Spatial and temporal operation of food webs: Scales of interaction in oceanic ecosystems

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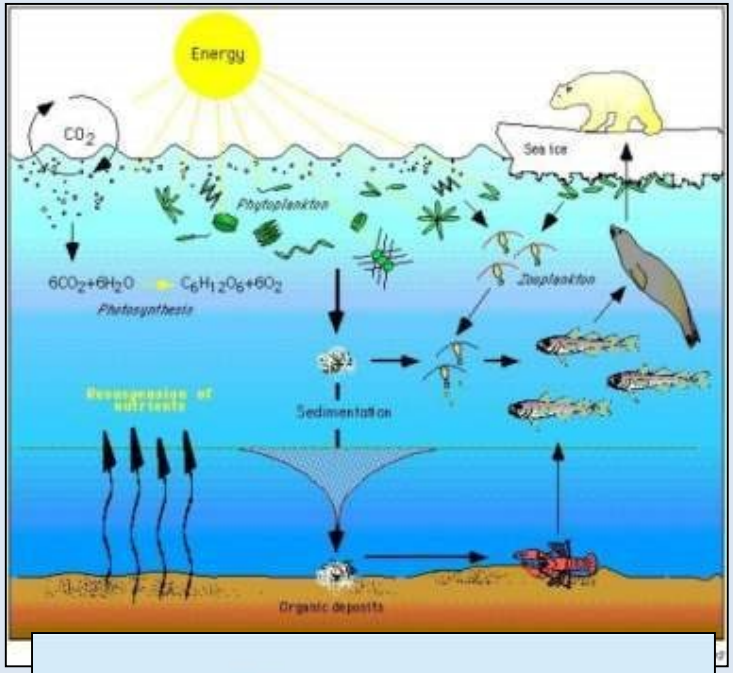
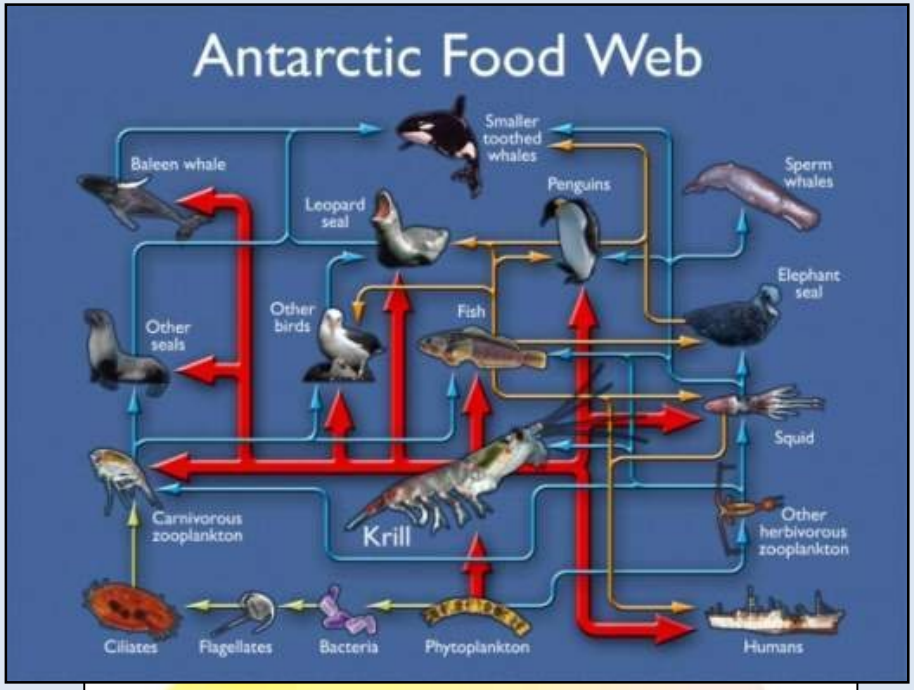
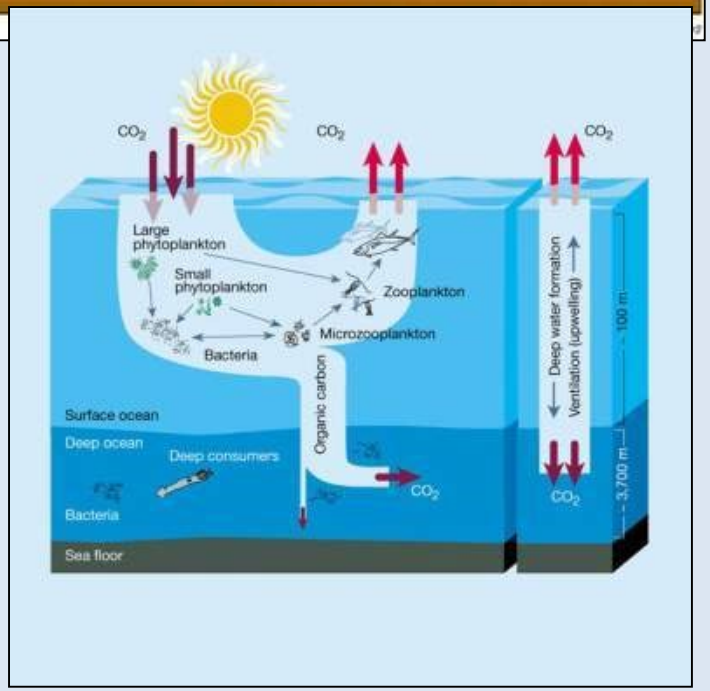
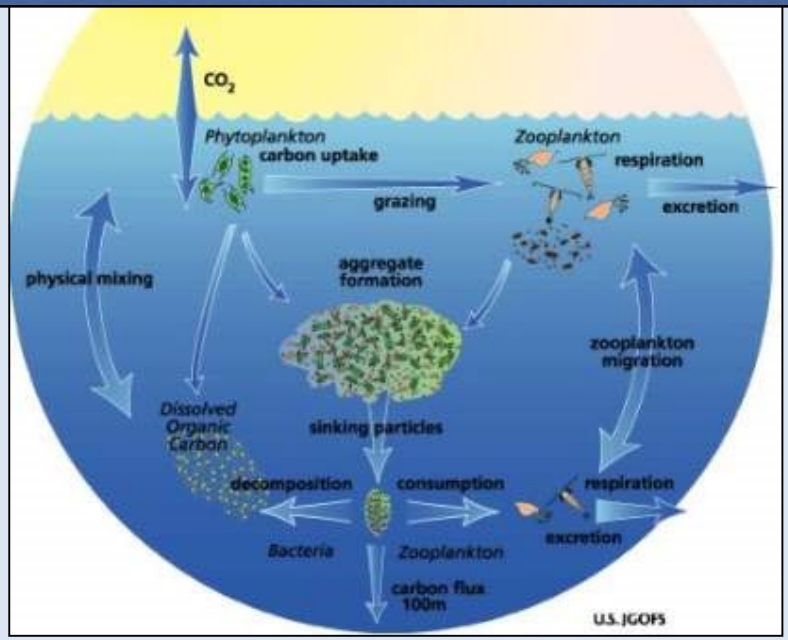
Outline of Presentation

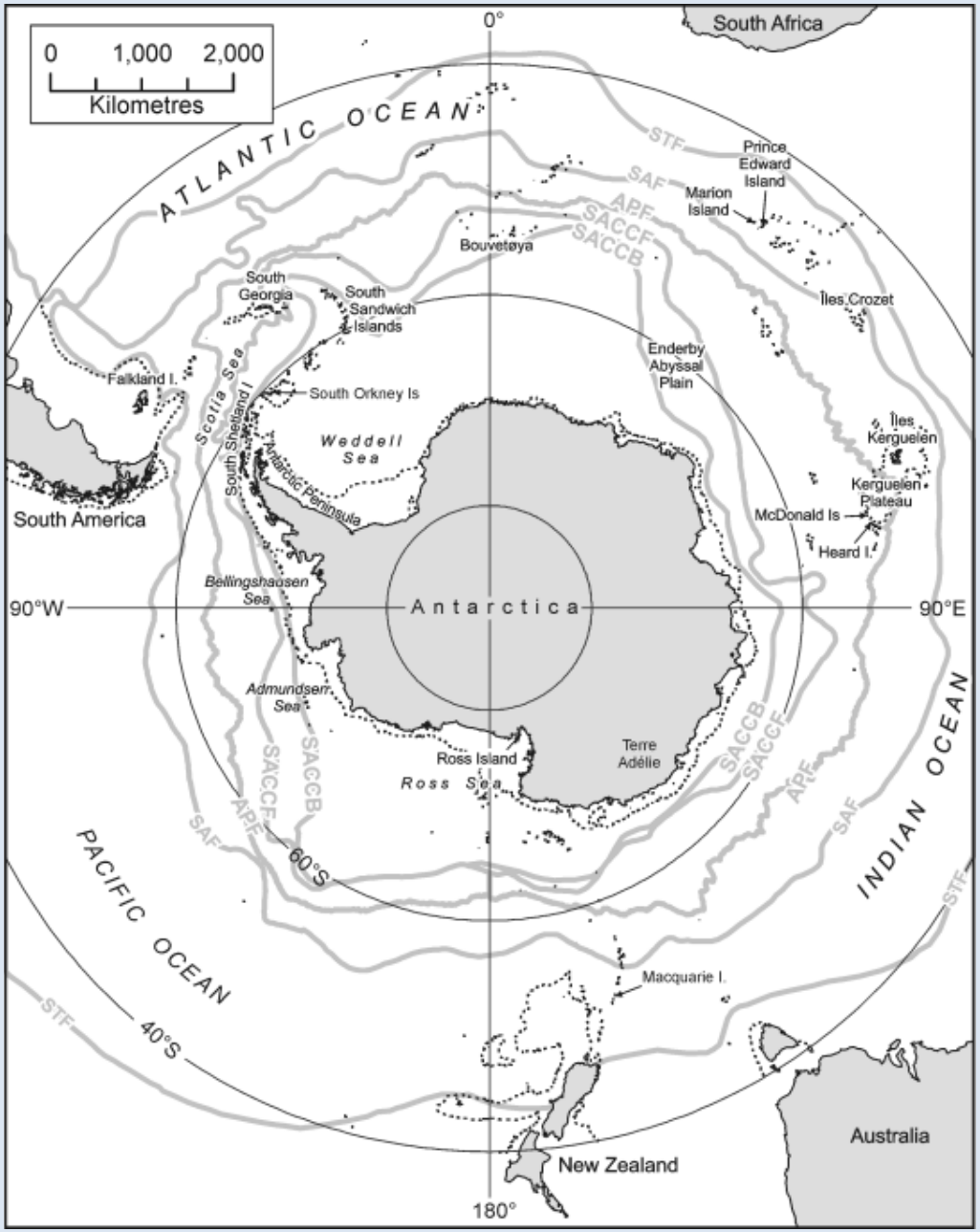
- General comments about food webs
- Scales of physical and biological processes and interactions
- Importance and implications of variability in food webs
- Concluding remarks
- ICED program


Energy
CO_2
Sea ice
Phytoplankton
$6CO_2+6H_2O \rightarrow C_6H_{12}O_6+6O_2$
Photosynthesis
Zooplankton
Regeneration of nutrients
Sedimentation
Organic deposits


Antarctic Food Web
Baleen whale
Smaller toothed whales
Sperm whales
Leopard seal
Penguins
Elephant seal
Other seals
Other birds
Fish
Squid
Carnivorous zooplankton
Krill
Other herbivorous zooplankton
Ciliates
Flagellates
Bacteria
Phytoplankton
Humans


CO_2
CO_2
CO_2
Large phytoplankton
Small phytoplankton
Zooplankton
Microzooplankton
Bacteria
Organic carbon
Deep water formation
Ventilation (upwelling)
100 m
3,700 m
Surface ocean
Deep ocean
Deep consumers
Bacteria
Sea floor
CO_2
CO_2


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
U.S. JGOFS



Southern Ocean Food Webs

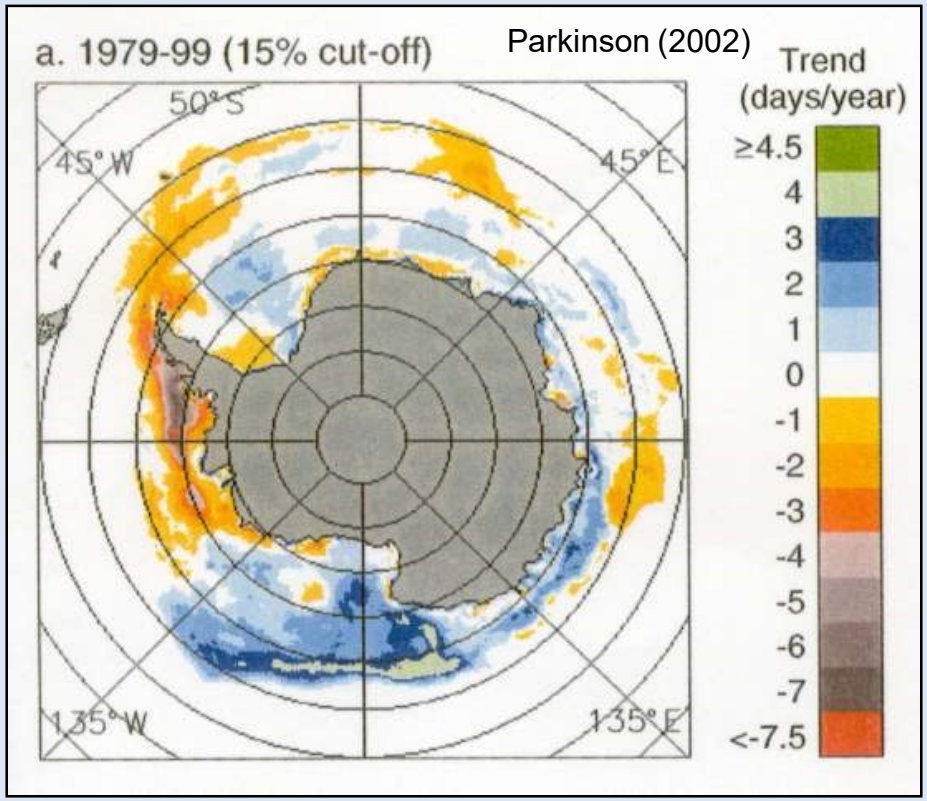
Circumpolar System

Not similar food web throughout

Considerable heterogeneity in forcing and habitat structure

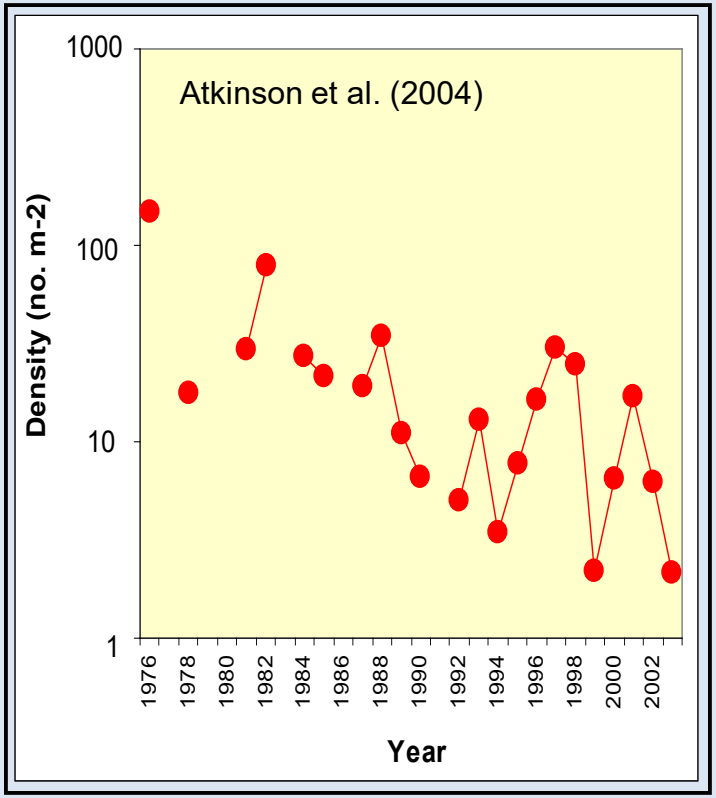
Regional differences in responses

Southern Ocean is Undergoing Major Environmental Changes

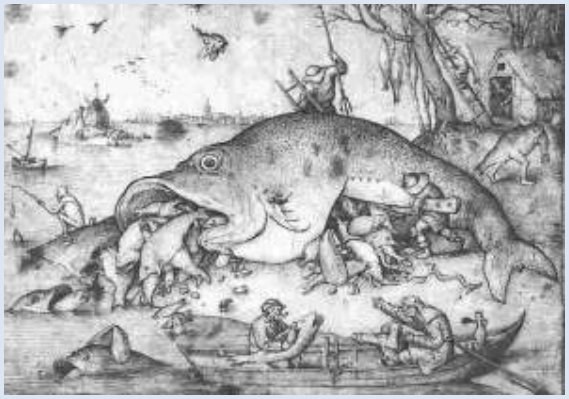


Upper ocean temperatures have increased by 1°C in the last 50 years -WAP most rapidly warming region on planet

30% decline in Antarctic krill in South Atlantic in last 30 years



What happened in the past?



Harvesting has generated massive perturbations over more than 2 centuries

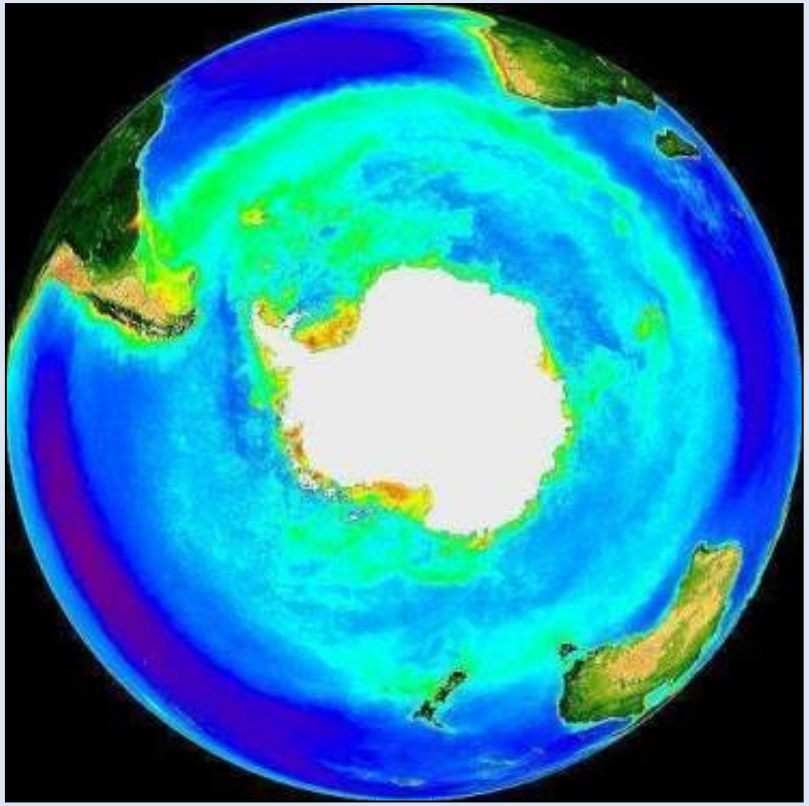
Fur-seals
From 1778; economic extinction within 35 years

Whales
1906 to 1966, residual thereafter

Fin-fish, krill
From late 1960s, continuing

Top-down effects => Krill surplus?

Challenges for Southern Ocean

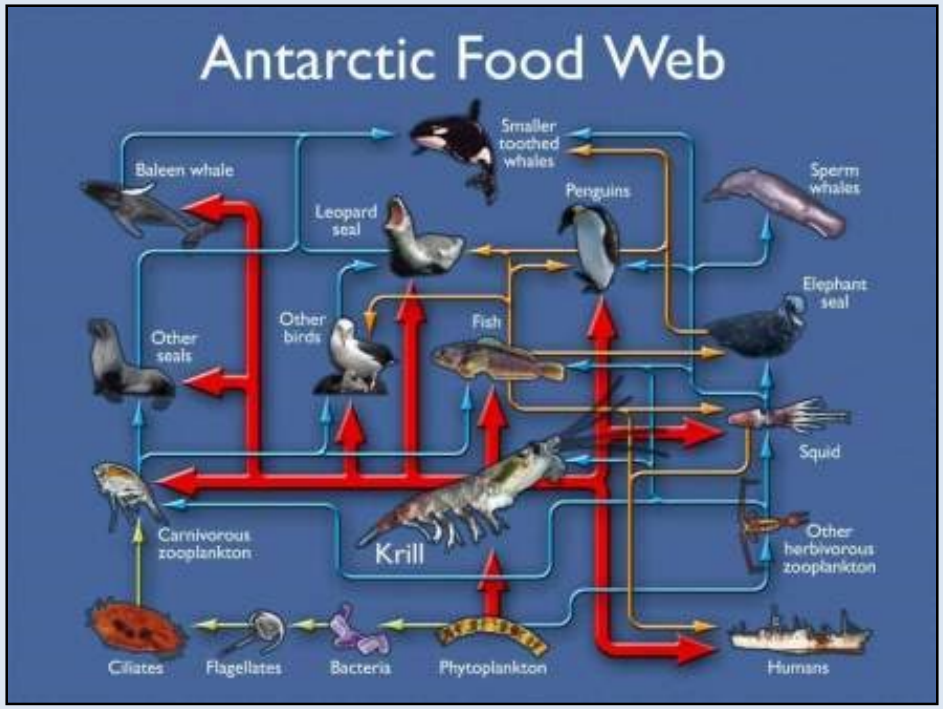


- Climate Impacts
- Harvesting Effects
- Biogeochemistry
- Food Webs

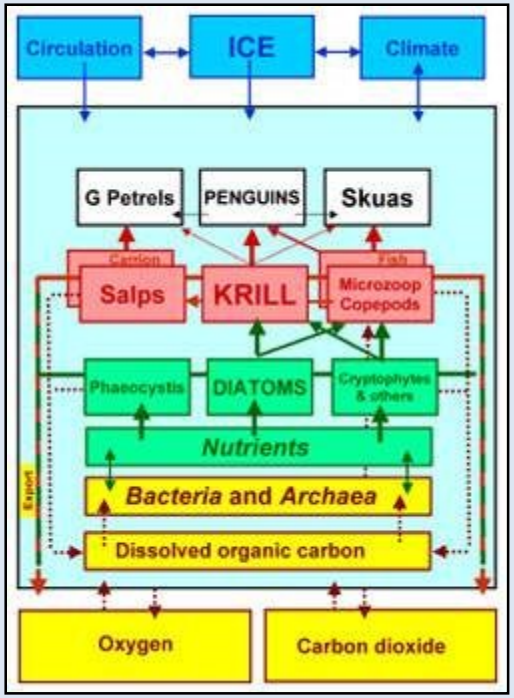
Can we develop experimental and modeling programs to address these effects and interactions at a circumpolar scale?

Types of Food Webs

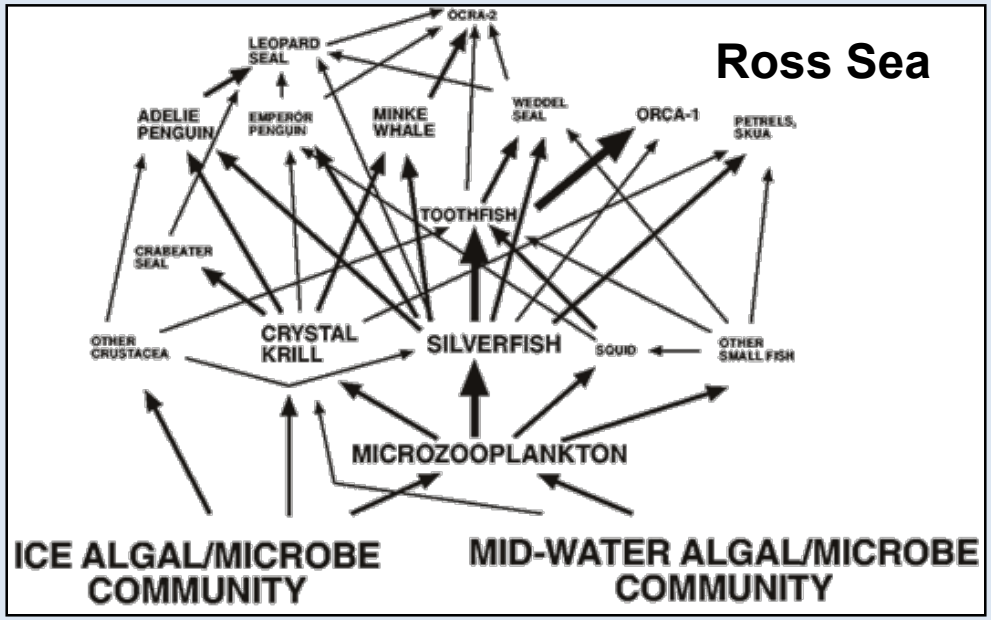
Classical Food Web



Western Antarctic Peninsula



Ross Sea

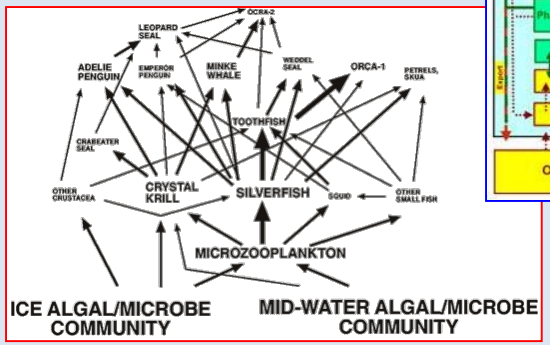


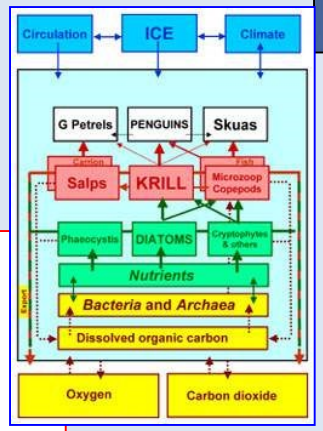
Why the Differences?

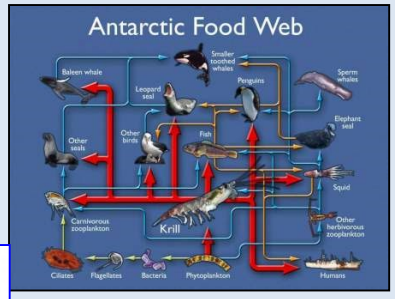
Seasonal length

Sub Antarctic

High Antarctic







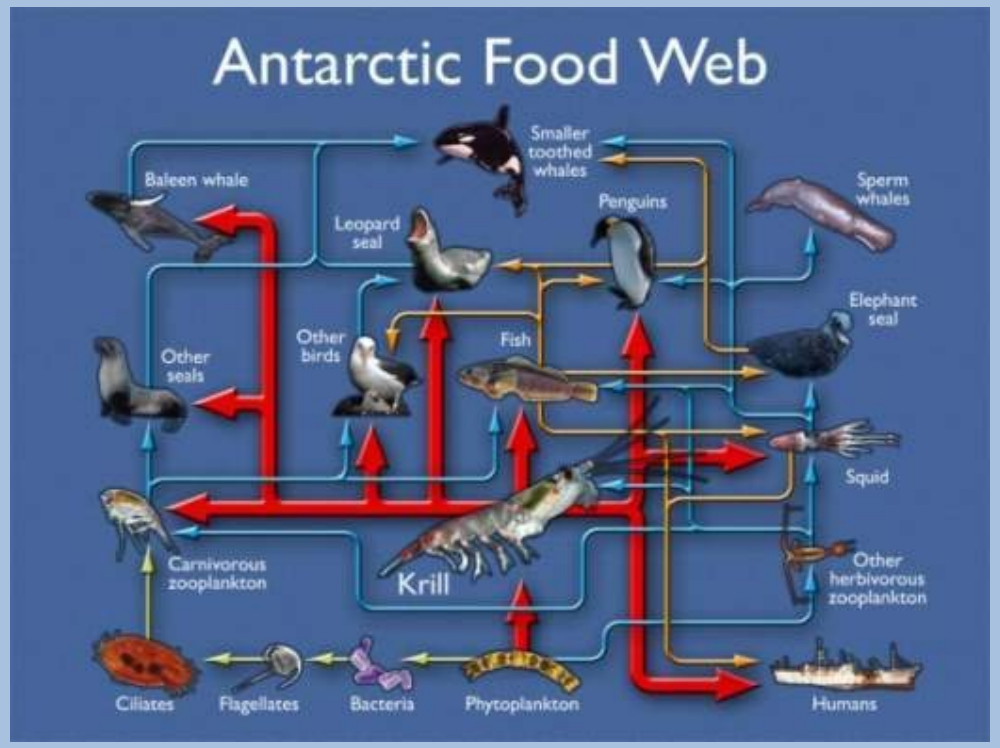
Differences due to
Circulation
Sea-ice
Biogeochemistry
Production
Seasonality

Low Production

High Production

External drivers

- Temperature
- Sea-ice
- Circulation
- Mixed-layer depth
- Seasonality



Cannot separate biological from physical processes in food webs

Network Construction

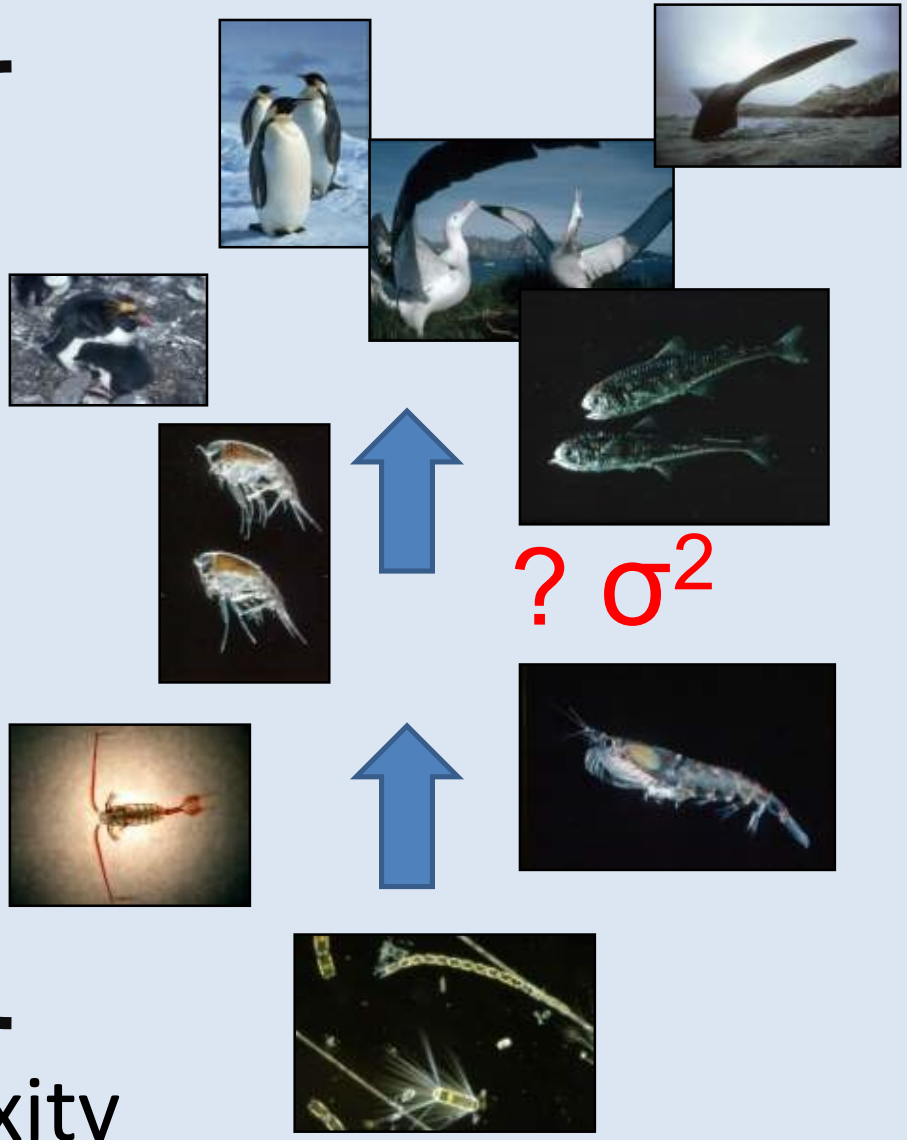
Temperature

Sea-ice

Circulation

Mixed-layer depth

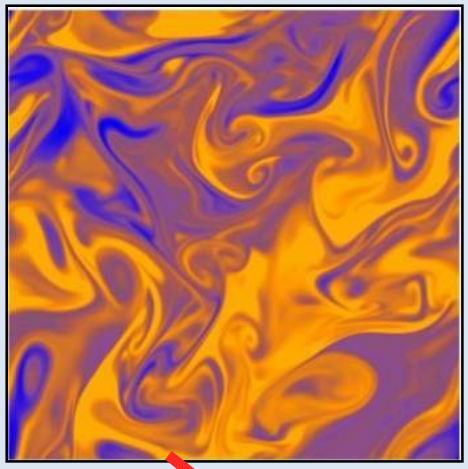
Seasonality

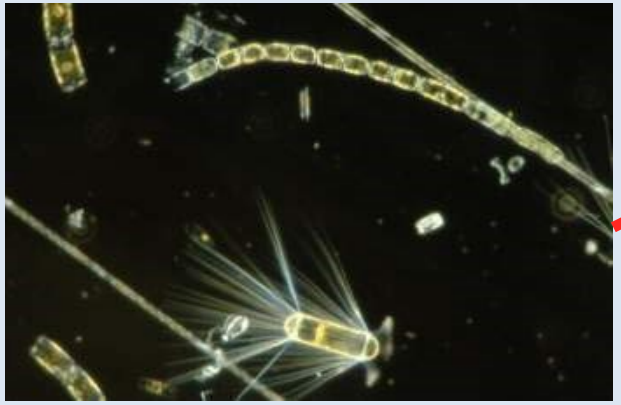


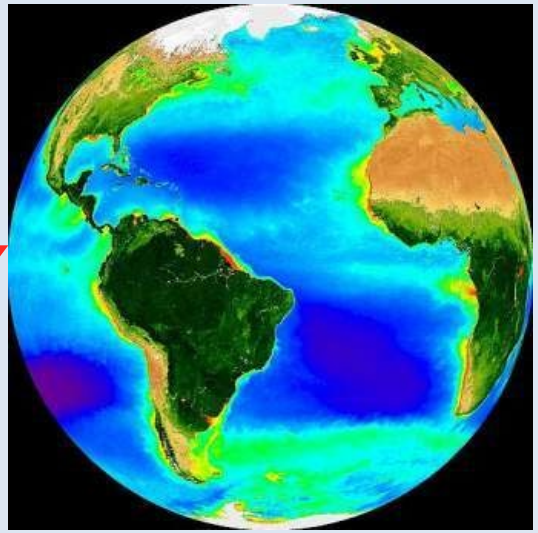
? σ^2

Adding complexity

Physical and biological processes operate at different scales - encompass a wide range



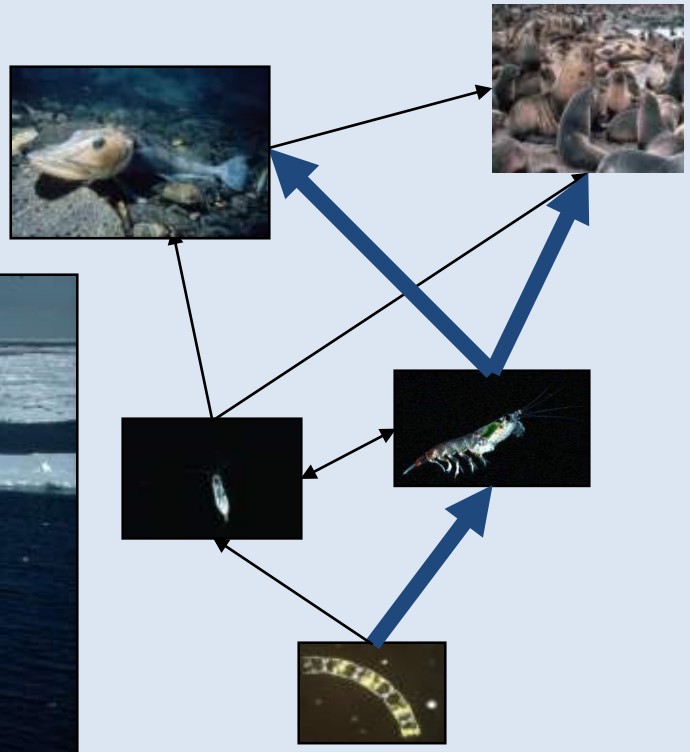




Ecosystems

Based on biological-physical interactions

Food web structure emerges from interactions at different scales



Abiotic ⟷ **Biotic**

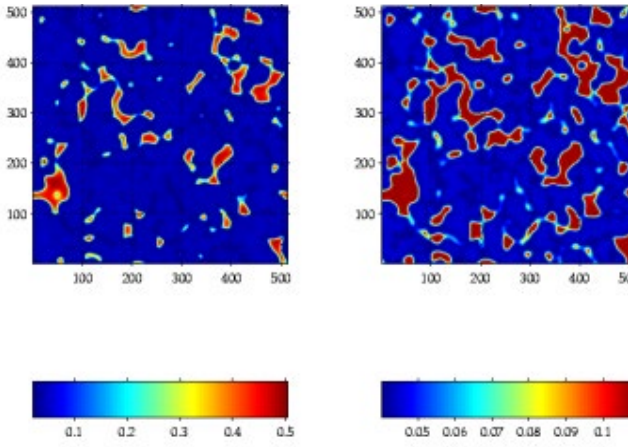
Why does heterogeneity matter?

Patchy systems ->

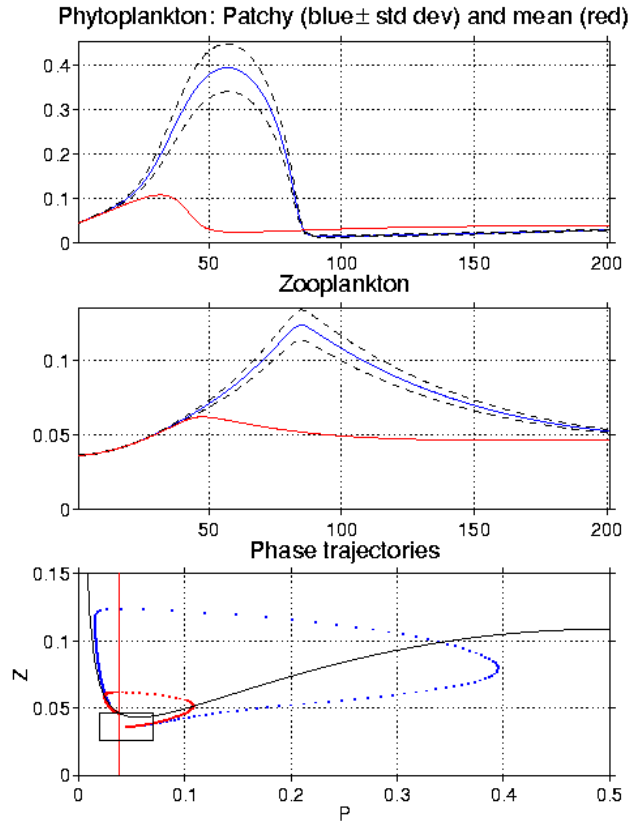
different answers

to homogeneous case

Phytoplankton Zooplankton



Linear, initialized near equilibrium



Reaction diffusion model *Brentnall et al, (2003)*

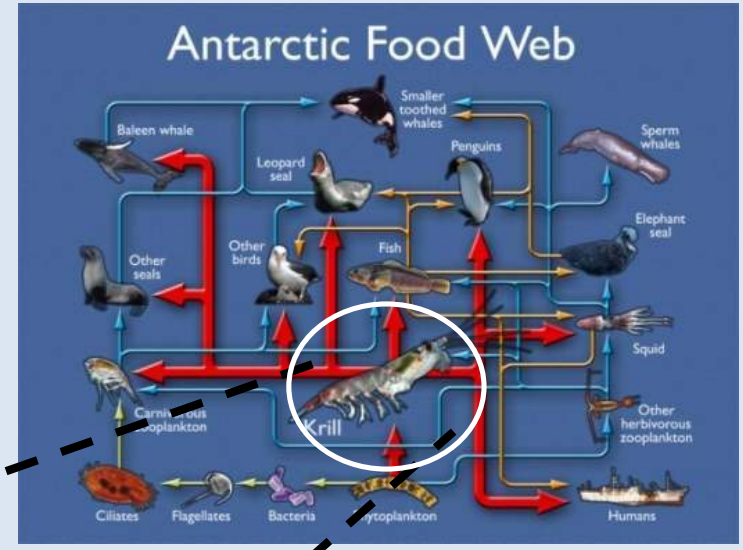
- Patchy ocean gets excited, average one doesn't

Implications for coupled modelling - food webs

Illustrate with Antarctic krill

Why is krill so important to higher predators?

Krill are a key prey species
transferring energy to higher trophic levels



Euphausia superba

Maximum size ~6 cm
-> 5-7 year lifetime

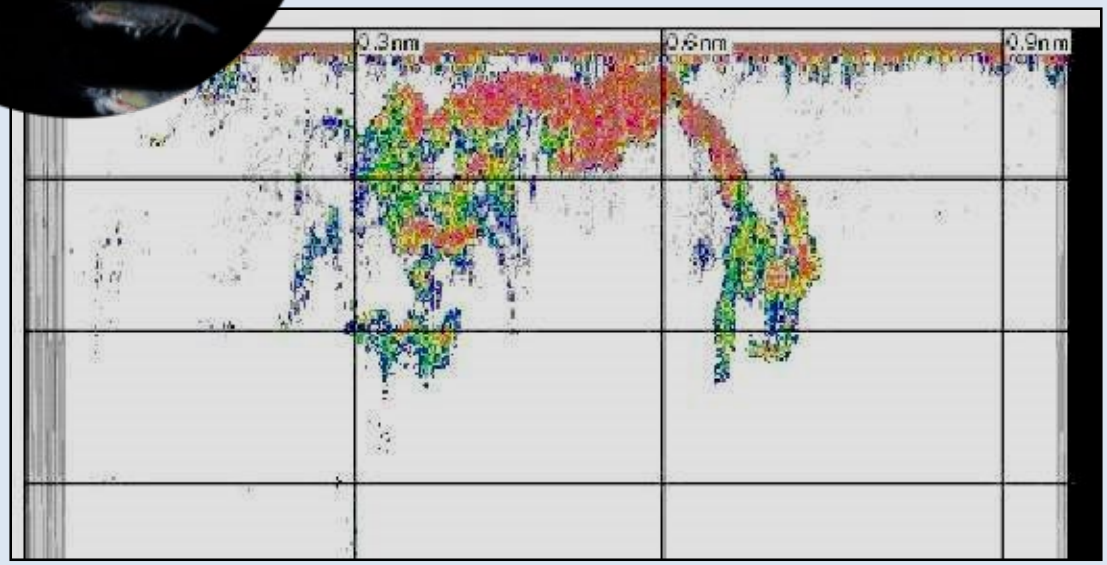
Abundance is important but so is spatial structure of distribution

Krill aggregations

Predators must be able to exploit patchy distributions

Typical dimensions
Vertical ~ 25 to 50 m
Horizontal ~100-200 m
1000-10000 individuals m^{-3}

100 m



Acoustic trace of a large aggregation

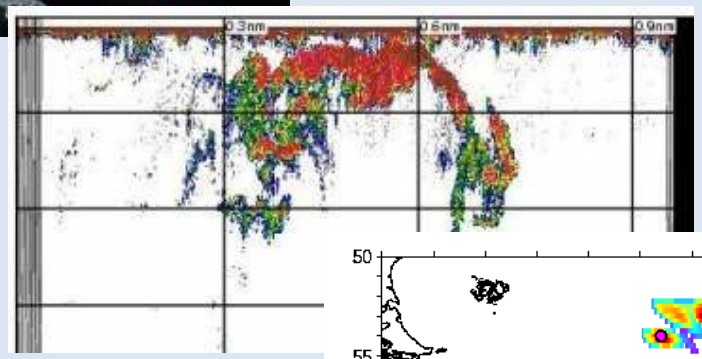
Space between aggregations

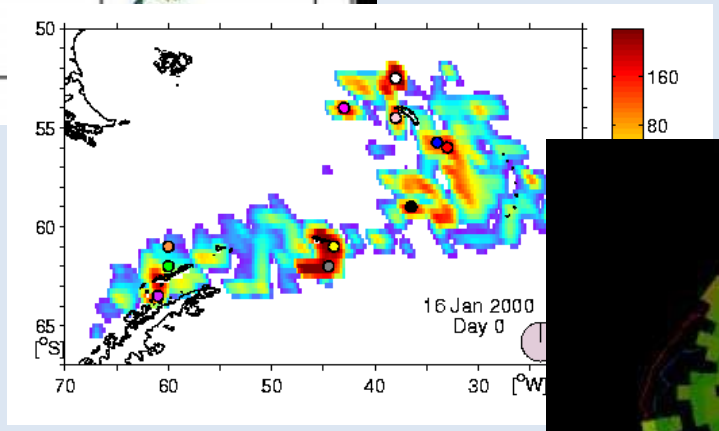
Physical and biological interaction generates structure

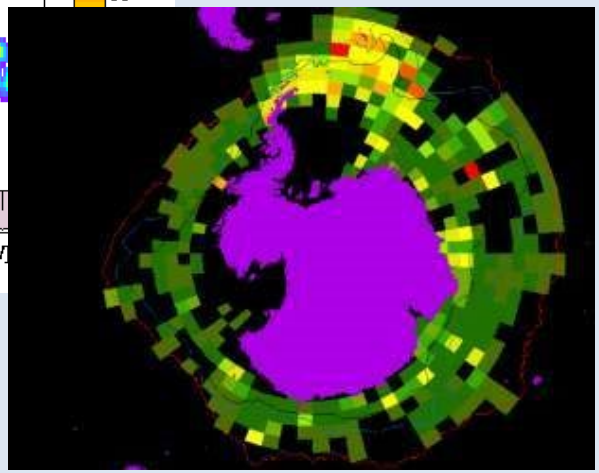
1000 m

Scales of spatial variation

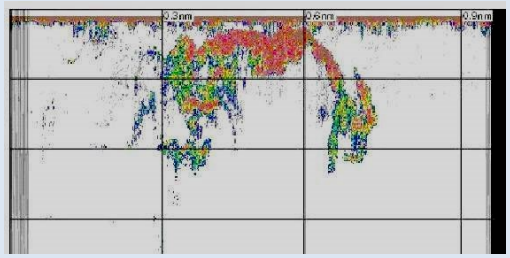
Scale of aggregation depends on view of system

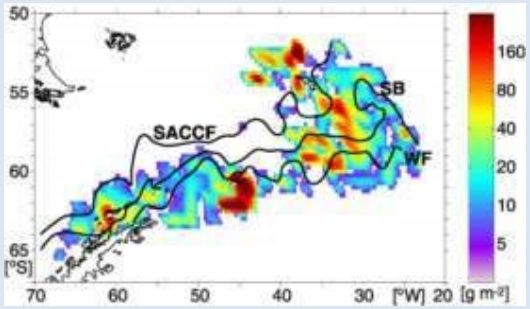






Structure modifies the operation of the ecosystem





Scale of aggregations - exploited by different predators

Krill are important to different parts of the food web because of a spatial structure that covers many scales

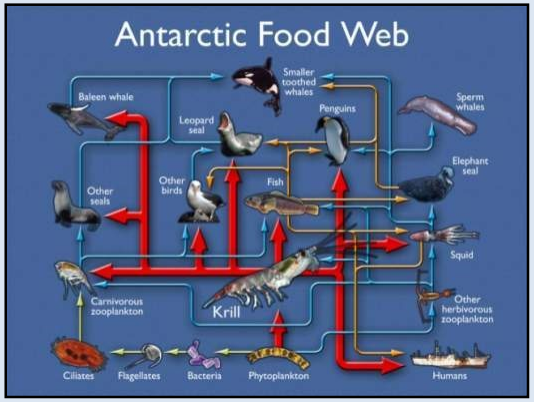
Longevity and overwinter survival allows spatial and temporal transfer

Makes energy available to predators

Food webs structure

- Food webs emerge from process interactions at different scales
  - Biological-physical interactions – not just biological
  - Involves integration of effects at particular scales
  - Interaction across scales
  - Heterogeneity and variability is a fundamental aspect of food web

- Analyses of food webs provide
  - Representation of material flows
  - Analyses of interactive effects



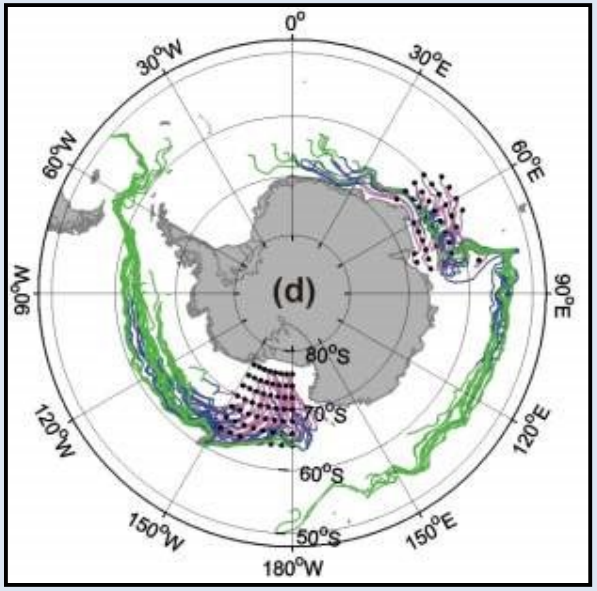
- Variability and Scale - circulation effects

Importance of movement and/or migration

- Diurnal migration
- Foraging
- Seasonal migration
- Advection

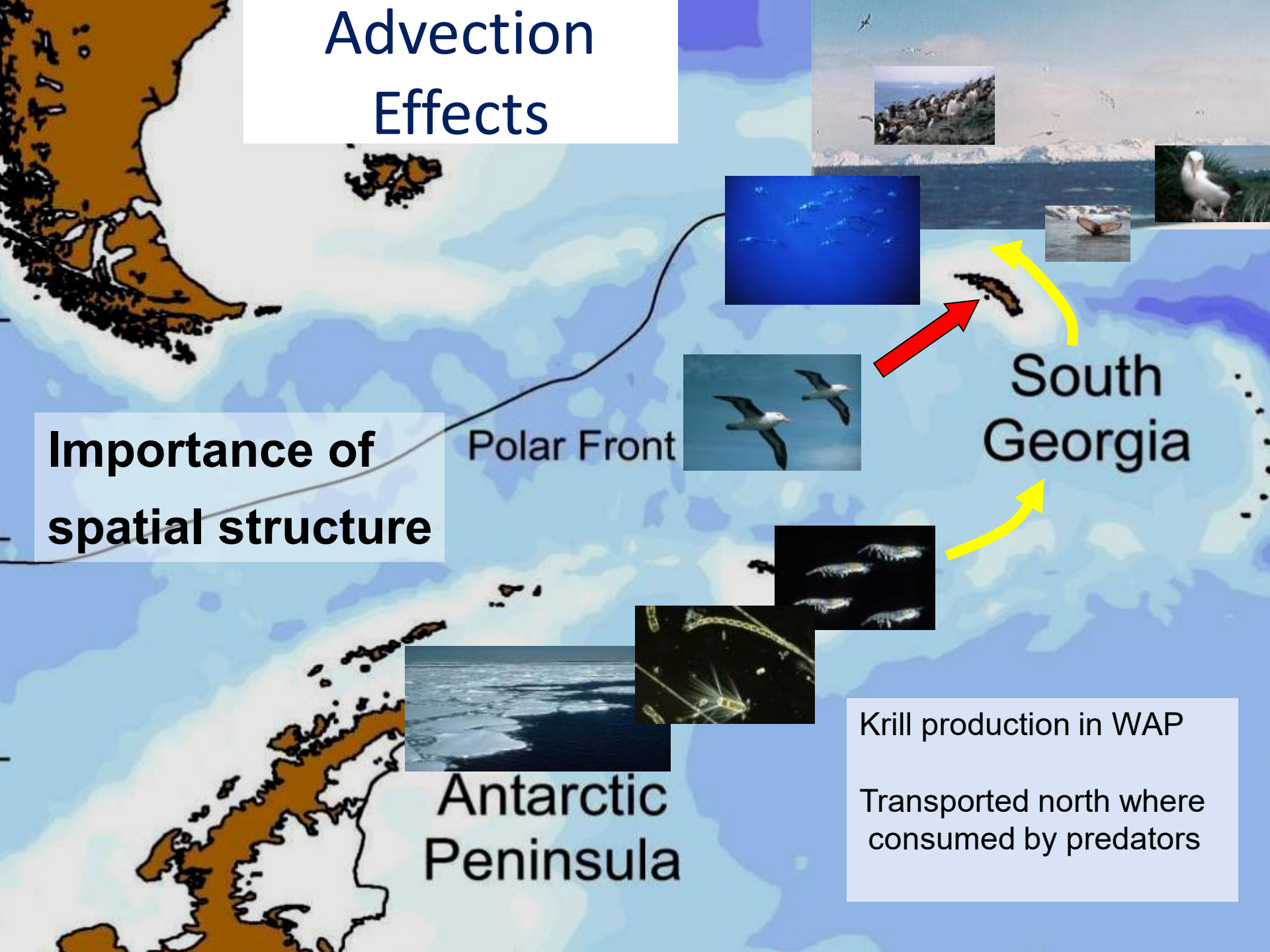
- Moves energy/material and disperses mortality

Advection



- Copepods and Krill
  - Krill in the Southern Ocean
  - Arctic
    - sea-ice
  - North Atlantic
    - Zooplankton onto shelf in the North Sea
    - *Calanus finmarchicus* in the Gulf of St. Lawrence and Scotian Shelf
- Secondary production contributes to local food webs
  - autochthonous vs allocthonous

Advection Effects



Importance of spatial structure

Krill production in WAP

Transported north where consumed by predators

Advection

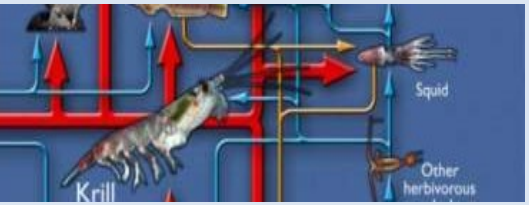
Autochtonous – Allocthonous production

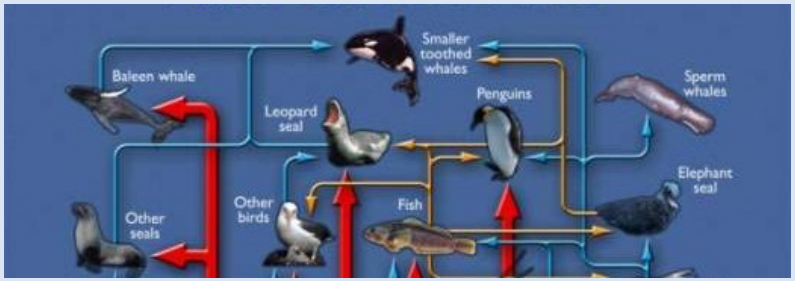
Displaces production

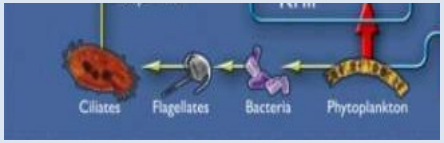
Disconnects

Production - Mortality

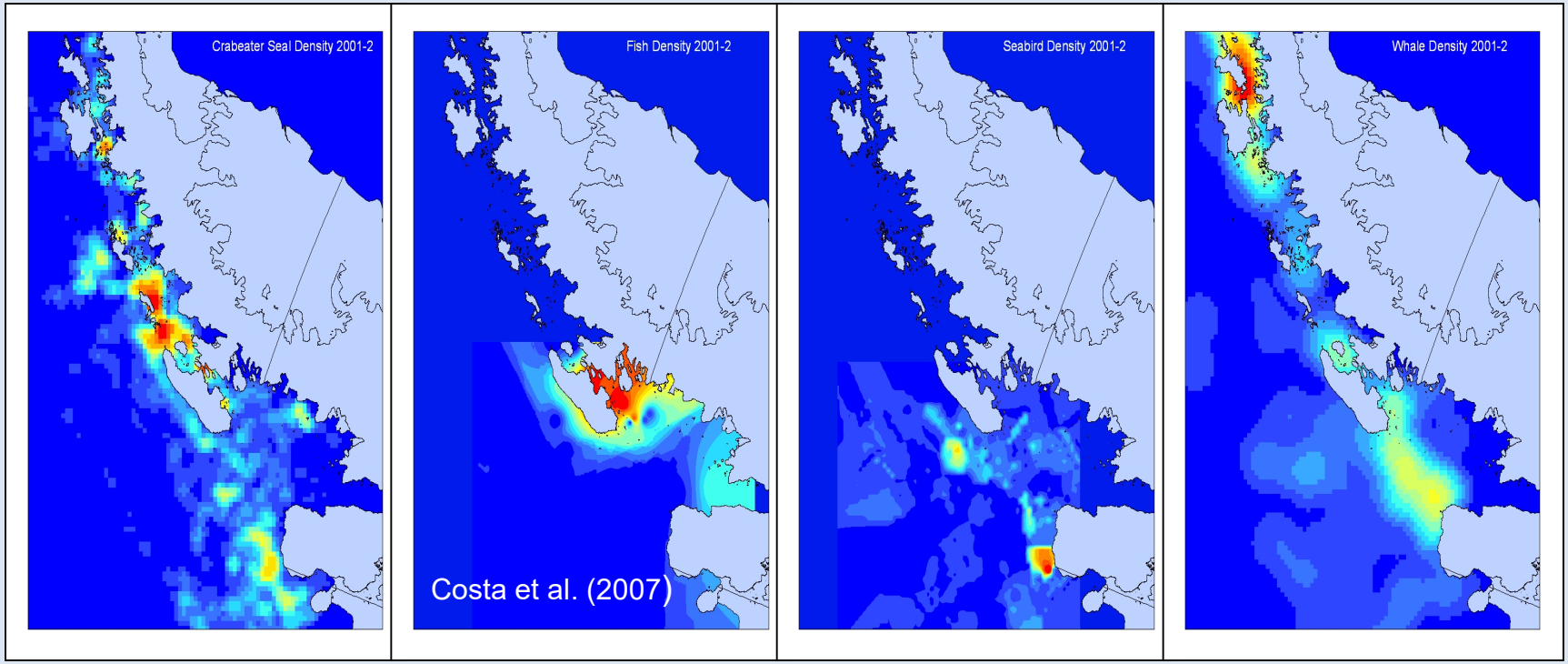
Production - Export



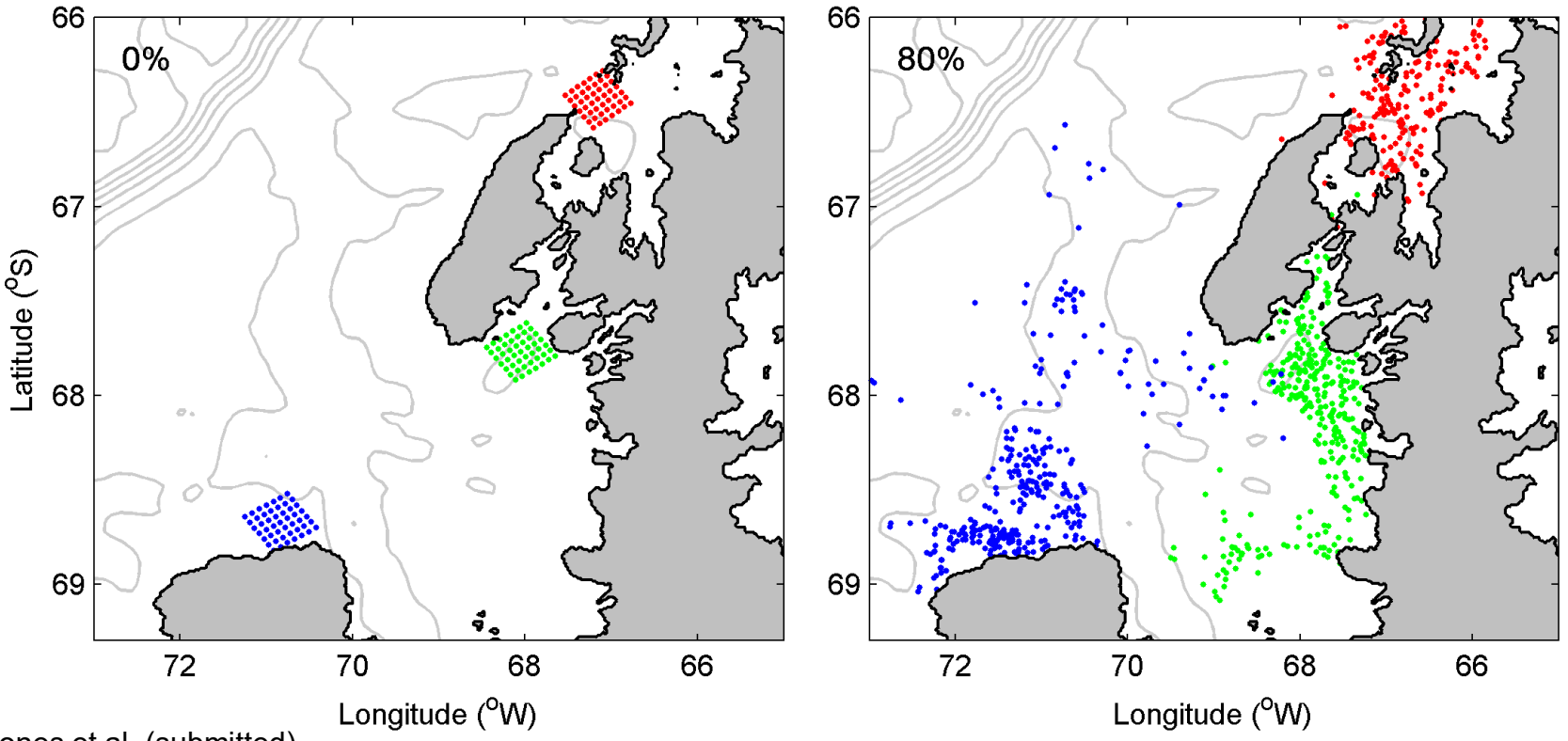




Biological Hot Spots



Not all parts of a system/region are biologically similar



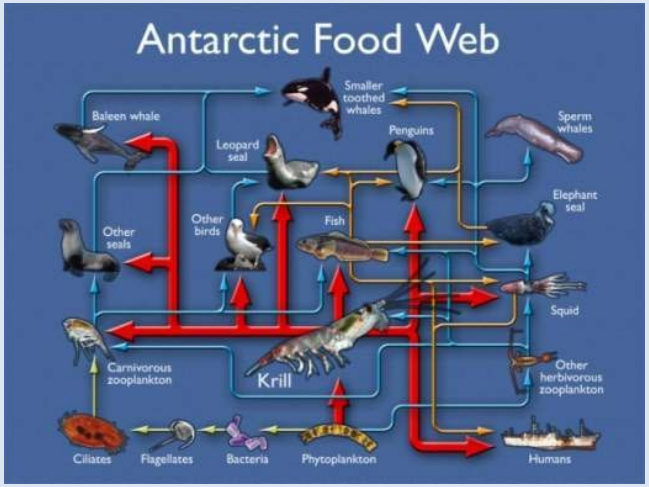
Pinones et al. (submitted)

Hot spots are distinct, may have exchange with each other, export material to larger region

Persistent over evolutionary time

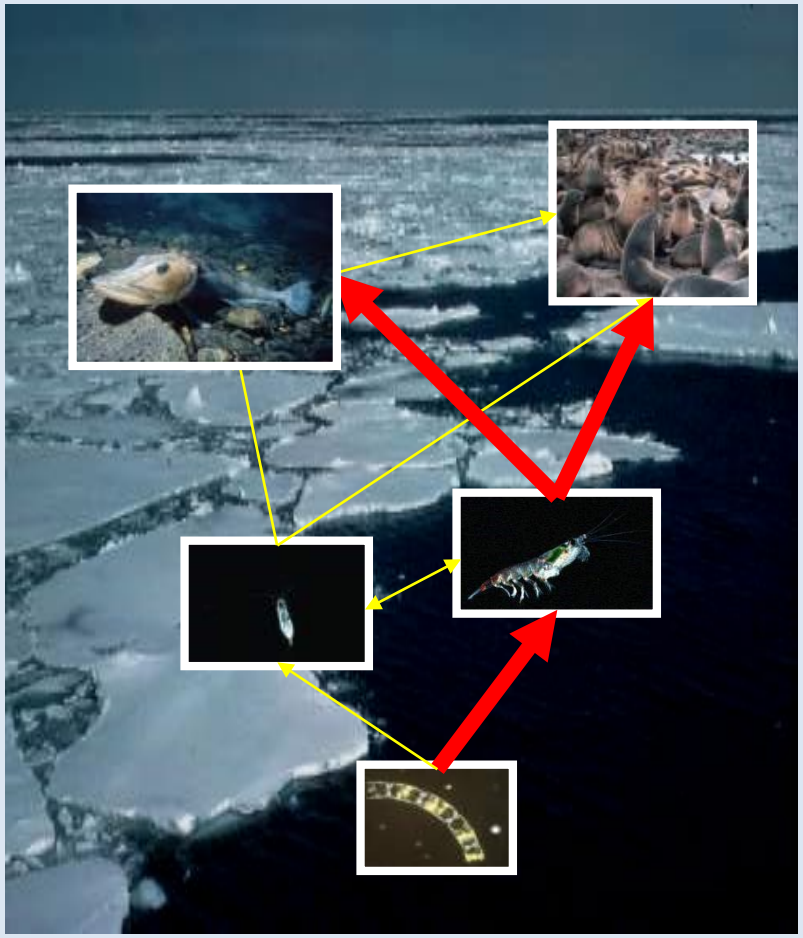
Food Web Variability

- Fluctuations in structure
  - Alternative pathways
- Food webs not at equilibrium
  - Transient effects
- Maintenance of food web
  - through fluctuation
  - sensitivity to changes in variation

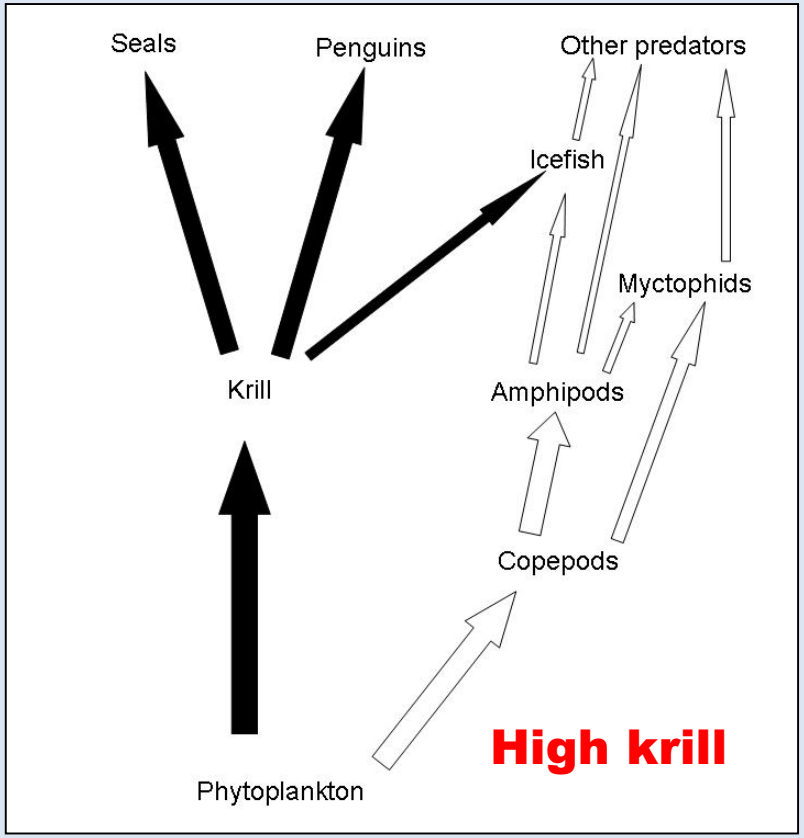


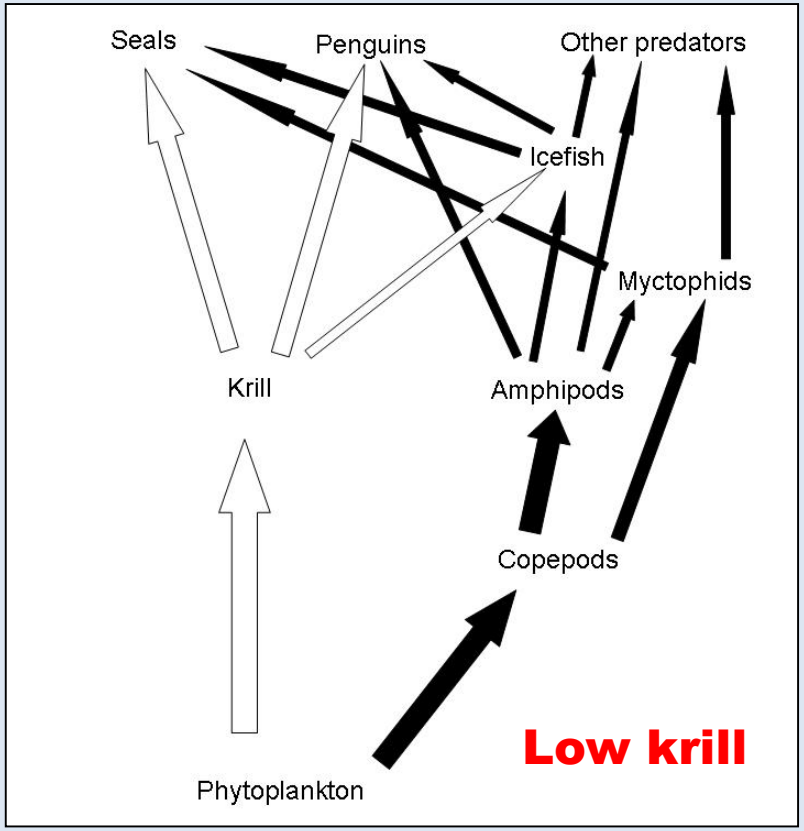
Food Web Variability

- Scales of interaction –> the basis of food webs
  - Biological-physical-chemical
    - patchiness, advection,
      movement, migration, variability
- Heterogeneity – spatial
- Variability - temporal
  - Complexity can generate stability
    - Includes variability
  - Modifies feedbacks
  - Variability
    - transient effects can be long-term,
    - past change
- Scaling–up food web analyses
  - Scale based analyses and models



Alternative Food Web Pathways

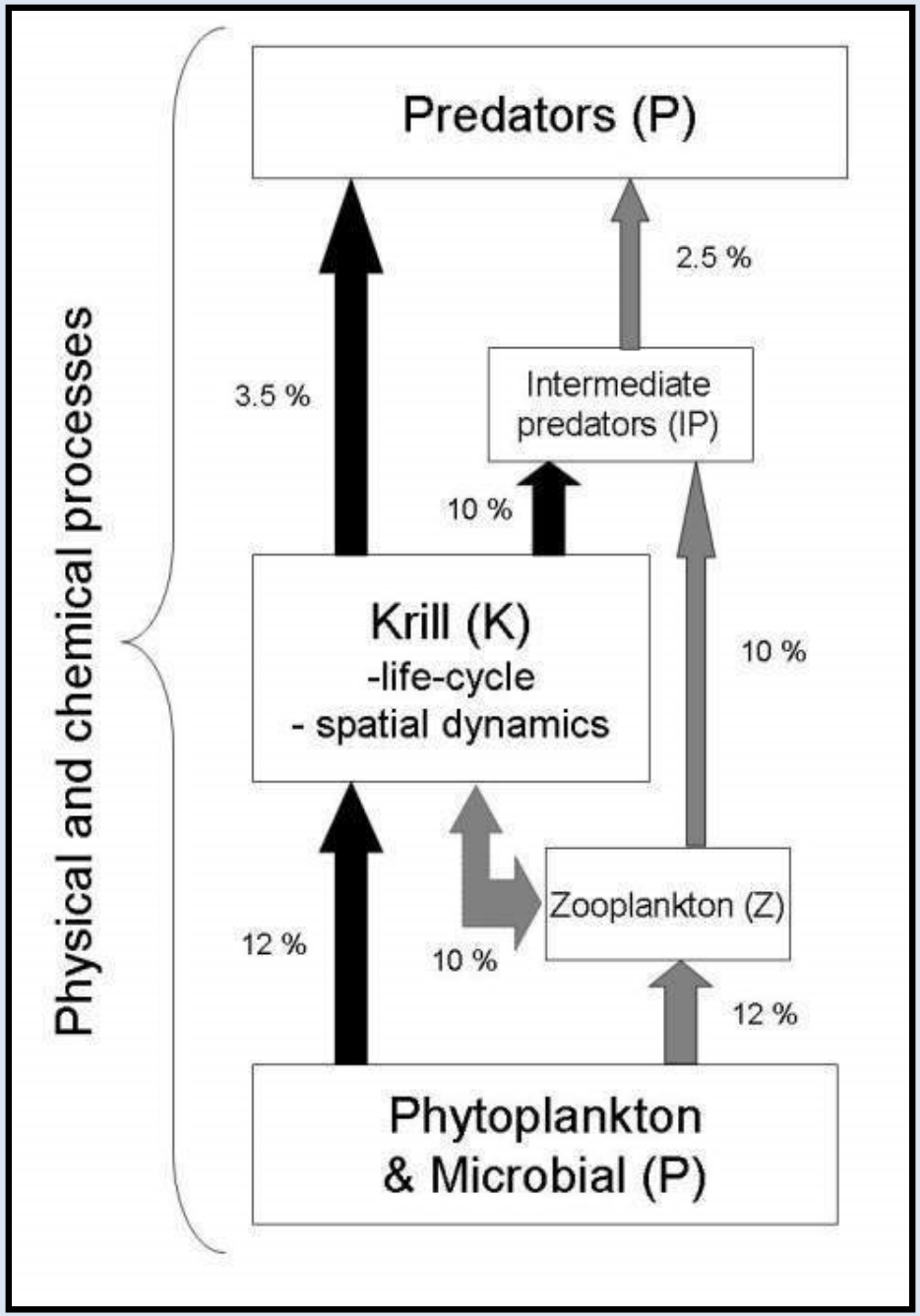




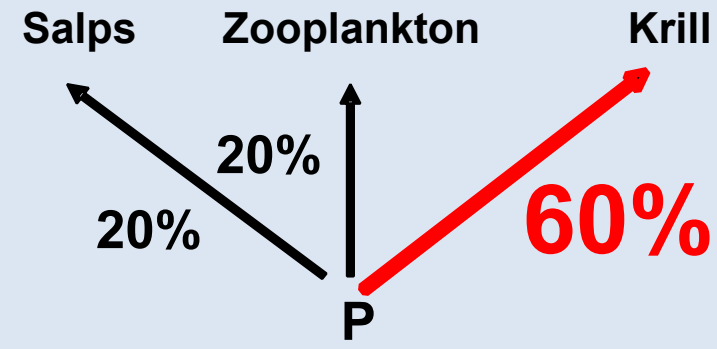
Alternative pathways buffer change - sustainable in long-term?
Need better quantification of alternative pathways

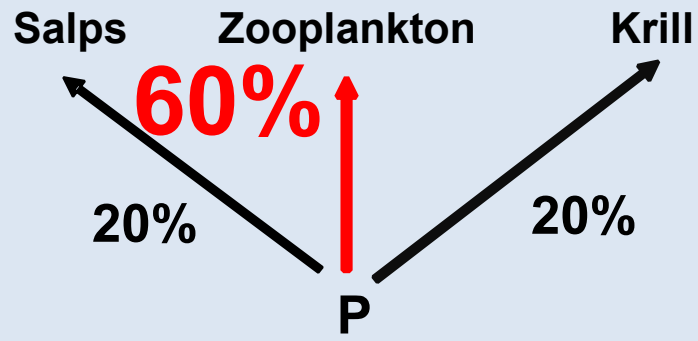
Energy flow in alternative food web pathways

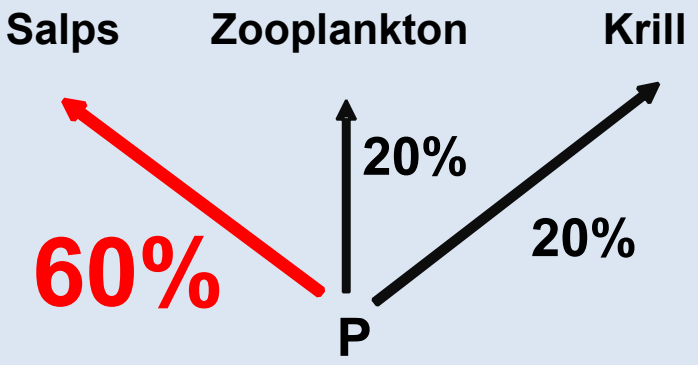
Less reaching higher trophic levels



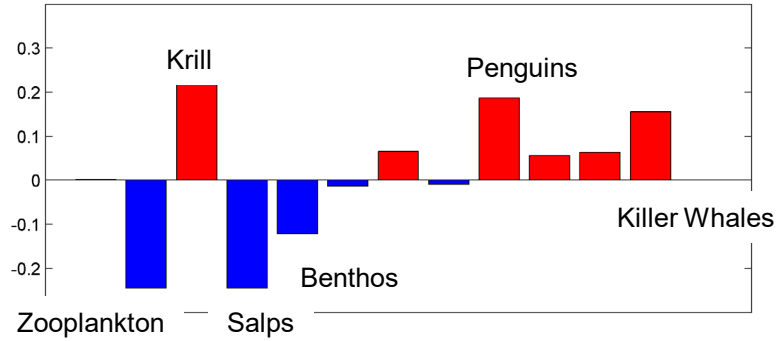
Change in production

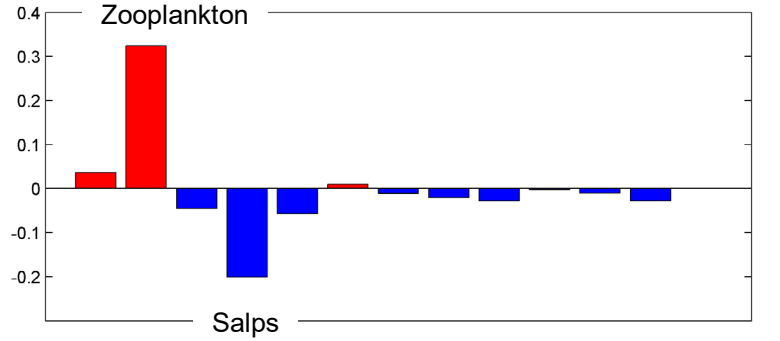


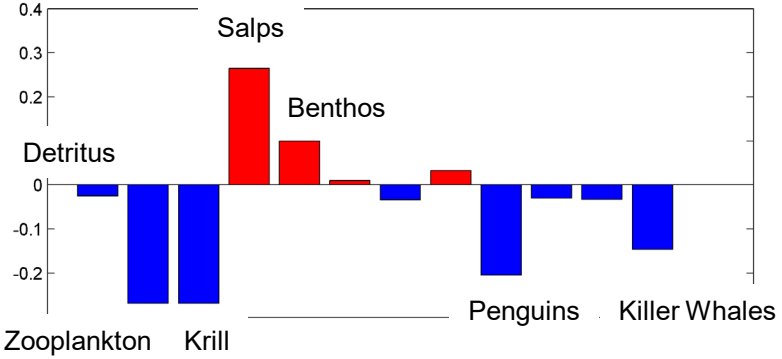




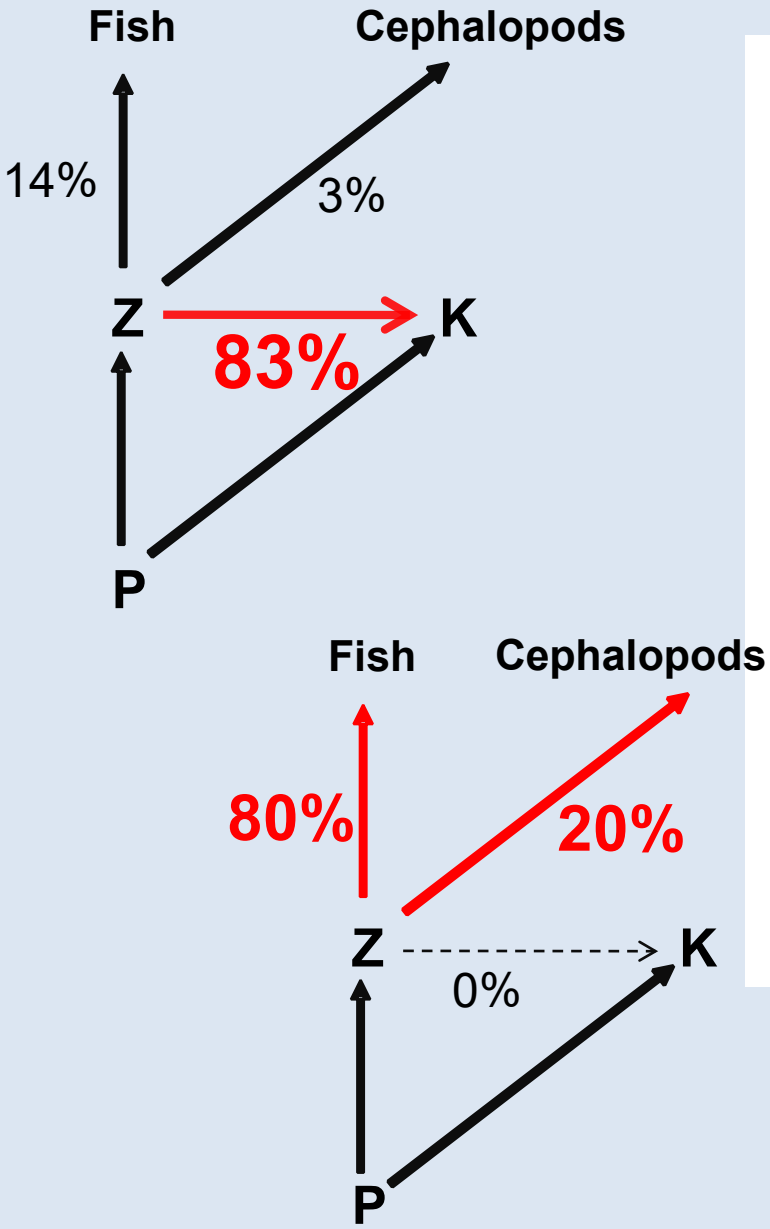
Ballerini et al. (in prep)

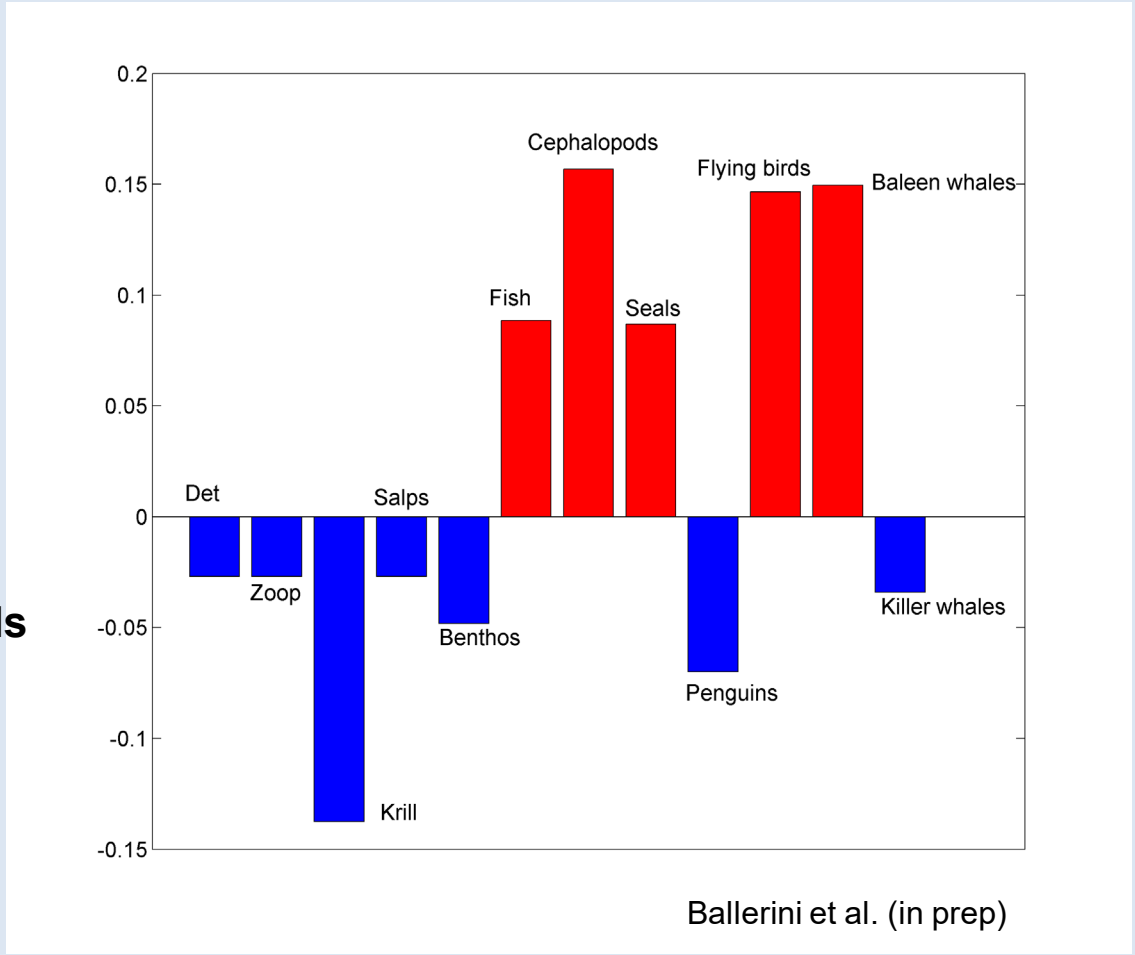






Change in production



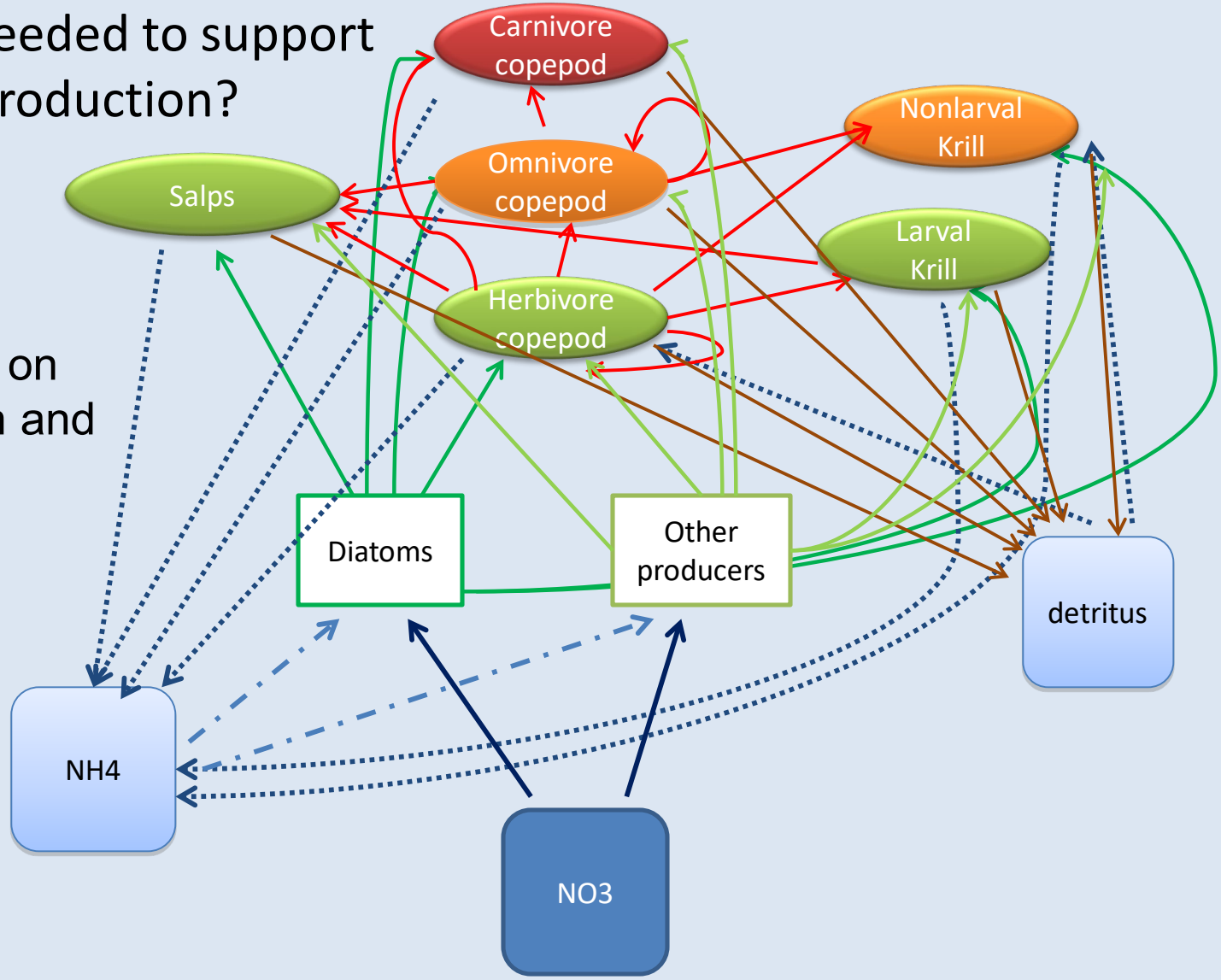


Ballerini et al. (in prep)

Bottom –up view of the lower food web

What is needed to support primary production?

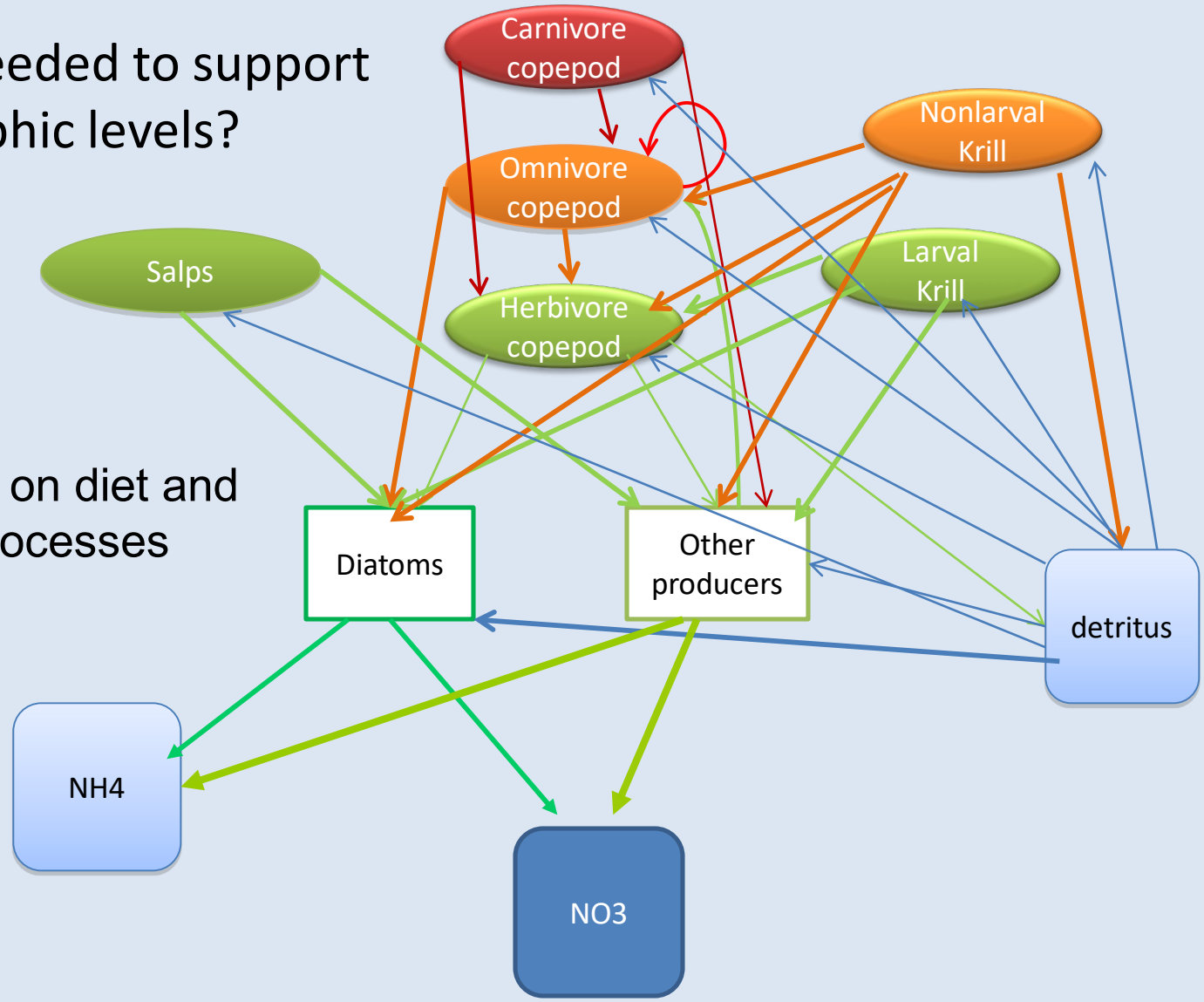
Emphasis on production and export

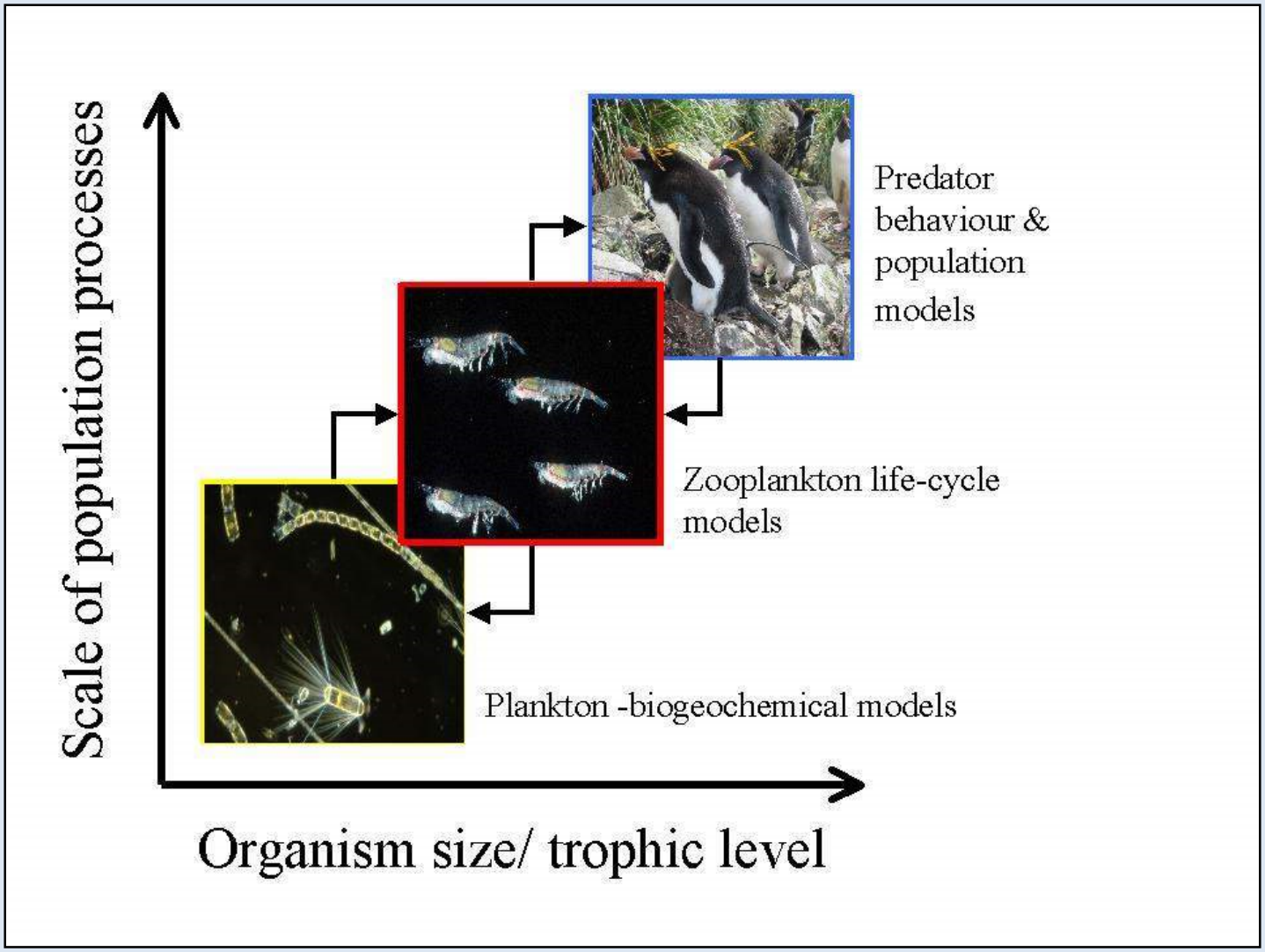


Top-down view of the lower food web

What is needed to support upper trophic levels?

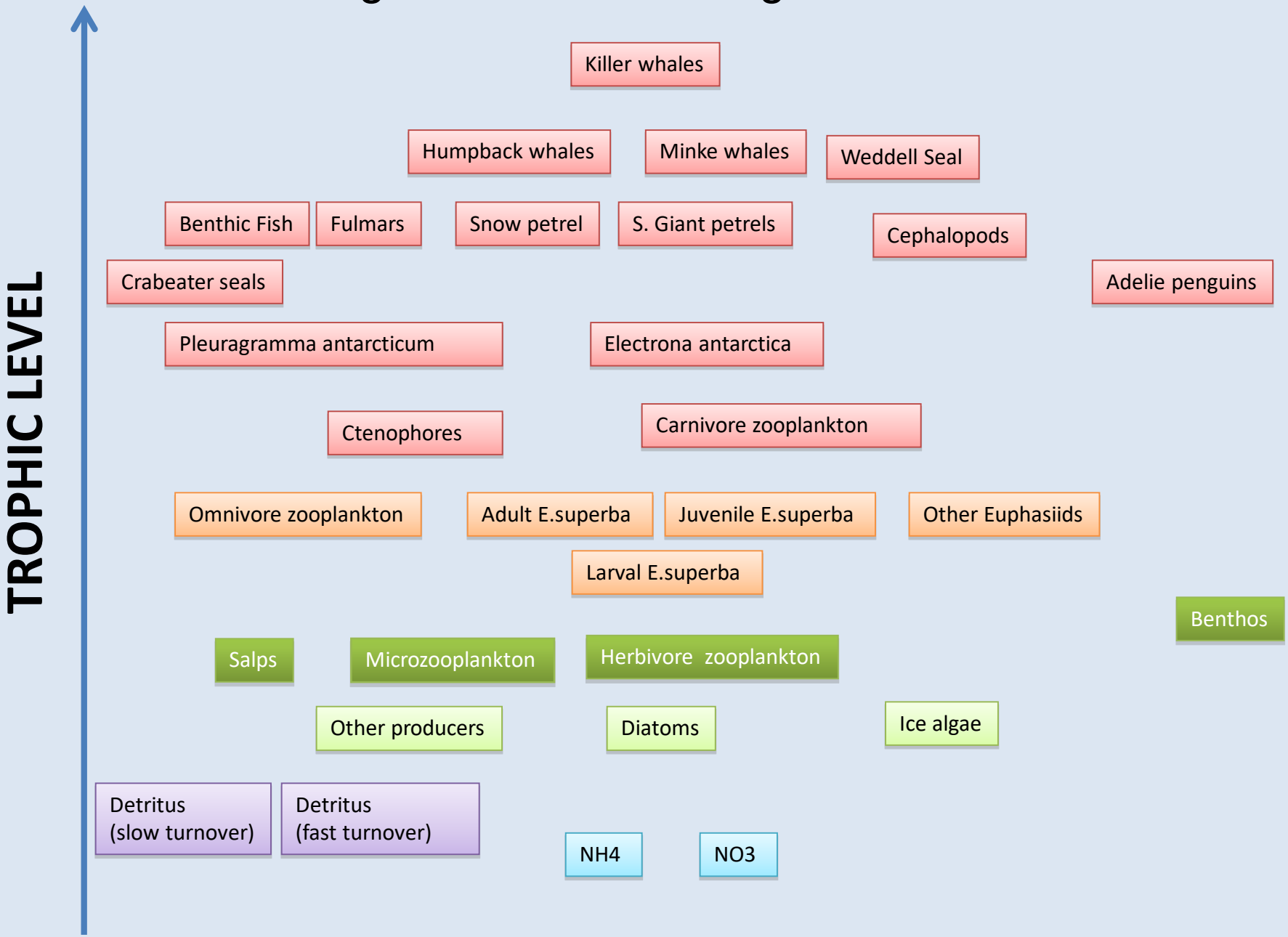
Emphasis on diet and feeding processes





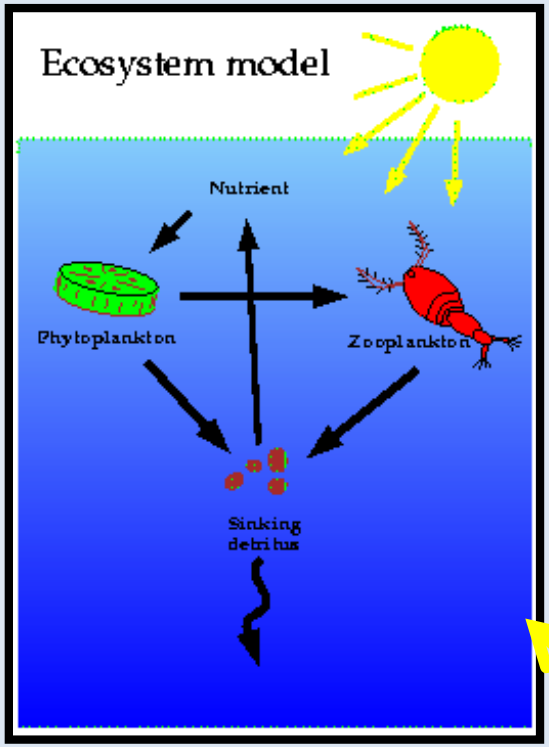
Top and bottom down controls operate simultaneously but relative effect of each is variable

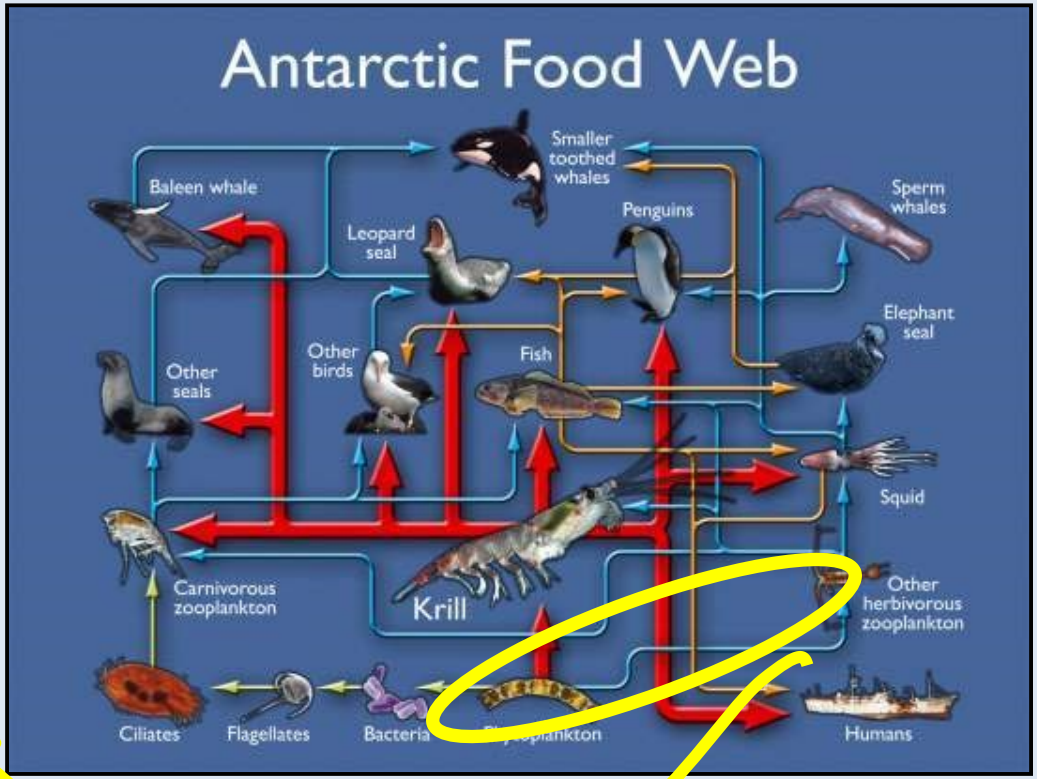
Emergent behavior from general food web



Relevance to Global Ecosystems

Global carbon budget models lack biological detail





Current models do not capture what is known about SO ecosystems

Key Question and Issues

- **Linking food web analyses with biogeochemical studies in the Southern Ocean**

→ Role of different zooplankton groups in recycling and vertical flux

- Krill, Salp, Copepod effects and interactions
- Top-down controls – magnitude and flux
- Seasonality - lack of information

Key Question and Issues

- **Linking food web analyses with biogeochemical studies in the Southern Ocean**

→ Food web processes in the vertical

- Mesopelagic
- Benthic-Pelagic coupling

→ Sea-ice food webs

- Summer - winter connections
- Critical for overwintering

Key Question and Issues

- **Linking food web analyses with biogeochemical studies in the Southern Ocean**

→ Hotspots of production, consumption, export

- Intense blooms in areas of natural iron fertilization
- Ice-edge blooms
- Long-term predator colonies

→ Ocean acidification

- Direct and indirect impacts on key pelagic species
- Physiological constraints and life-history sensitivity

Key Question and Issues

- **Linking food web analyses with biogeochemical studies in the Southern Ocean**

→ Food web processes in the vertical

- Mesopelagic
- Benthic-Pelagic coupling

→ Sea-ice food webs

- Summer - winter connections

Key Question and Issues

- **Linking food web analyses with biogeochemical studies in the Southern Ocean**

→ Impacts of change

- Effects of change in food web structure on biogeochemical cycles
  - Change in sea-ice, temperature, harvesting, bottom-up/top-down issues
  - Seasonality shifts, timing effects and phenology
  - Regional comparisons

Key Question and Issues - **What Needed?**

- Monitoring systems
  - Development of a range of long-term large scale systems/sensors
    - e.g. Acoustics, CPR
    - SOOS and Southern Ocean Sentinel
- Integrated views
  - Targeted food web–biogeochemical studies to consider impacts of variation on food web structure on biogeochemical processes
    - Regional comparisons (ICED)
    - Hotspots (ICED,SOOS)
- Modelling – need all
  - Large scale modelling – towards generic views (ICED)
  - High resolution localised models
  - New approaches

Concluding points

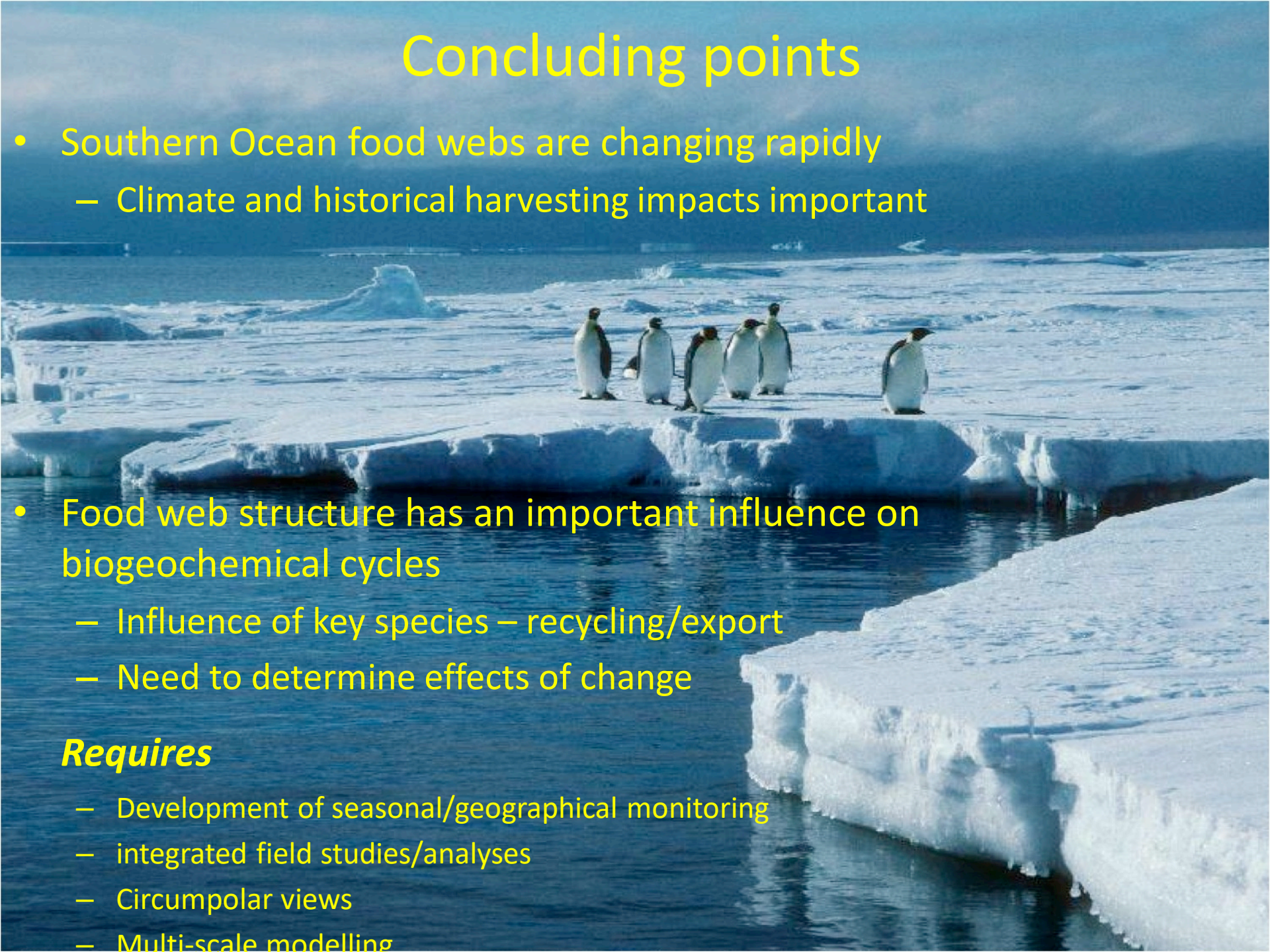
- Variability and heterogeneity is fundamental in food web studies
  - Scale based
- Structure generated through physical-biological interactions
  - Underpins food web
- Analyses of spatial and temporal variability

Requires

- Quantification of variation at range of scales
- Integration of scale effects
- Multi-scale models - feedback effects

Concluding points

- Southern Ocean food webs are changing rapidly
  - Climate and historical harvesting impacts important



- Food web structure has an important influence on biogeochemical cycles
  - Influence of key species – recycling/export
  - Need to determine effects of change

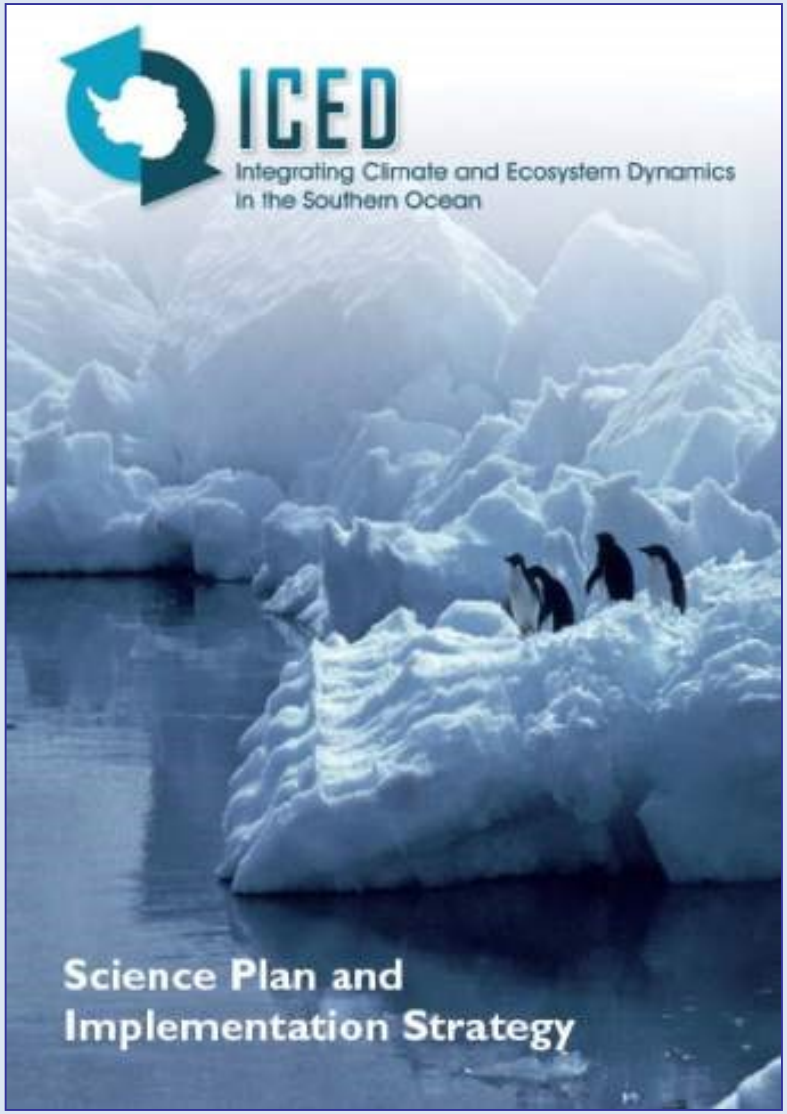
Requires

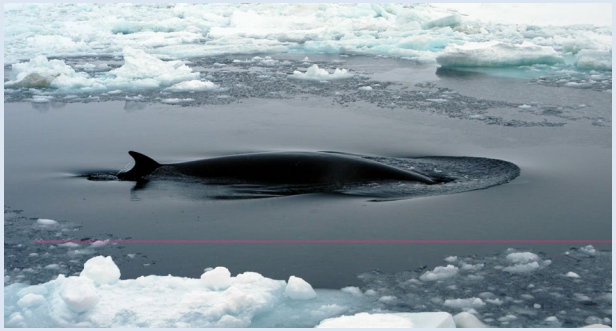
- Development of seasonal/geographical monitoring
- integrated field studies/analyses
- Circumpolar views
- Multi-scale modelling

ICED
Integrating Climate and Ecosystem Dynamics

Joint program under IMBER and GLOBEC - 10 year effort

- Circumpolar, interdisciplinary program focused on climate interactions and feedbacks to ecosystem function and biogeochemical cycles
- Extend and further develop circulation, ecosystem, and biogeochemical models
- Focus on end-to-end food web models
- Combine food web and biogeochemical communities





Thank you!

Photos by D. Costa