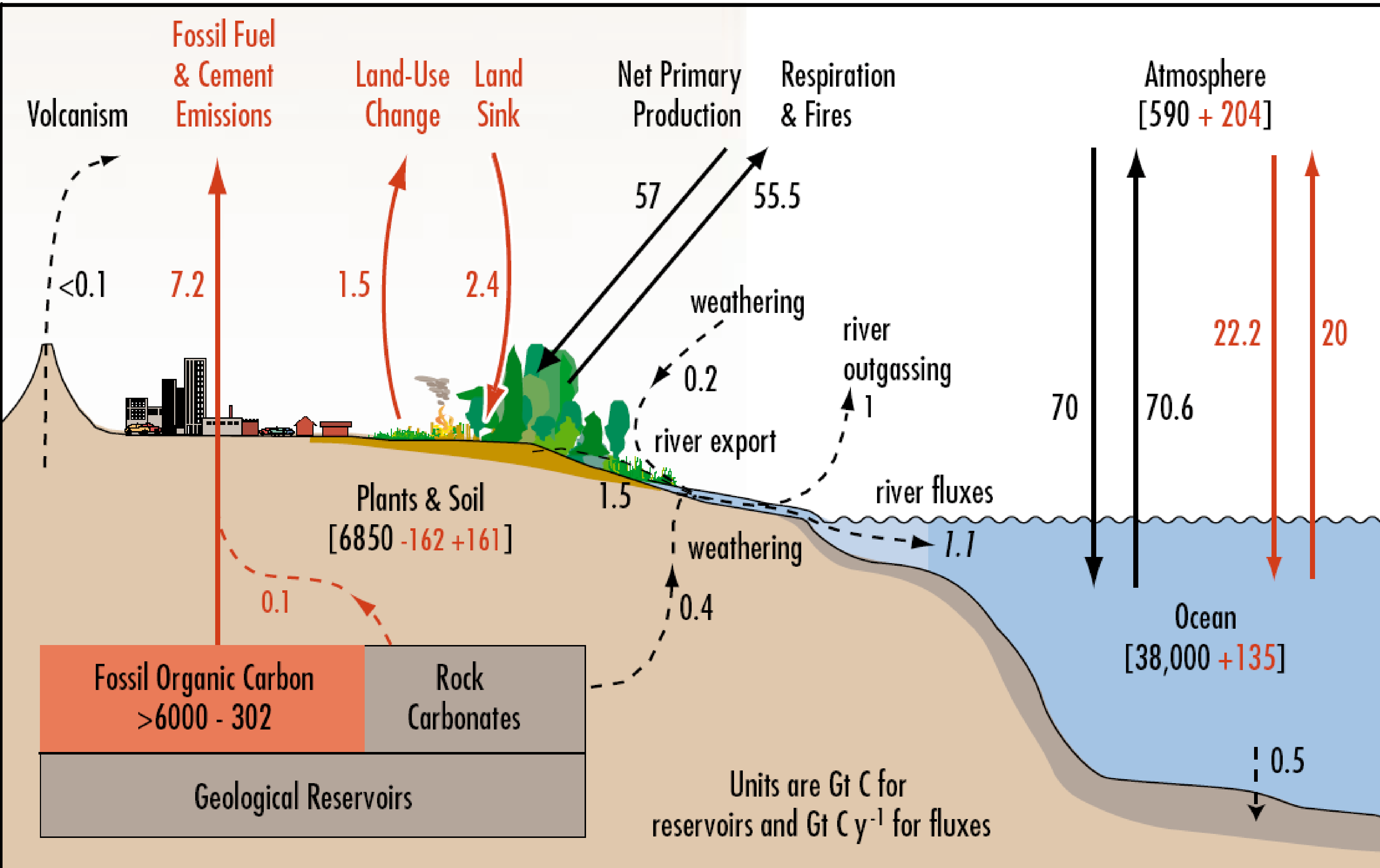


Extra Slides

Some specific questions

- How will increasing temperatures under climate change effect ecology?
  - Enhanced autotrophic rates?
  - Enhanced metazoan and microbial metabolism?
  - Increased stratification increasing mixed-layer-light levels and decreasing nutrient supply?
  - Increased winds decreasing mixed-layer-light levels and increasing nutrient supply?
  - Concomitant ecological community shifts?
  - Increased hypoxia?
- How will decreasing pH under climate change effect ecology?
  - Will increased aqueous CO_2 stimulate photosynthesis?
  - How does calcification decrease above saturation?
  - Does calcification occur below saturation?
  - Will coccolithophorids and foraminifera be favored (T, ecology) or disfavored (solubility)?
  - Will coral reefs be eroded?, and what of Pteropods? Will an ecological cascade result?
- Fisheries impacts
  - How much of a direct control does temperature and oxygen play in defining habitat and success?
  - Does bottom-up control exist in fisheries? Can it be modeled?
- How can we downscale to the land-ocean interface?
  - How can we bring global models towards the near-shore (Coral reef, mangrove, sea grass, wetland)
  - What is the role of continental shelves in a global context?
  - How do land inputs of nutrients, sediment and pollution influence these systems, and the global cycles?
  - Are there important sediment interactions that we are missing (e.g. cystation, benthic habitat, etc.)
- Is the harmfulness of algal blooms predictable?
  - Dynamics of diatoms vs. autotrophic dinoflagellates vs. heterotrophic dinoflagellates
  - Are HABs random?, driven by non-Redfield stoichiometry? Specific light and T conditions?

Carbon Cycling: Natural and Human



UNESCO (2006) Updated from Sabine et al (2004), SCOPE 62