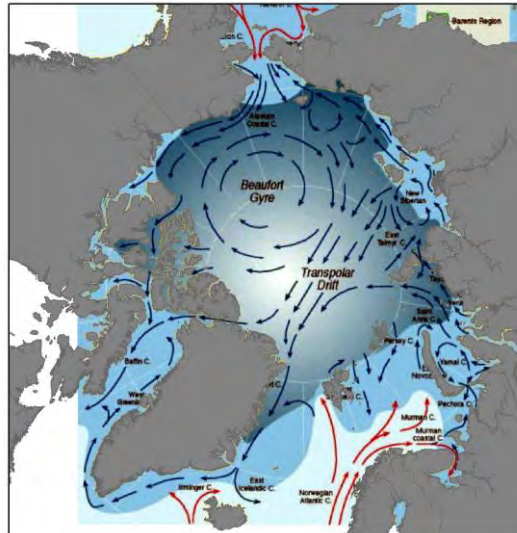


Modeling Tools for Designing for Resilience – Connectivity Under Changed Conditions

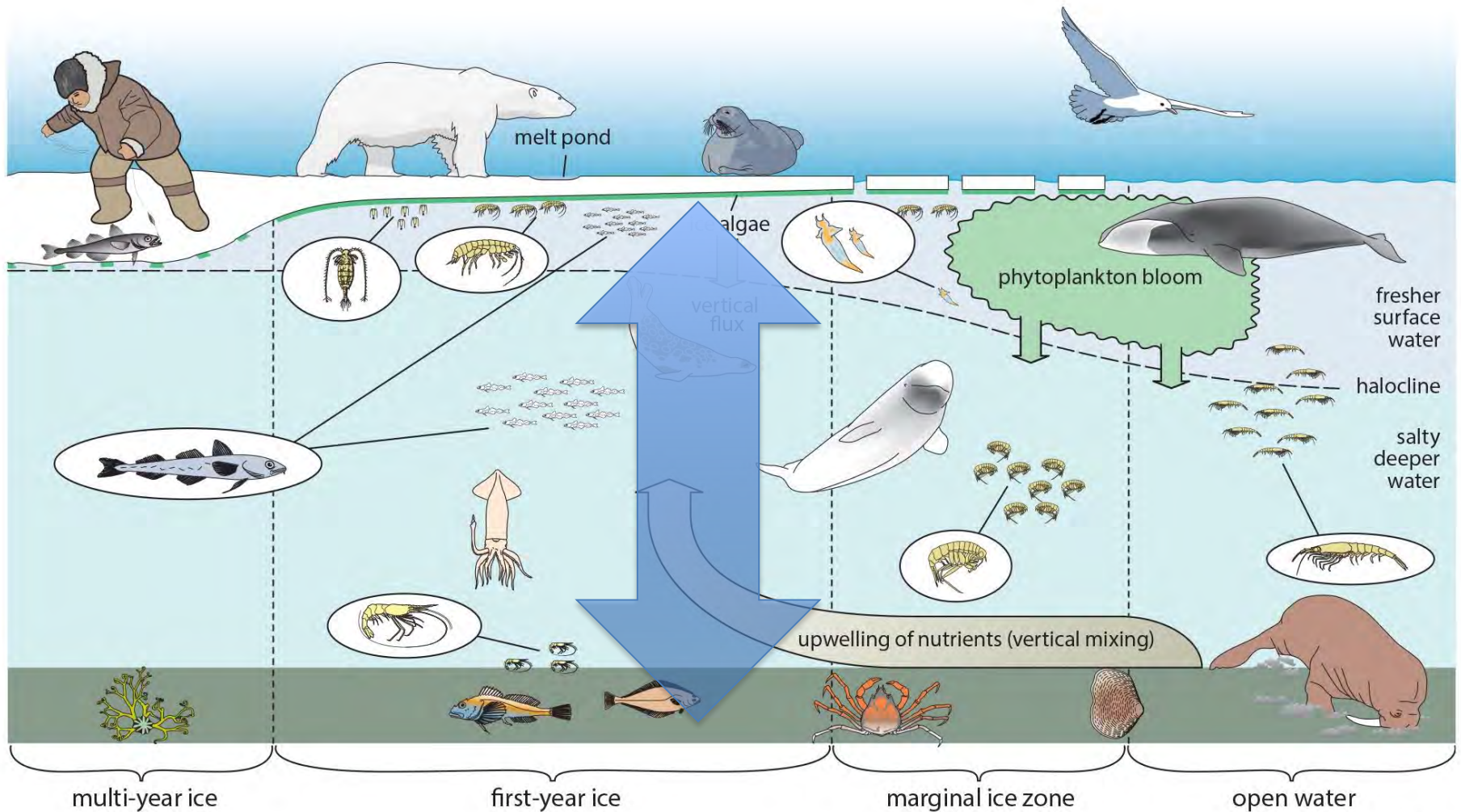
Patrick Halpin, Jesse Cleary, John Fay
Marine Geospatial Ecology Lab, Duke University
Eric Trembl
University of Melbourne



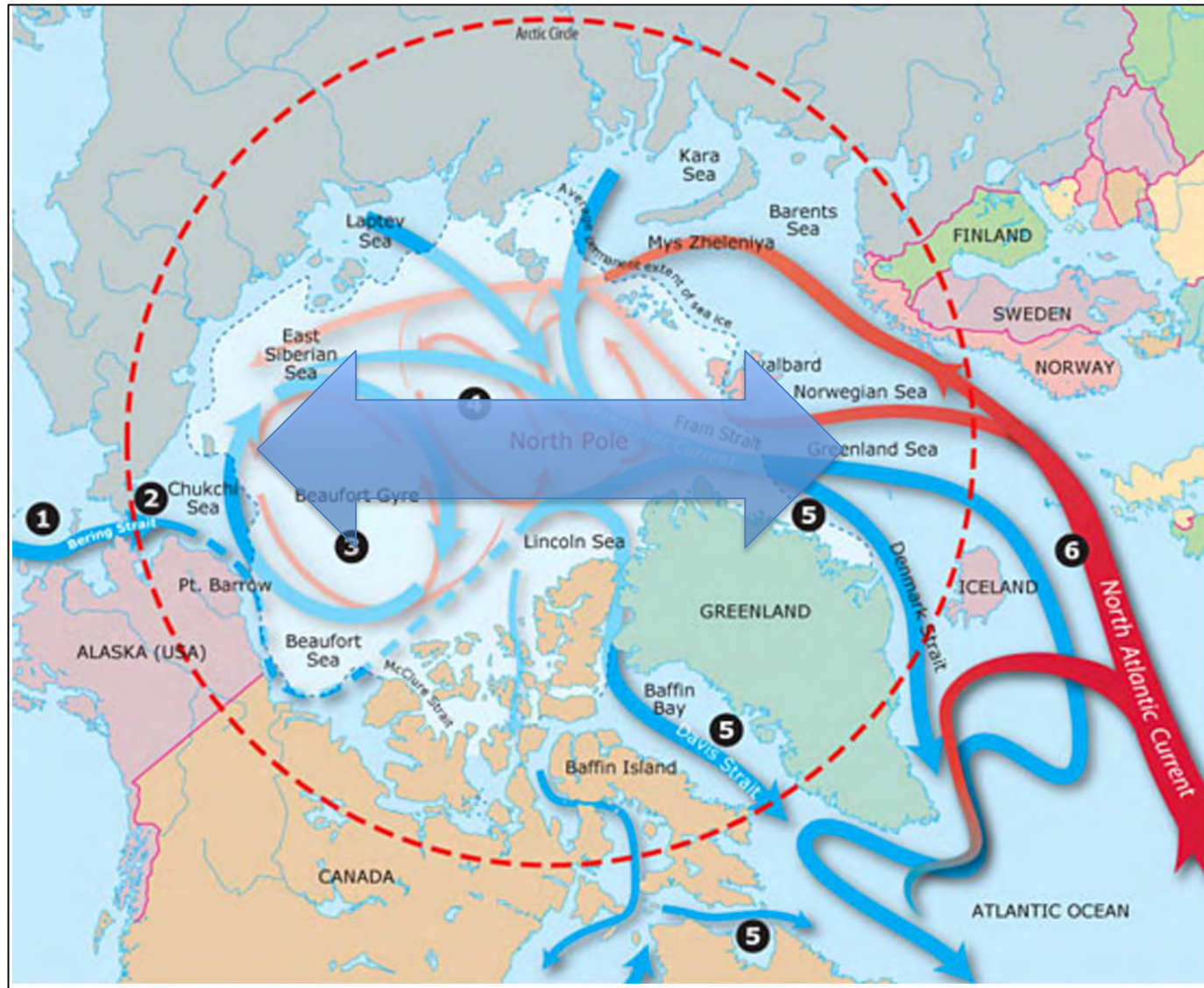
ARCTIC COUNCIL/PAME WORKSHOP

Science and Tools for Developing Arctic MPA Networks:
Understanding MPA Networks as Tools for Resilience in a Changing Arctic
Copenhagen, Denmark
February 3, 2017

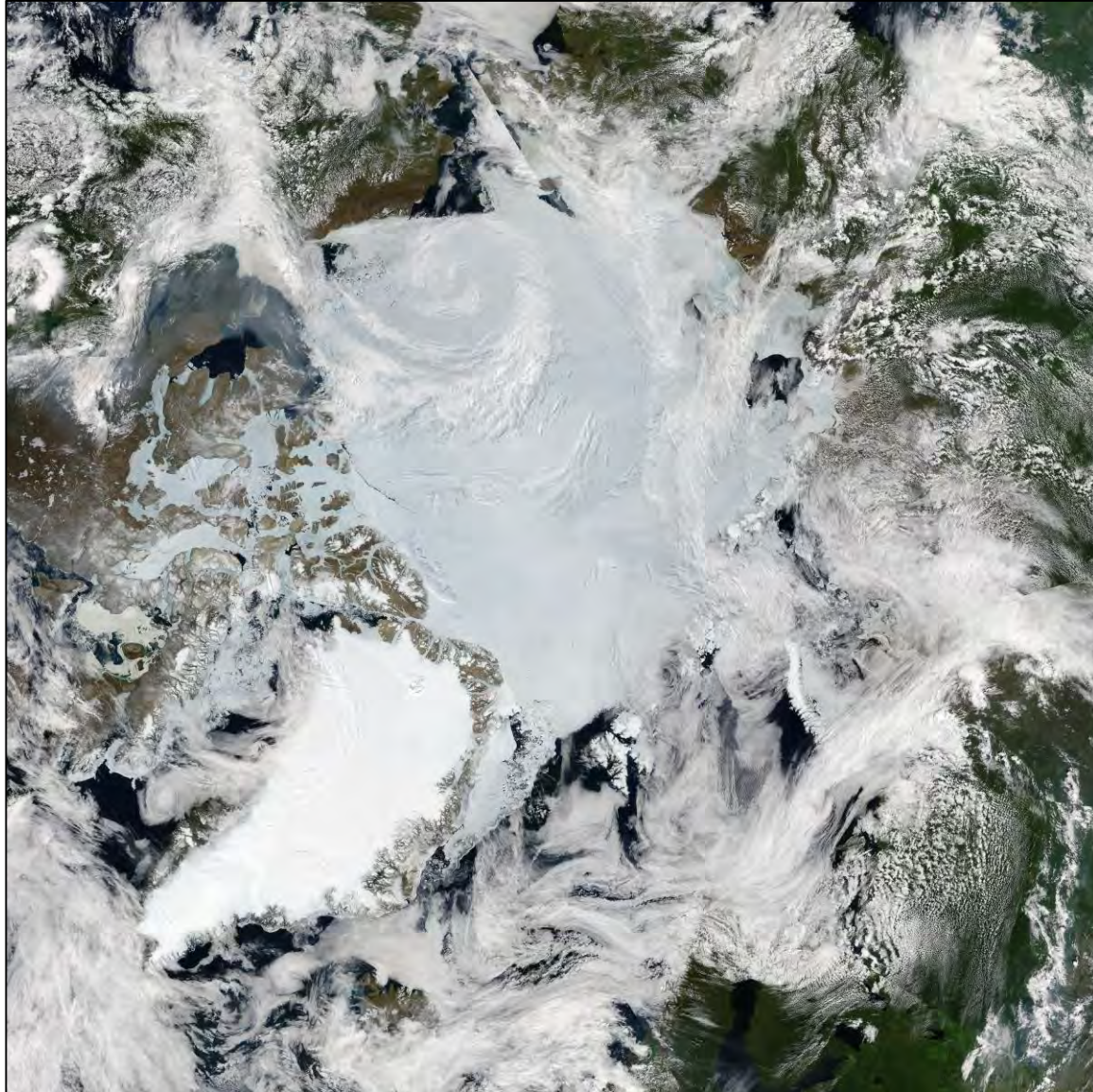
We tend to view Arctic marine ecosystems in terms of *vertical connections* across seasonal ice conditions...



...but there is significant ***horizontal connectivity*** in the Arctic that controls the distribution of species, habitats and exchanges of resources

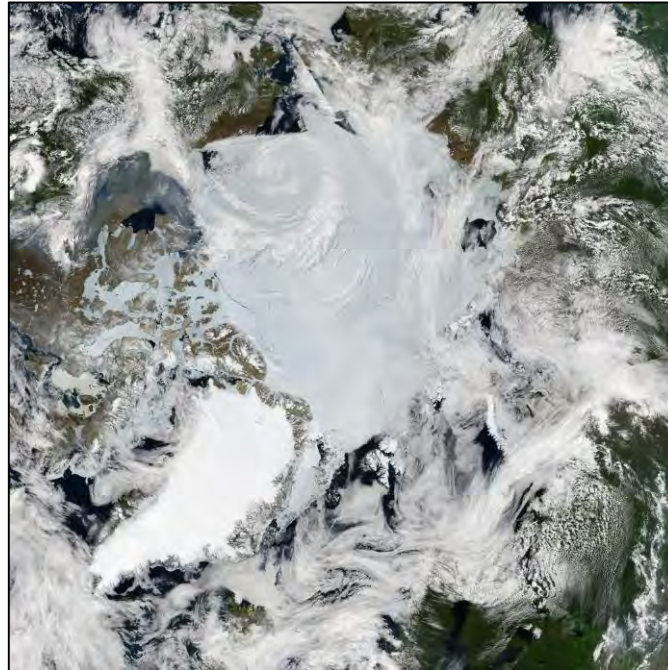


Movement and connectivity in the Arctic is highly dynamic at multiple spatial and temporal scales...



Physical factors effecting marine connectivity

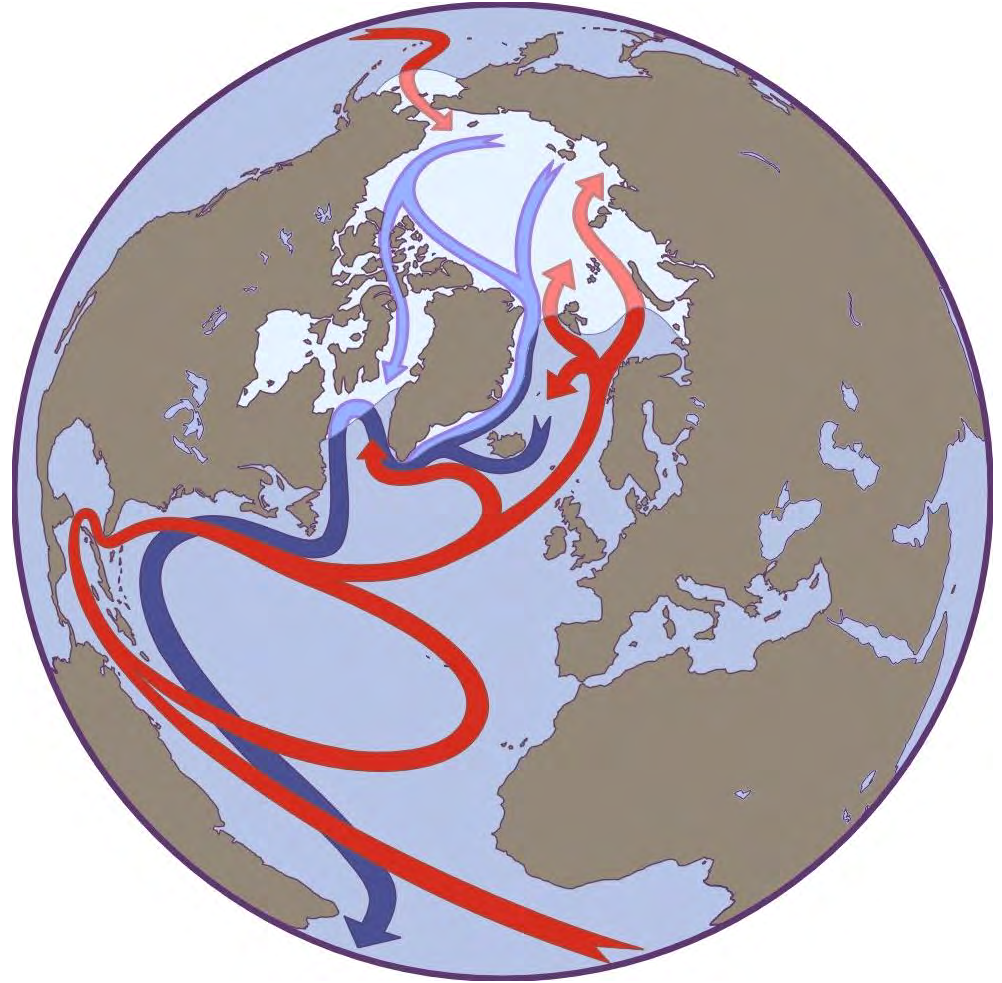
- Ocean currents (surface & sub-surface)
- Water mass properties (temperature, salinity...)
- Surface wind
- Sea ice
- Seasonality



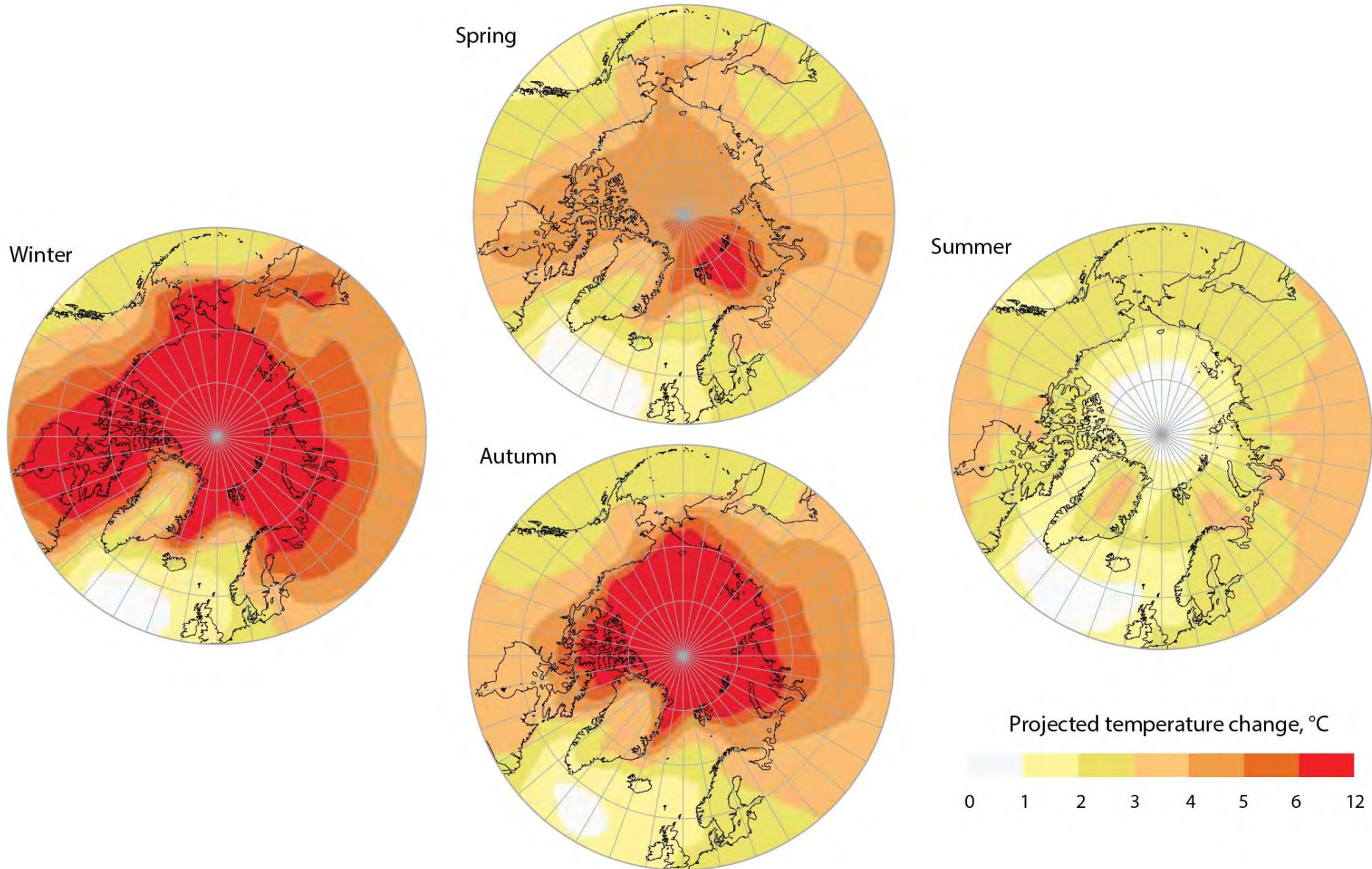
All of these factors are changing...

Changing currents

Potential changes to the oceanographic regimes at multiple depths

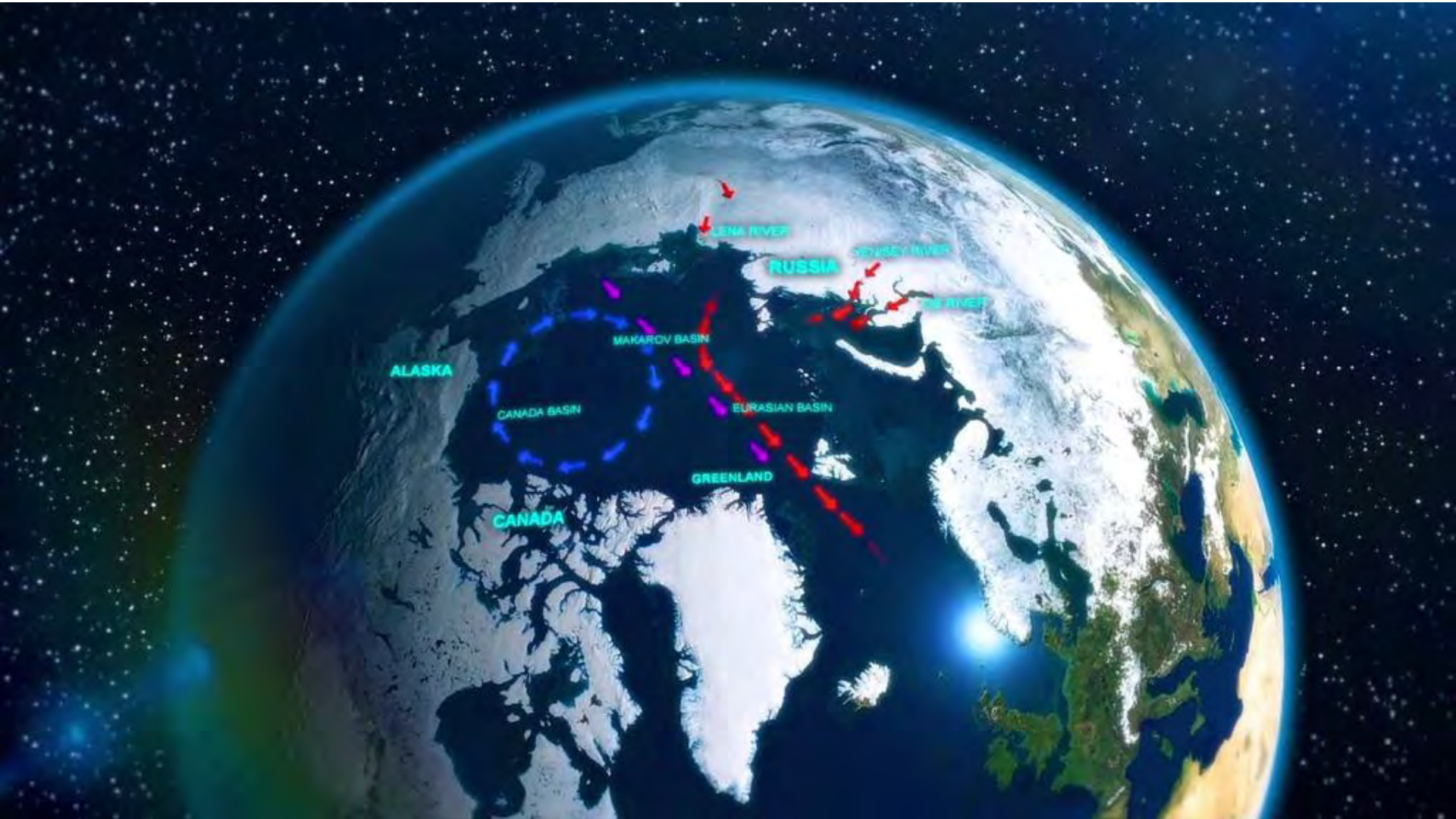


Changing surface temperature



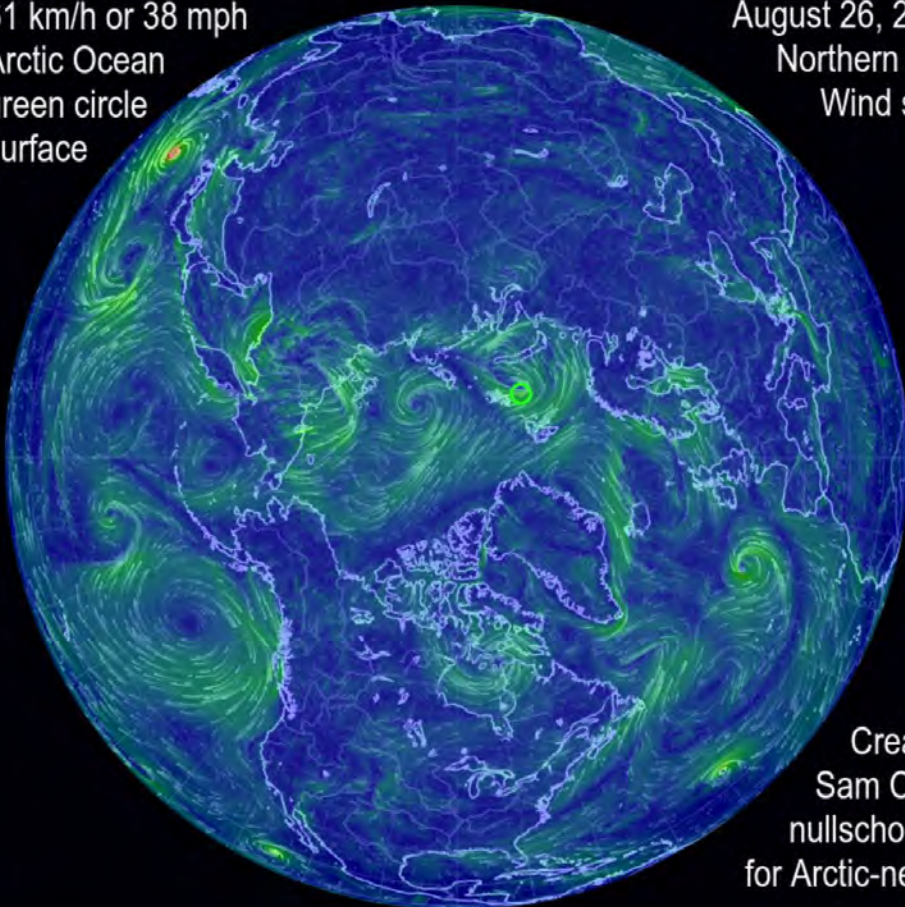
Changing freshwater circulation

Russian runoff “freshening” Canadian waters...



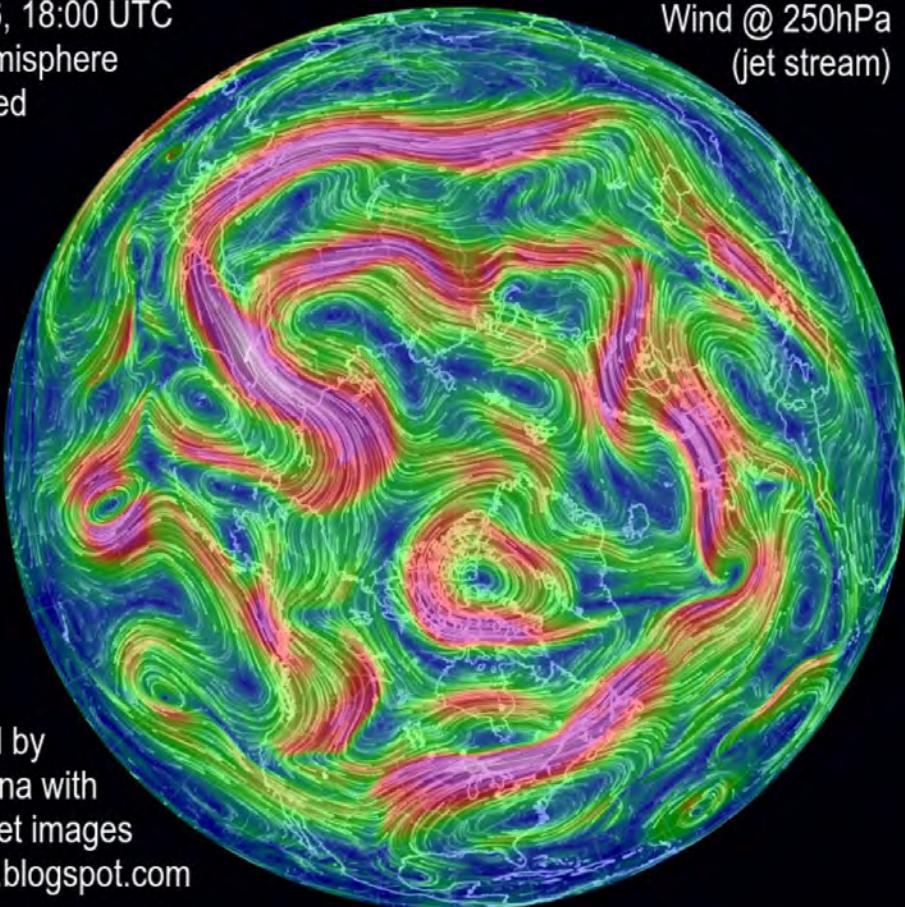
Changing wind regimes

61 km/h or 38 mph
Arctic Ocean
green circle
surface



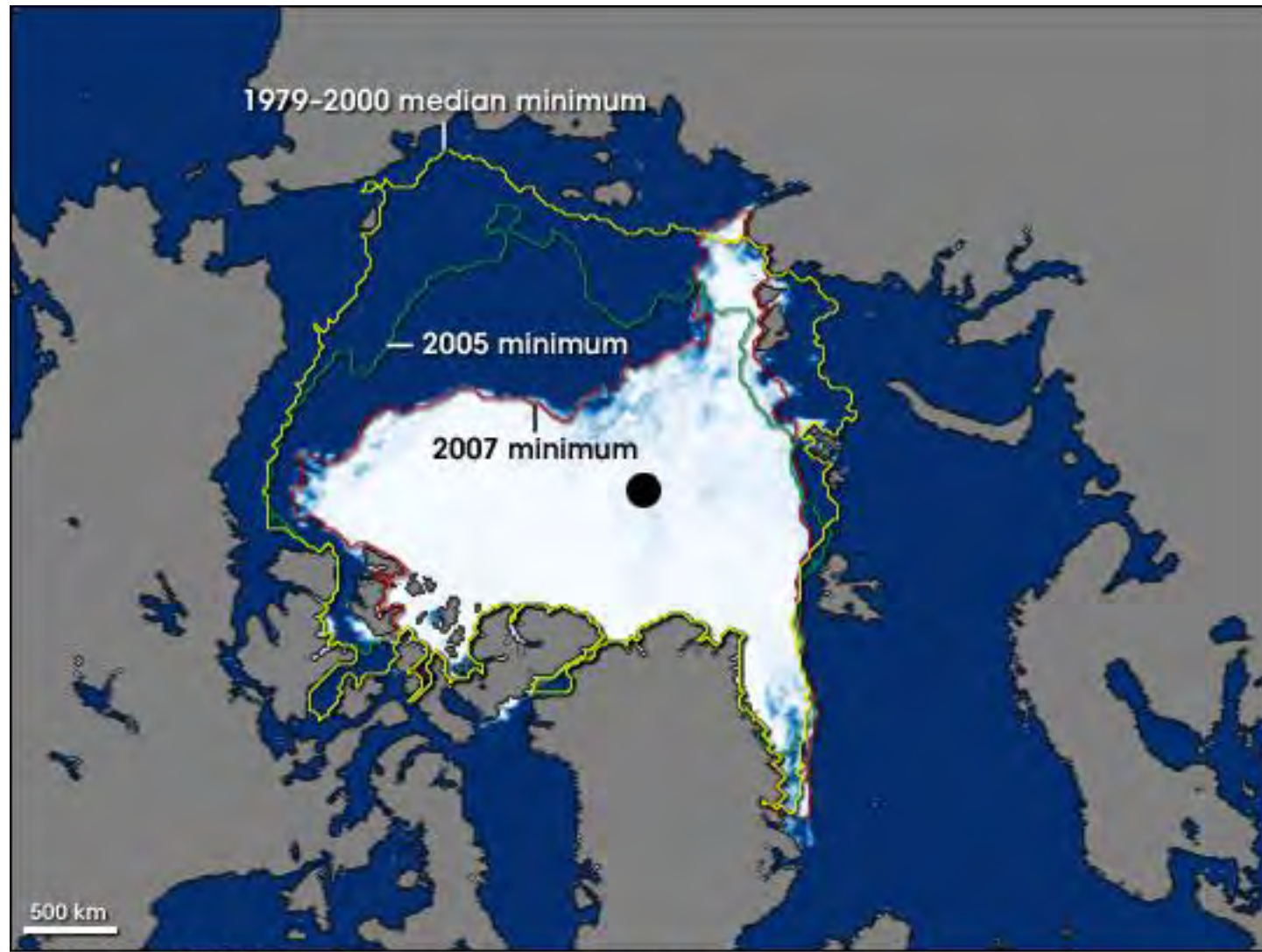
August 26, 2016, 18:00 UTC
Northern Hemisphere
Wind speed

Wind @ 250hPa
(jet stream)

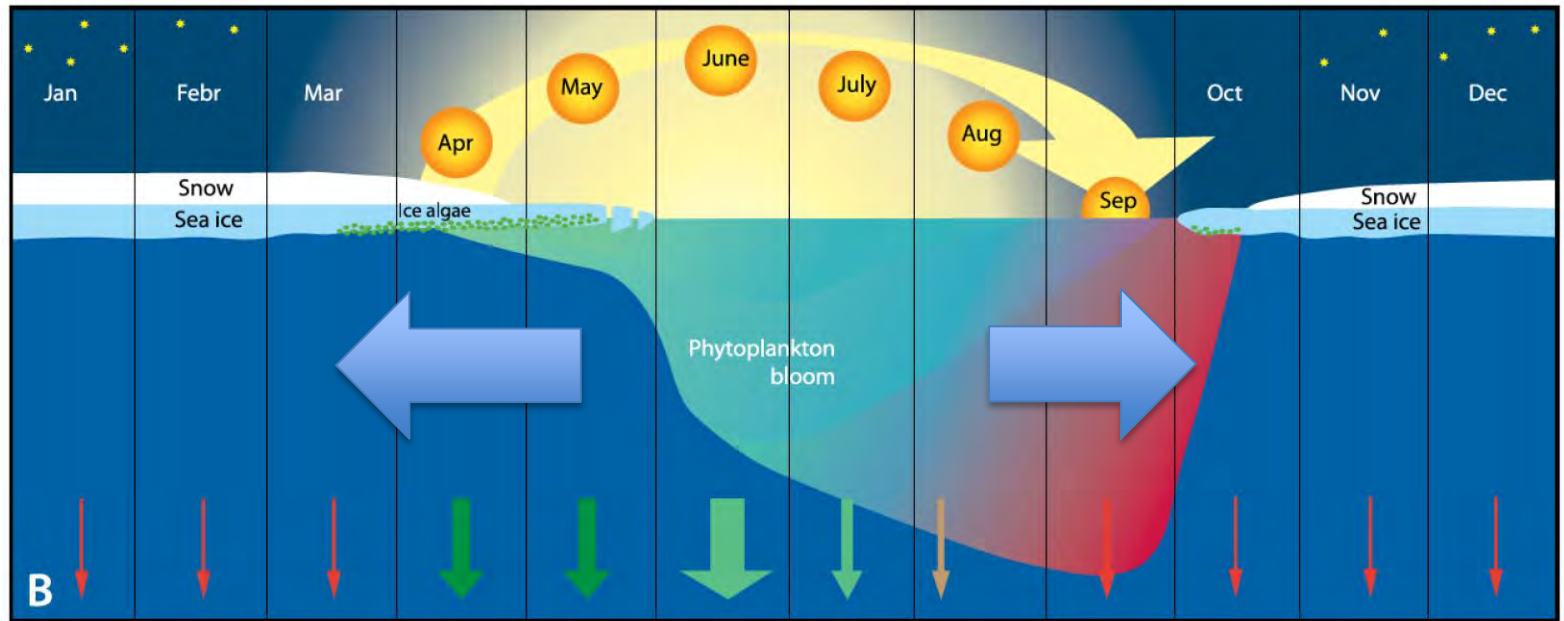
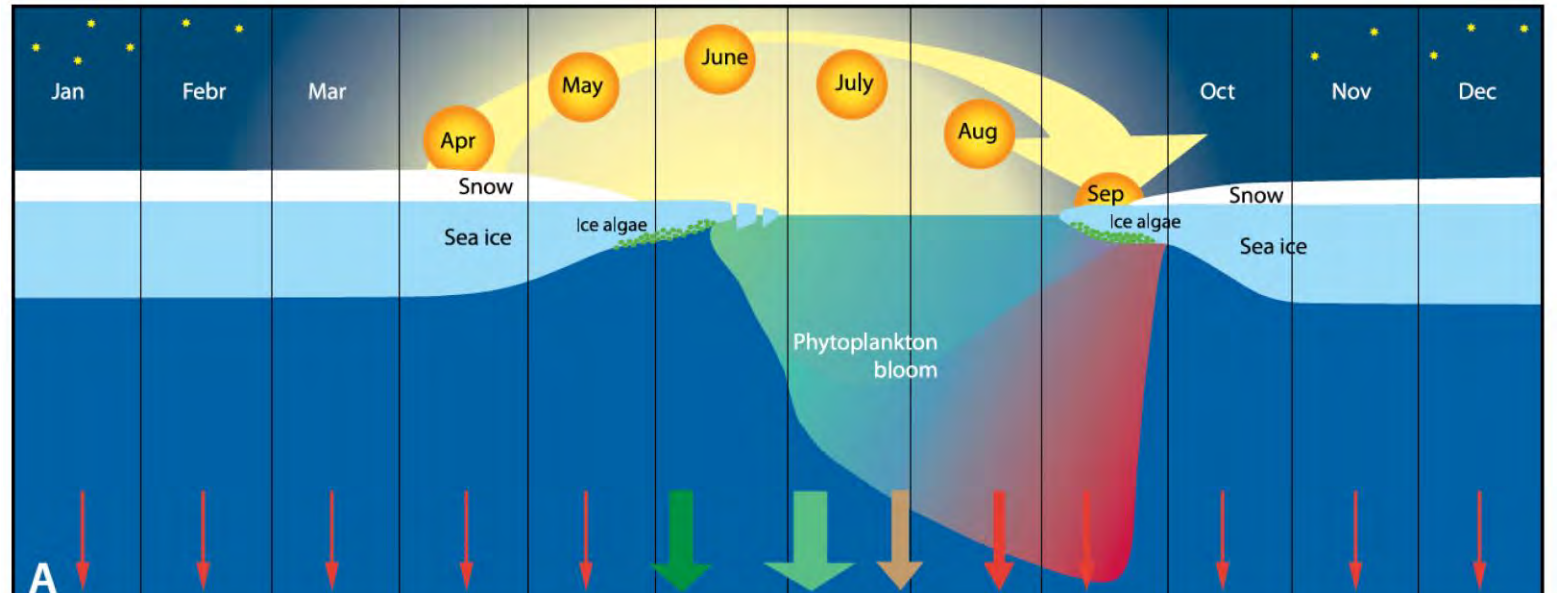


Created by
Sam Carana with
nullschool.net images
for Arctic-news.blogspot.com

Changing sea ice



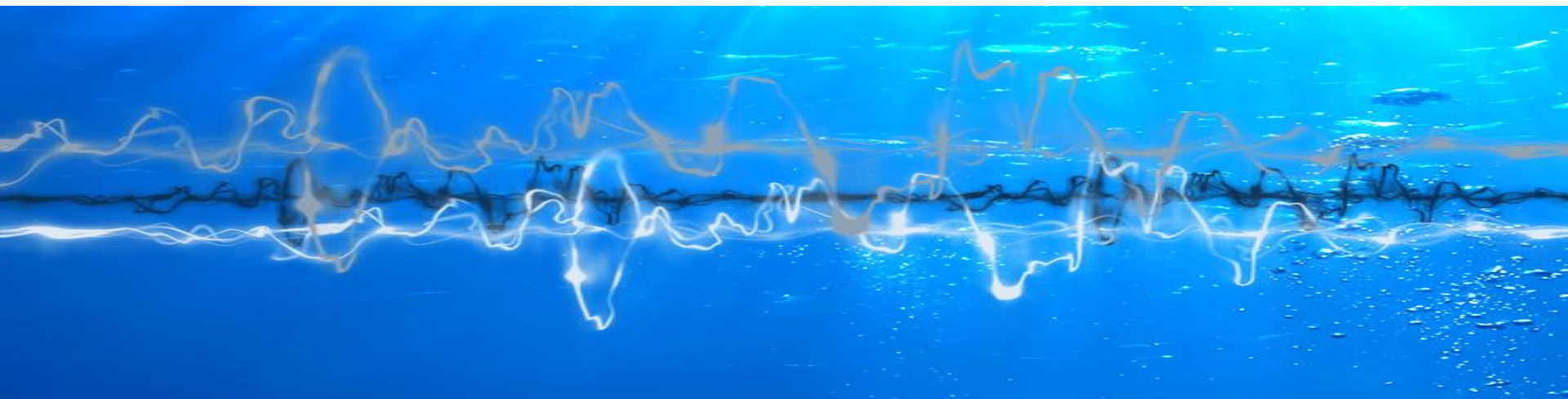
Changing seasonality/phenology



Autotroph Heterotroph
Biomass

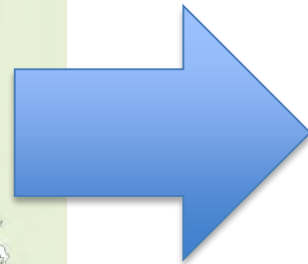
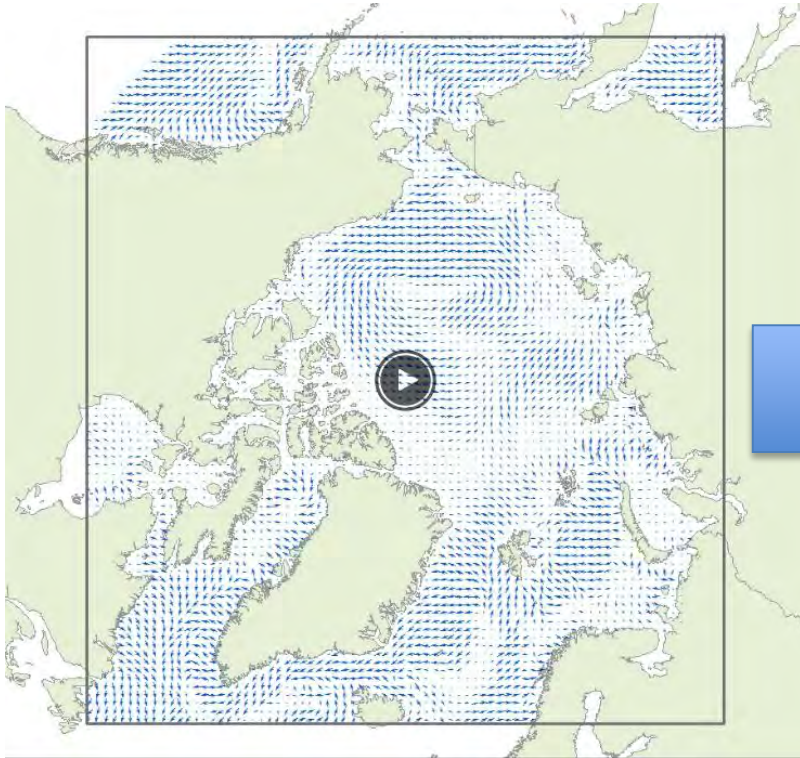
Topics:

- The Arctic context
- **Connectivity modeling framework**
- Arctic connectivity pilot studies
- Conclusions

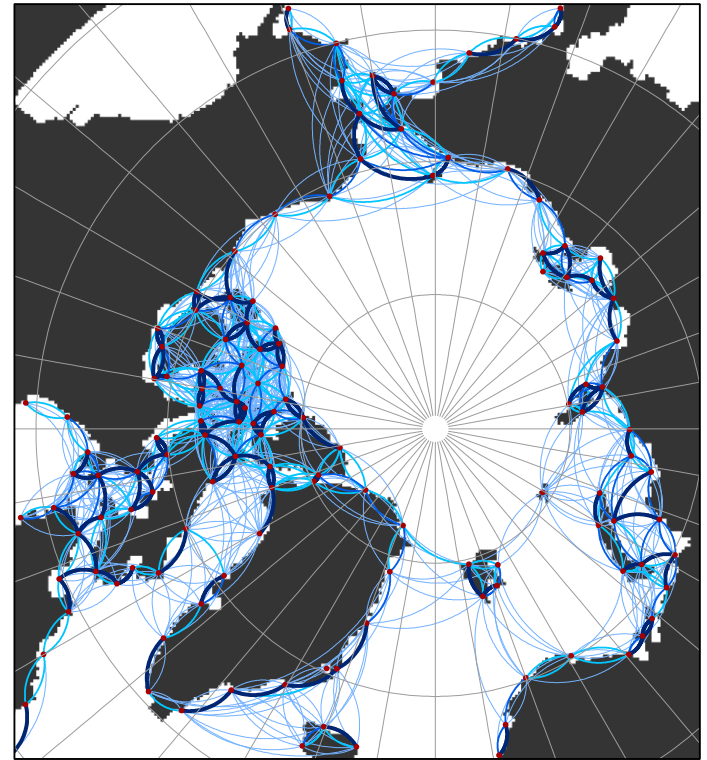


Arctic connectivity analysis framework

Models of surface currents



Network Models



How do we represent physical and ecological processes of connectivity...

How do we ask questions about connectivity...

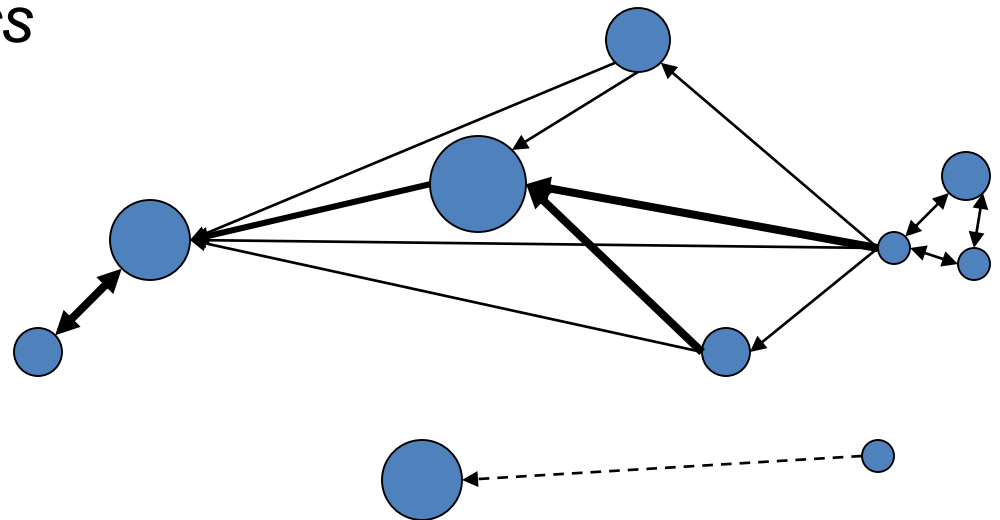
Marine Connectivity via Larval dispersal

Connectivity

- Recruitment/recovery from disturbances
- Source/sink implications
- Flow of genetic information
- Range expansion
- Biogeographic and phylogeographic patterns

Driven by hydrodynamics

- Sub-networks
- Stepping stones
- Betweenness

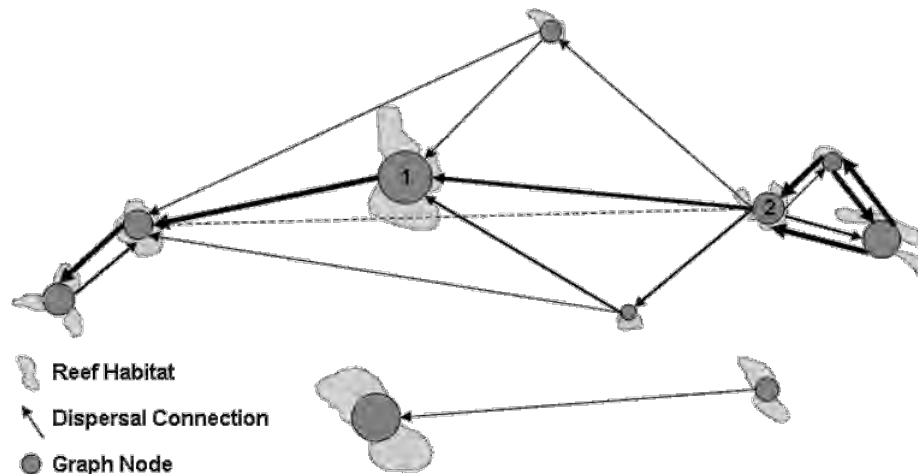
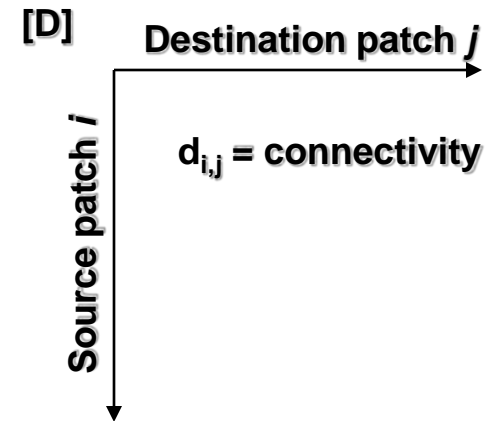


Modeling Connectivity

Data Structure

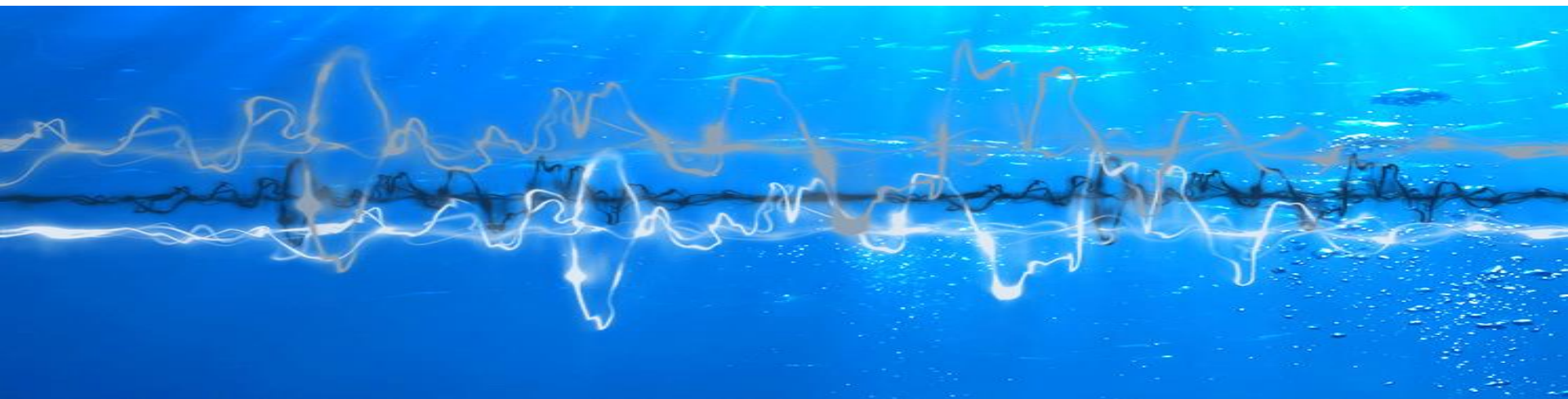
Data model

- Connectivity matrix [D]
 - Drifting days **
 - Probability
 - Geographic distance
- Location matrix (patch id, longitude, latitude)
- Habitat properties (area, density, quality, etc)



Topics:

- The Arctic context
- Connectivity modeling framework
- **Arctic connectivity pilot studies**
- Conclusions



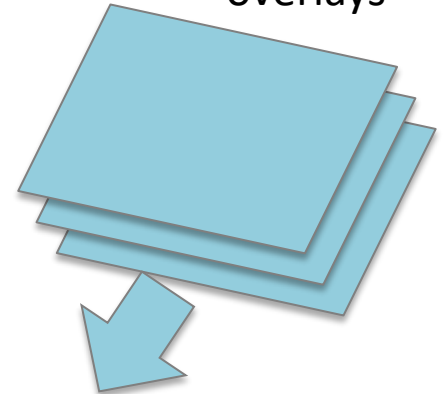
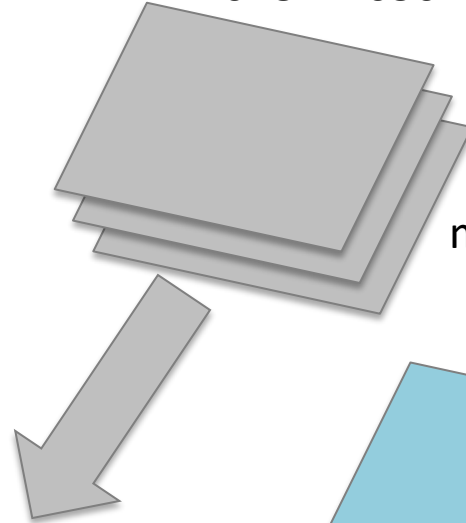
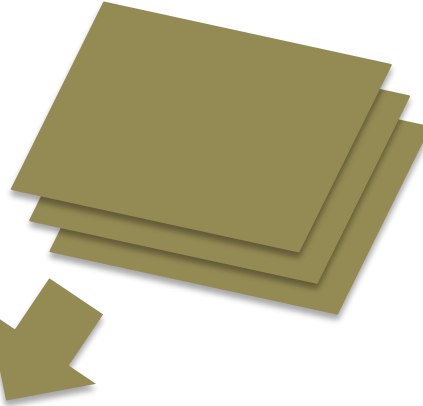
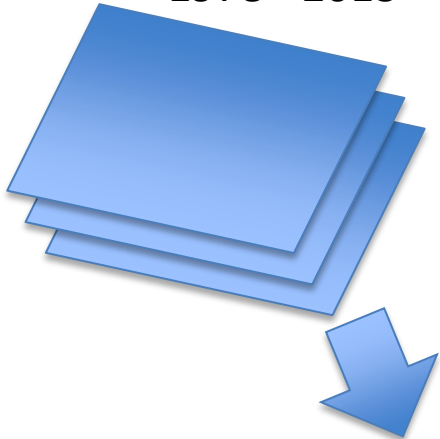
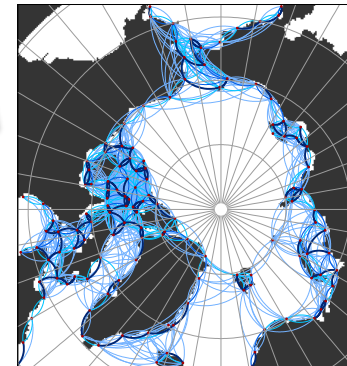
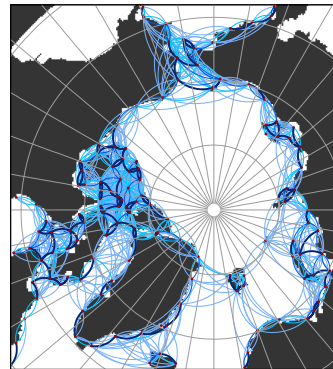
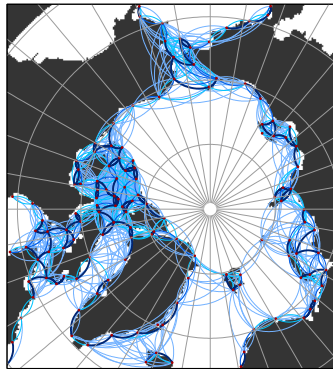
Arctic connectivity pilot analysis

surface currents
1978 - 2013

source/destination
scenarios

forecasts
2018 - 2050+

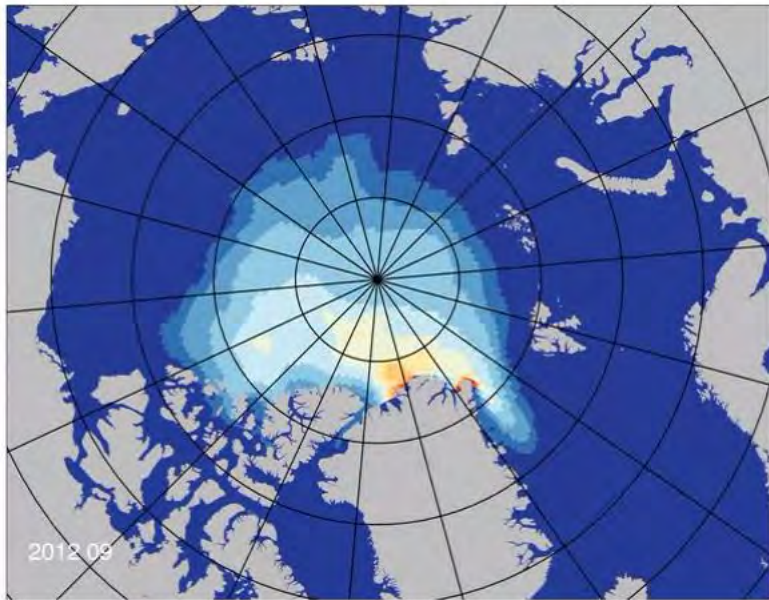
management &
jurisdictional
overlays



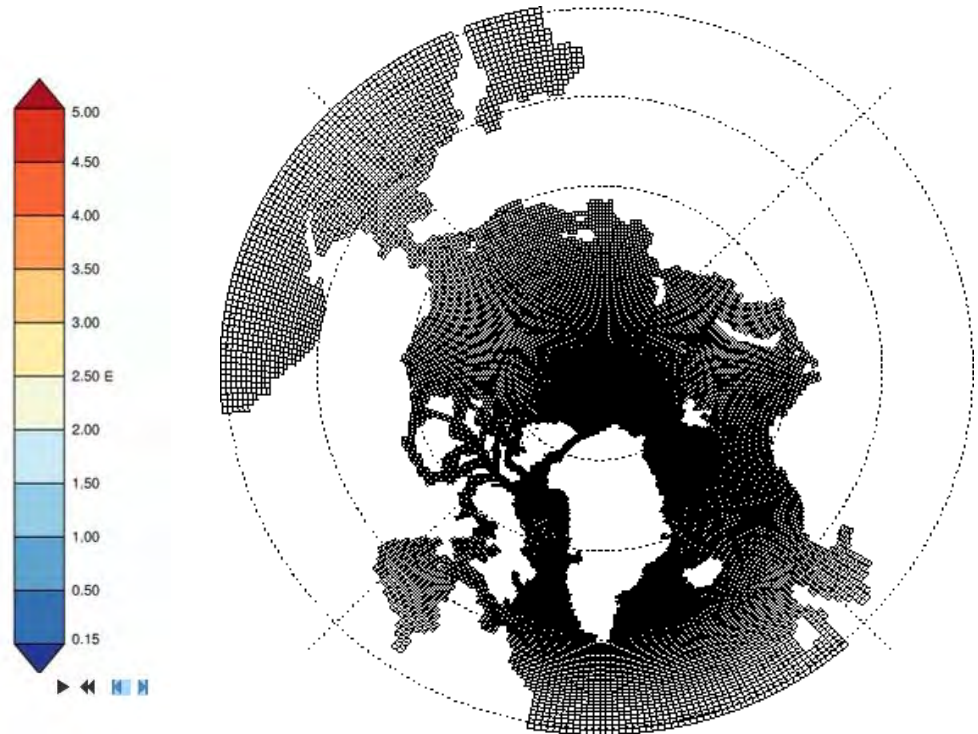
Arctic connectivity pilot analysis

Surface Currents:

Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS, version 2.1),
Zhang and Rothrock (2003)



Monthly Ice Thickness from 1979-2015

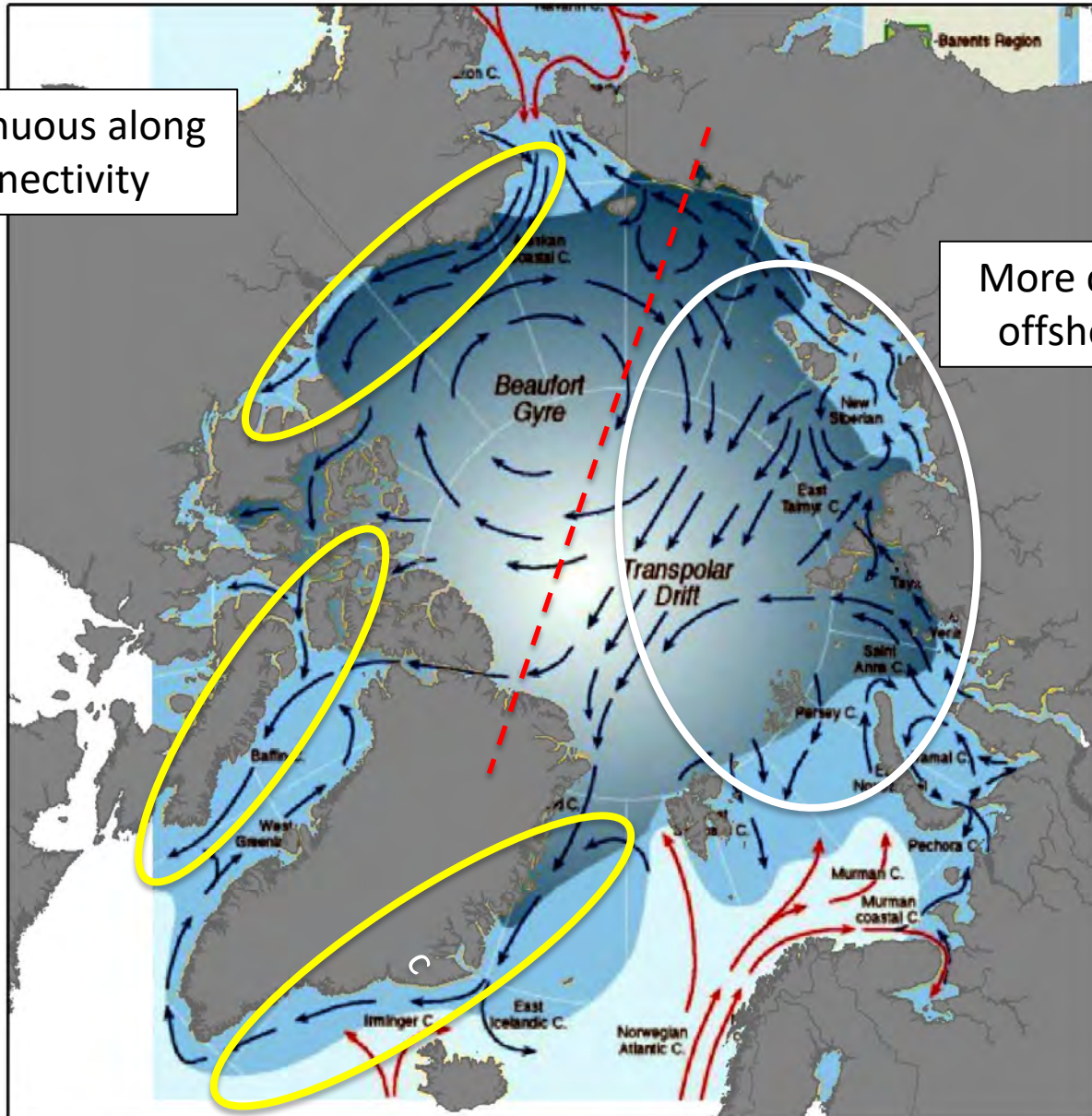


Monthly data, 1978 – 2013
partially-coupled, data assimilative

General surface currents

Longer continuous along shore connectivity

More complex shore to offshore connections



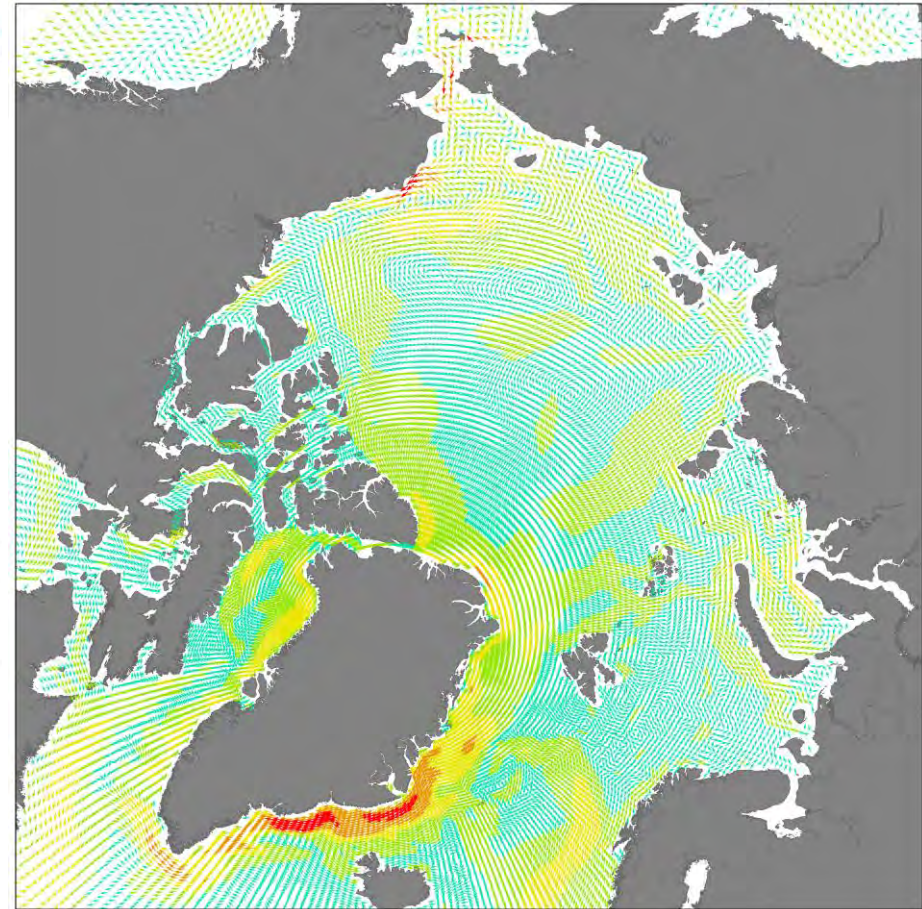
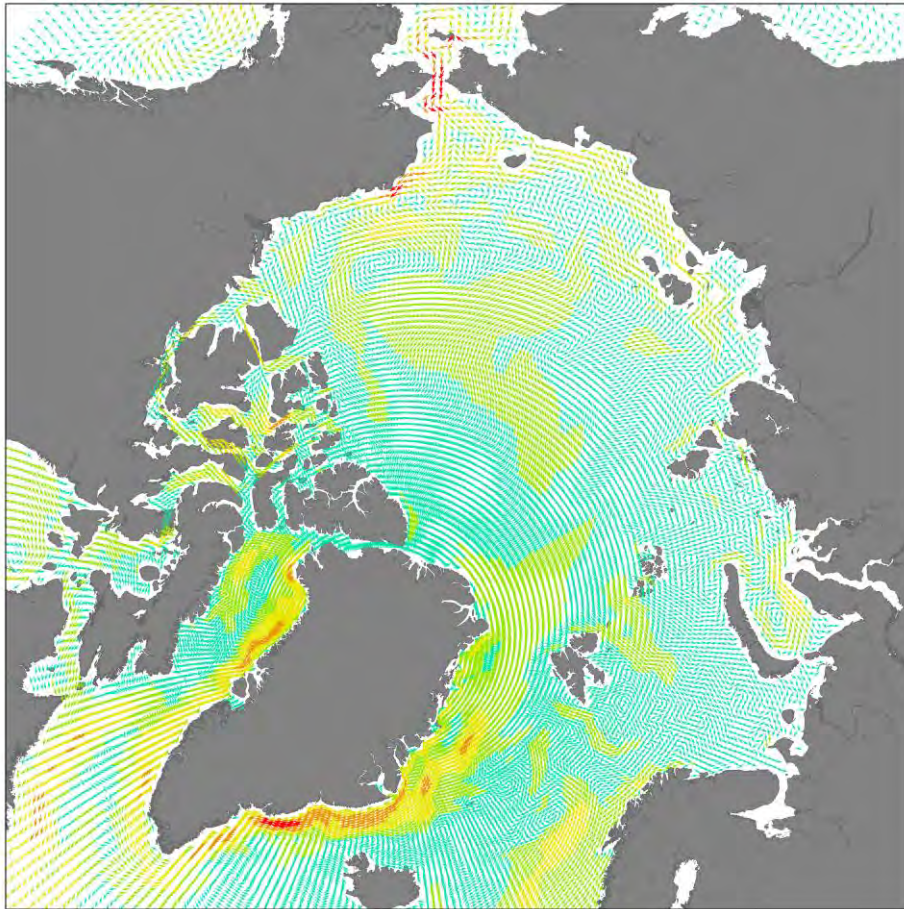
Surface Current Schematic

Arctic connectivity pilot analysis

Surface Currents velocities:

Forecast 2018

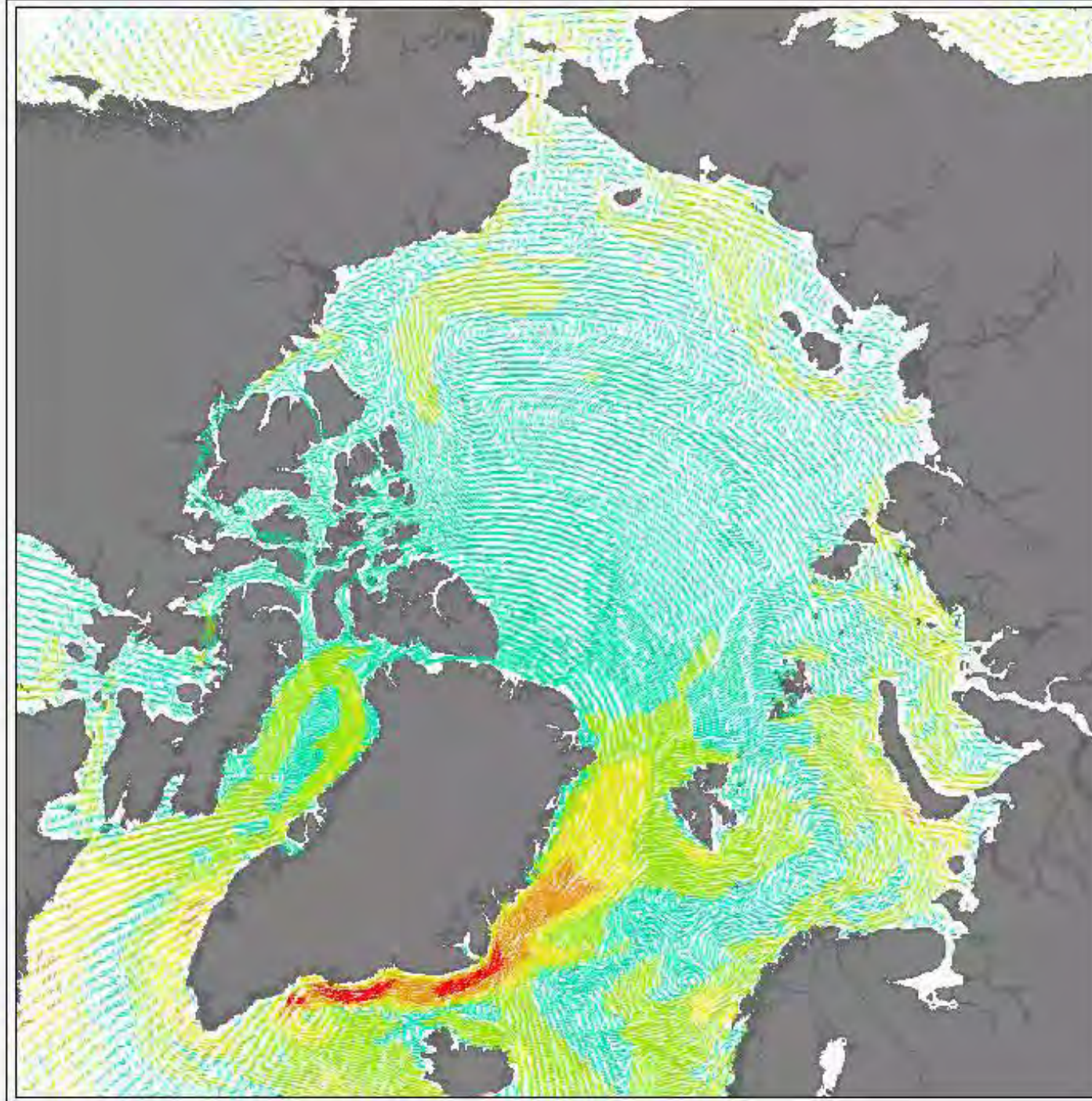
Forecast 2050



From models after: Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS, version 2.1), Zhang and Rothrock (2003)

Surface Current Velocities:

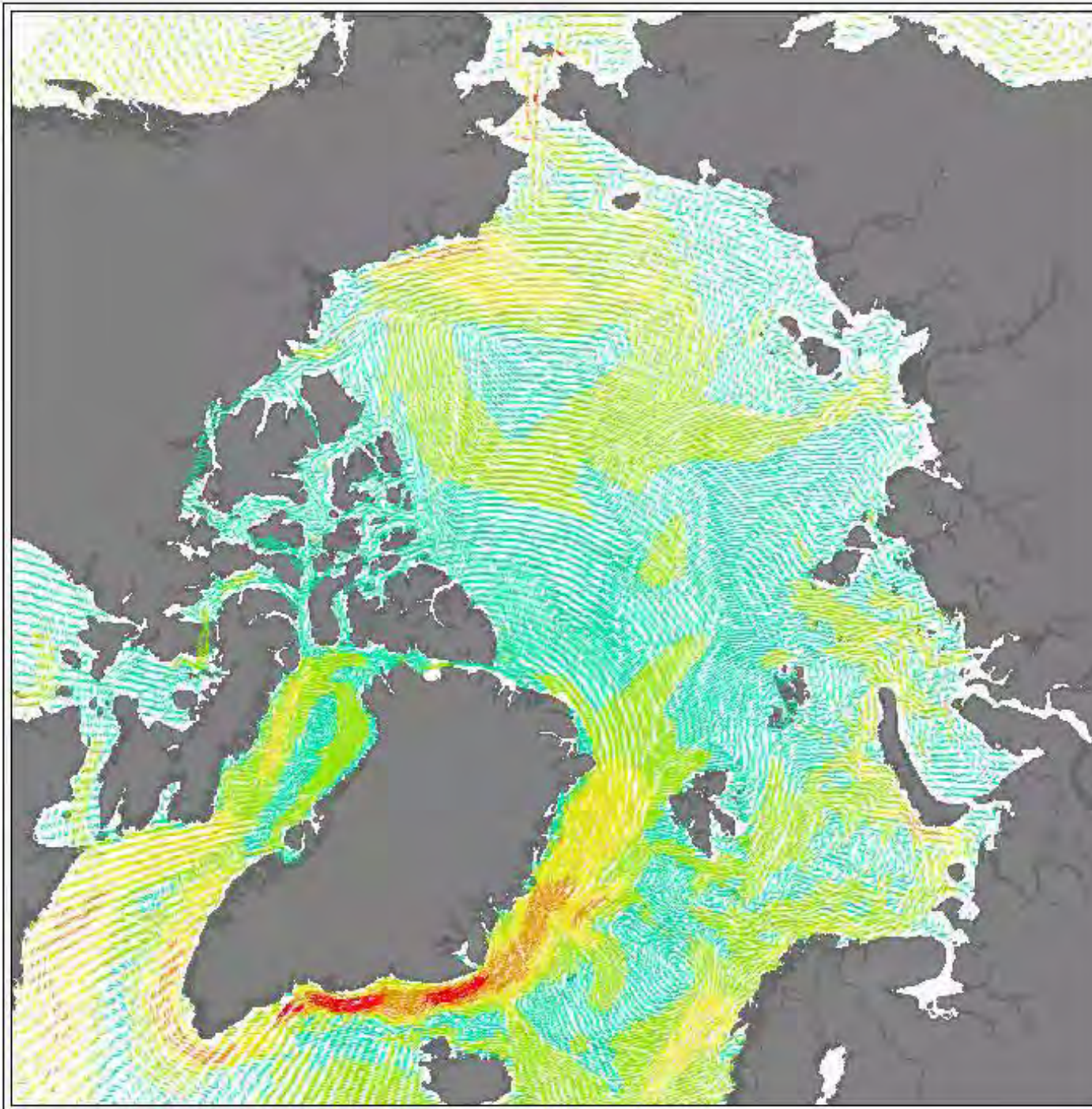
Forecast **2018**



From models after: Pan-Arctic Ice
Ocean Modeling and Assimilation
System (PIOMAS, version 2.1),
Zhang and Rothrock (2003)

Surface Current Velocities:

Forecast **2050**



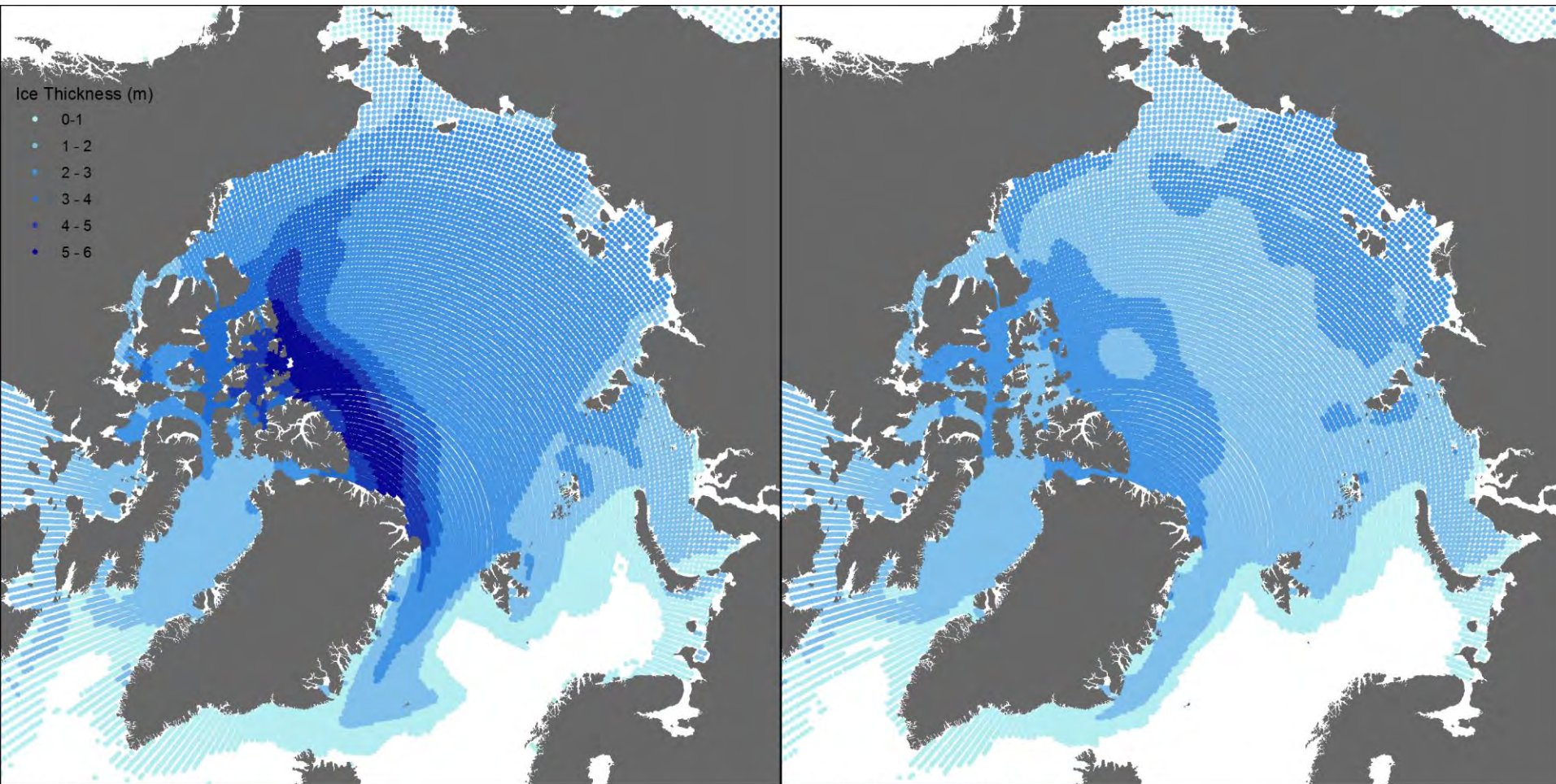
From models after: Pan-Arctic Ice
Ocean Modeling and Assimilation
System (PIOMAS, version 2.1),
Zhang and Rothrock (2003)

Arctic connectivity pilot analysis

Ice Thickness: **Winter**

2005

2051



Ice Thickness, 02-2005

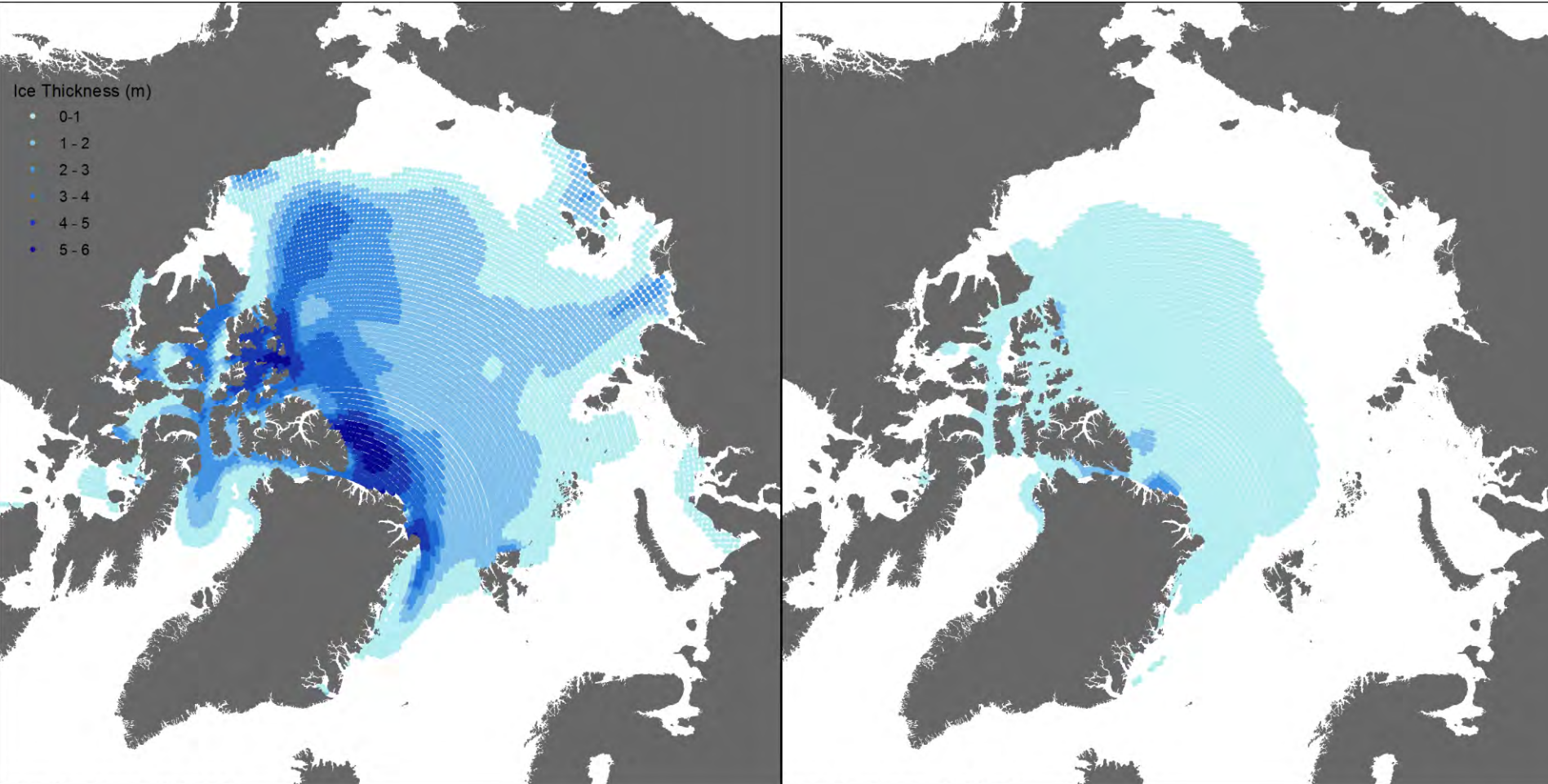
Ice Thickness, 02-2051

Arctic connectivity pilot analysis

Ice Thickness: Summer

2005

2051



Ice Thickness, 09-2005

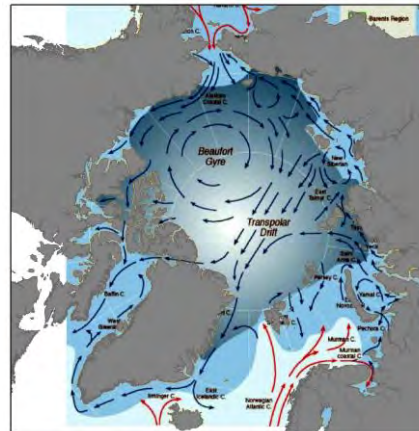
Ice Thickness, 09-2051

Arctic connectivity pilot analysis

Potential pilot scenarios

3 x 2 x 2 = 12 initial pilot scenarios

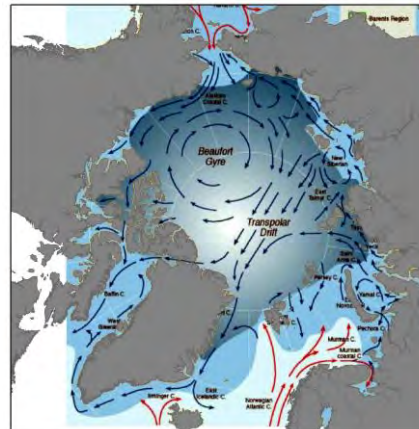
Source / destination targets	“normal” ice year		“low” ice year	
Coastal areas (500km regions)	winter	summer	winter	summer
Fish spawning areas	winter	summer	winter	summer
Important feeding grounds	winter	summer	winter	summer



Arctic connectivity pilot analysis

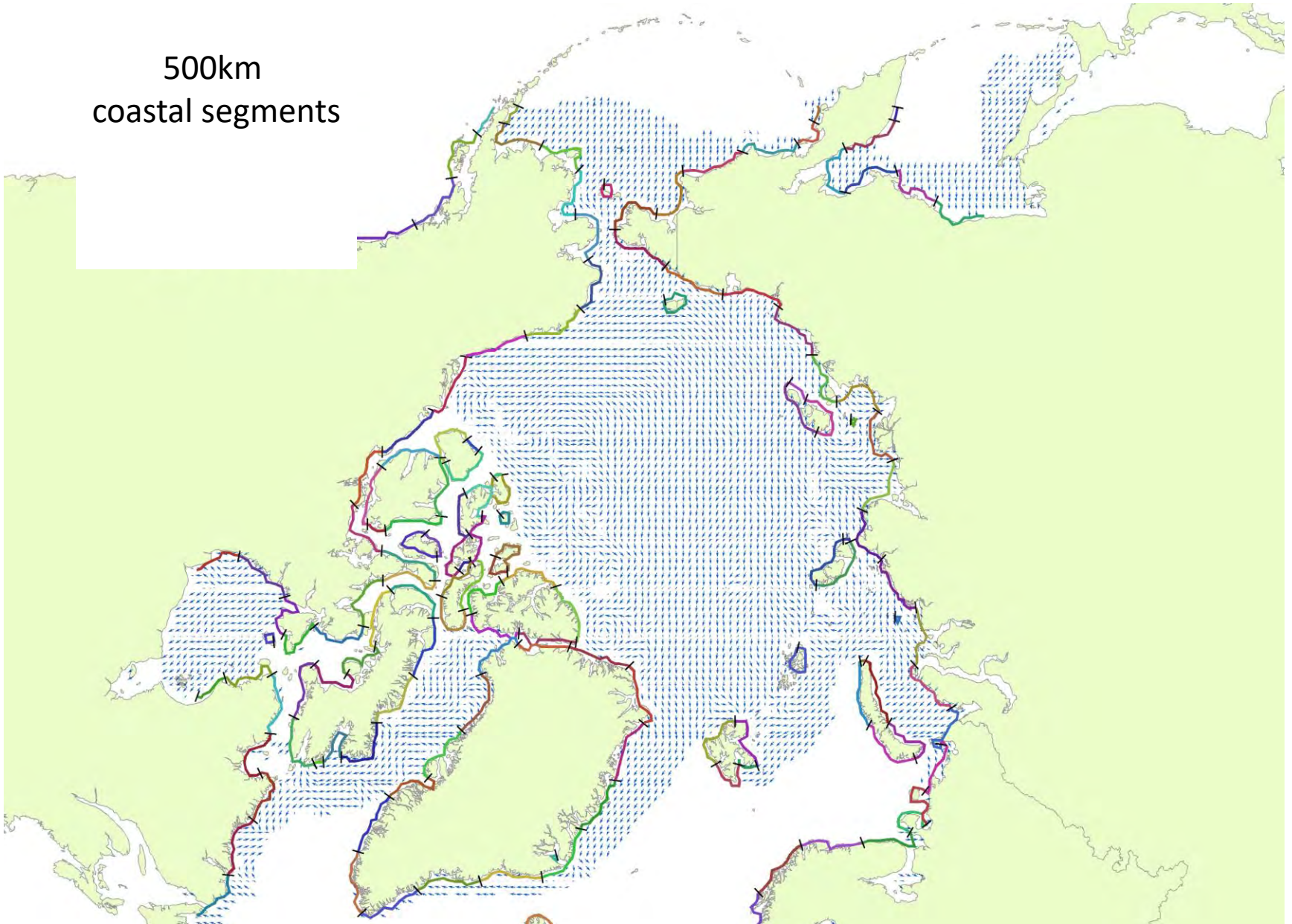
Potential pilot scenarios

Source / destination targets	“normal” ice year		“low” ice year	
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Fish spawning areas	winter	summer	winter	summer
Important feeding grounds	winter	summer	winter	summer



Arctic connectivity pilot analysis

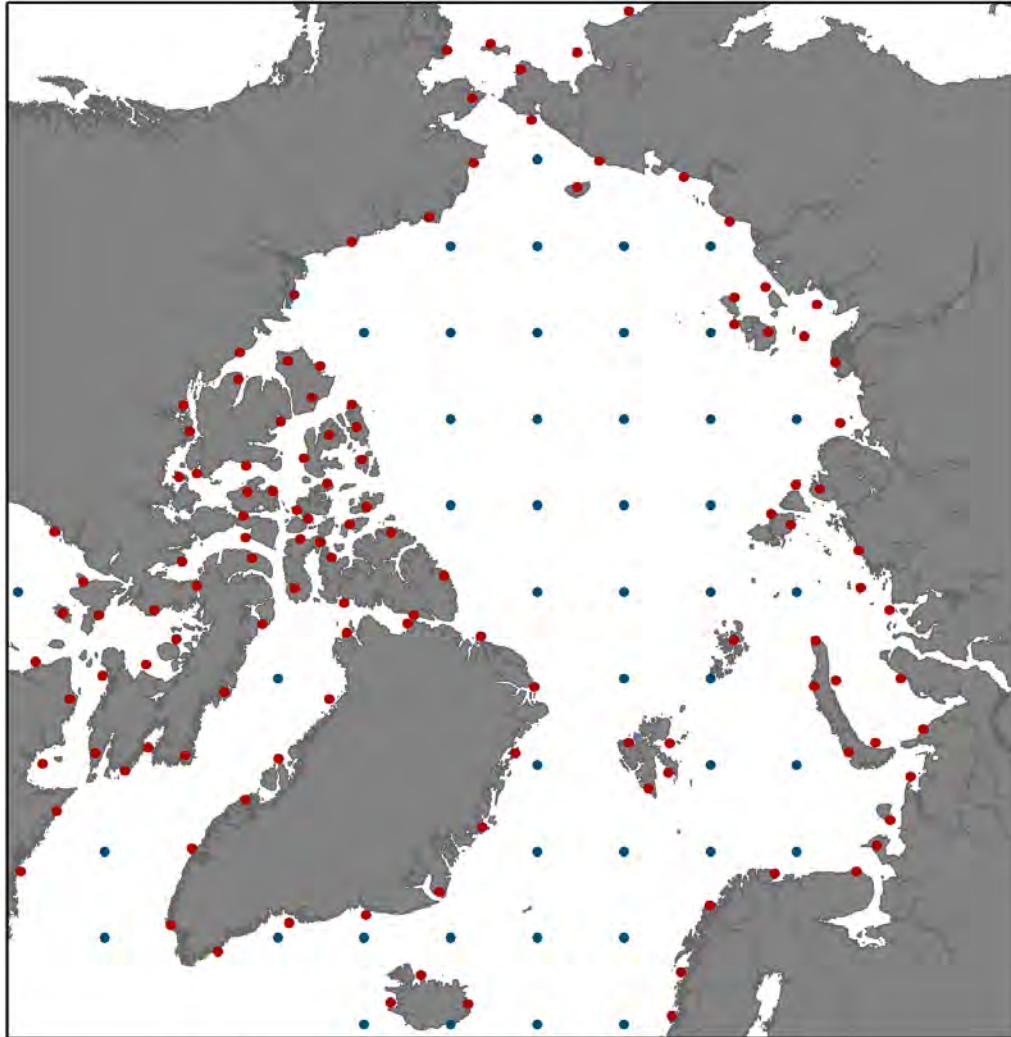
500km
coastal segments



Arctic connectivity pilot analysis

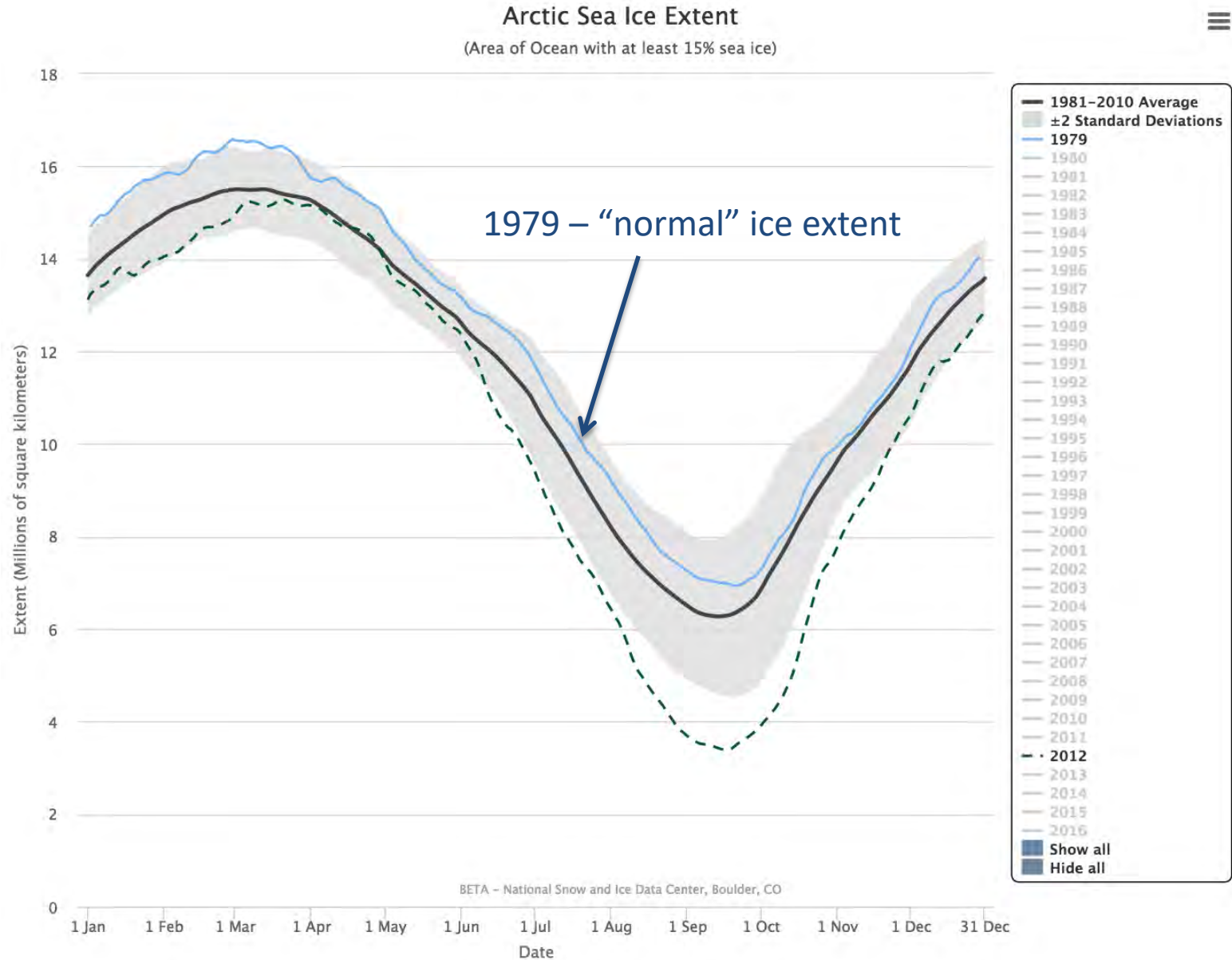
Surface Currents:

Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS, version 2.1), Zhang and Rothrock (2003)



Shoreline and Offshore Grid

Arctic connectivity pilot analysis



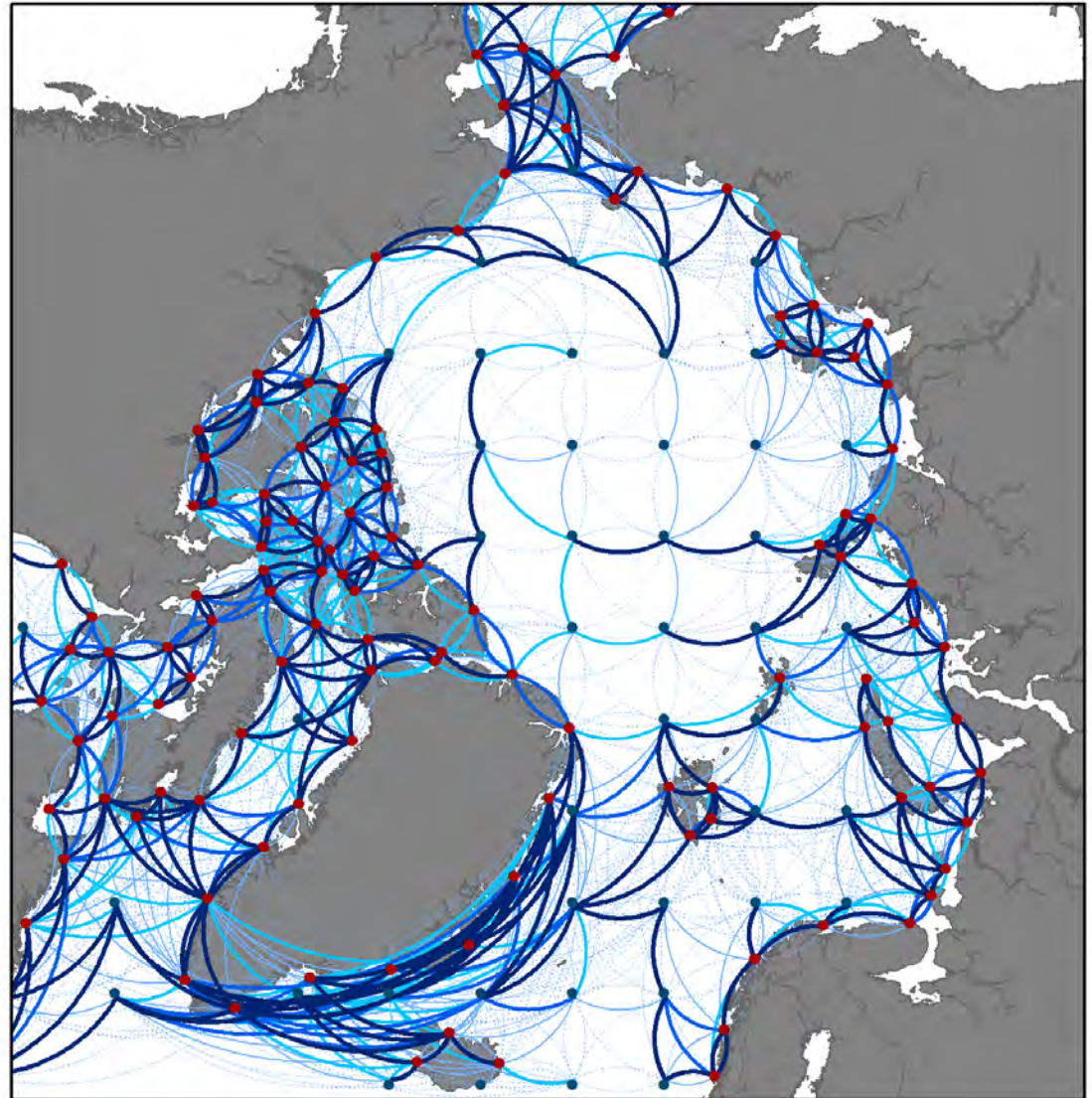
Arctic connectivity pilot analysis

Summer

September 1979 connectivity
500km coastline regions

Connectivity

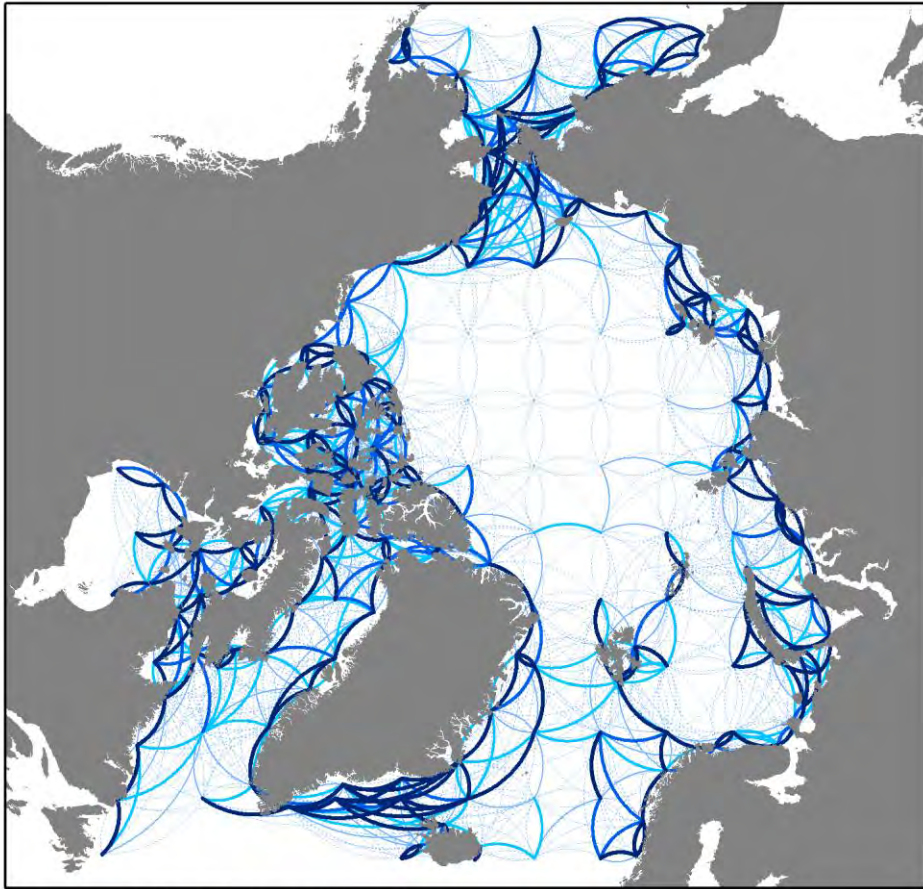
What coastal areas are
connected to other coastal
areas on a 100 day period



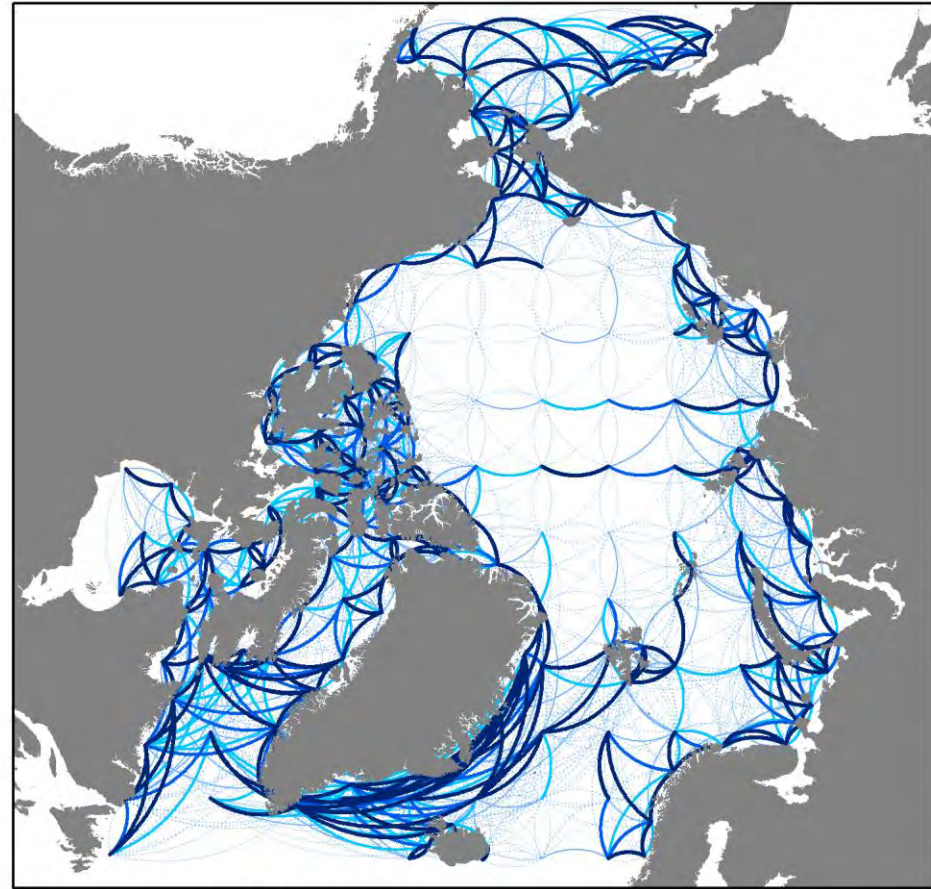
Shoreline and Offshore Grid

Coastal water connectivity

summer vs. winter normal year (1979)



Summer 1979, 100 day connectivity

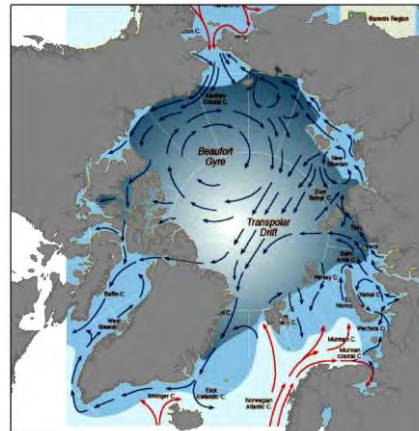


Winter 1979, 100 day connectivity

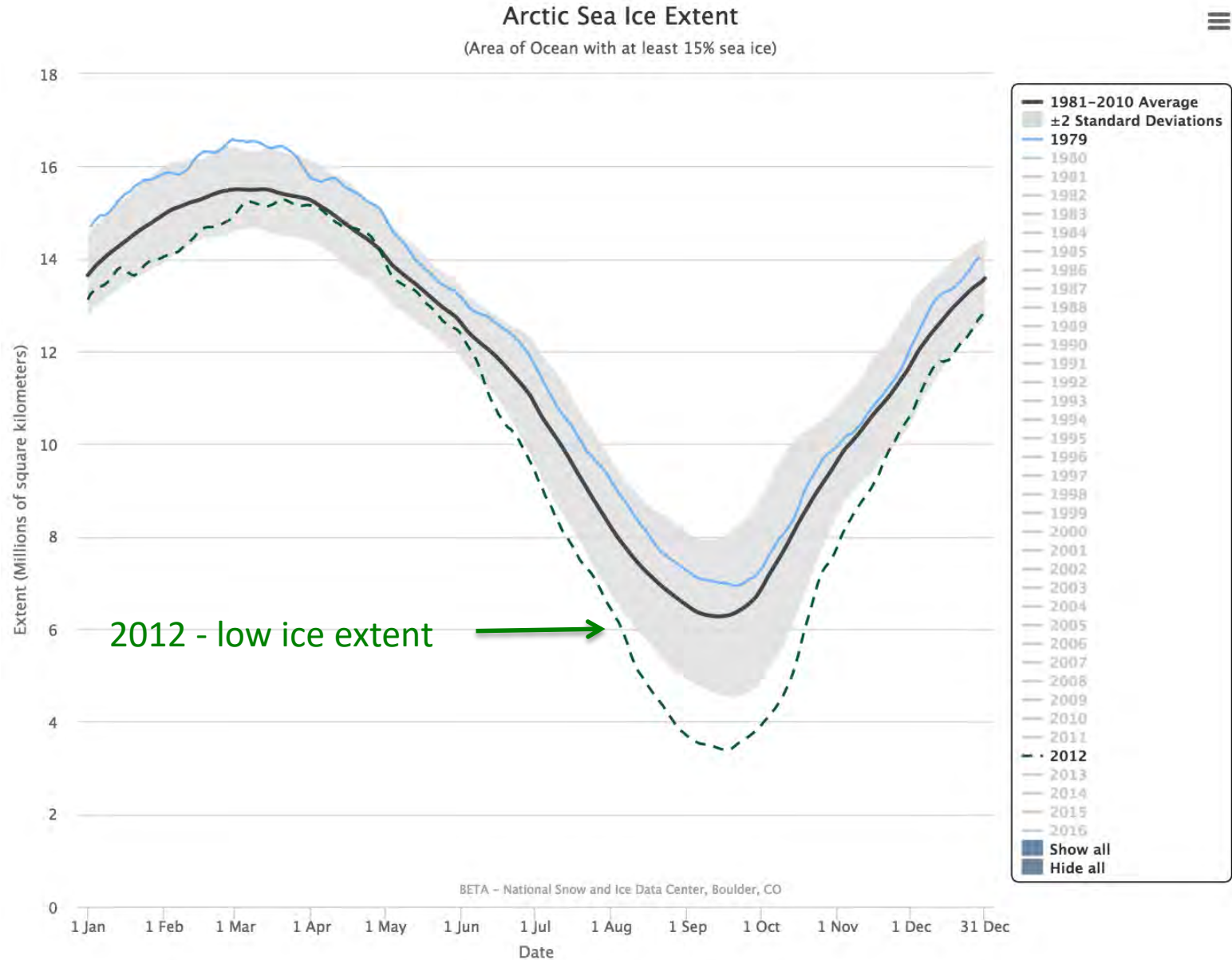
Arctic connectivity pilot analysis

Potential pilot scenarios

Source / destination targets	“normal” ice year		“low” ice year	
Coastal areas (500km regions)	winter	summer	winter	summer
Fish spawning areas	winter	summer	winter	summer
Important feeding grounds	winter	summer	winter	summer



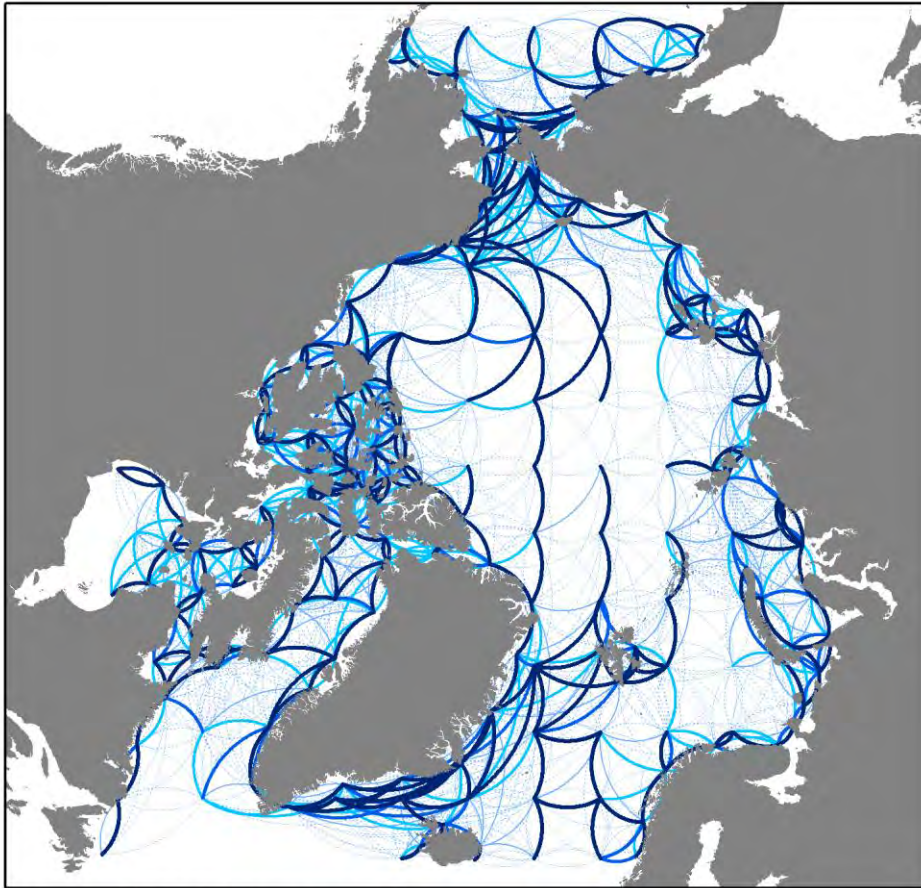
Arctic connectivity pilot analysis



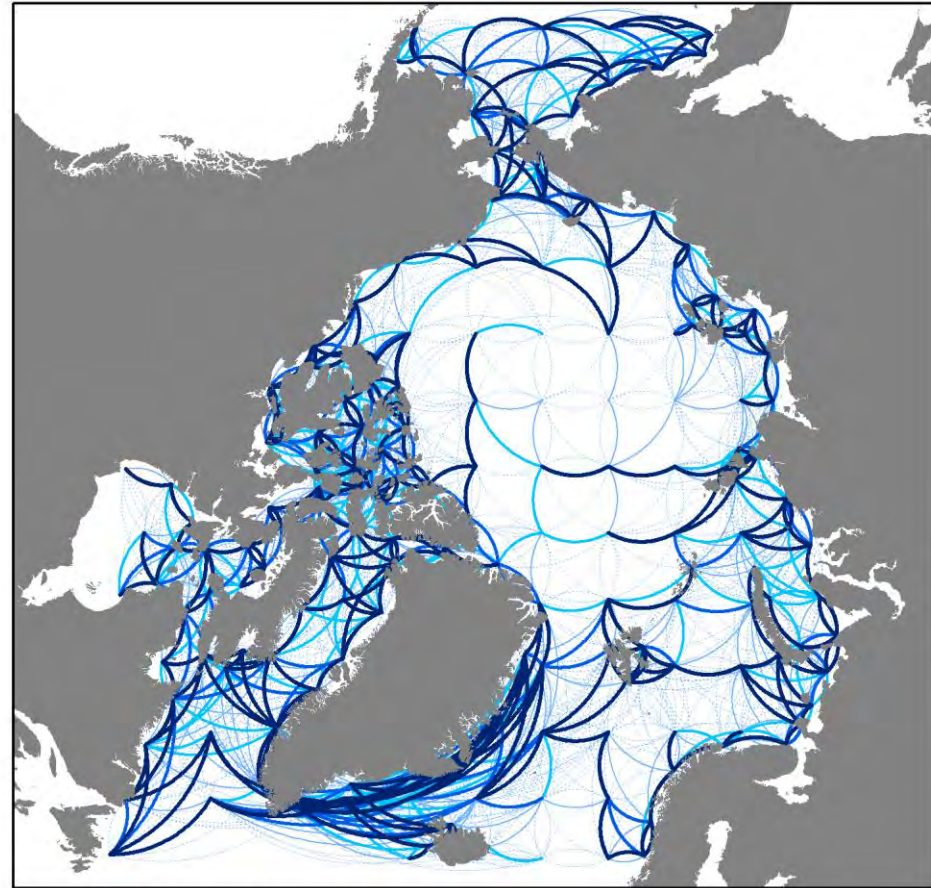
Arctic connectivity pilot analysis

summer / winter comparison

2012



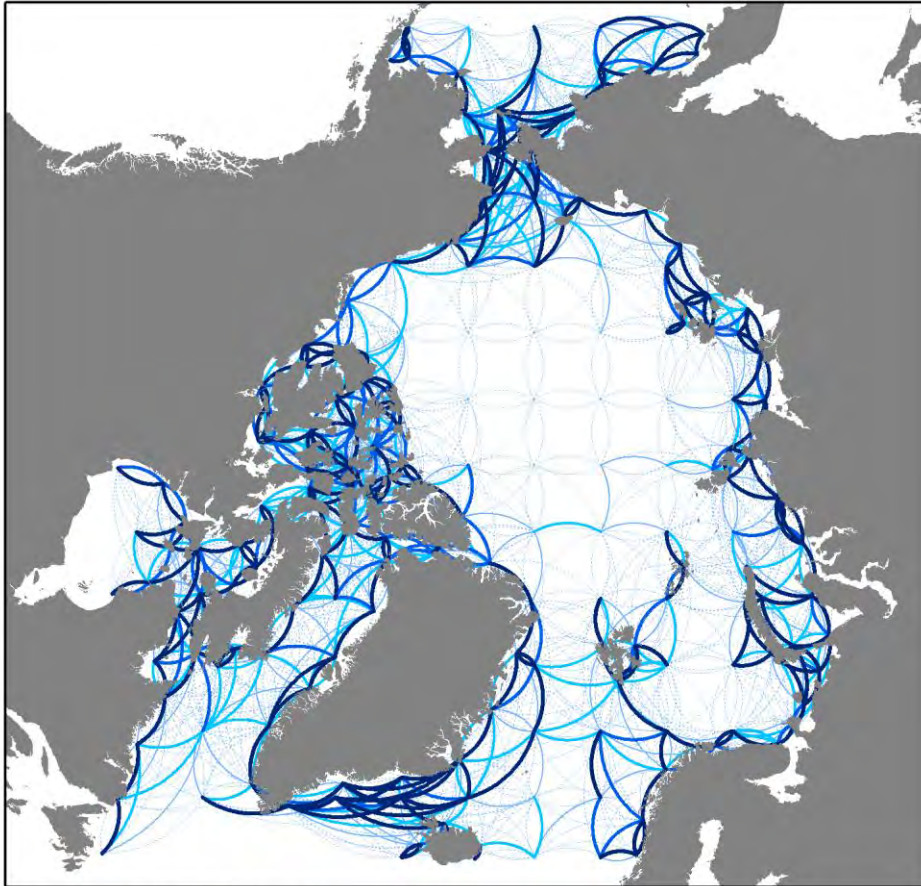
Summer 2012, 100 day connectivity



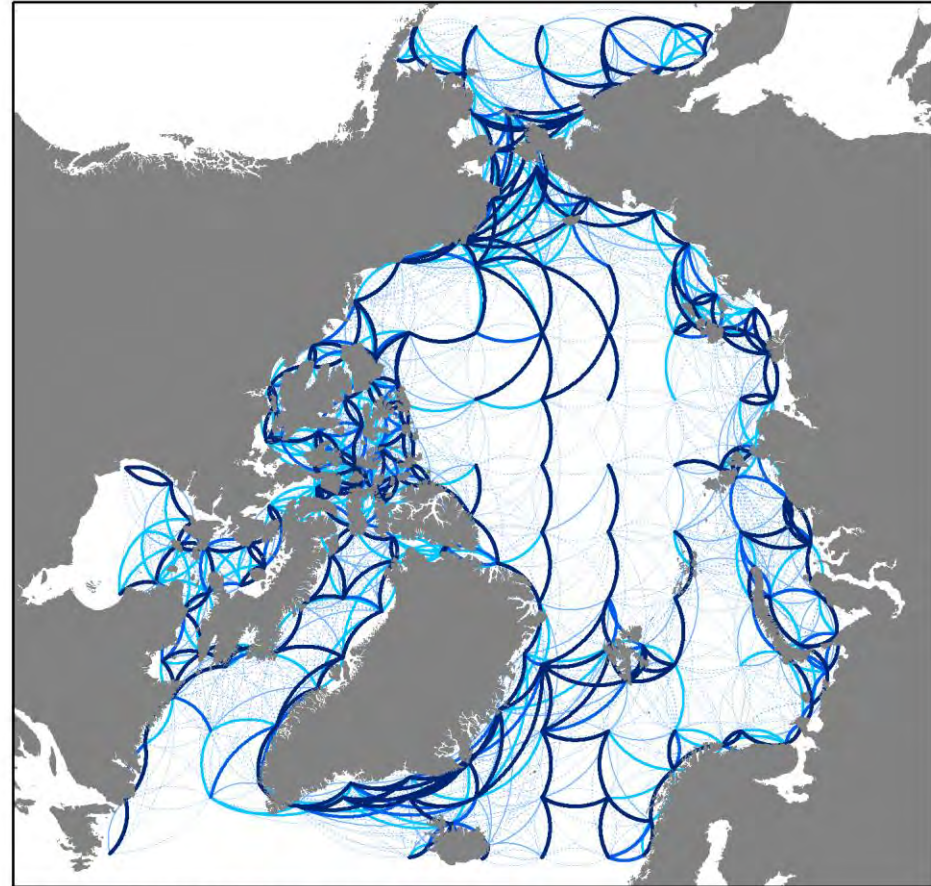
Winter 2012, 100 day connectivity

Arctic connectivity pilot analysis

Summer 1979 (normal) vs. 2012 (low ice)



Summer 1979, 100 day connectivity

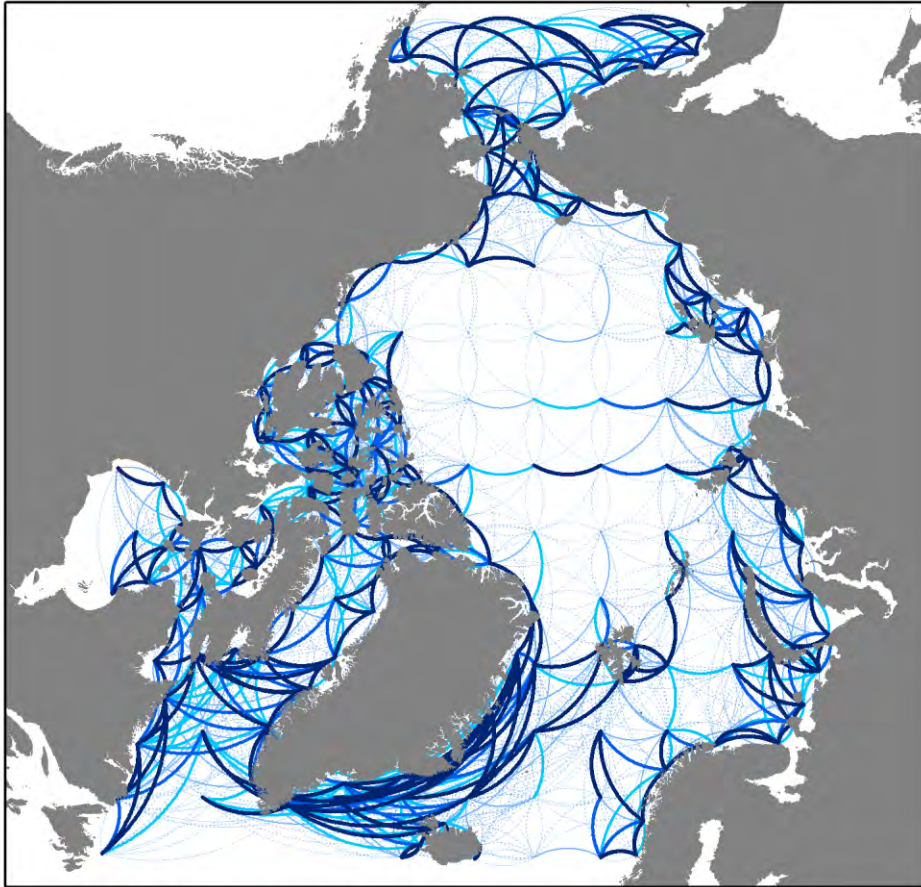


Summer 2012, 100 day connectivity

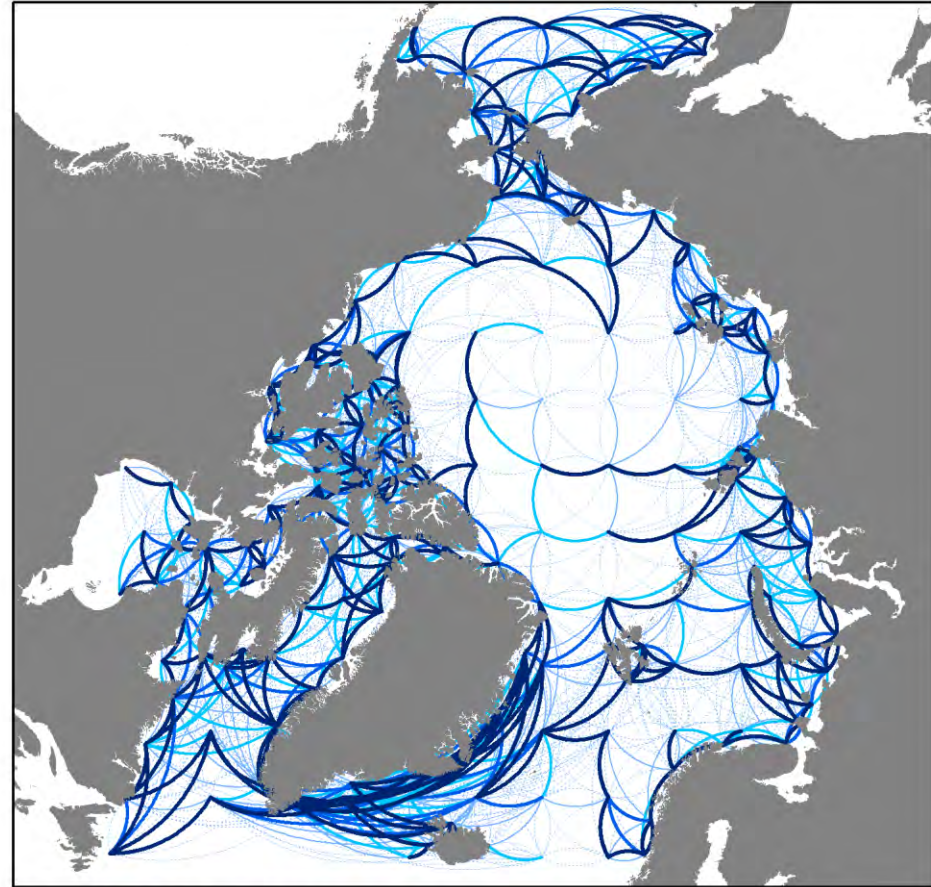
More longer distance & offshore connections

Arctic connectivity pilot analysis

Winter 1979 (normal) vs. 2012 (low ice)



Winter 1979, 100 day connectivity



Winter 2012, 100 day connectivity

More offshore connections

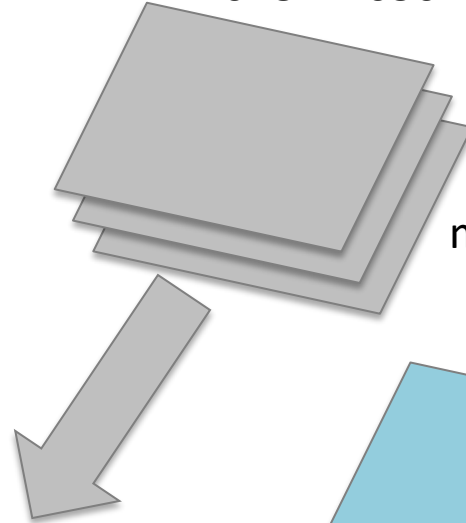
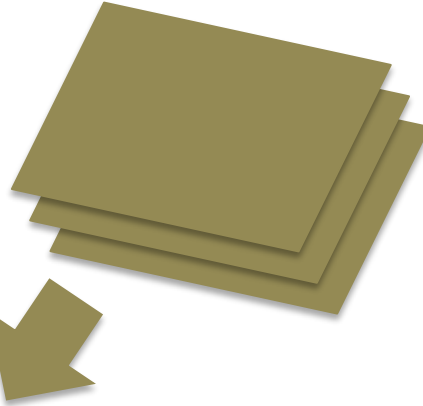
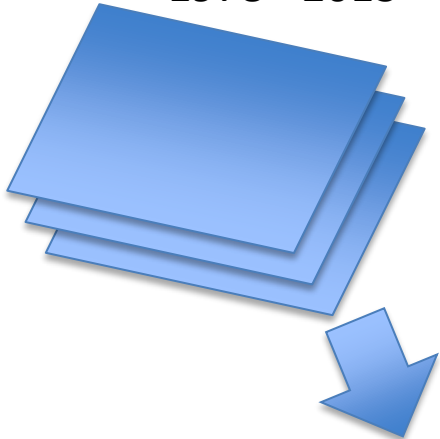
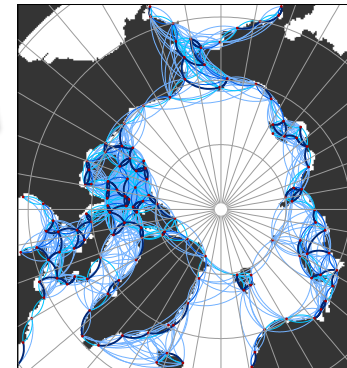
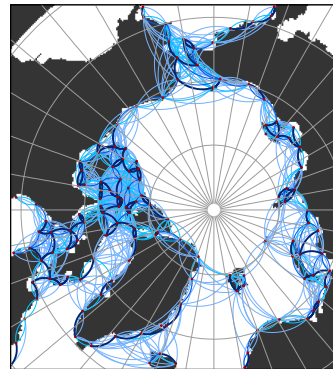
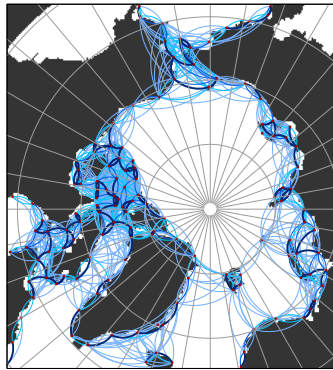
Arctic connectivity pilot analysis

surface currents
1978 - 2013

source/destination
scenarios

forecasts
2018 - 2050+

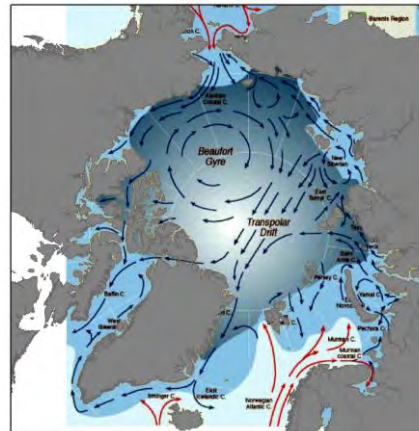
management &
jurisdictional
overlays



Arctic connectivity pilot analysis

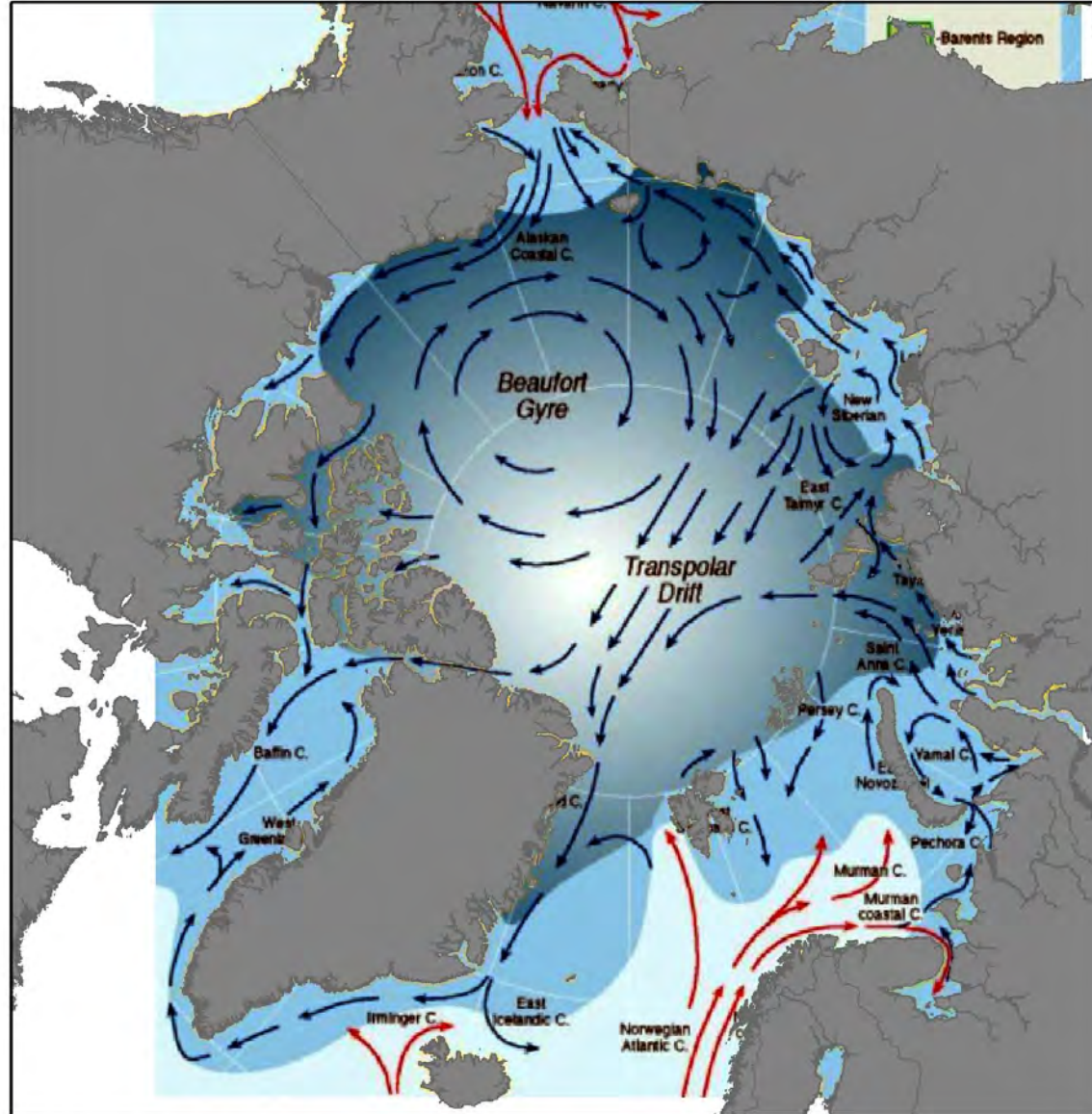
Potential pilot scenarios

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Fish spawning areas	winter	summer	winter	summer
Important feeding grounds	winter	summer	winter	summer



Arctic connectivity pilot analysis

Foraging areas
AMSA-IIc
(multiple types)



Surface Current Schematic

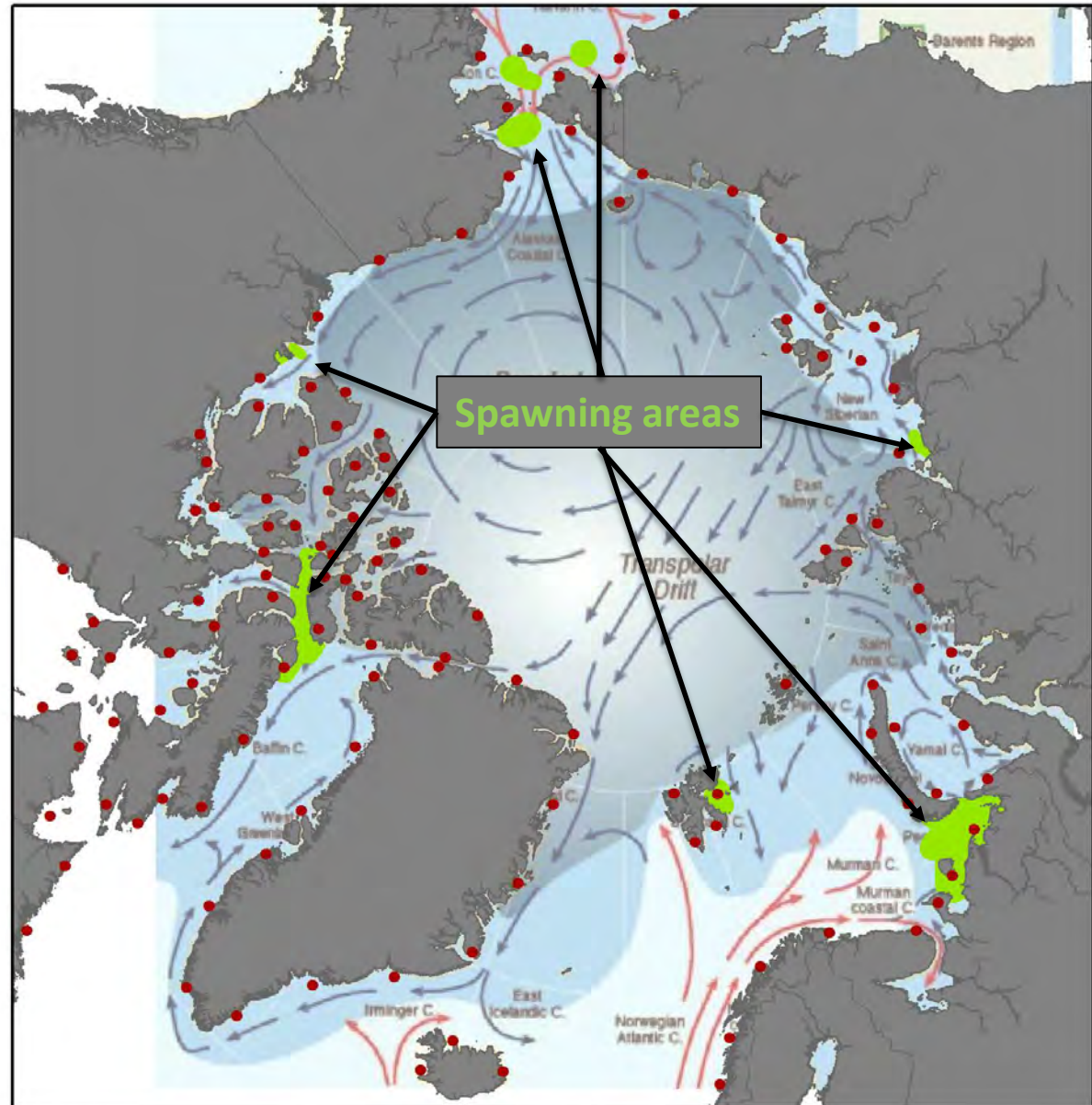
Arctic connectivity pilot analysis

Polar cod

Boreogadus saida

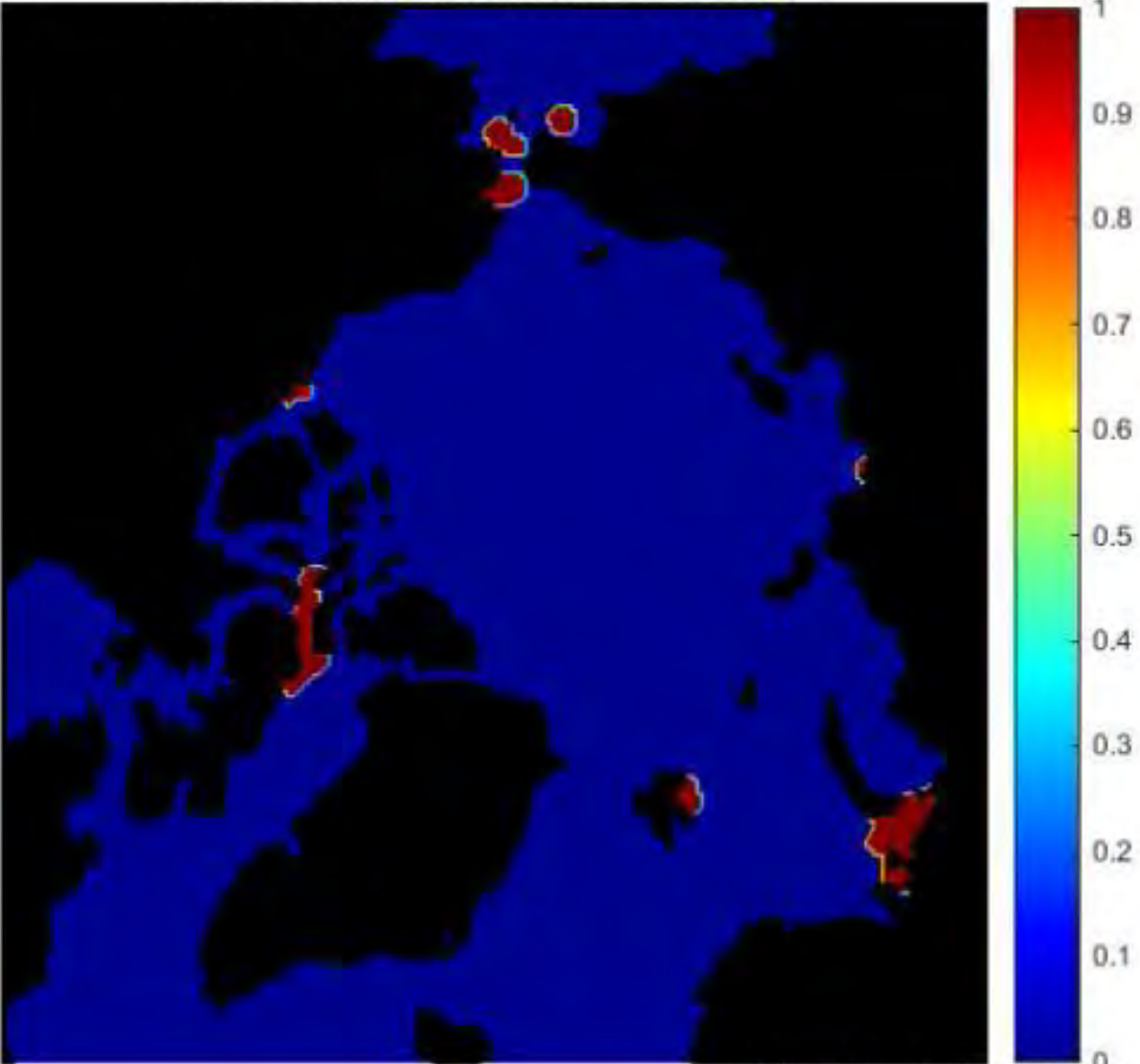
Spawning areas

From: AMSA-IIc



Surface Current Schematic - Polar Cod Spawning

day 1



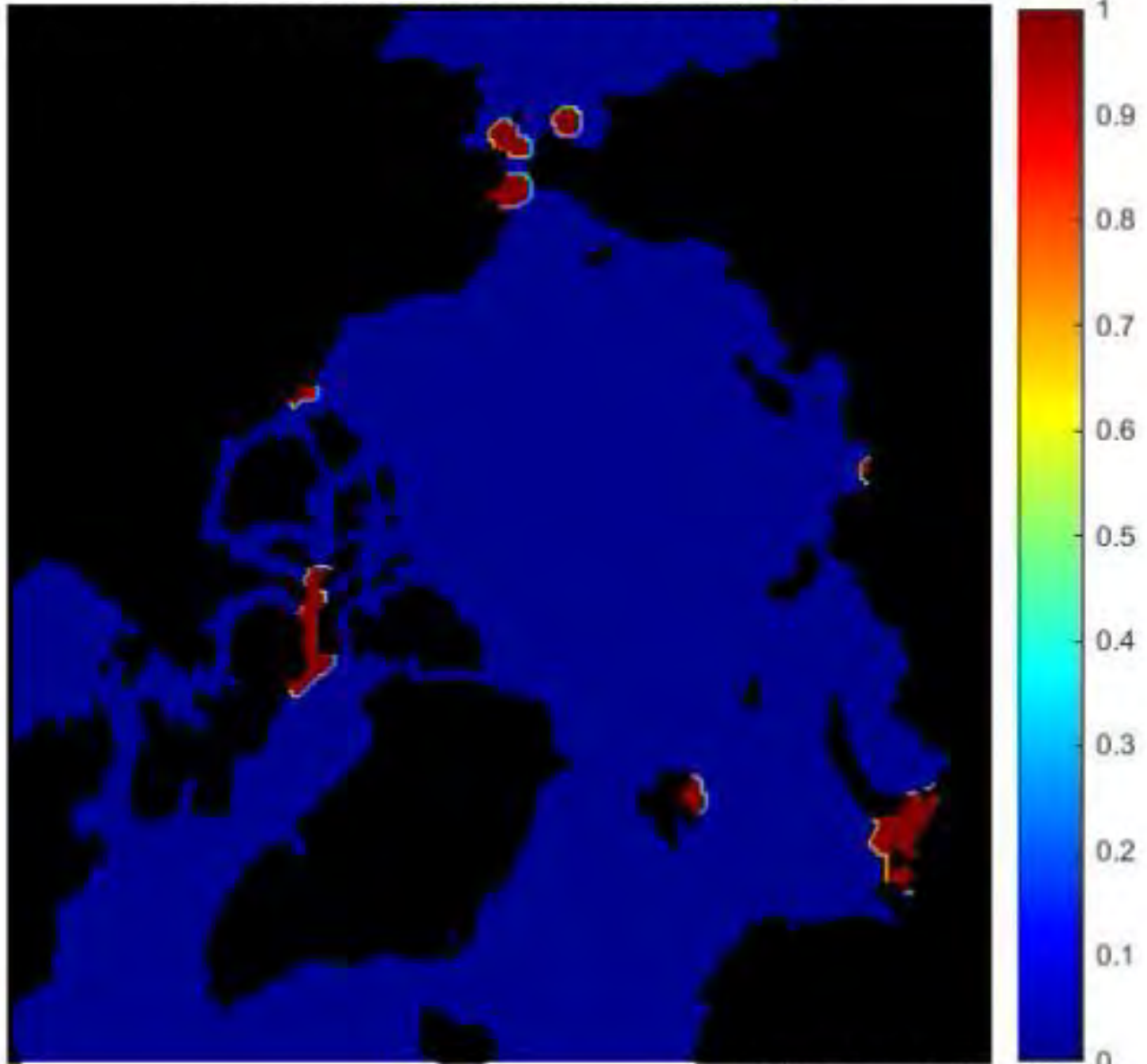
Polar cod
Boreogadus saida
Spawning areas

From: AMSA-IIc

Winter 1979
"normal" ice
year

Tremblay, Fay et al. 2016

day 1



1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Polar cod
Boreogadus saida
Spawning areas

From: AMSA-IIc

Winter 2012
"low" ice year

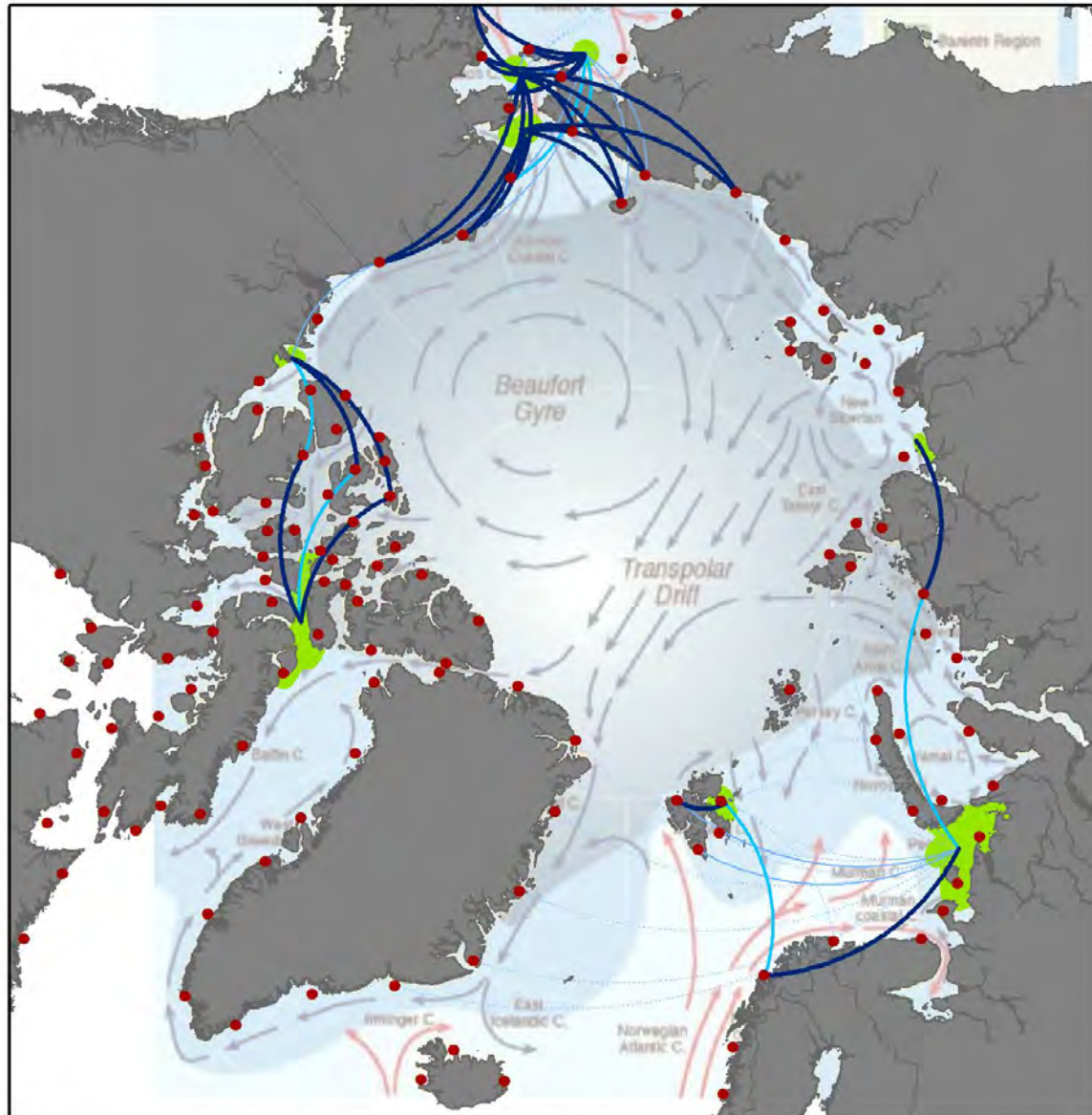
Treml, Fay et al. 2016

Arctic connectivity pilot analysis

Polar cod
Boreogadus saida
Spawning areas

From: AMSA-IIc

connectivity
winter 1979
“normal” ice year



Surface Current Schematic - Polar Cod Spawning Connectivity (1979)

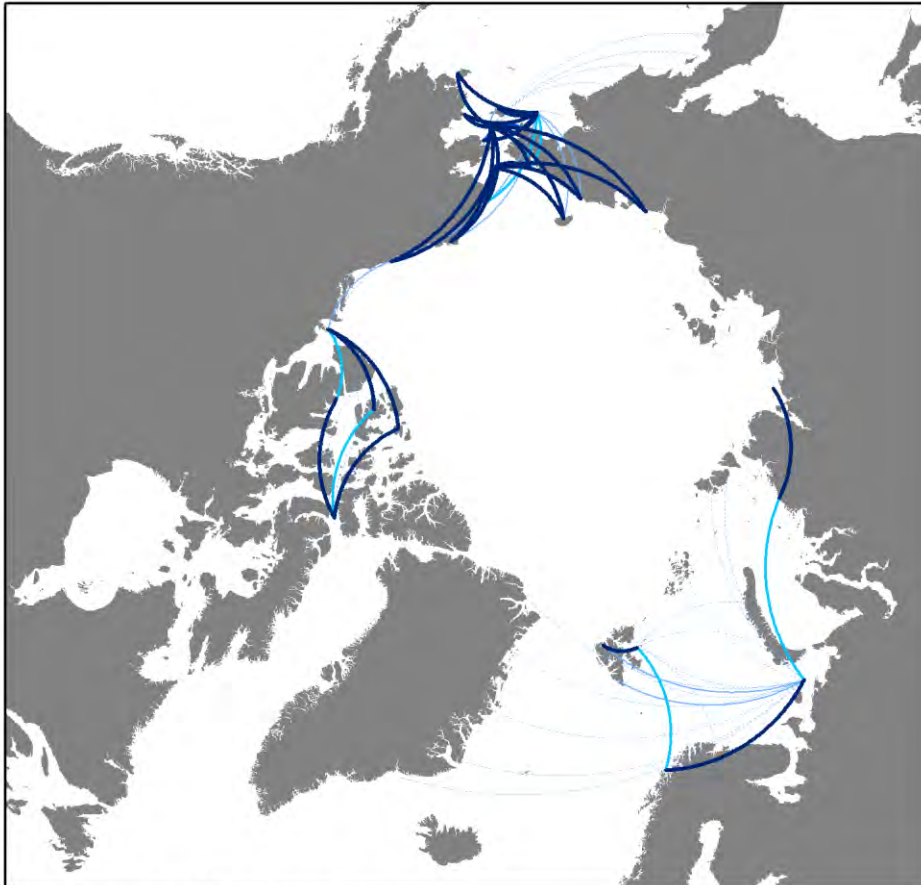
Arctic connectivity pilot analysis

connectivity winter 1979 - 2012

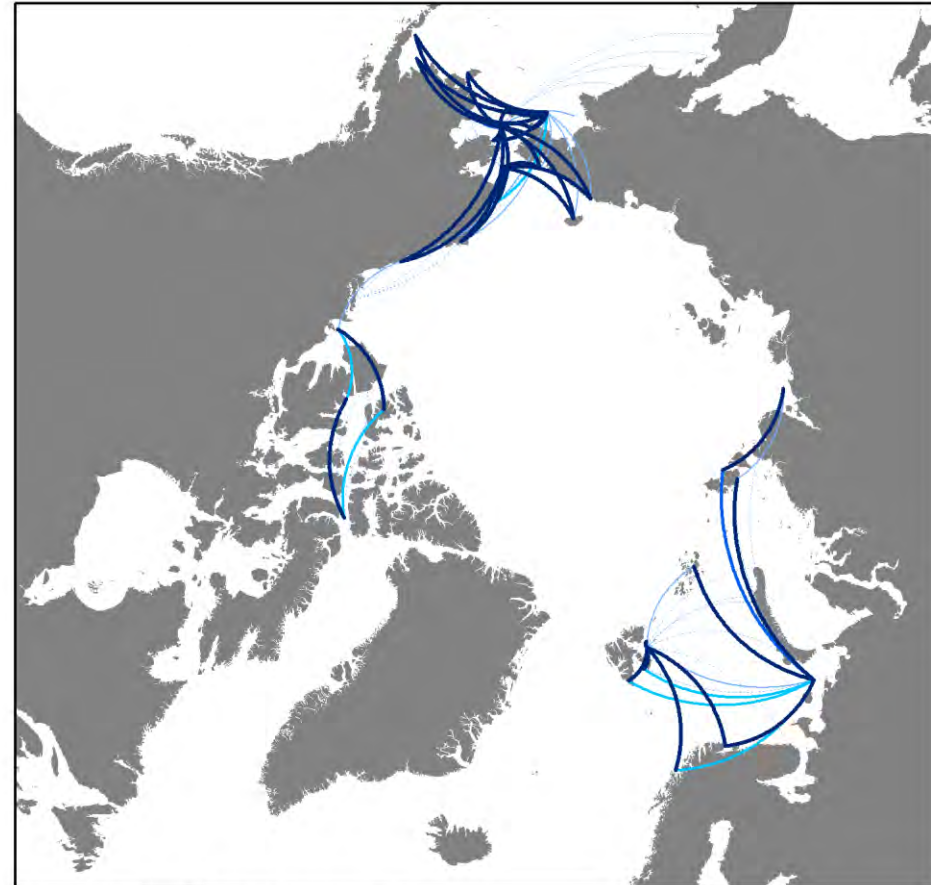
Polar cod *Boreogadus saida* Spawning areas

From: AMSA-IIc

Winter 1979 (normal ice year)



Winter 2012 (low ice year)



Winter 1979, 275 day connectivity

Winter 2012, 275 day connectivity

Arctic connectivity pilot analysis

Polar Biol
DOI 10.1007/s00300-015-1774-0



ORIGINAL PAPER

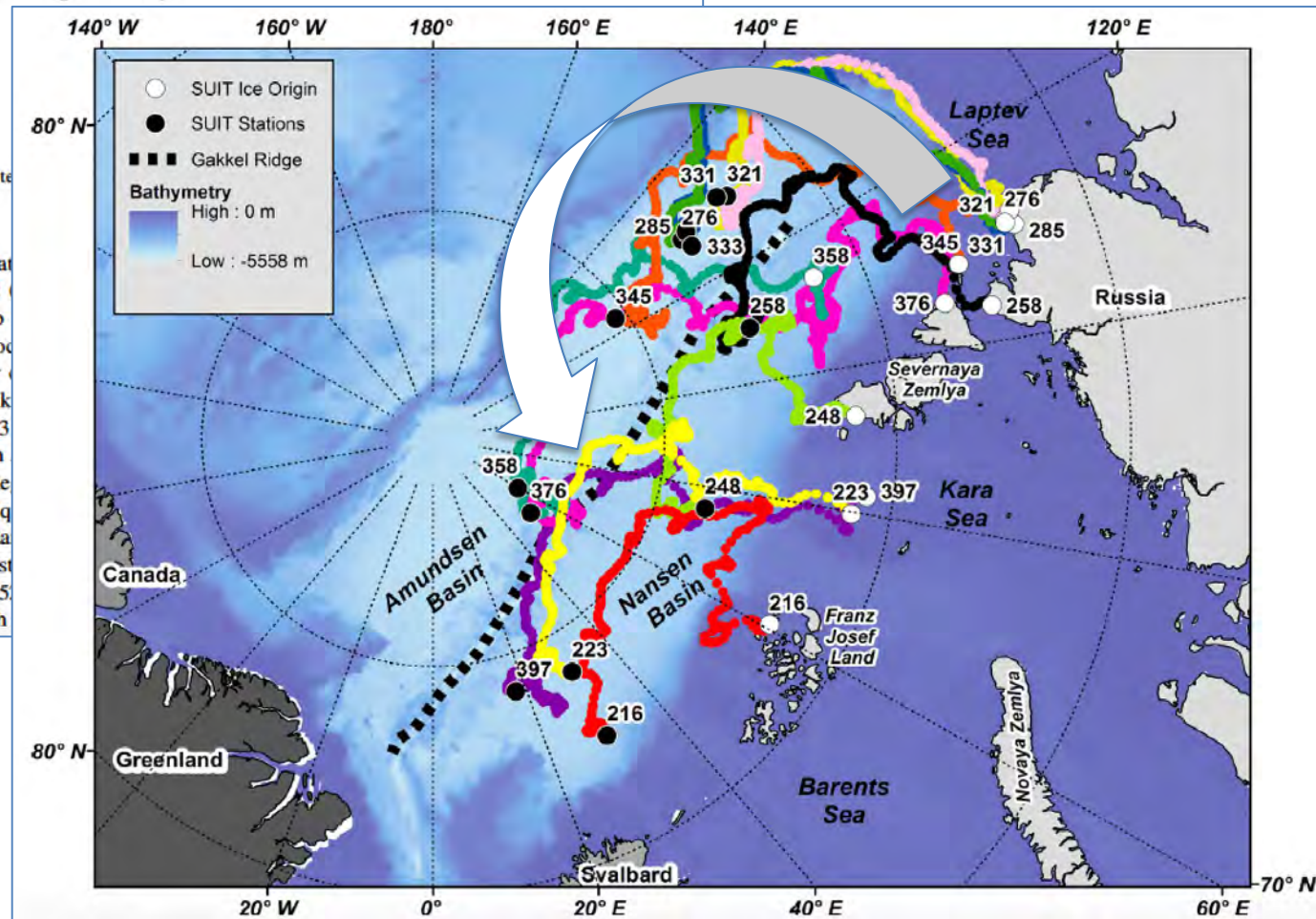
Under-ice distribution of polar cod *Boreogadus saida* in the central Arctic Ocean and their association with sea-ice habitat properties

Carmen David^{1,2} · Benjamin Lange^{1,2} · Thomas Krumpen¹ · Fokje Schaafsma³ ·
Jan Andries van Franeker³ · Hauke Flores^{1,2}

Received: 28 February 2015 / Revised: 16 July 2015 / Accepted: 16 July 2015
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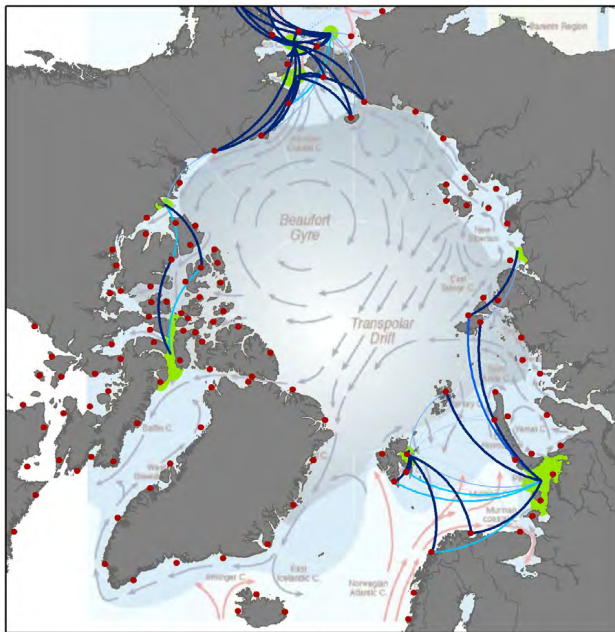
Abstract In the Arctic Ocean, sea-ice habitat is undergoing rapid environmental change. Polar cod (*Boreogadus saida*) is the most abundant fish known to live under the pack-ice. The under-ice distribution, association with sea-ice habitat properties and origins of polar cod in the central Arctic Ocean, however, are largely unknown. During the RV *Polarstern* expedition ARK XXVII/3 Eurasian Basin in 2012, we used for the first time in the waters a Surface and Under Ice Trawl with an integrated bio-environmental sensor array. Polar cod was ubiquitous throughout the Eurasian Basin with a median abundance of 5000 ind. km⁻². The under-ice population consisted of young specimens with a total length between 5 and 140 mm, dominated by 1-year-old fish. Higher fish

Need to compare & validate models to empirical observations

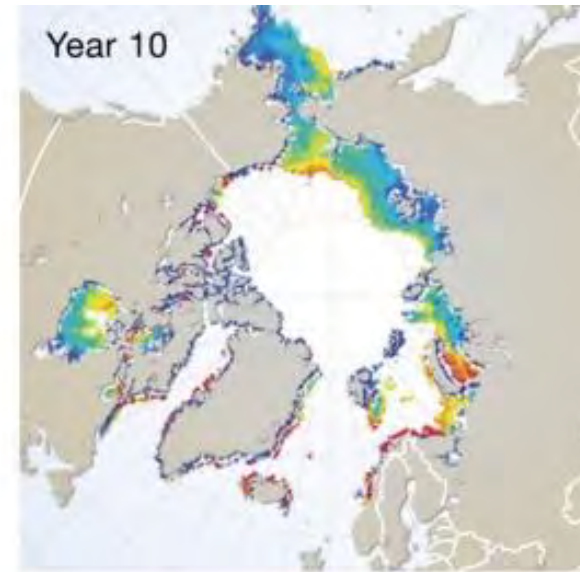


Arctic connectivity pilot analysis

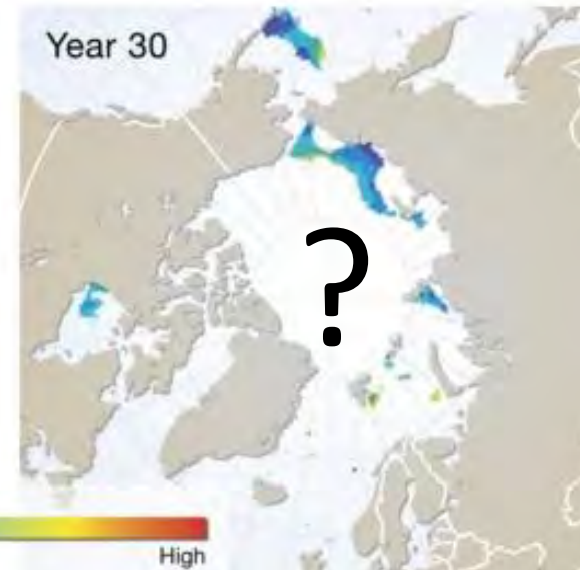
Simulated projections
for Polar cod
distribution with
global warming



Surface Current Schematic - Polar Cod Spawning Connectivity (2012)



Potential connectivity & potential distribution

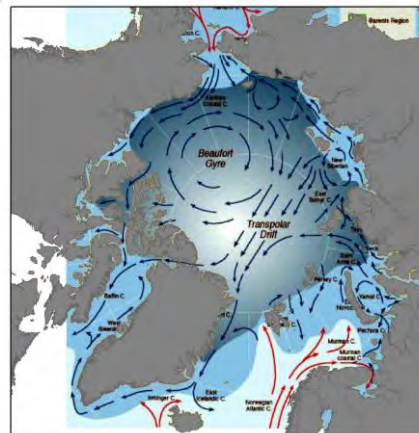


Relative abundance
Low High

Arctic connectivity pilot analysis

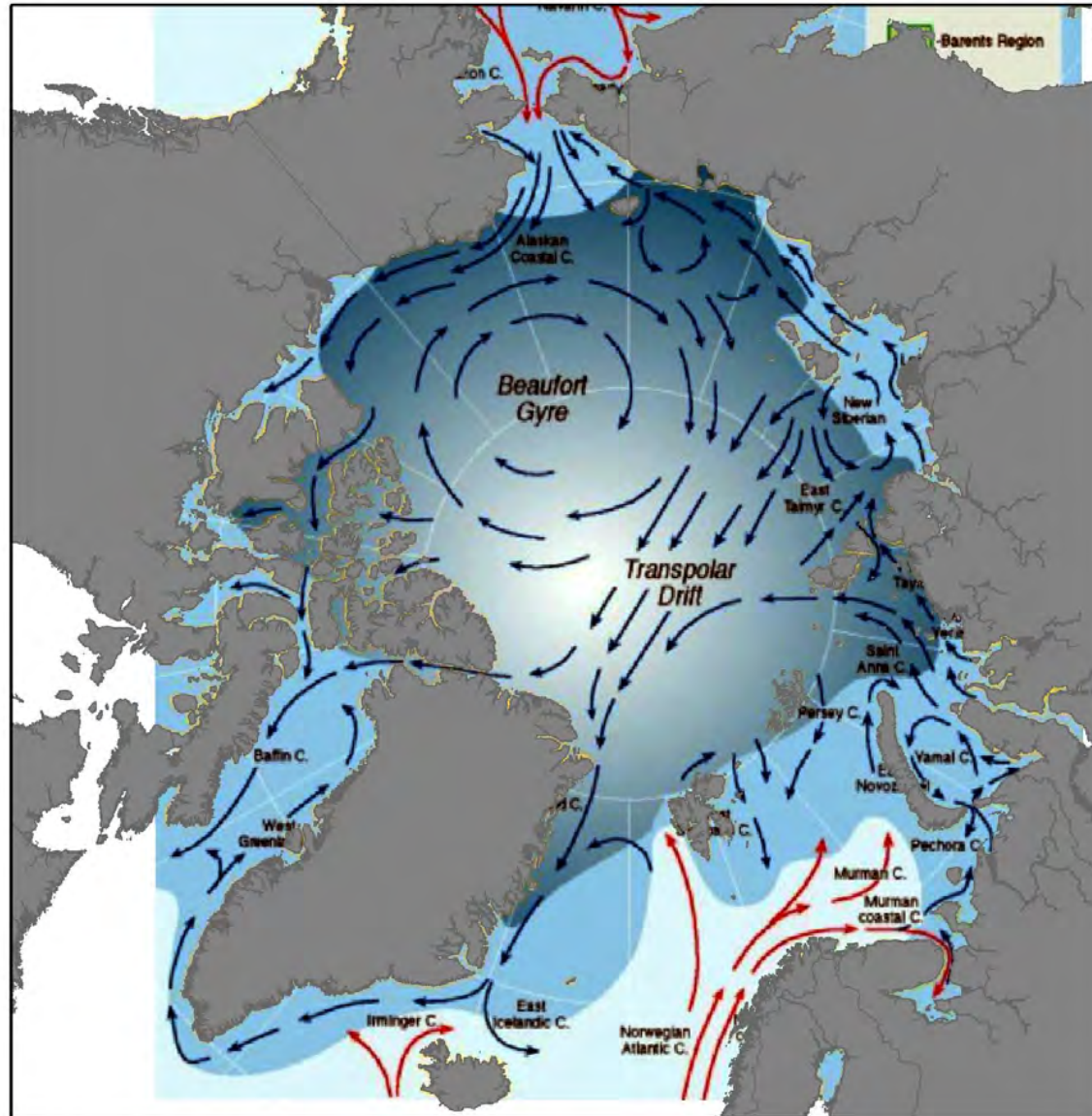
Potential pilot scenarios

Source / destination targets	“normal” ice year		“low” ice year	
Coastal areas (500km regions)	winter	summer	winter	summer
Fish spawning areas	winter	summer	winter	summer
Important feeding grounds	winter	summer	winter	summer



Arctic connectivity pilot analysis

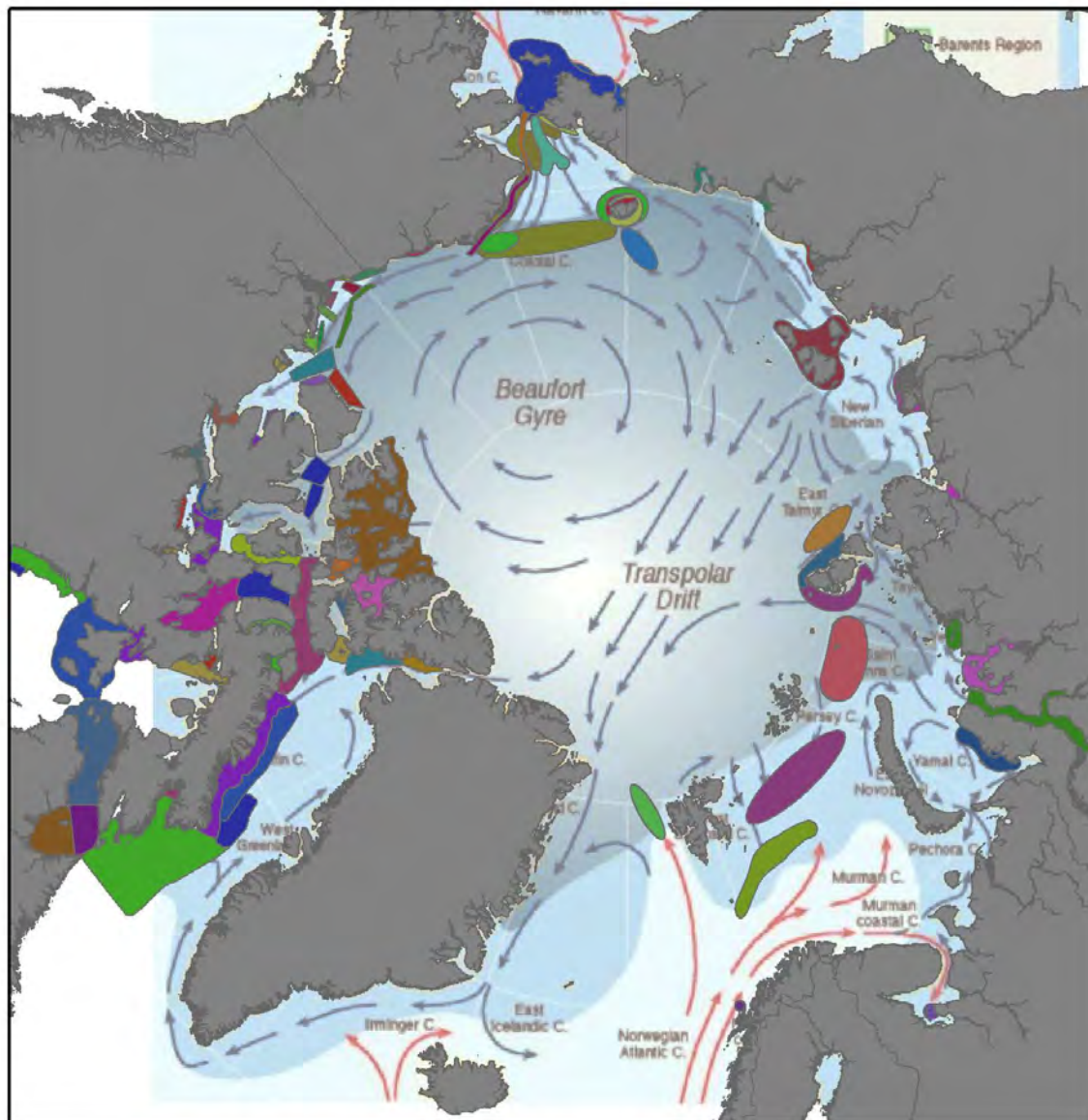
Foraging areas
AMSA-IIc
(multiple types)



Surface Current Schematic

Arctic connectivity pilot analysis

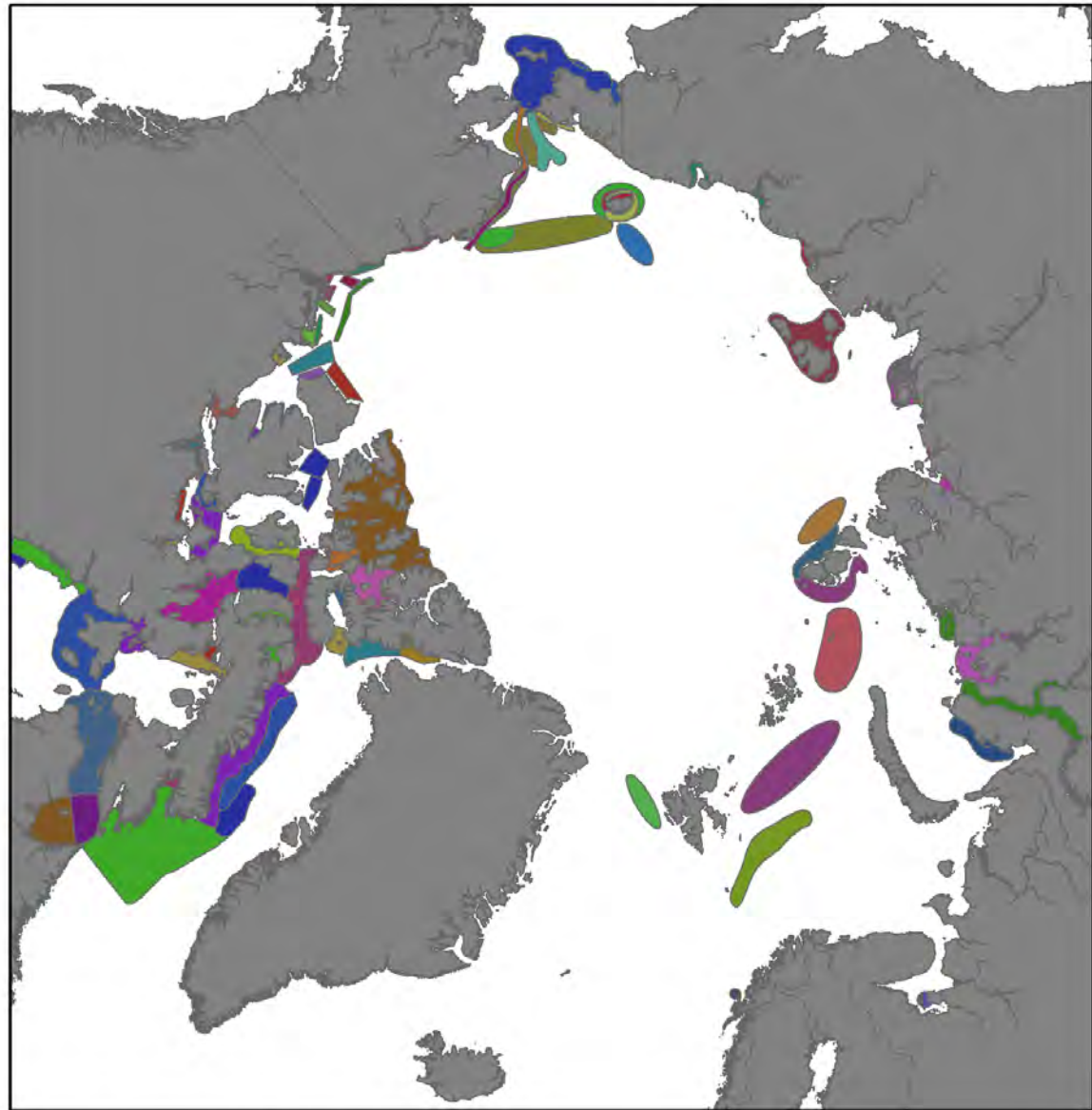
Foraging areas
AMSA-IIc
(multiple types)



Surface Current Schematic - AMSA IIC Feeding Areas

Arctic connectivity pilot analysis

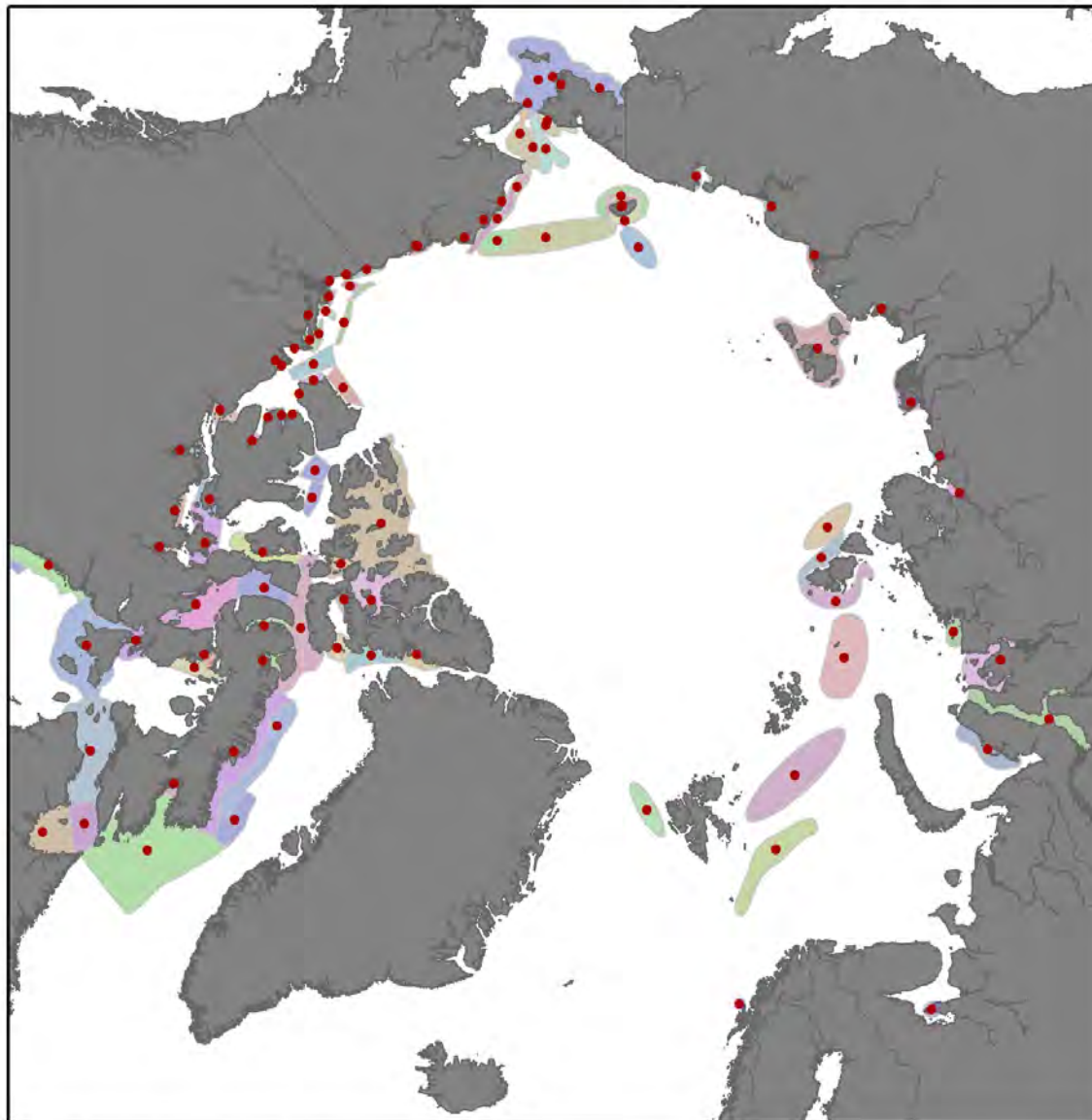
Foraging areas
AMSA-IIC
(multiple types)



AMSA IIC Feeding Areas

Arctic connectivity pilot analysis

Foraging areas
AMSA-IIC
(multiple types)

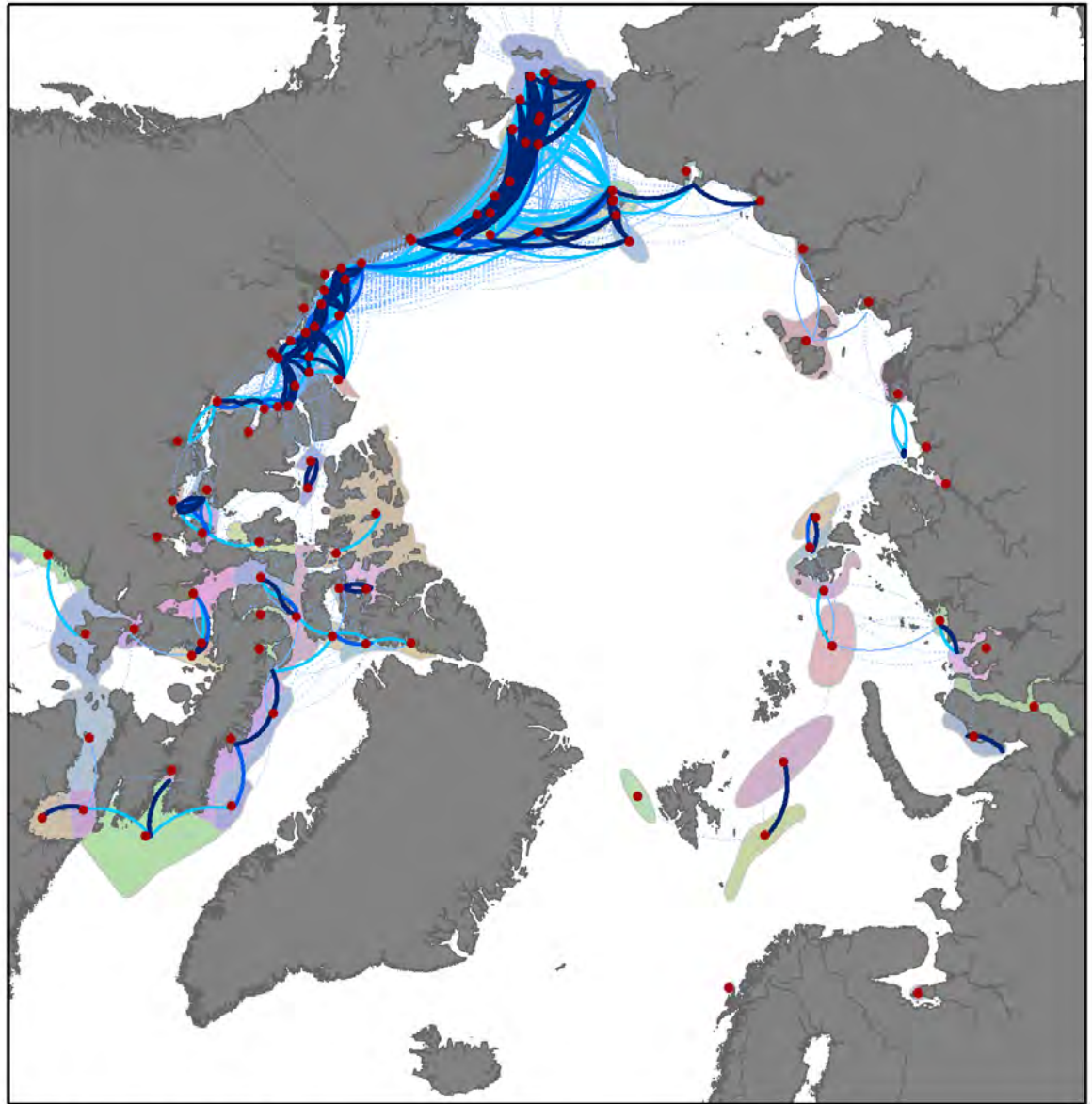


AMSA IIC Feeding Areas

Arctic connectivity pilot analysis

Foraging areas
AMSA-IIC
(multiple types)

Summer 2012
(representative low ice year)

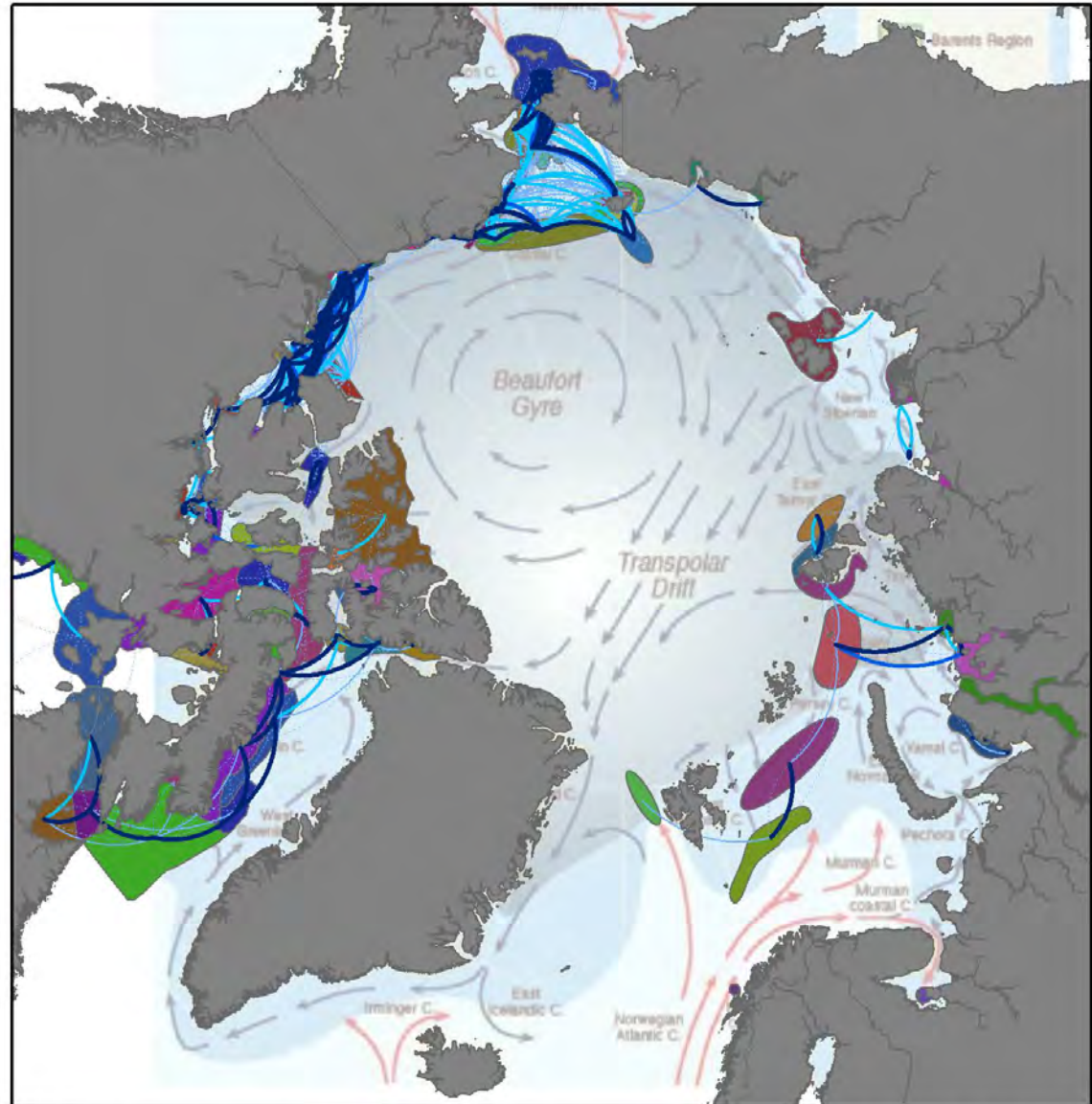


AMSA IIC Feeding Areas

Arctic connectivity pilot analysis

Foraging areas
AMSA-IIc
(multiple types)

Winter 2012
(representative low ice year)



Surface Current Schematic - AMSA IIC Feeding Connectivity (Winter 2012)

Arctic connectivity pilot analysis

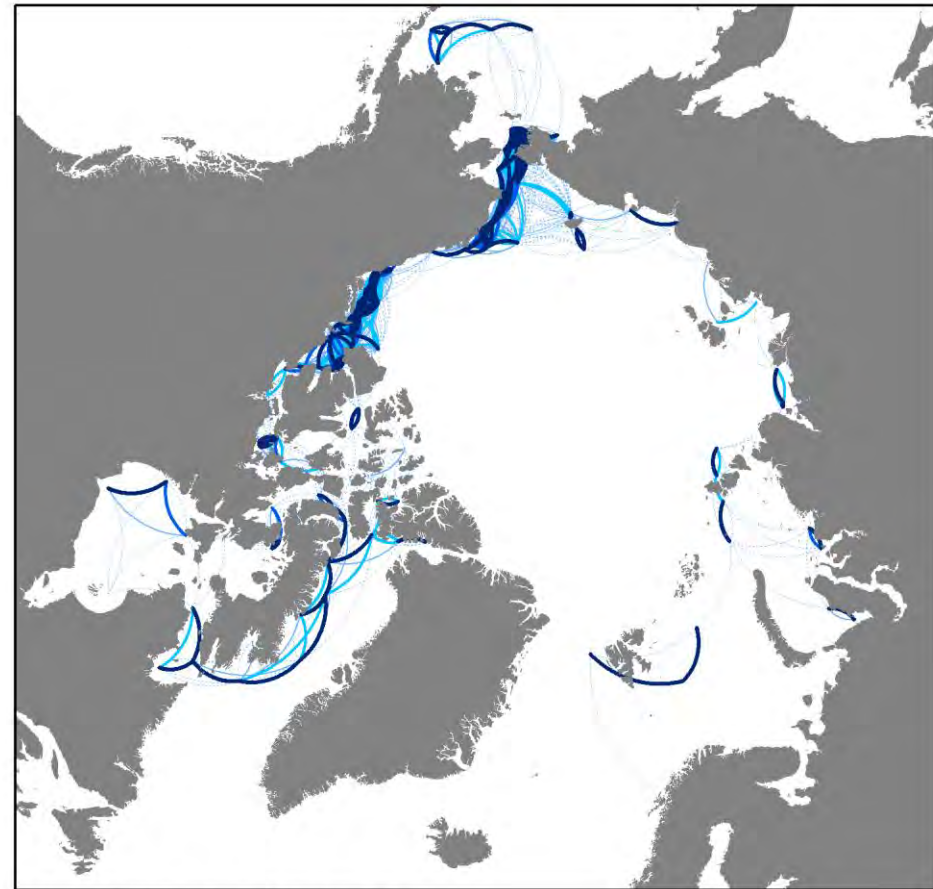
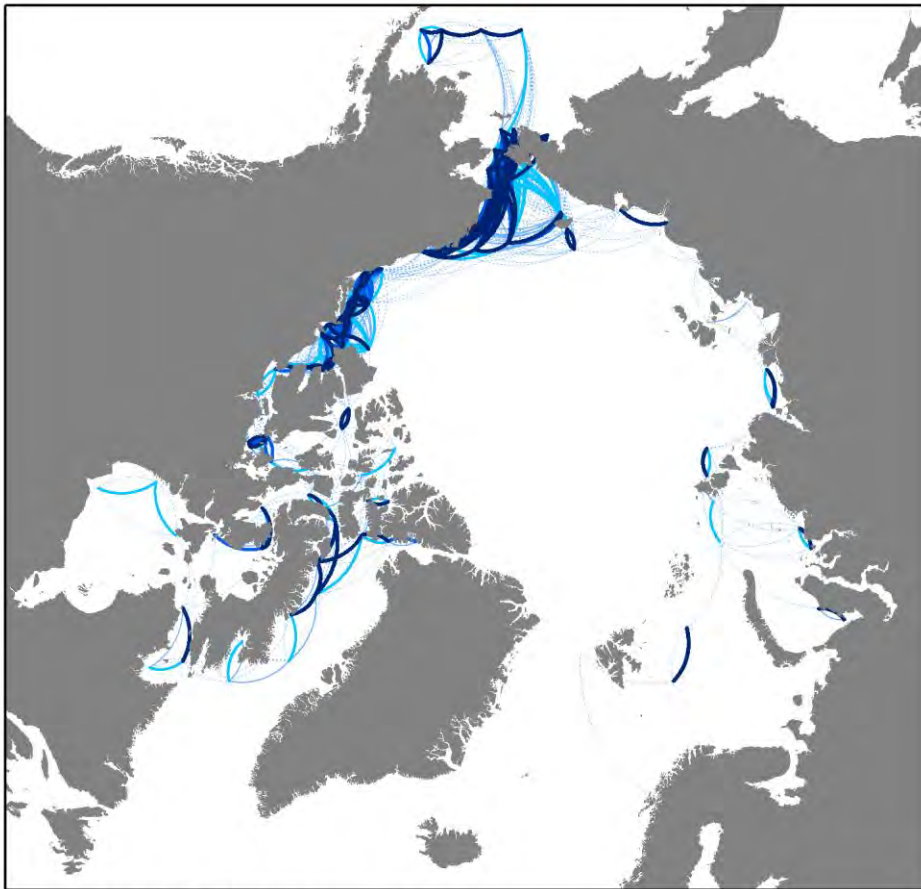
Foraging areas

AMSA-lic (multiple types)

“normal” ice year (1979)

summer

winter



Summer 1979, 100 day connectivity

Winter 1979, 100 day connectivity

Arctic connectivity pilot analysis

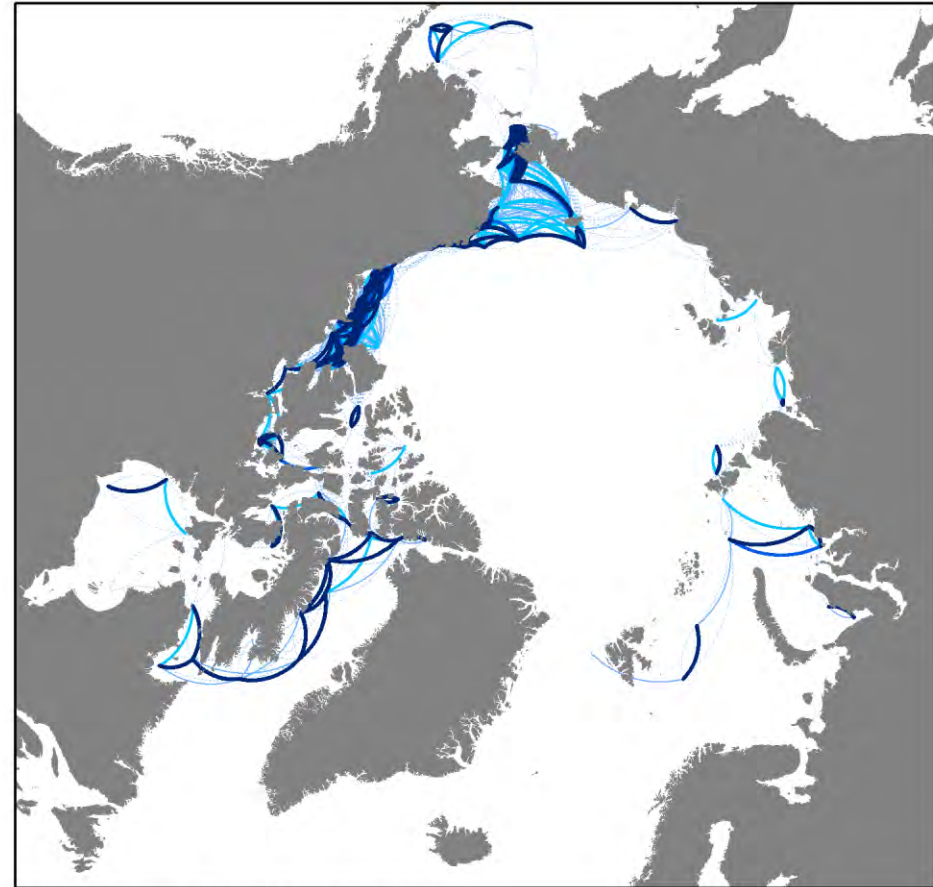
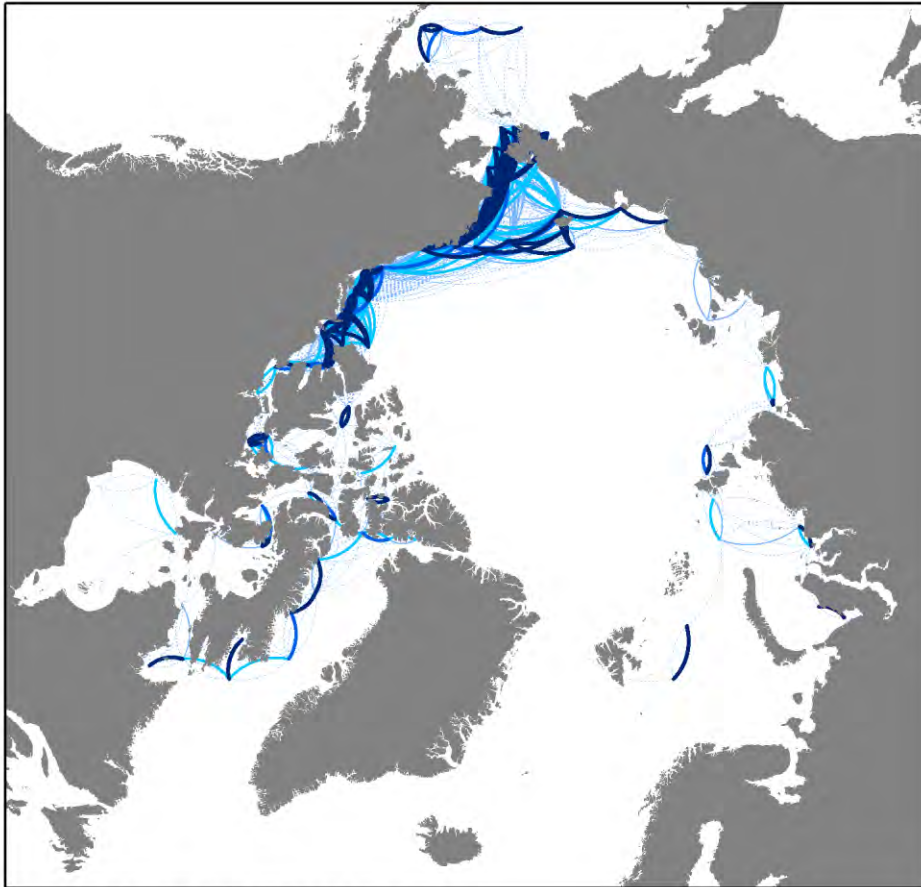
Foraging areas

AMSA-lic (multiple types)

low ice year (2012)

summer

winter



Summer 2012, 100 day connectivity

Winter 2012, 100 day connectivity

Arctic connectivity pilot analysis

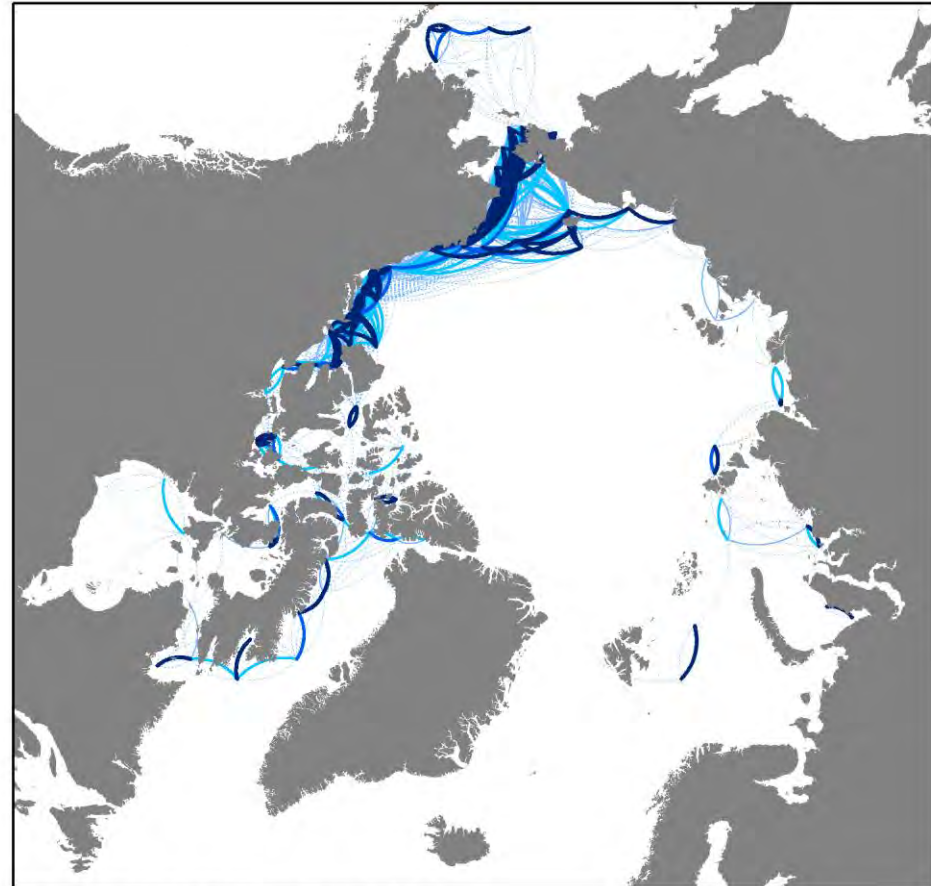
Foraging areas

AMSA-lic (multiple types)

summer normal ice year (1979) vs. summer low ice year (2012)



Summer 1979, 100 day connectivity



Summer 2012, 100 day connectivity

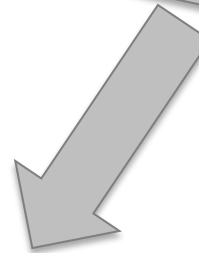
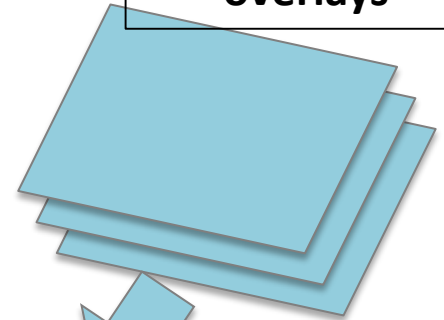
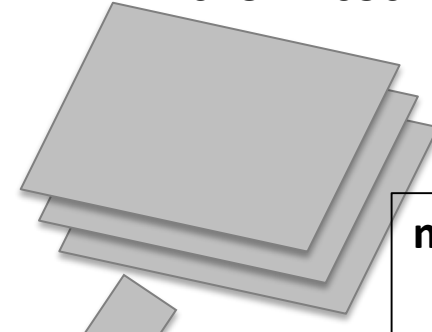
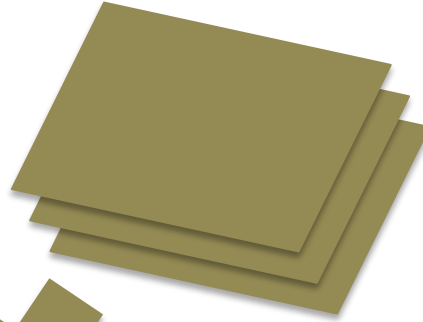
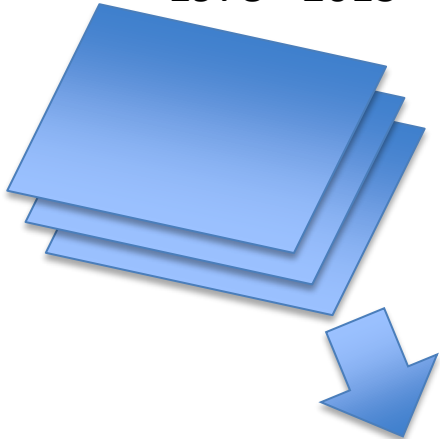
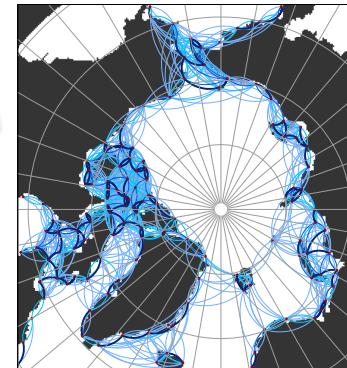
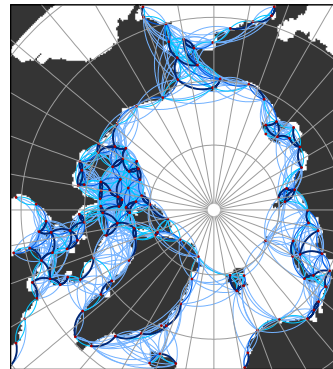
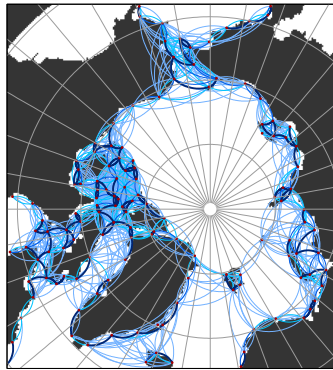
Arctic connectivity pilot analysis

surface currents
1978 - 2013

source/destination
scenarios

forecasts
2018 - 2050+

management &
jurisdictional
overlays

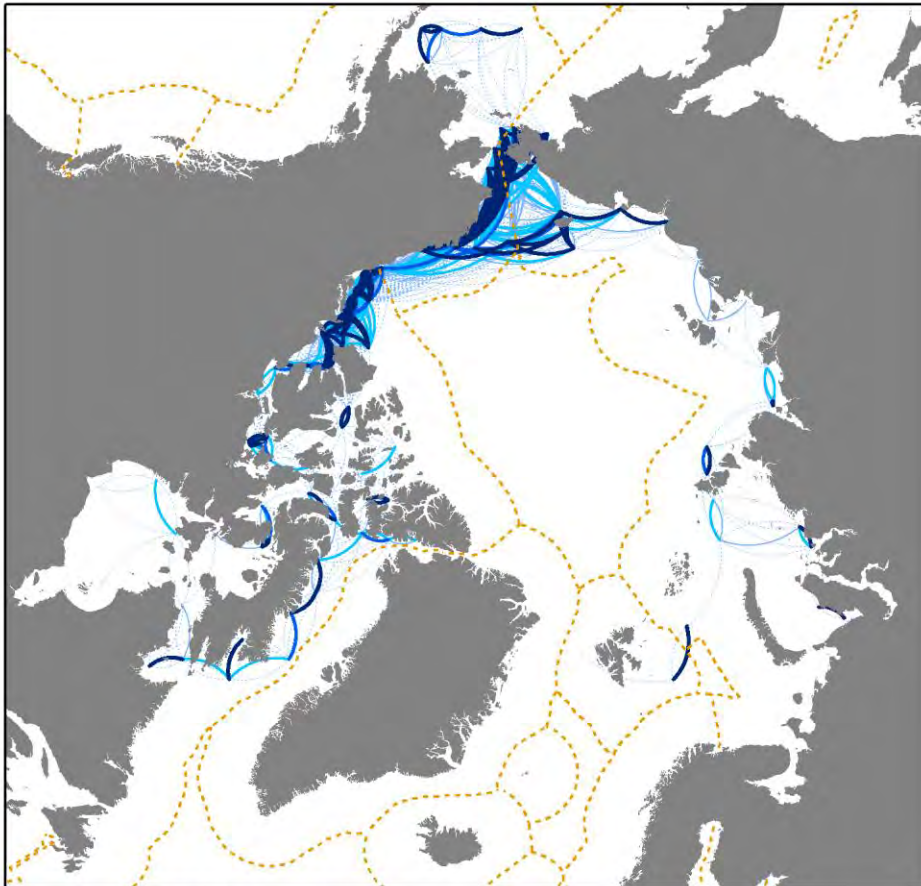


Arctic connectivity pilot analysis

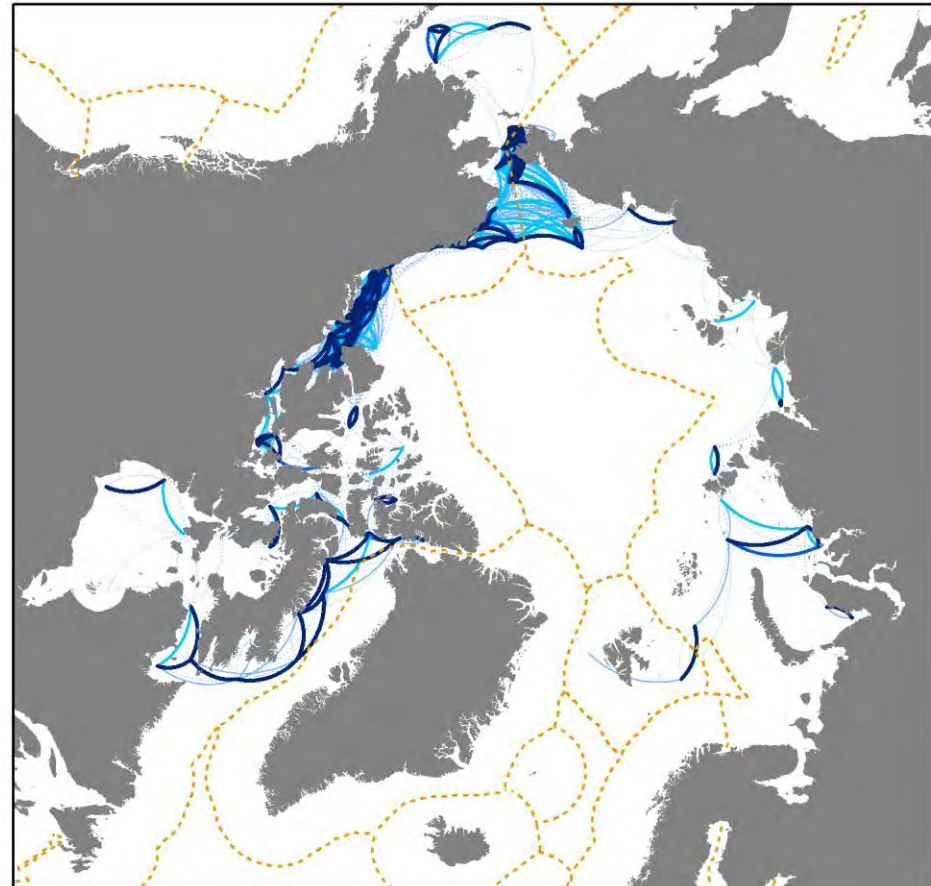
Foraging areas

AMSA-IIc (multiple types)

Foraging area connectivity across EEZ boundaries



Summer 2012, 100 day connectivity



Winter 2012, 100 day connectivity

Areas of oil & gas potential vs. ecological importance

Ecologically or Biologically Important Areas



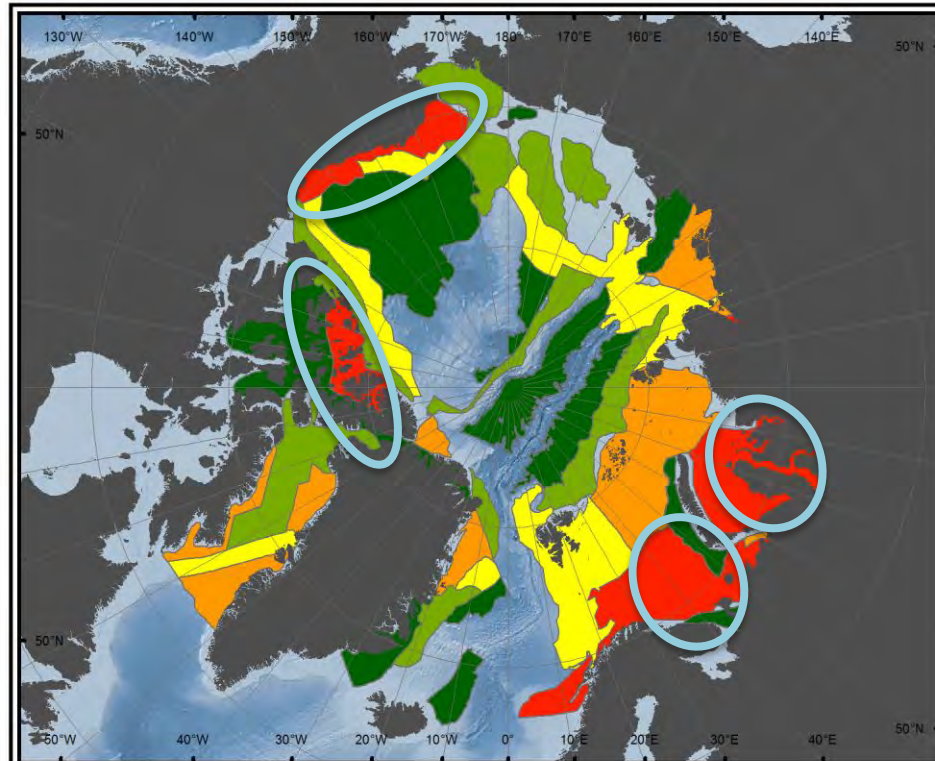
CBD EBSA process
 [Red outline] Spatially Stable EBSA
 [Yellow dashed outline] Spatially Dynamic EBSA

Canadian EBSA process
 [Dark red] Newfoundland / Labrador
 [Brown] Beaufort / N. Foxe Basin
 [Green] Canadian Arctic

US Biologically Important Areas - Cetaceans
 [Blue] Bowhead, Beluga, Gray whales

Marine Geospatial Ecology Lab, Duke University (2014)

Oil & Gas Potential



Oil and Gas Potential
 [Green] <10%
 [Light Green] 10% - 30%
 [Yellow] 30% - 50%
 [Orange] 50% - 100%
 [Red] 100%

Marine Geospatial Ecology Lab, Duke University (2014)

USGS 2008/2011. Circum-Arctic Resource Appraisal: Estimates of undiscovered oil and gas north of the Arctic Circle.

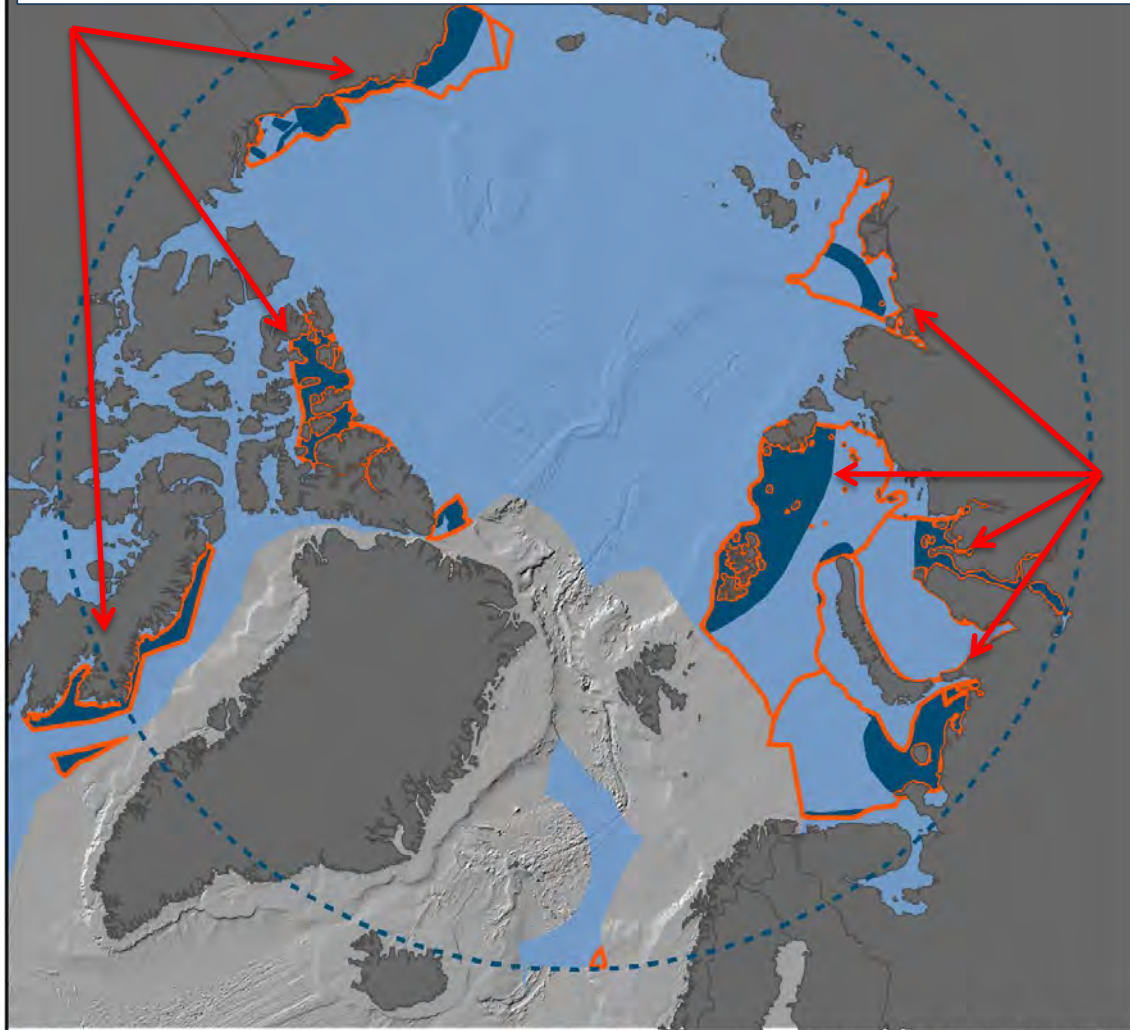
"Assessment units (AUs) in the Circum-Arctic Resource Appraisal (CARA) color-coded by assessed probability of the presence of at least one undiscovered oil and/or gas field with recoverable resources greater than 50 million barrels of oil equivalent (MMBOE).

Areas of oil & gas potential vs. ecological importance

All of the high value oil & gas exploration regions contained EBSAs




* Percent EBSA/BIA coverage of 100% O/G potential areas: 44.1%

* Percent EBSA/BIA coverage of 50-100% O/G potential areas: 46.5%



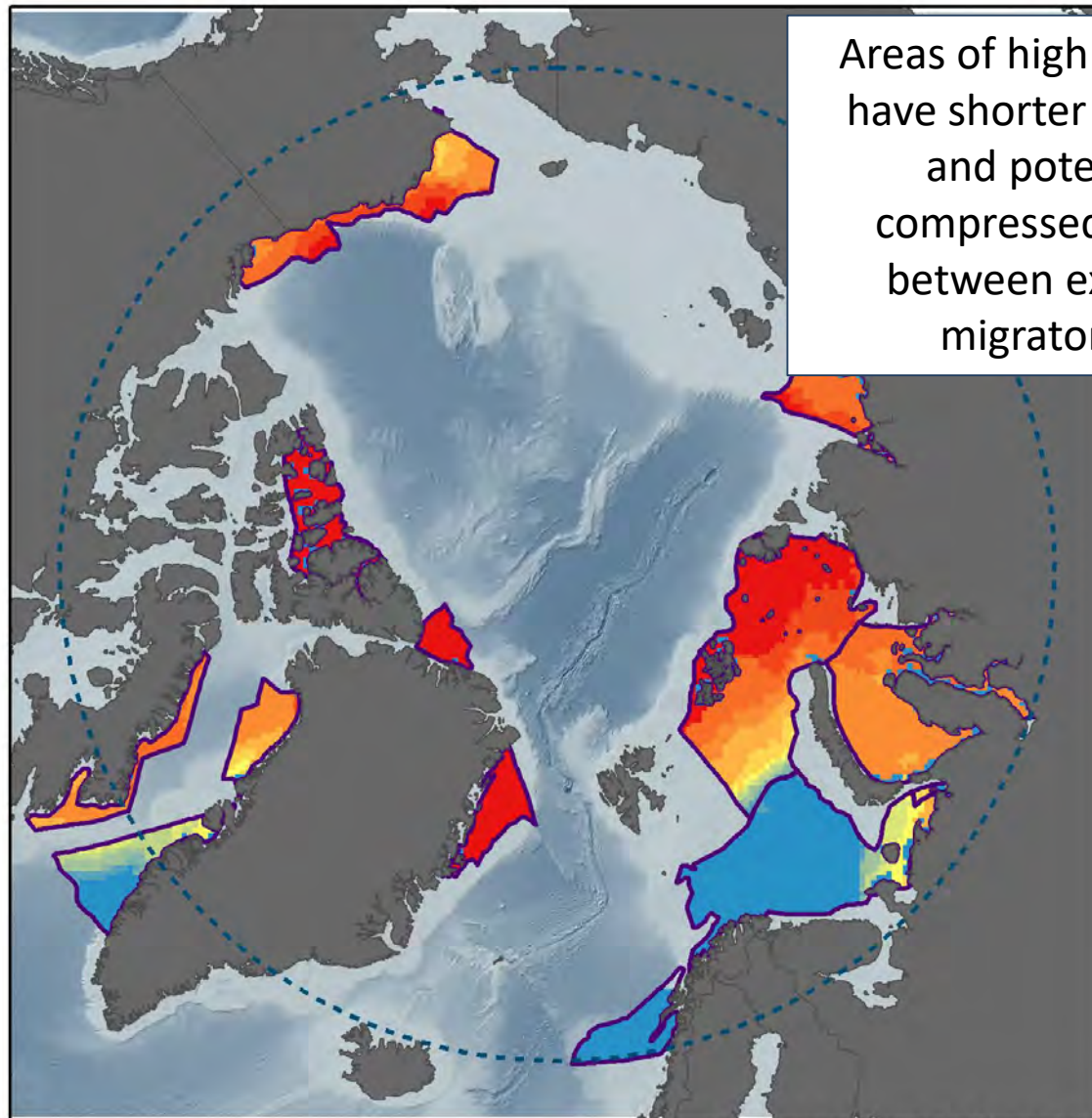
Manne Geospatial Ecology Lab, Duke University (2014)

Ecologically Important Areas and Oil and Gas Potential

-  >50% Oil or Gas Potential (within EBSA/BIA evaluation areas)
-  EBSA/BIA in High Oil or Gas Potential Areas
-  EBSA/BIA evaluation area


Ice months
vs. oil & gas
potential

Areas of high ice coverage will
have shorter ice-free seasons
and potentially more
compressed time overlaps
between exploration and
migratory species...

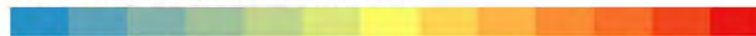


Marine Geospatial Ecology Lab, Duke University (2014)

Ice Coverage and Oil and Gas Potential

 >50% Oil or Gas Potential

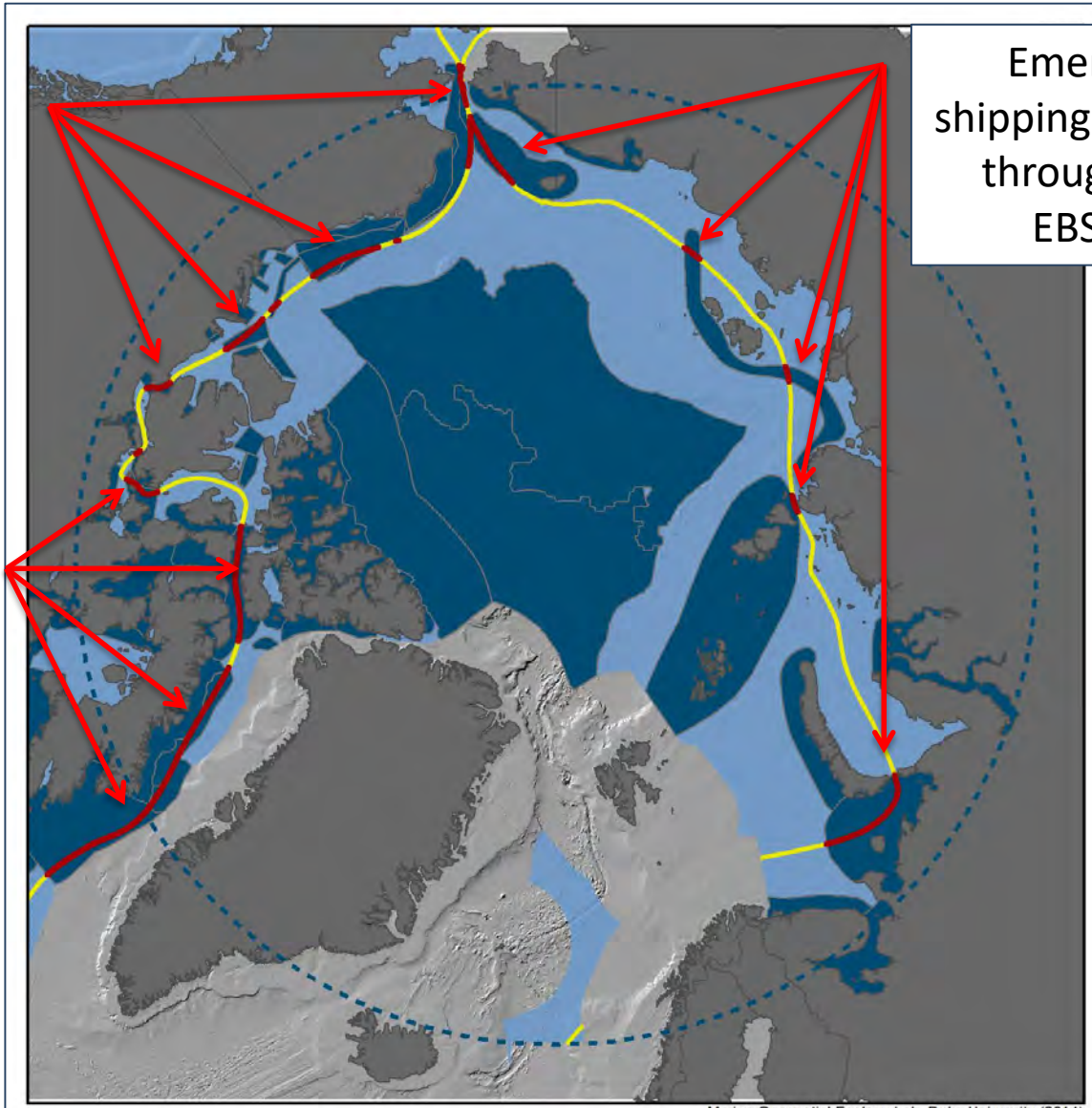
Median Ice Coverage (months covered)



0 1 2 3 4 5 6 7 8 9 10 11 12

EBSAs vs. oil & Arctic shipping routes

Emerging arctic shipping lanes will pass through identified EBSA areas...



Ecologically Important Areas and Shipping Lanes

- NEP/NWP crossing EBSA/BIA
- NEP/NWP shipping lane in EBSA/BIA evaluation area
- EBSA/BIA
- EBSA/BIA evaluation area

Connectivity risk assessment

Wetlands, low coastal tundra, lagoons:

Provide refuge, nesting, and spawning areas. Highly productive.

OIL IMPACT

Oiled, degraded or eroding habitat reduces productivity.

Pelagic Zone

Productive area for food web.

OIL IMPACT

Surface and dispersed oil affects food web. Fish eggs and larvae are especially sensitive.

Benthos

Can be highly productive, important in cycling nutrients.

OIL IMPACT

Oil in sediments reduces productivity and affects food web.

Top Predators

Marine mammal and bird populations are of global significance.

OIL IMPACT

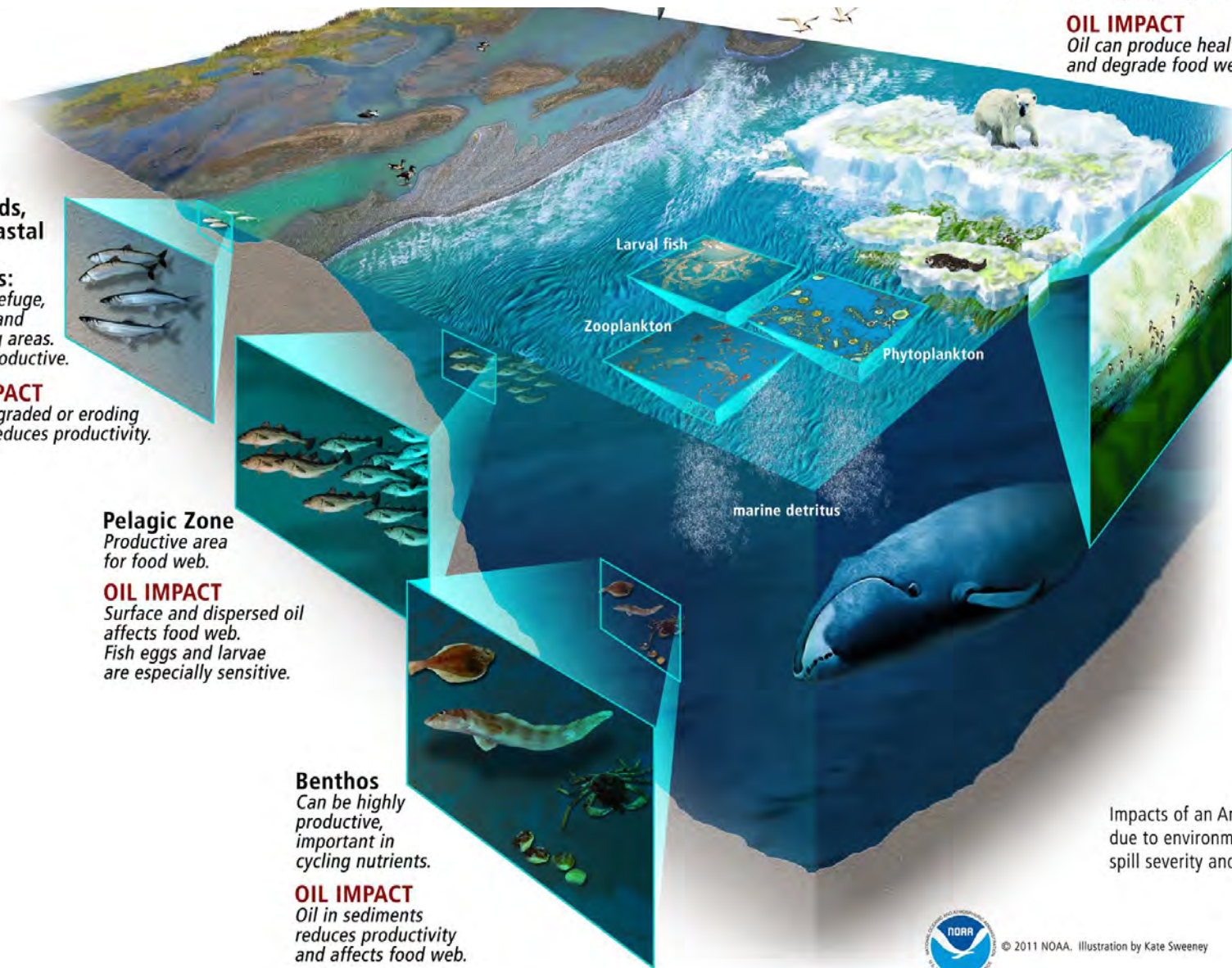
Oil can produce health effects and degrade food web.

Ice Habitat

Seasonally important source of production, habitat for marine mammals.

OIL IMPACT

Sensitivity to oiling is poorly studied.

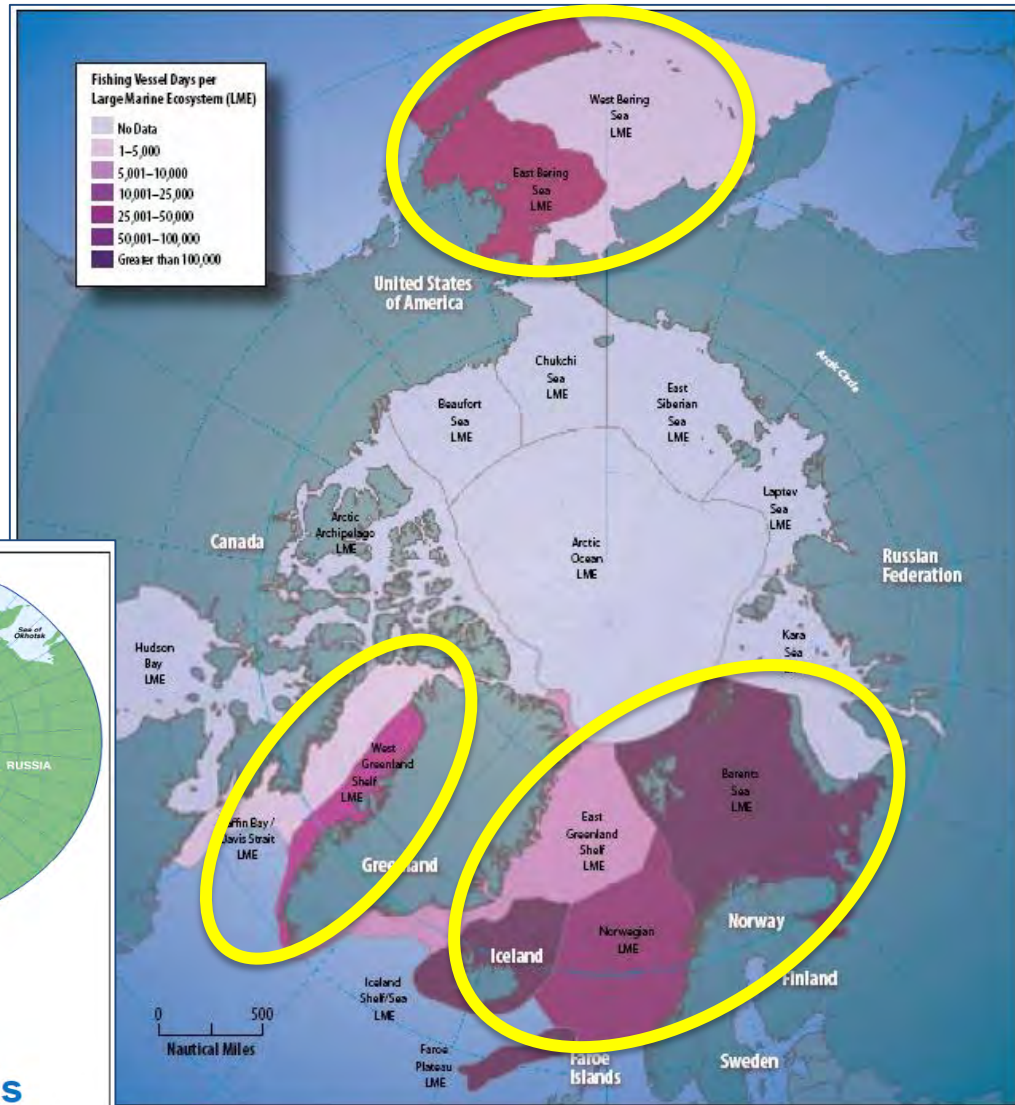


Impacts of an Arctic oil spill will vary due to environmental conditions, spill severity and response capacity.

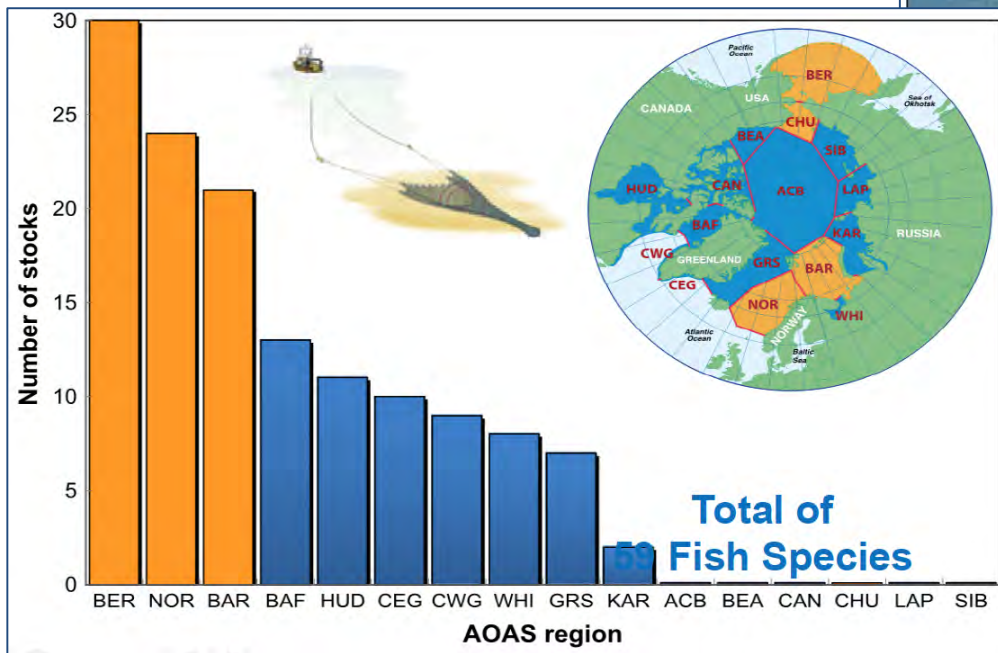


© 2011 NOAA. Illustration by Kate Sweeney

Fishing activity by Large Marine Ecoregions (LME) & AOAS regions

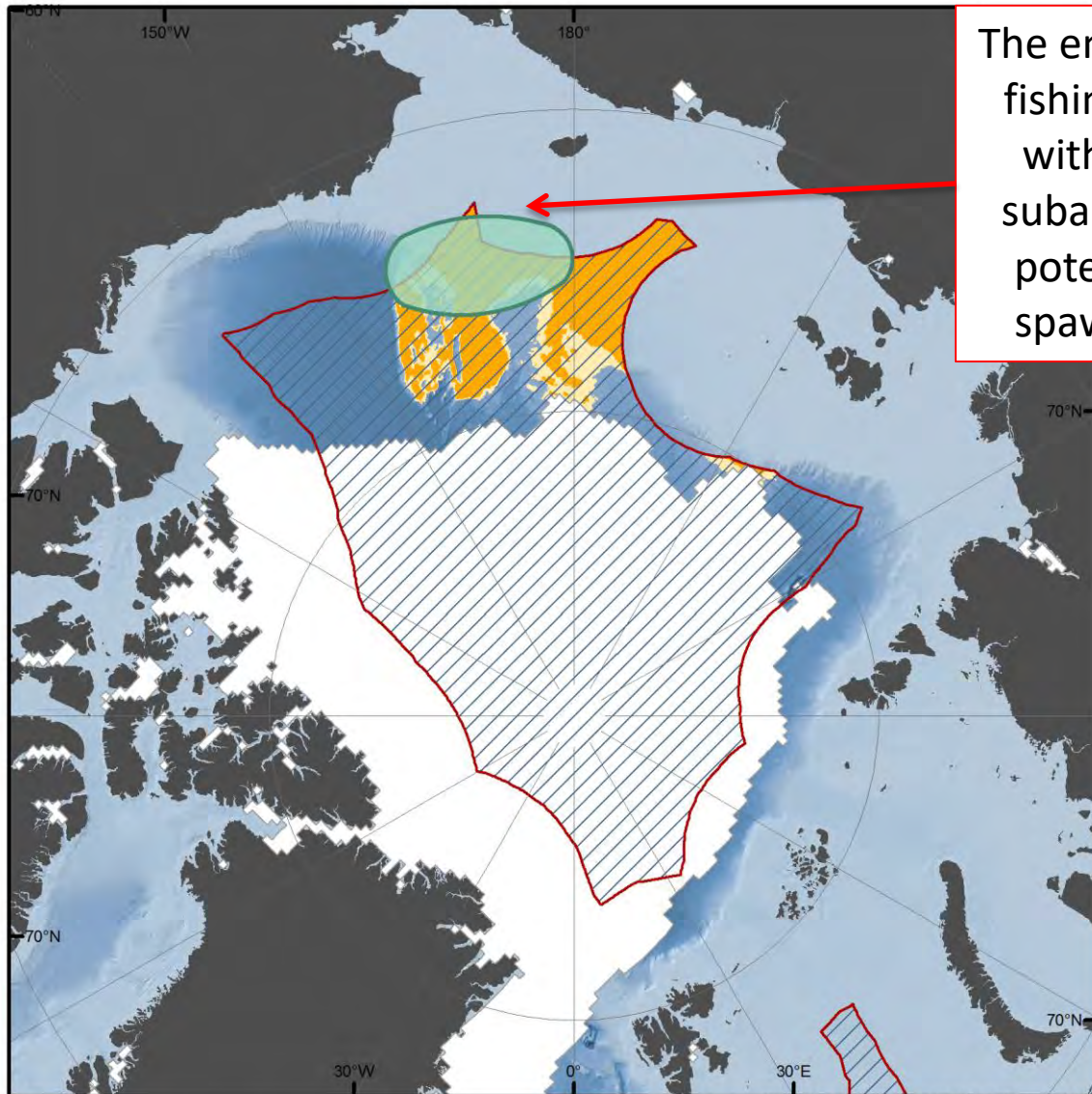


Fishing vessel activity. Source: AMSA



Potential deep sea fishing areas

Potential Arctic cod (*Arctogadus glacialis*) spawning area



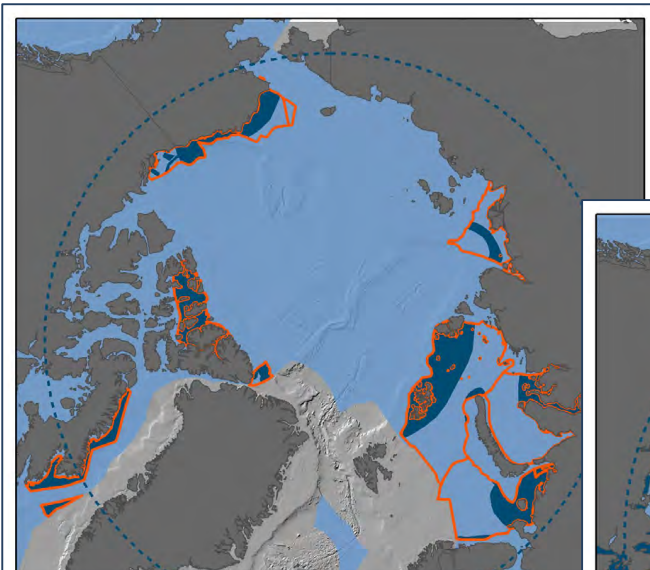
The emerging deep sea fishing area overlaps with an AMSA-II(c) subarea identified as potential Arctic cod spawning habitat ...

-  Area Beyond National Jurisdiction
-  Ice Extent, September 2012
-  1500 - 2000m deep
-  < 1500m deep
-  AMSA II(c) - subarea F3, potential Arctic Cod spawning

Marine Geospatial Ecology Lab, Duke University (2014)

Oil & gas vs. ecological importance

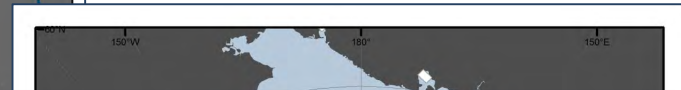
Potential space & time overlaps



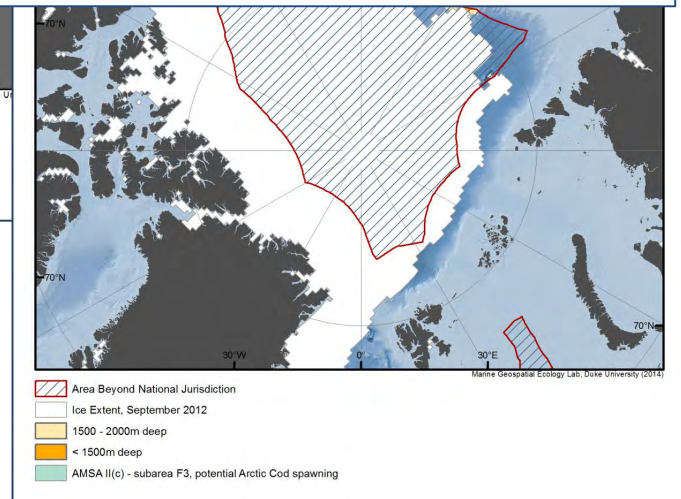
Shipping vs. ecological importance



New fisheries vs. ecological importance



Need for dynamic ocean management and near real-time decision support, data sharing, and analysis capabilities

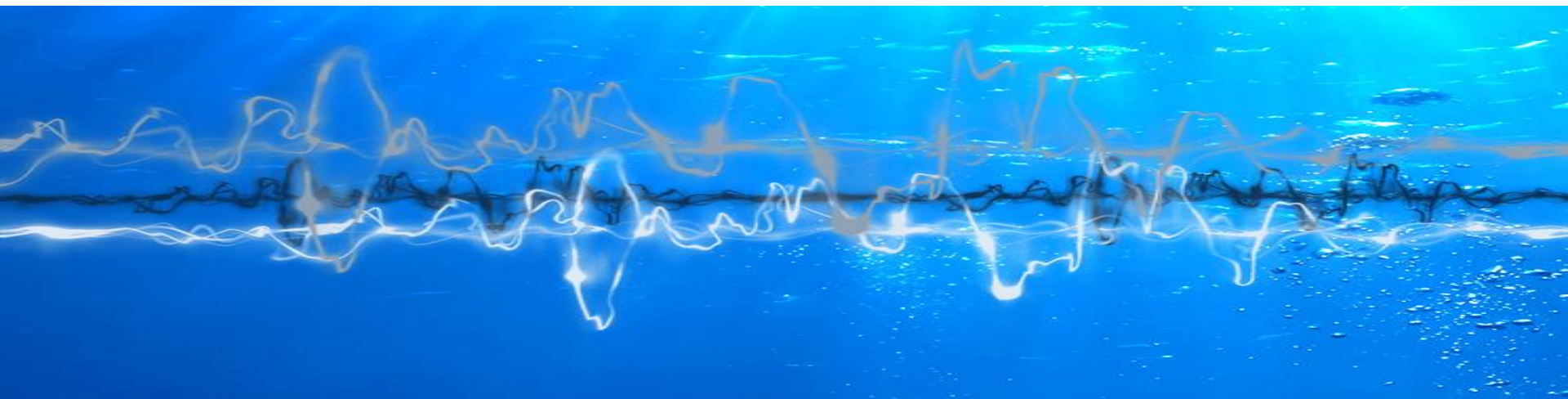


General comment: *The arctic is noteworthy for having resources use and ecological importance compressed in space & time.*



Conclusions:

- Patterns of physical connectivity in the Arctic are **not uniform** and are **rapidly changing**;
- Assessments of connectivity need to be tied to specific cases (**species**, **processes** or **functions**);
- Connectivity needs to be assessed in **space and time** across **multiple scales**;
- Connectivity cannot be assessed in isolation from **human uses in space and time**.



Discussion

