Biophysical response of the Bering Sea to projected global climate of the 21st century

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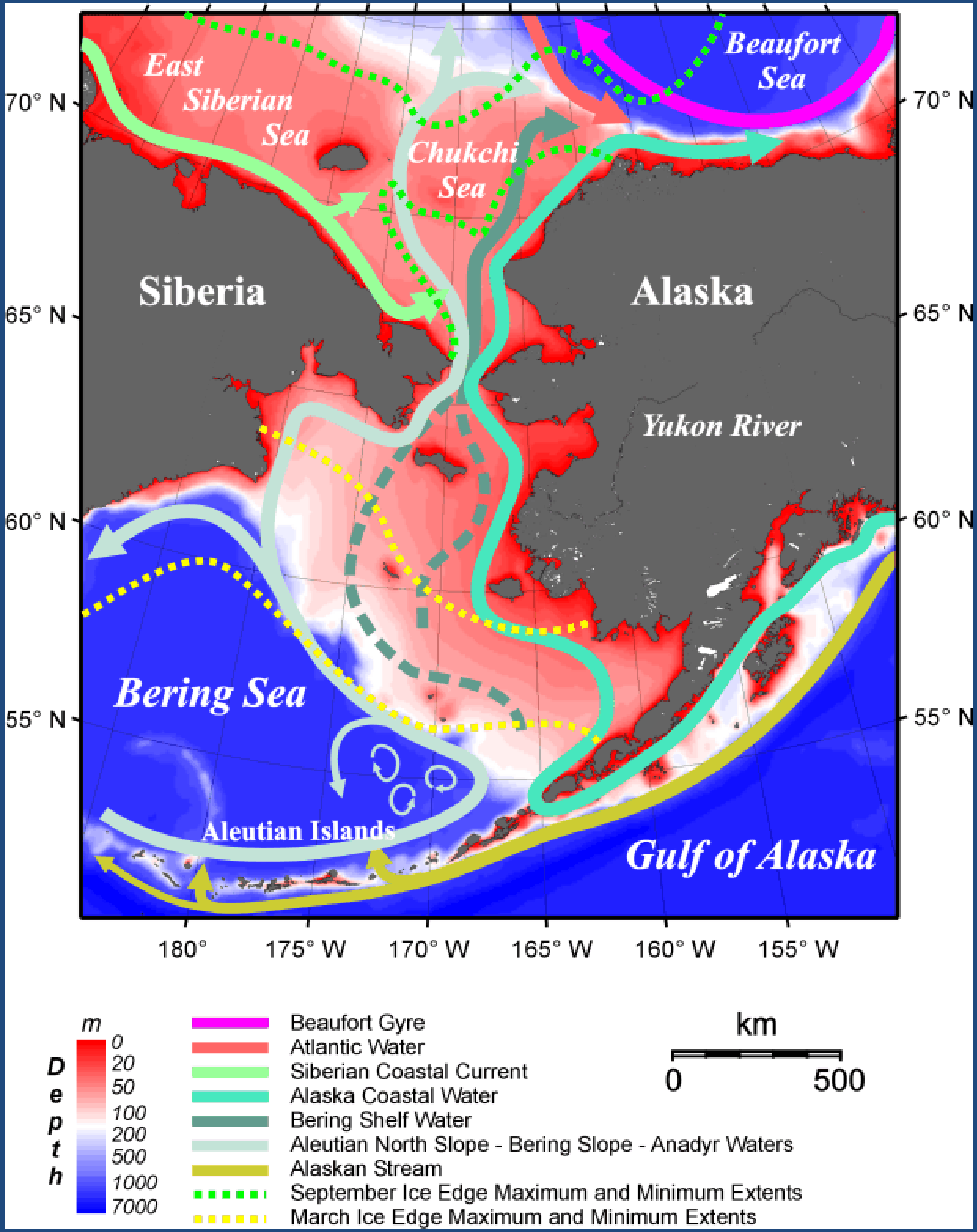
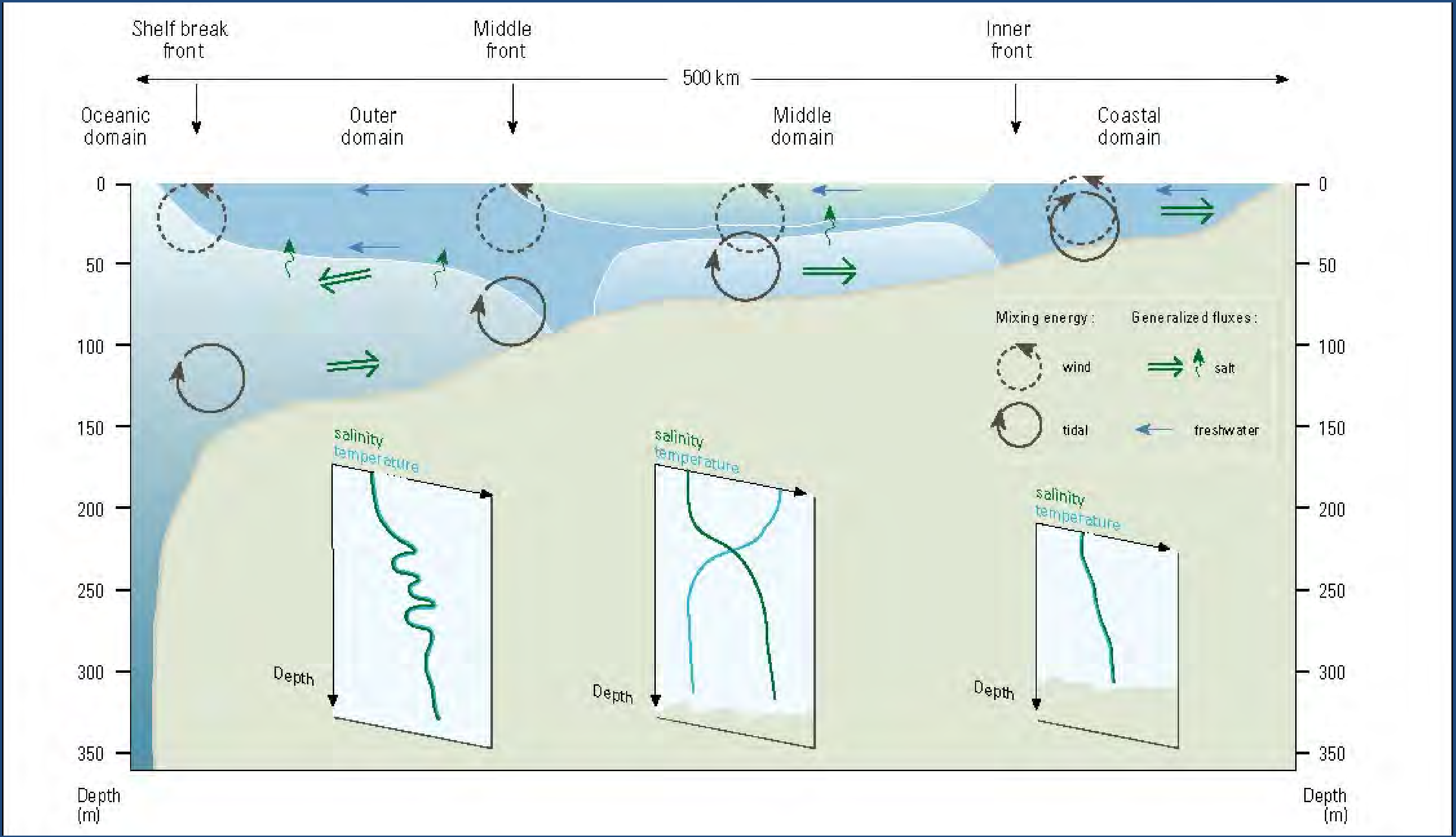
What is unique about the Bering Sea?



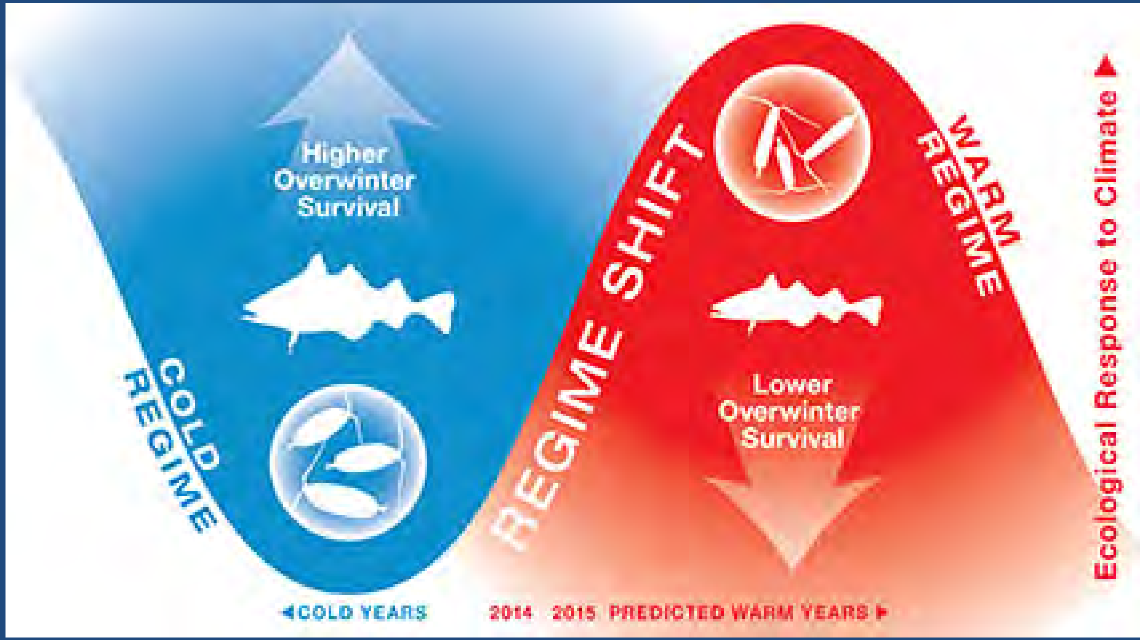
- Physical
  - Seasonal ice with advection to the south
  - Tidal mixing sets up distinct biophysical regimes
- Biological
  - Ice plankton may be a major food source to higher trophic levels
  - Benthic food chain is a major player

Biophysical domains of the Bering Sea shelf

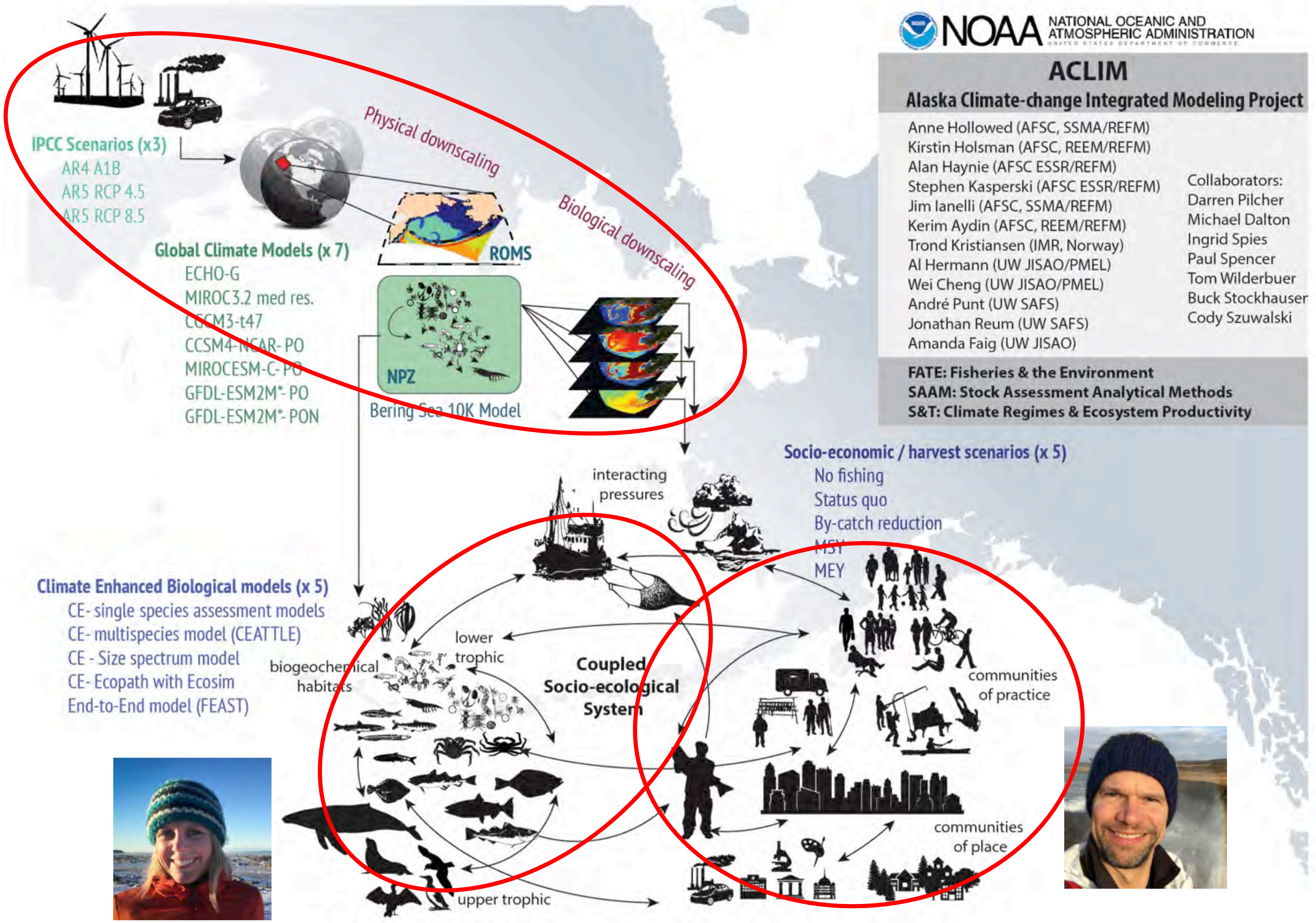


Van Pelt et al., 2015

One prevailing paradigm: cold years are good for walleye pollock



Duffy-Anderson et al., 2014


NOAA NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
ACLIM
Alaska Climate-change Integrated Modeling Project
Anne Hollowed (AFSC, SSMA/REFM)
Kirstin Holsman (AFSC, REEM/REFM)
Alan Haynie (AFSC ESSR/REFM)
Stephen Kasperski (AFSC ESSR/REFM)
Jim Ianelli (AFSC, SSMA/REFM)
Kerim Aydin (AFSC, REEM/REFM)
Trond Kristiansen (IMR, Norway)
Al Hermann (UW JISAO/PMEL)
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André Punt (UW SAFS)
Jonathan Reum (UW SAFS)
Amanda Faig (UW JISAO)
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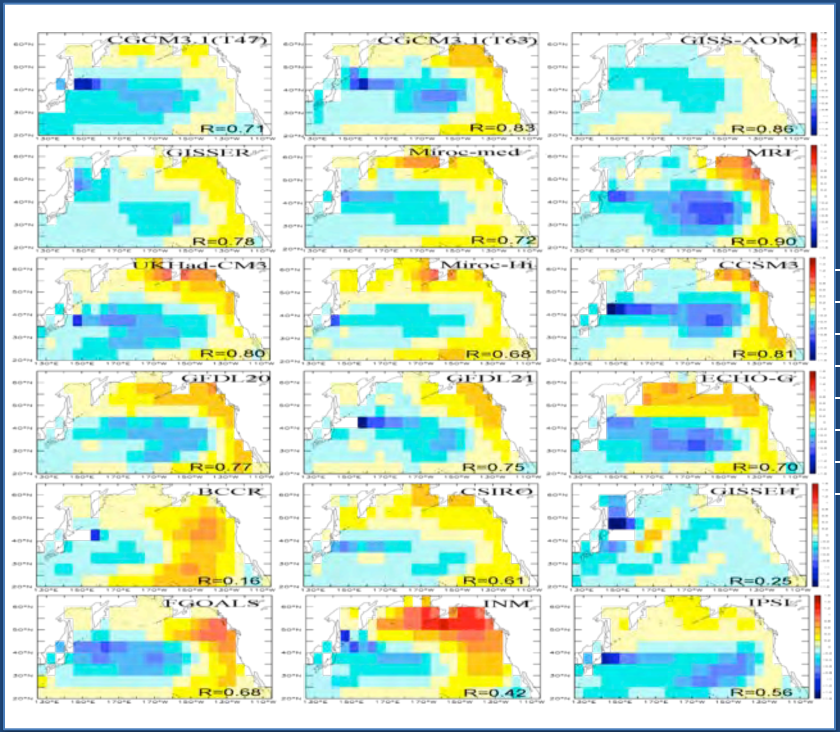
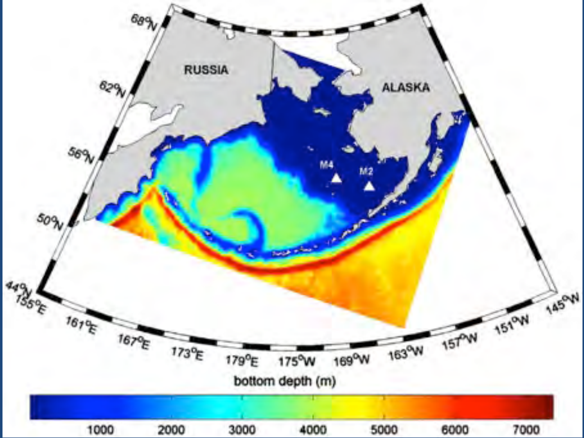
Michael Dalton
Ingrid Spies
Paul Spencer
Tom Wilderbuer
Buck Stockhauser
Cody Szuwalski
FATE: Fisheries & the Environment
SAAM: Stock Assessment Analytical Methods
S&T: Climate Regimes & Ecosystem Productivity
IPCC Scenarios (x3)
AR4 A1B
AR5 RCP 4.5
AR5 RCP 8.5
Global Climate Models (x 7)
ECHO-G
MIROC3.2 med res.
CGCM3-t47
CCSM4-NCAR-PO
MIROCESM-C-PO
GFDL-ESM2M*-PO
GFDL-ESM2M*-PON
Physical downscaling
Biological downscaling
ROMS
NPZ
Bering Sea 10K Model
Socio-economic / harvest scenarios (x 5)
No fishing
Status quo
By-catch reduction
MSY
MEY
interacting pressures
Climate Enhanced Biological models (x 5)
CE- single species assessment models
CE- multispecies model (CEATTLE)
CE - Size spectrum model
CE- Ecopath with Ecosim
End-to-End model (FEAST)
lower trophic
biogeochemical habitats
Coupled Socio-ecological System
communities of practice
communities of place
upper trophic

Climate models **provide BCs/ICs to** ***regional coupled models***

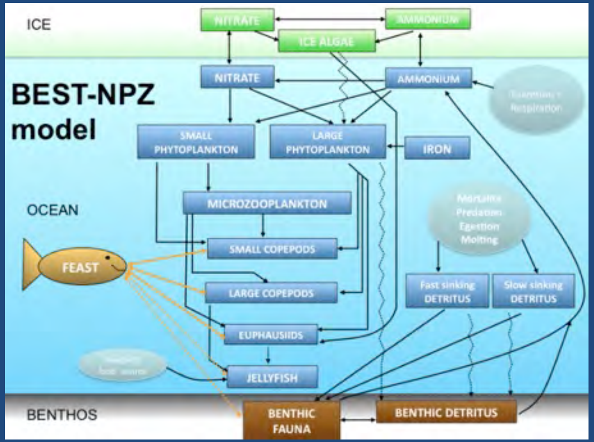


ensemble of runs

Bering10K

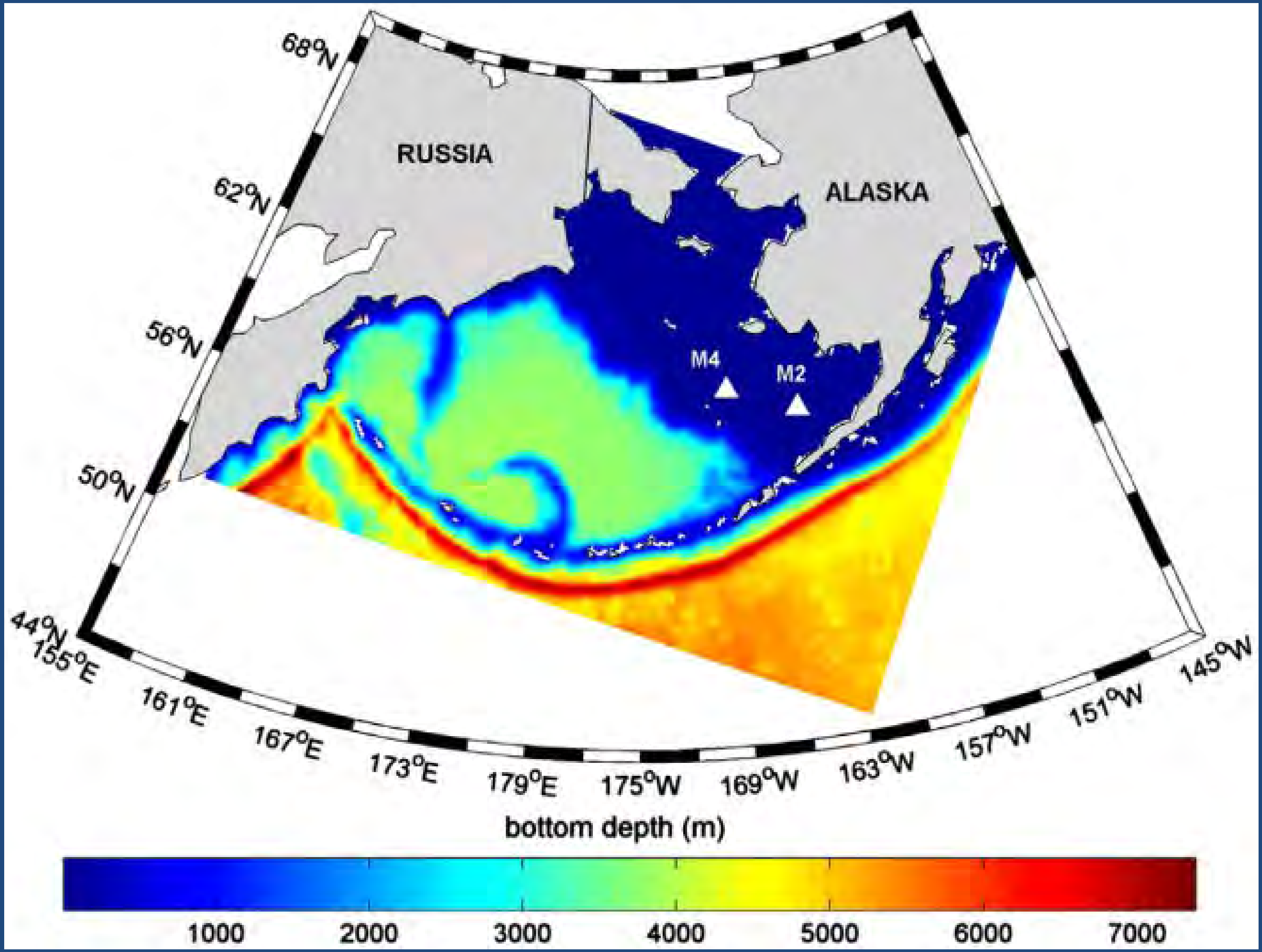


NPZ



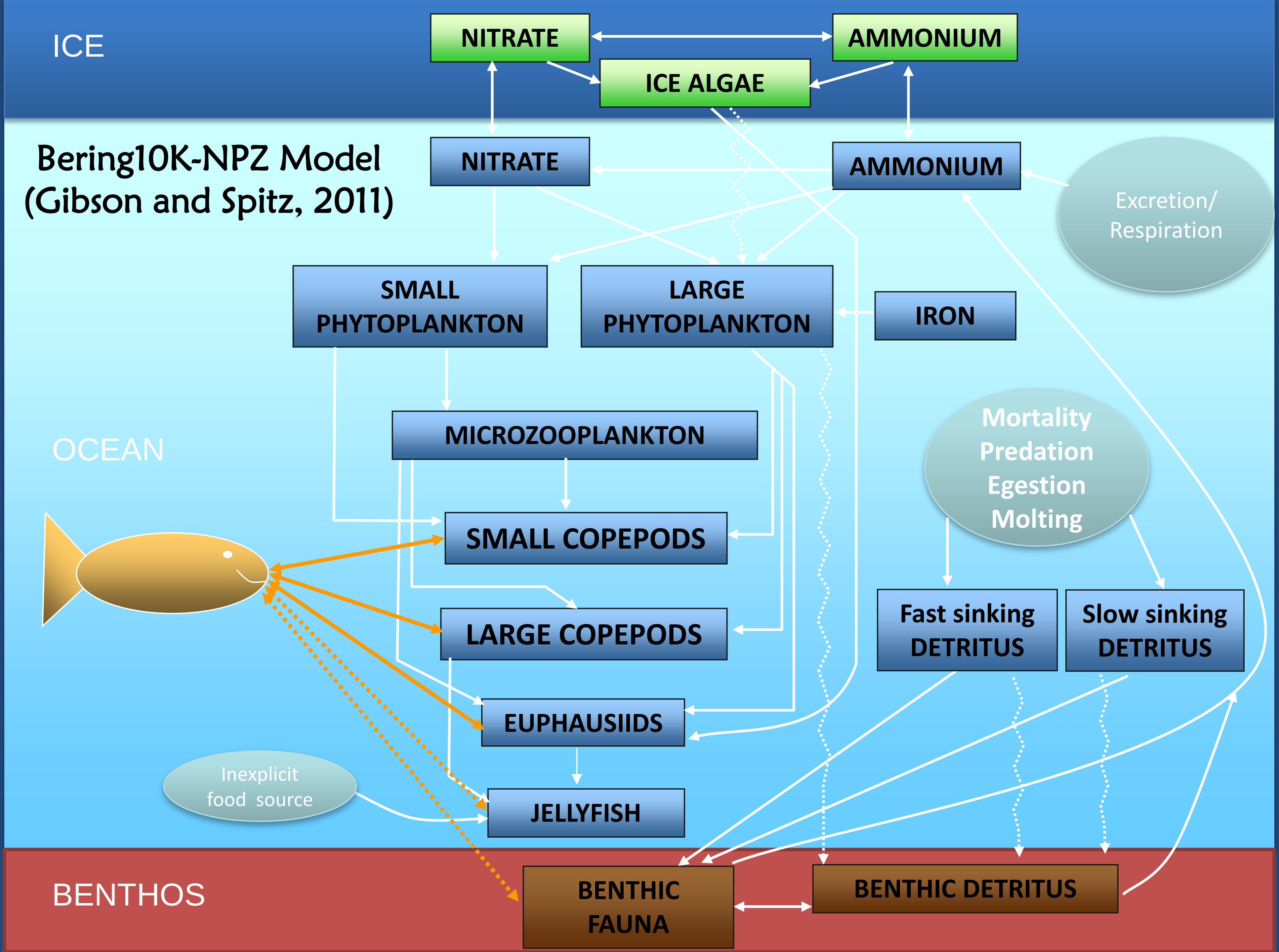
GOAL:
mutidecadal
projections of physics and biology in the Bering Sea

ensemble of projected futures



Bering10K model

- Regional Ocean Modeling System (ROMS)
- Descendent of NEP5 (Danielson et al. 2012)
- 10 layers, 10-km grid
- Includes ice and tides
- CCSM bulk flux
- Details in Hermann et al. (DSR2, 2013, 2016)



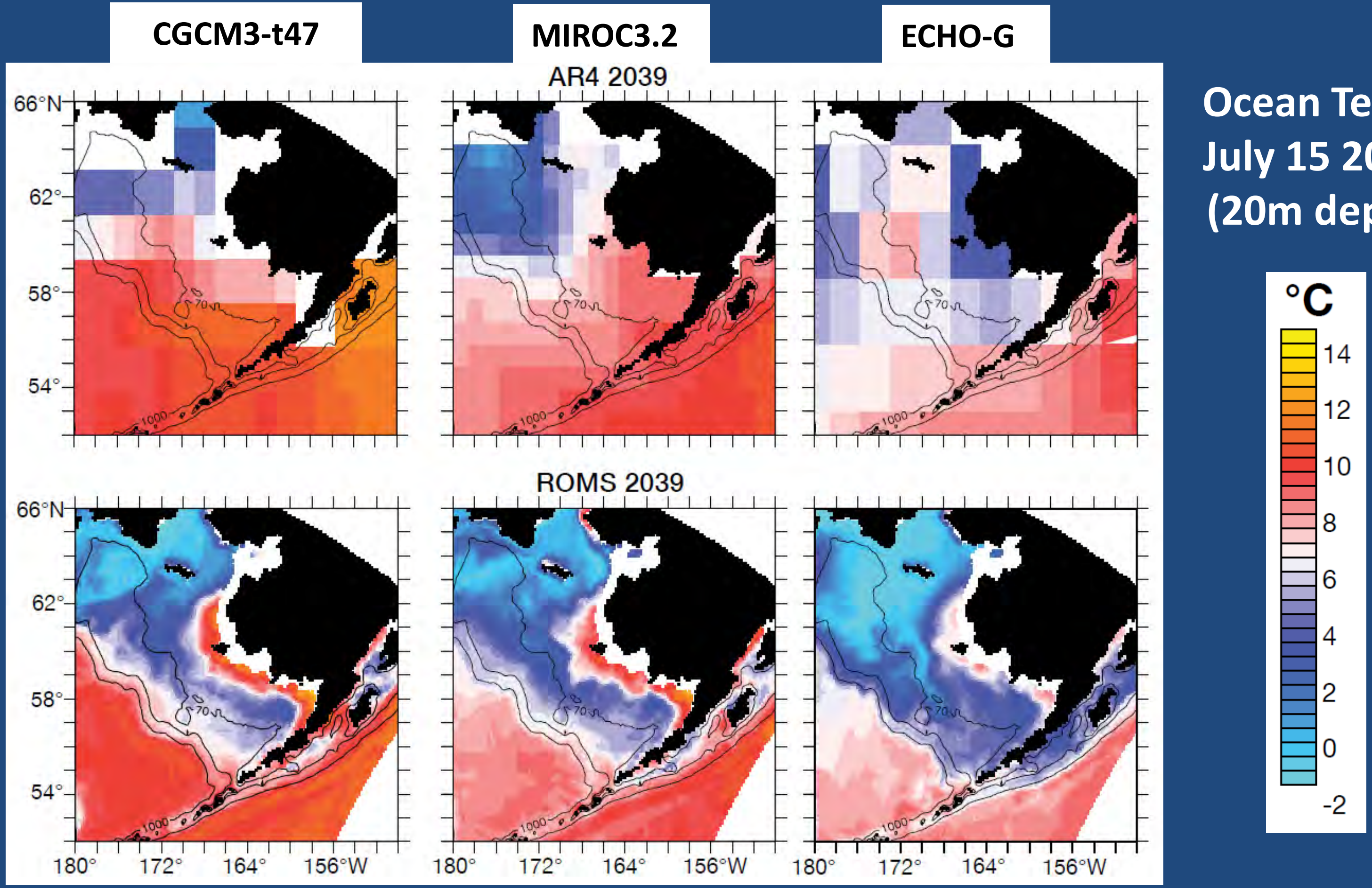
Calibration:
K. Kearney

Newly added
carbonate system
(D. Pilcher)

Dynamical downscaling achieves finer spatial resolution

Global models
(AR4)

Regional model
(Bering10K)

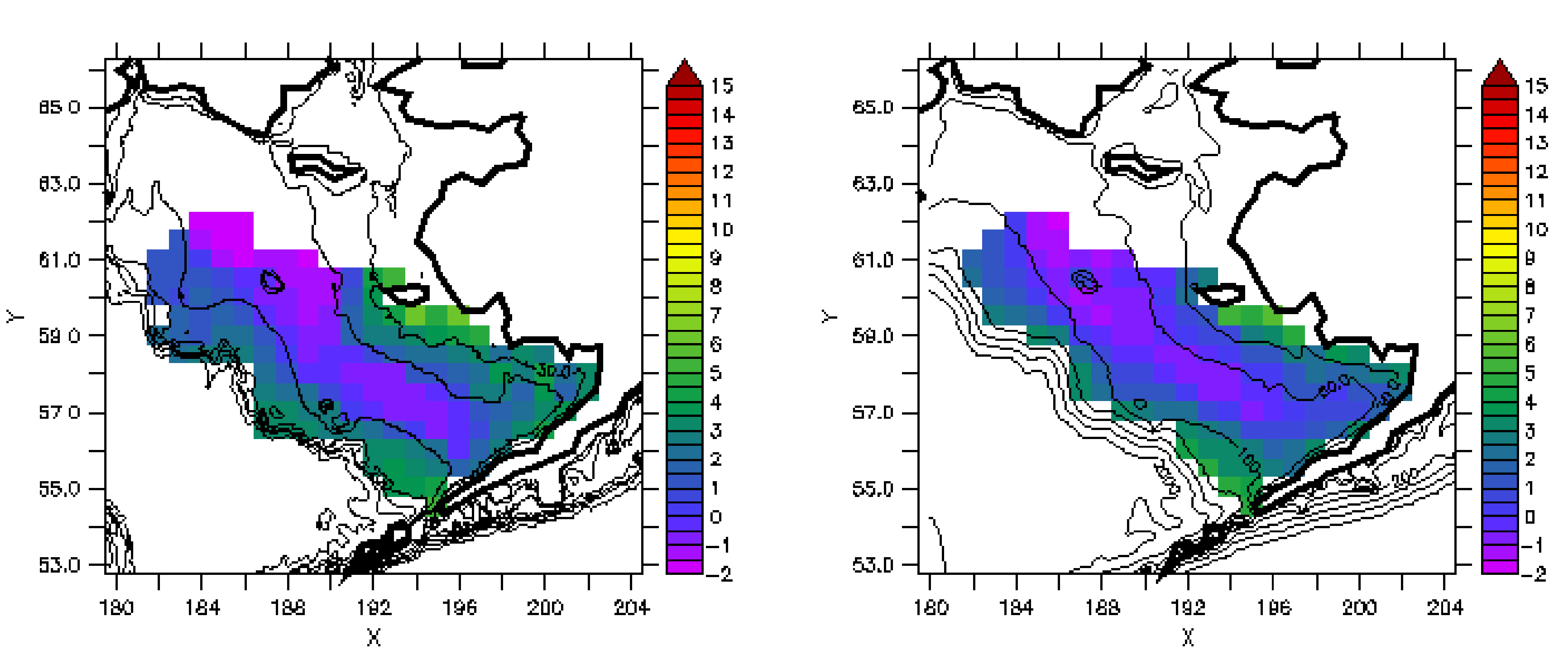


Ocean Temp
July 15 2039
(20m depth)

IPCC global atmosphere provides *surface forcing*
IPCC global ocean provides *boundary conditions*

Bering10K validation: the "Cold Pool"

DATA MODEL



Bottom Temp in deg C, summer 2009

Hindcasts and seasonal forecasts of the cold pool

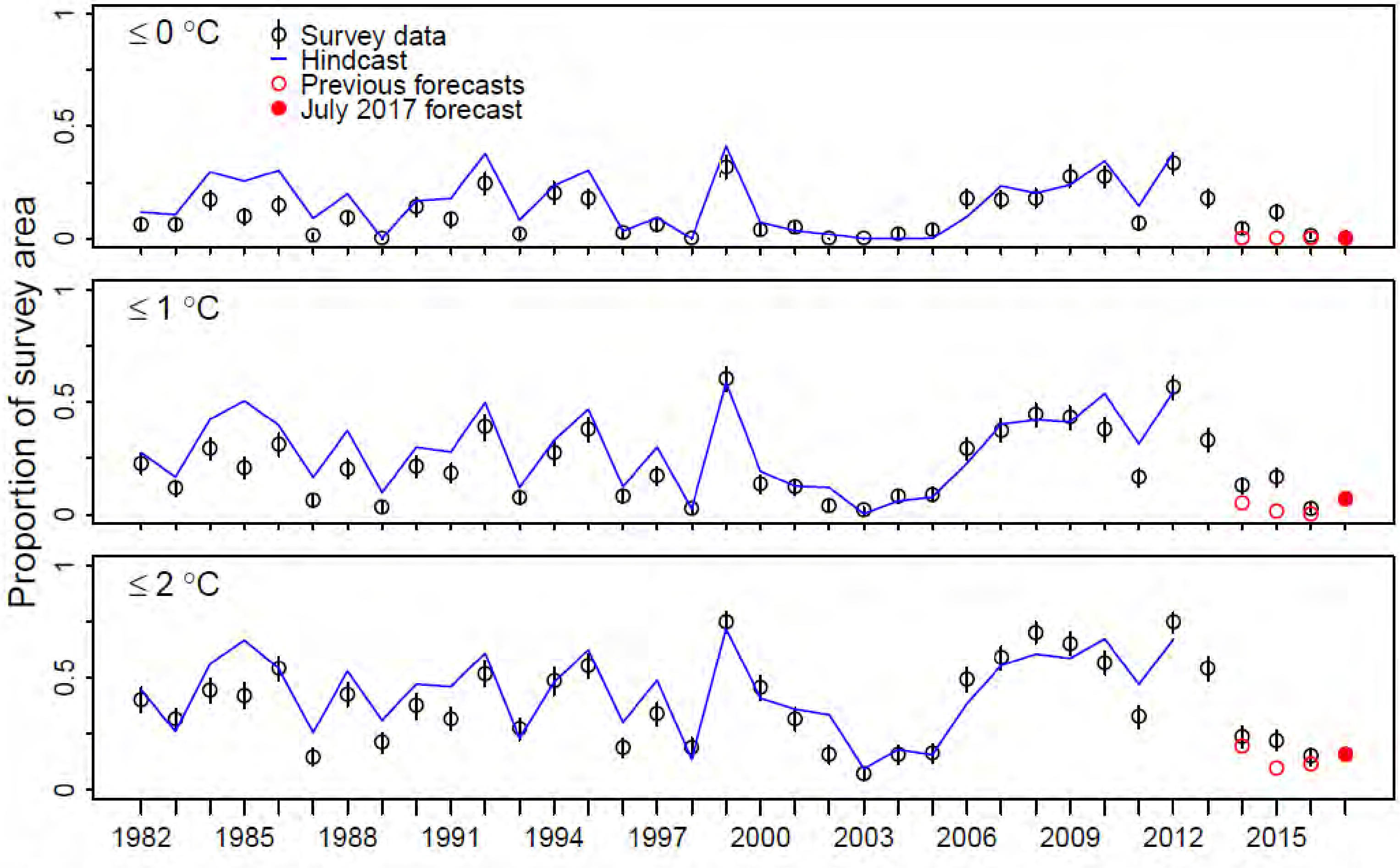
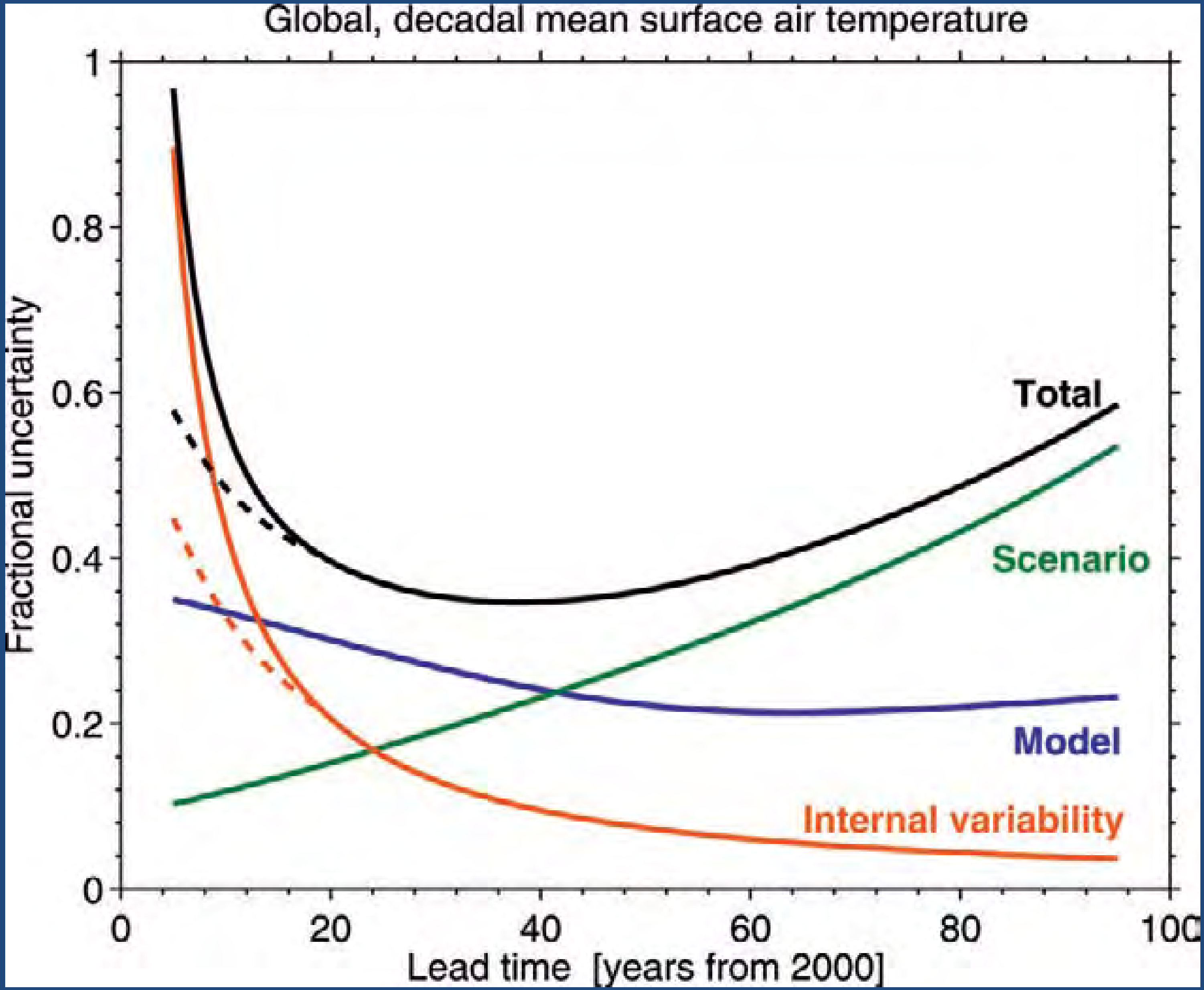


Figure 5: The eastern Bering Sea cold pool with limits of 0°C, 1°C, and 2°C. Shown are BTS survey data, ROMS hindcast results 1982-2012, and ROMS 9-month ahead predictions. The most recent prediction, made in October 2016, is shown for summer 2017.

Seasonal forecasts provided annually to management!

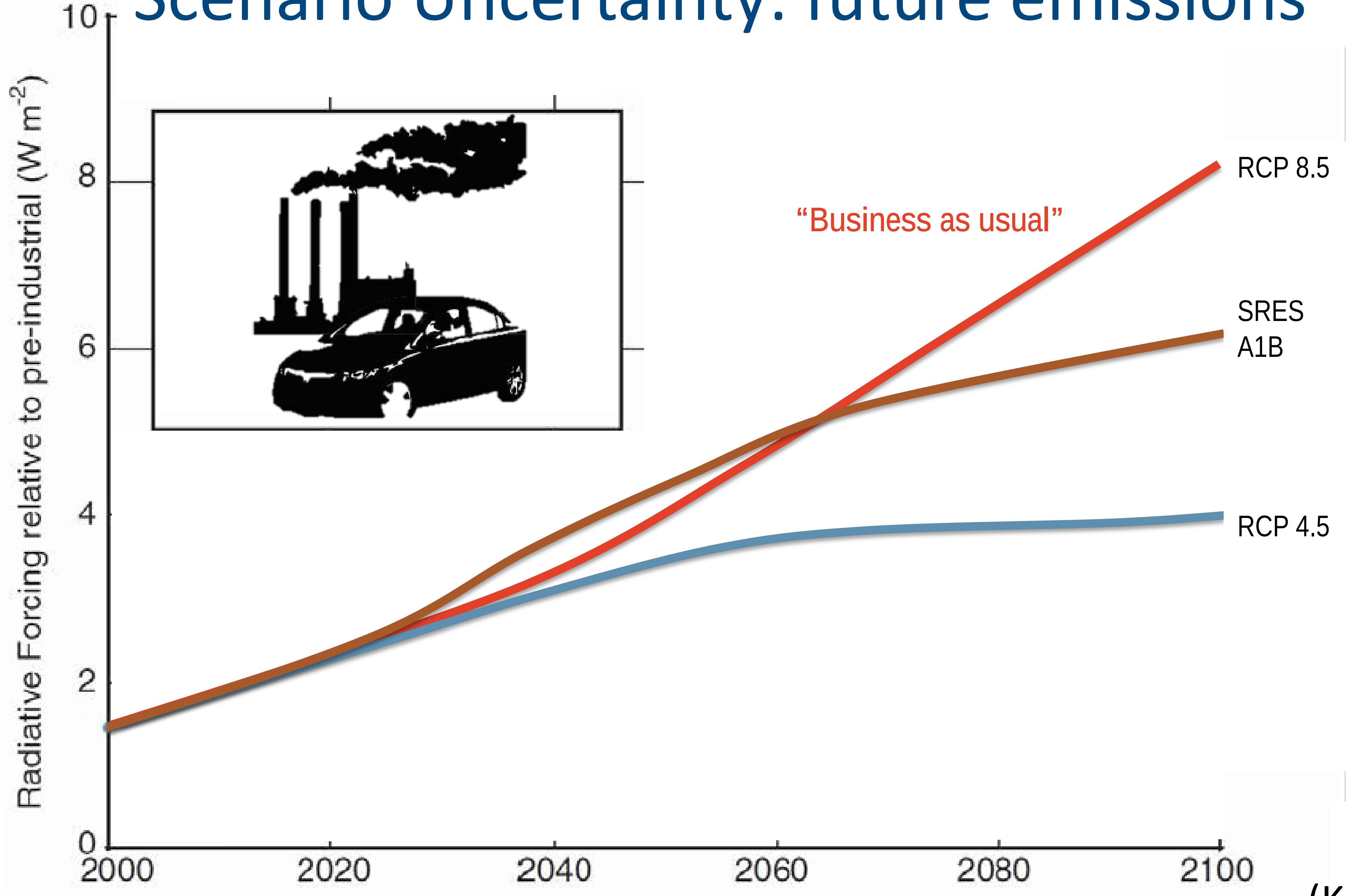
(Zador et al., 2016)

Sources of uncertainty in climate predictions (Hawkins and Sutton, 2009)



- Scenario (emissions)
- Structural (model)
- Internal (intrinsic)

Scenario Uncertainty: future emissions



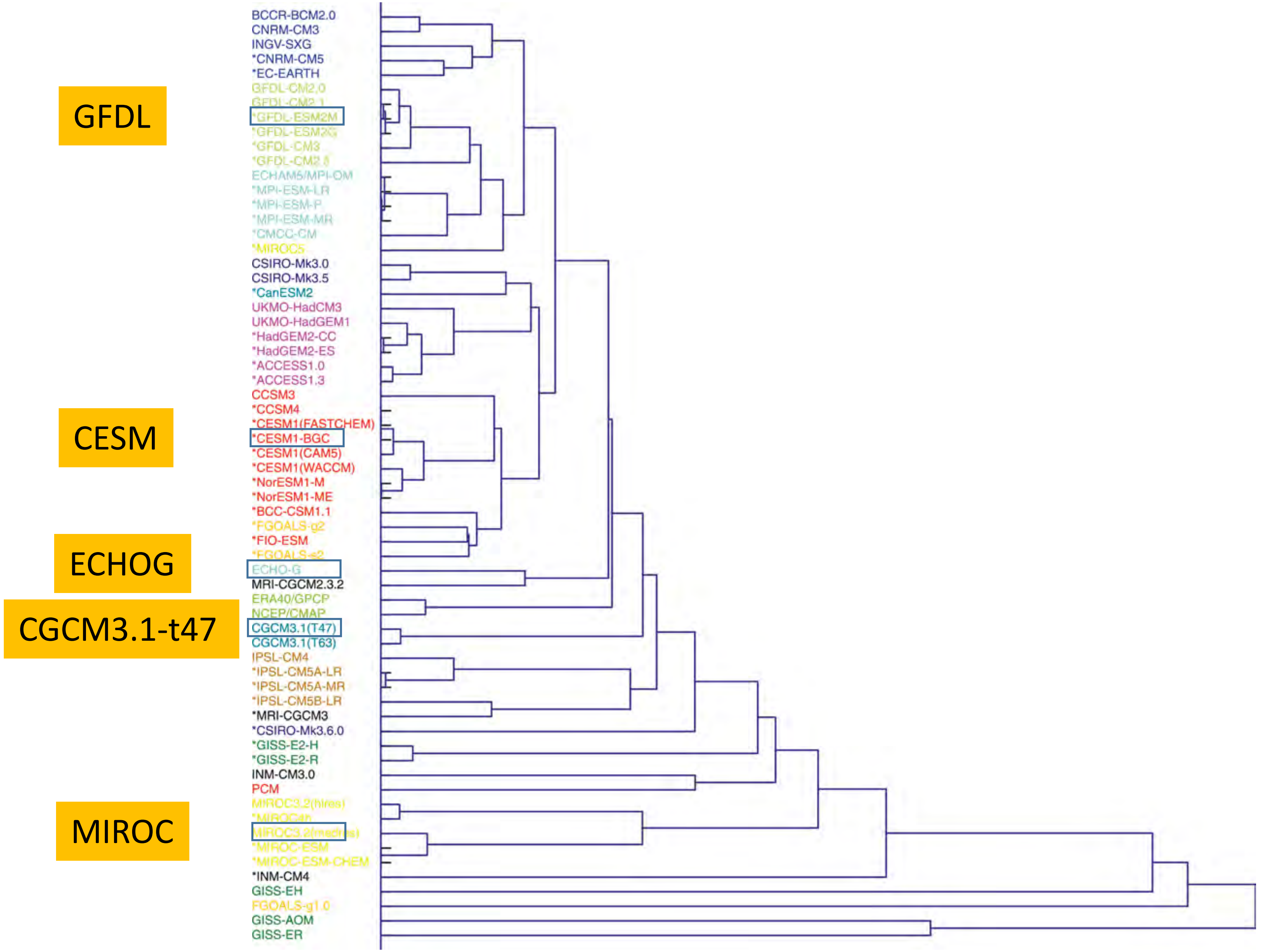
(K. Holsman)

Scenario/Structural uncertainty in this study

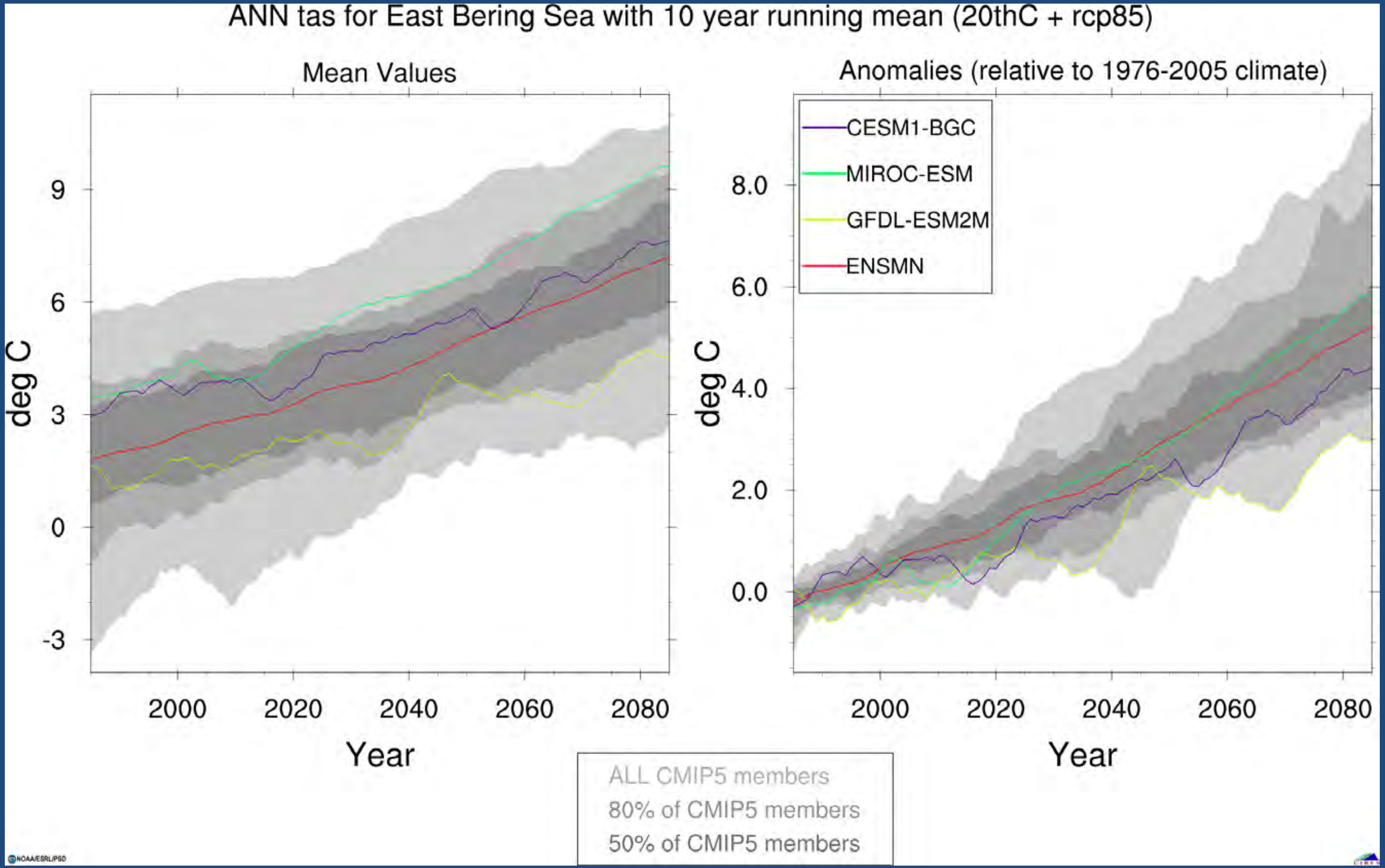
- A1B
  - CGCM3.1-t47
  - ECHOG
  - MIROC
- rcp4.5
  - GFDL
  - CESM
  - MIROC
- rcp8.5
  - GFDL
  - GFDL w/bio
  - CESM
  - CESM w/bio
  - MIROC

- A1B runs used for 2000-2040
- rcp4.5/rcp8.5 runs used for 2010-2100

Knutti et al. dendogram of CMIP3/CMIP5 control states (based on SST and precip fields)

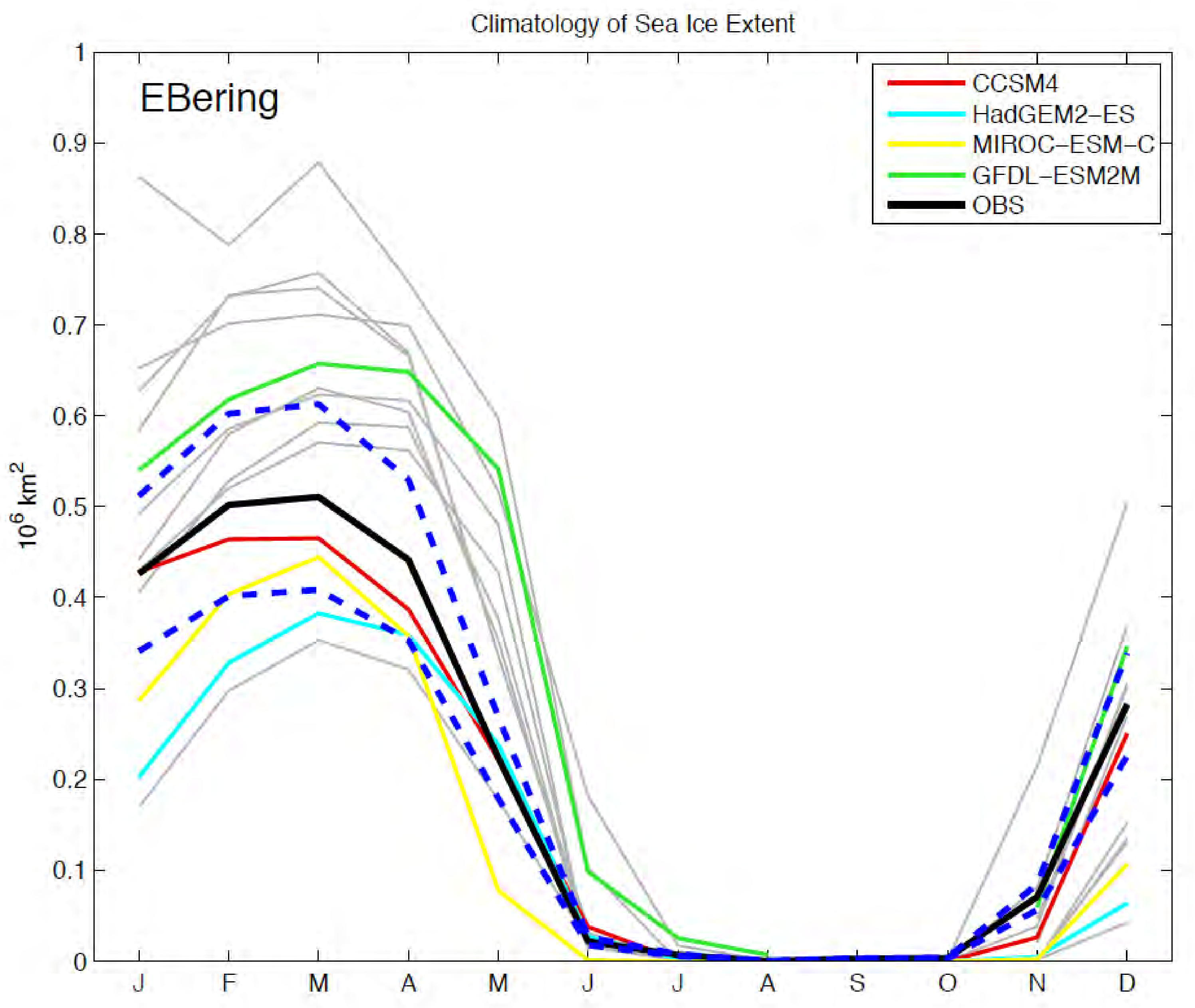


CMIP5 projected air temperature in the EBS (rcp8.5)

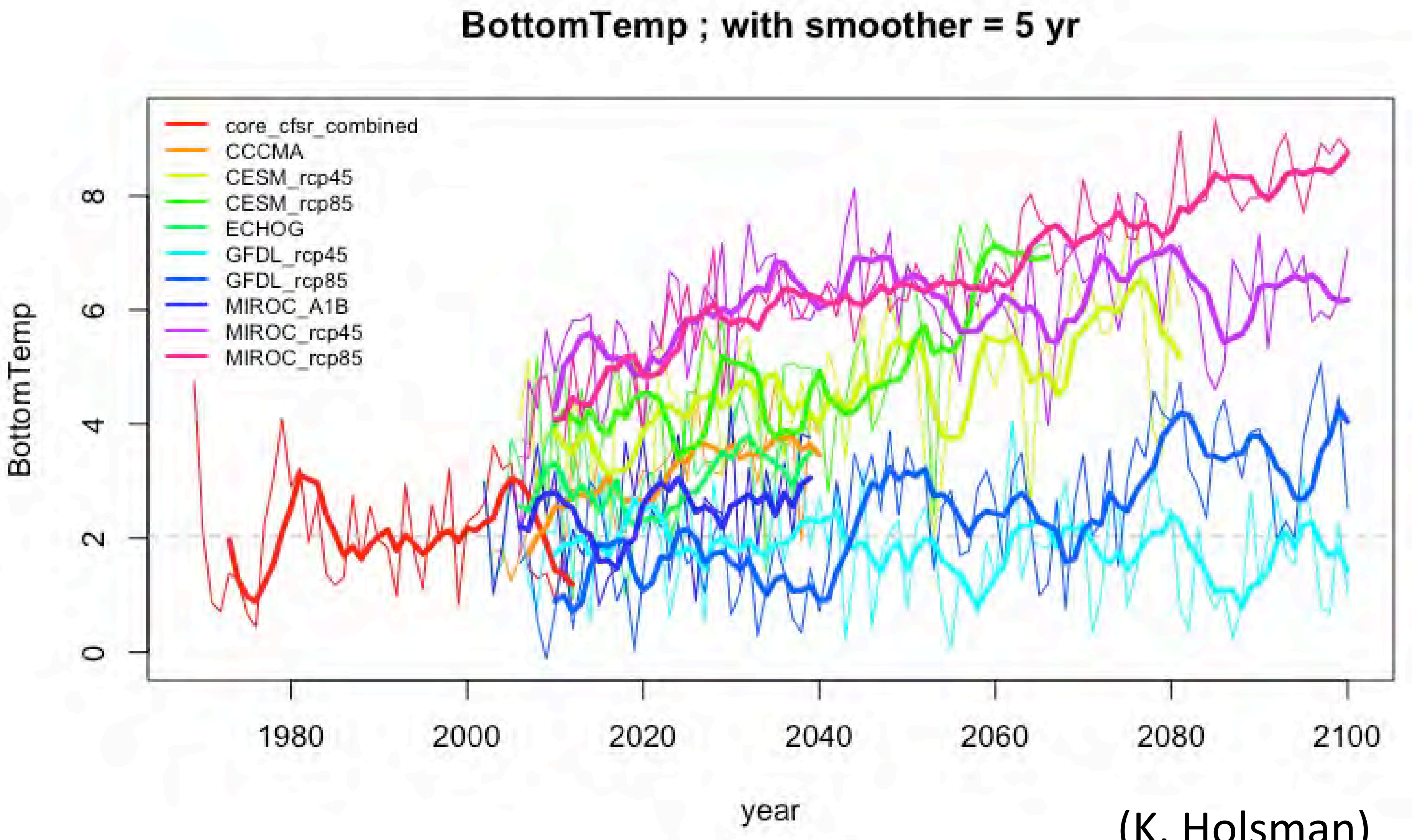


(from NOAA climate change web portal)

Ice climatology for the Eastern Bering Sea (M. Wang)



Downscaling results: SE shelf sea bottom temperature



(K. Holsman)

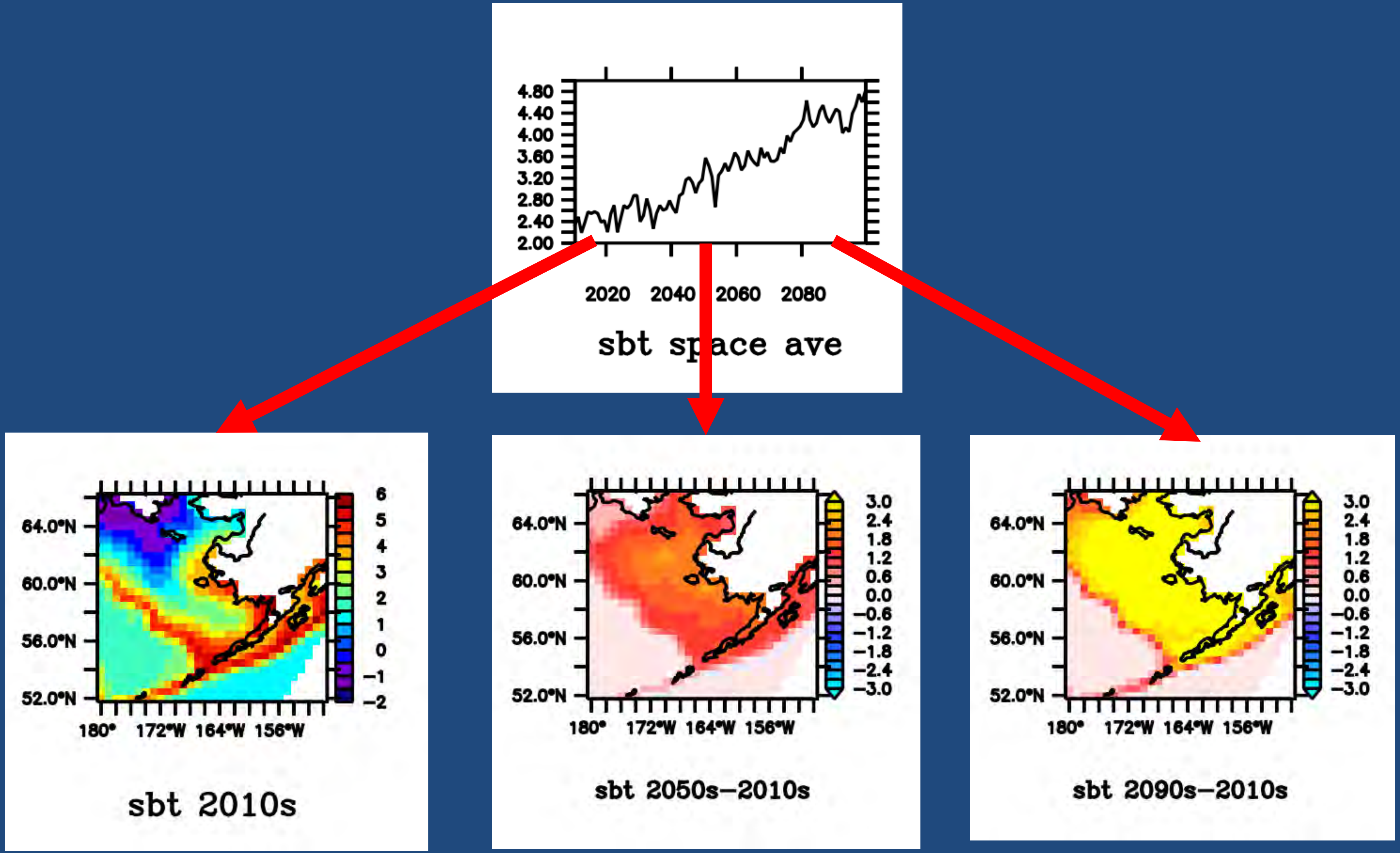
Variables analyzed

Sea bottom temperature — Bottom Temperature

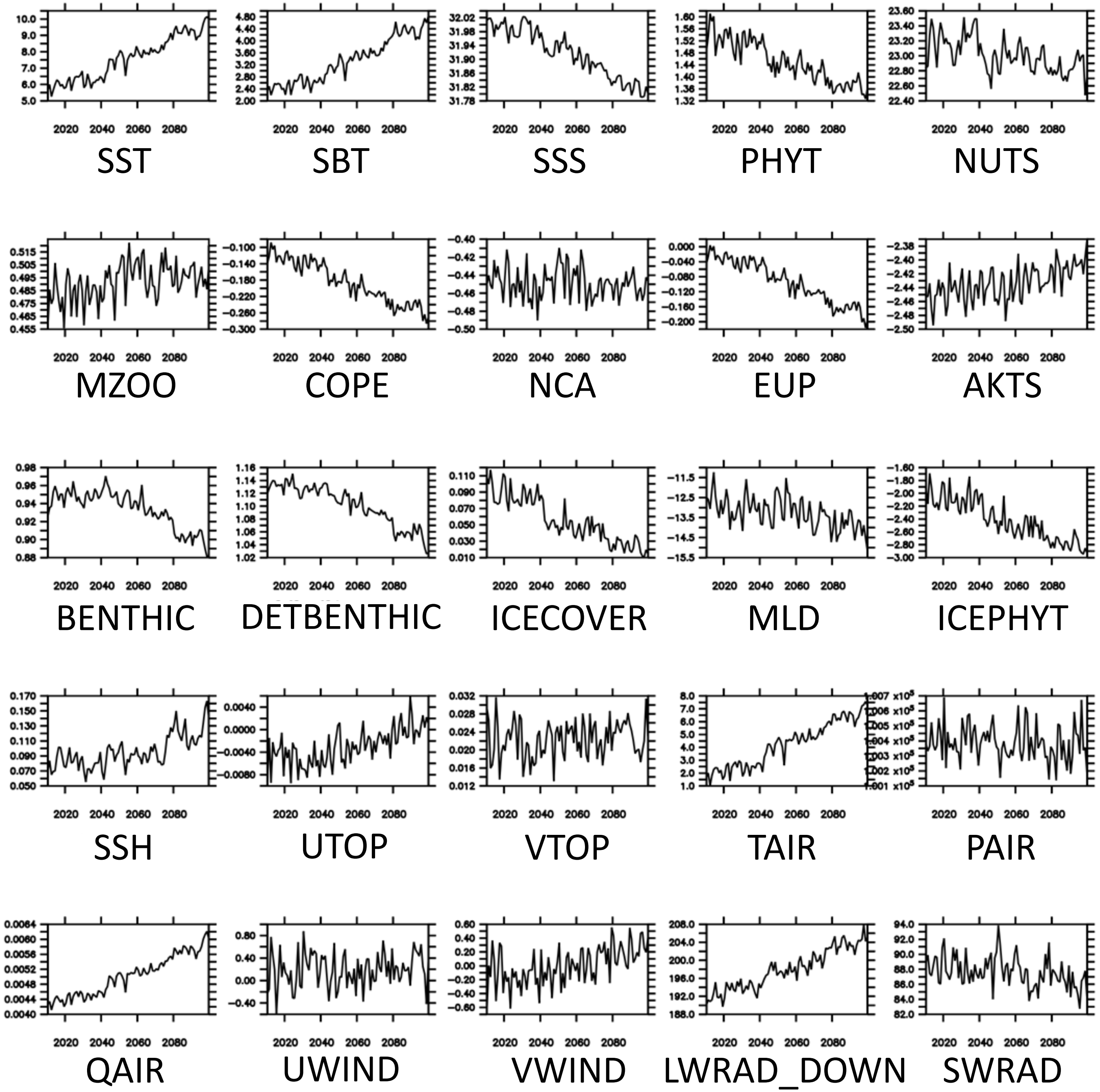
Large crustacean zooplankton — Small Copepods, Neocalanus, Euphausiids

Surface Temperature	SST	^oC
Bottom Temperature	SBT	^oC
Surface Salinity	SSS	psu
Ice cover	ICECOVER	fractional area
Mixed Layer Depth	MLD	m (positive up coordinates; hence negative change denotes deepening MLD)
Vertical Mixing (depth ave)	AKTS	$m^2 s^{-1}$
Nitrate + Ammonium (depth ave)	NUT	$mgN\ m^{-3}$
Ice Phytoplankton	ICEPHYT	$mgC\ m^{-3}$
Small plus Large Phytoplankton (depth ave)	PHYT	$mgC\ m^{-3}$
Microzooplankton (depth ave)	MZOO	$mgC\ m^{-3}$
Small Copepods (depth ave)	COPE	$mgC\ m^{-3}$
Neocalanus (depth ave)	NCA	$mgC\ m^{-3}$
Euphausiids (depth ave)	EUP	$mgC\ m^{-3}$
Benthic detritus	DETBENTHIC	$mgC\ m^{-2}$
Benthic infauna	BENTHIC	$mgC\ m^{-2}$
Sea Surface Height	SSH	m
Sea Surface cross-shelf velocity	UTOP	$m\ s^{-1}$
Sea Surface alongshelf velocity	VTOP	$m\ s^{-1}$
Air Temperature	TAIR	^oC
Air Pressure	PAIR	mbar
Specific Humidity	QAIR	$kg\ kg^{-1}$
Zonal wind	UWIND	$m\ s^{-1}$
Meridional wind	VWIND	$m\ s^{-1}$
Downward longwave radiation	LWRAD_DOWN	$W\ m^{-2}$
Downward shortwave radiation	SWRAD	$W\ m^{-2}$

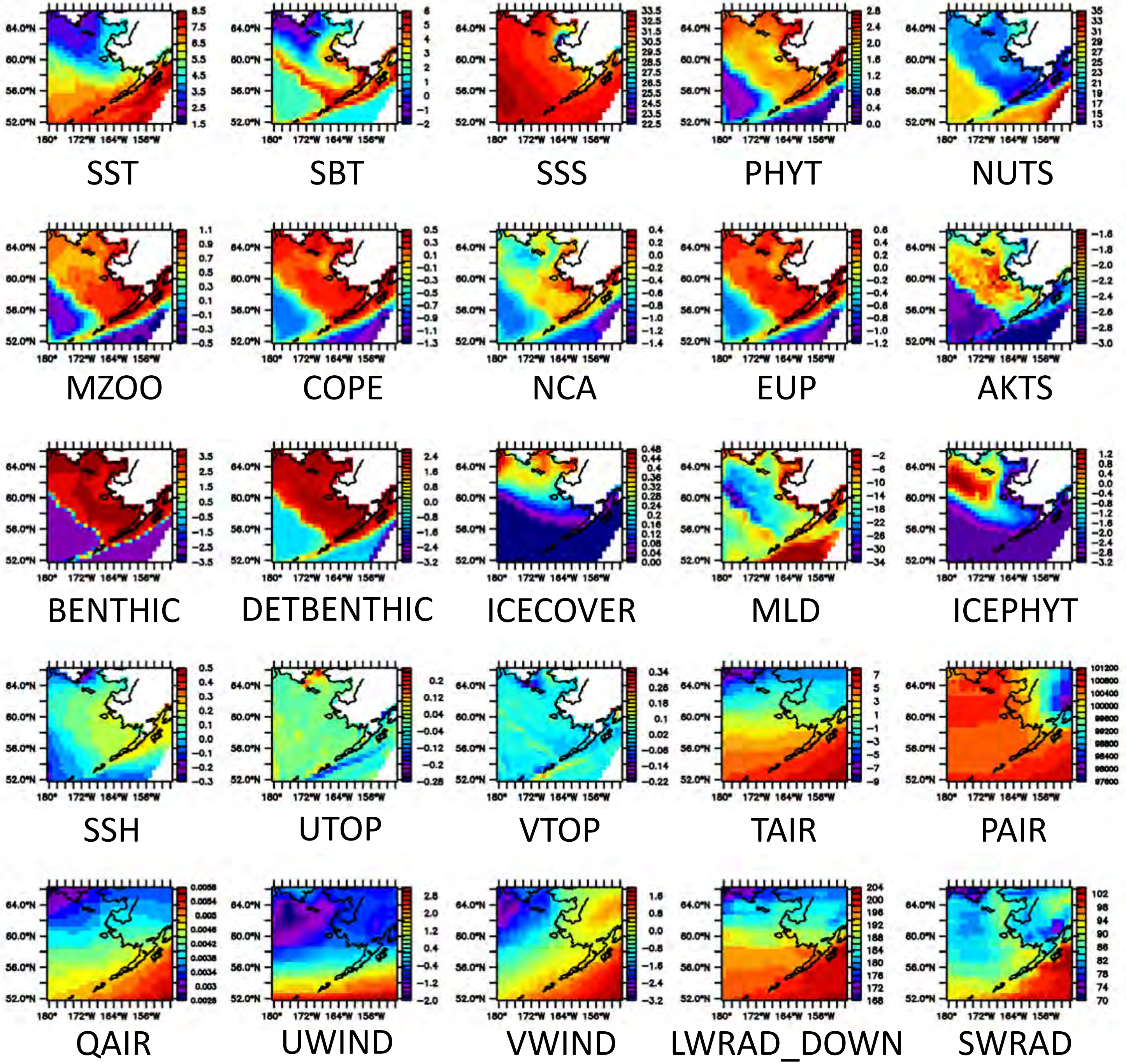
Decadal average change in bottom temperature (rcp8.5)



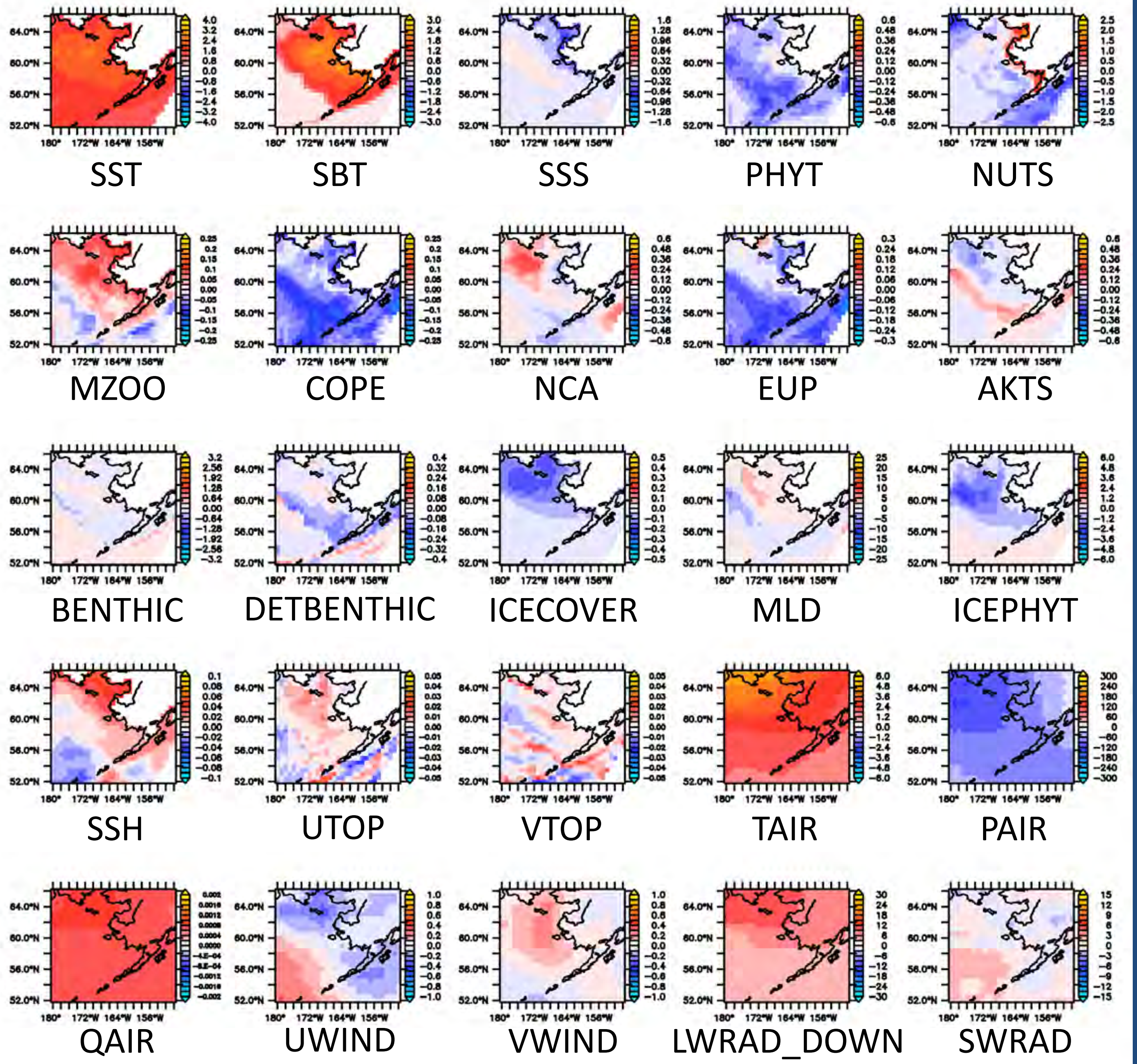
Trends of spatial averages 2010-2100 (rcp8.5)



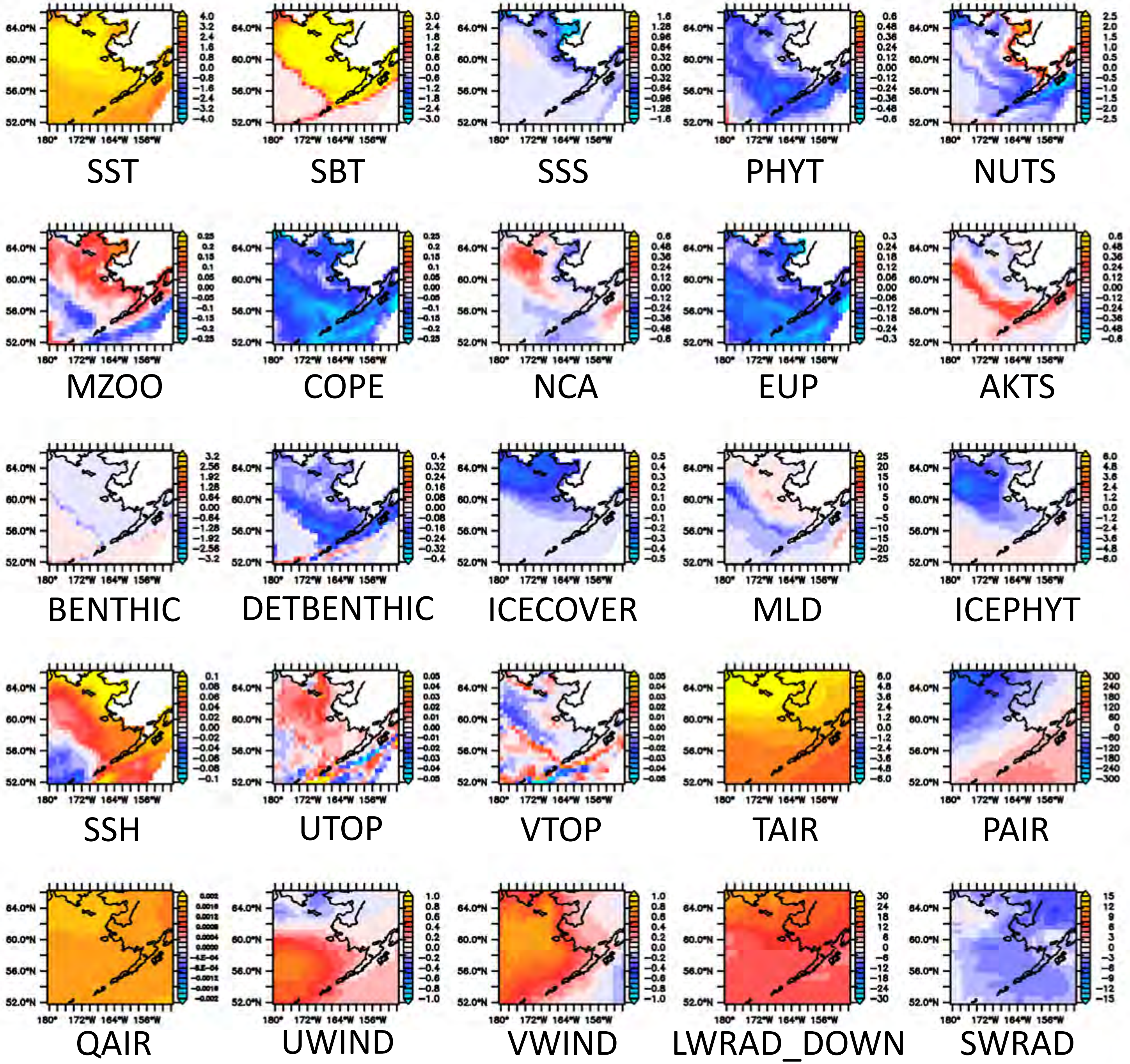
Average present conditions



Change by 2050s (rcp8.5)

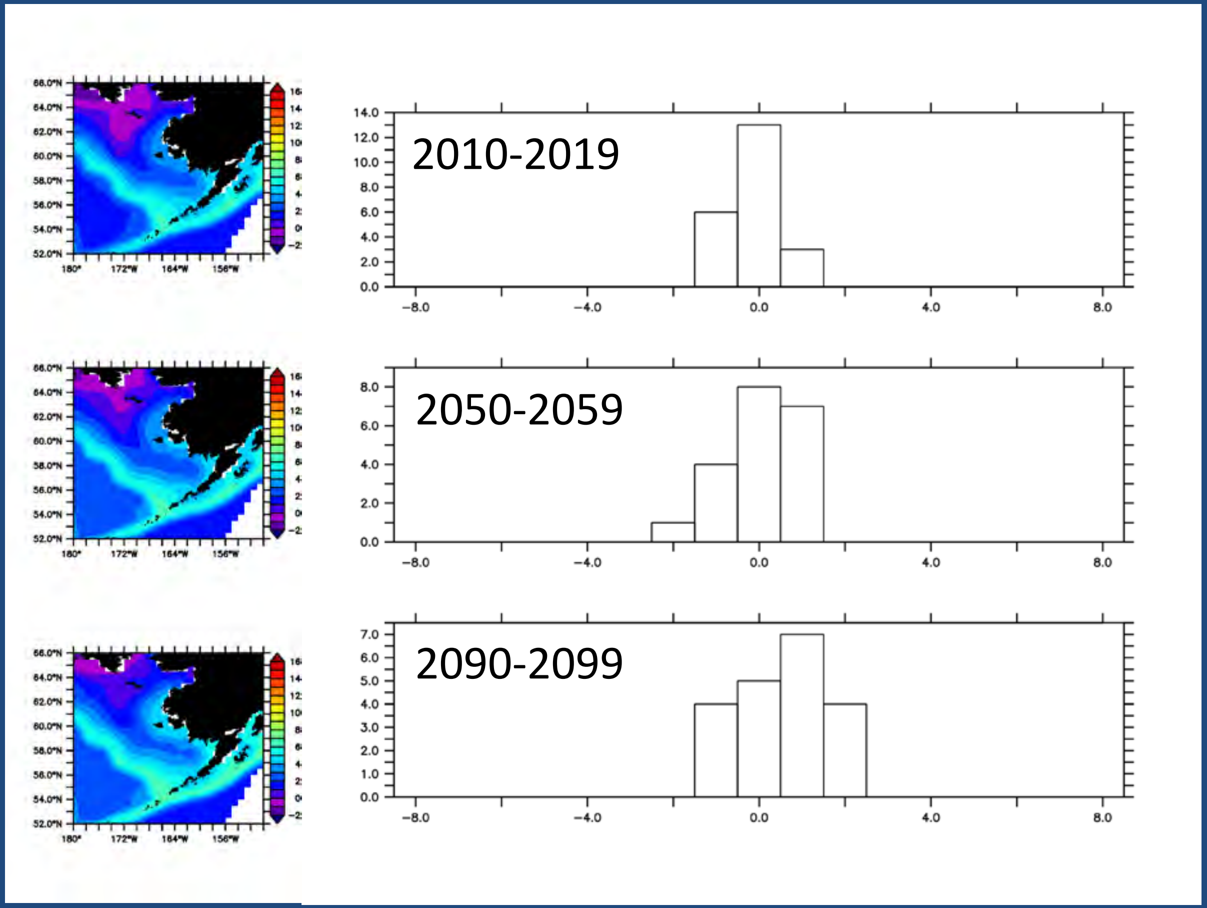


Change by 2090s (rcp8.5)

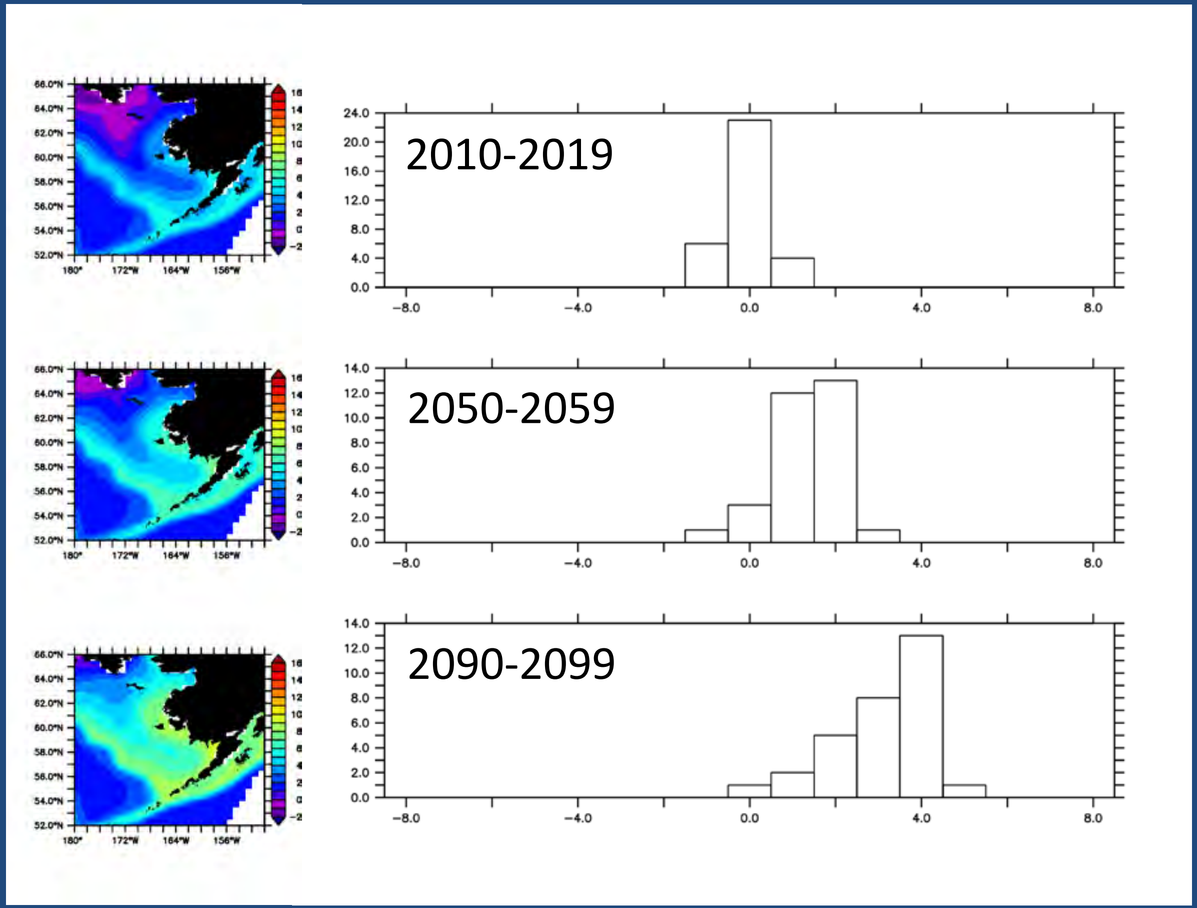


Interannual statistics of projected change SE shelf sea bottom temperature (°C)

rcp4.5

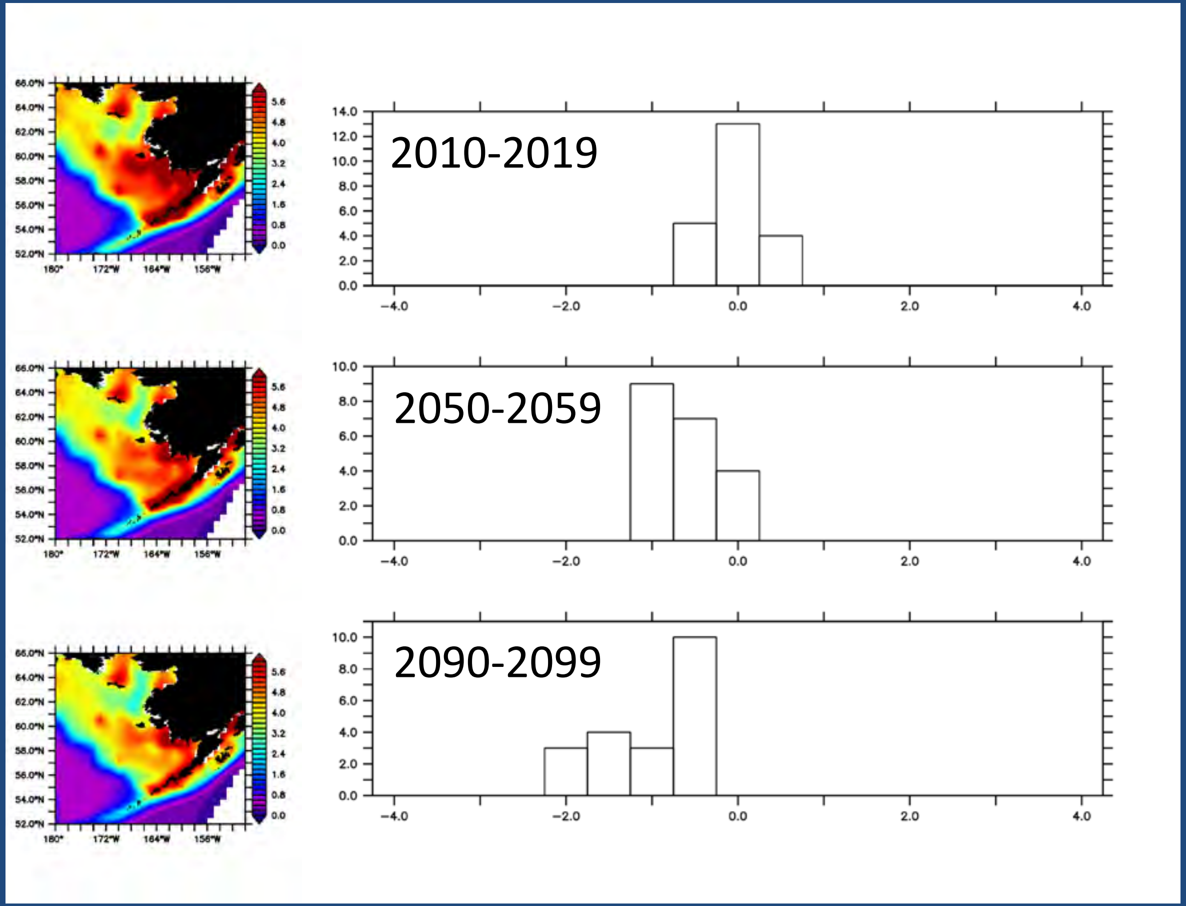


rcp8.5

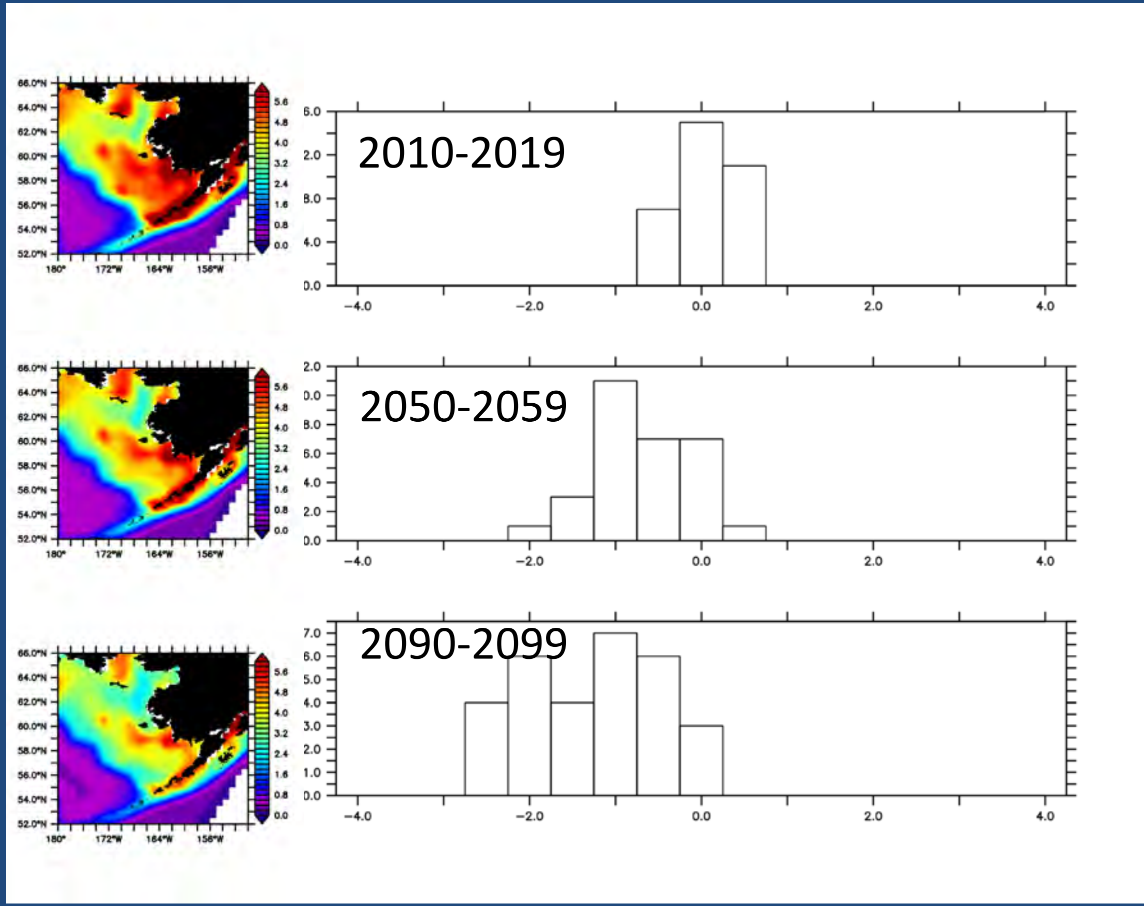


Intereannual statistics of projected change
SE shelf large crustacean zooplankton (mg C m^{-3})

rcp4.5



rcp8.5

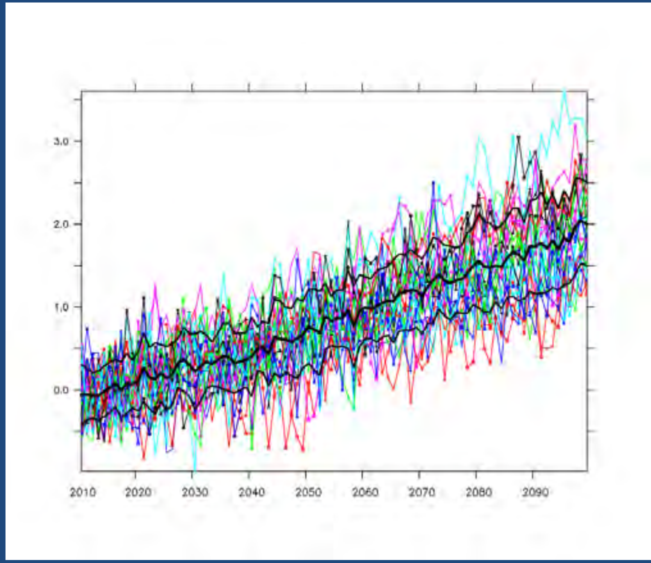


Can we expand this mini-ensemble?

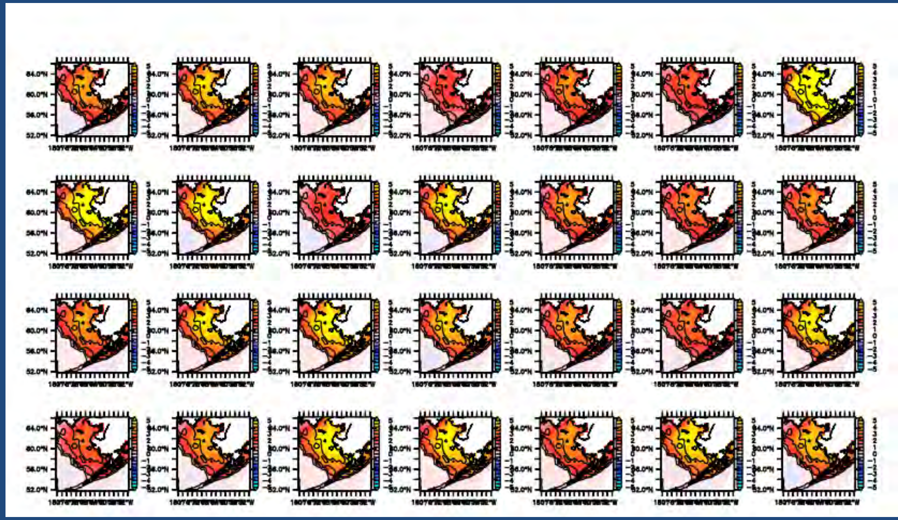
- Dynamical downscaling is computationally expensive
- Statistics of mini-ensemble can be used to infer what would be obtained from a larger ensemble
- *Hybrid dynamical-statistical method* uses EOFs of all biophysical variables; multivariate correlation at the pattern level
  - How does the regional bell "ring" when struck in various ways
- Project atmospheric forcing from more CMIP5 members onto the multivariate patterns obtained from the mini-ensemble
- For details see poster S2-P13

Hybrid dynamical-statistical downscaling: projected change in sea bottom temperature (rcp8.5)

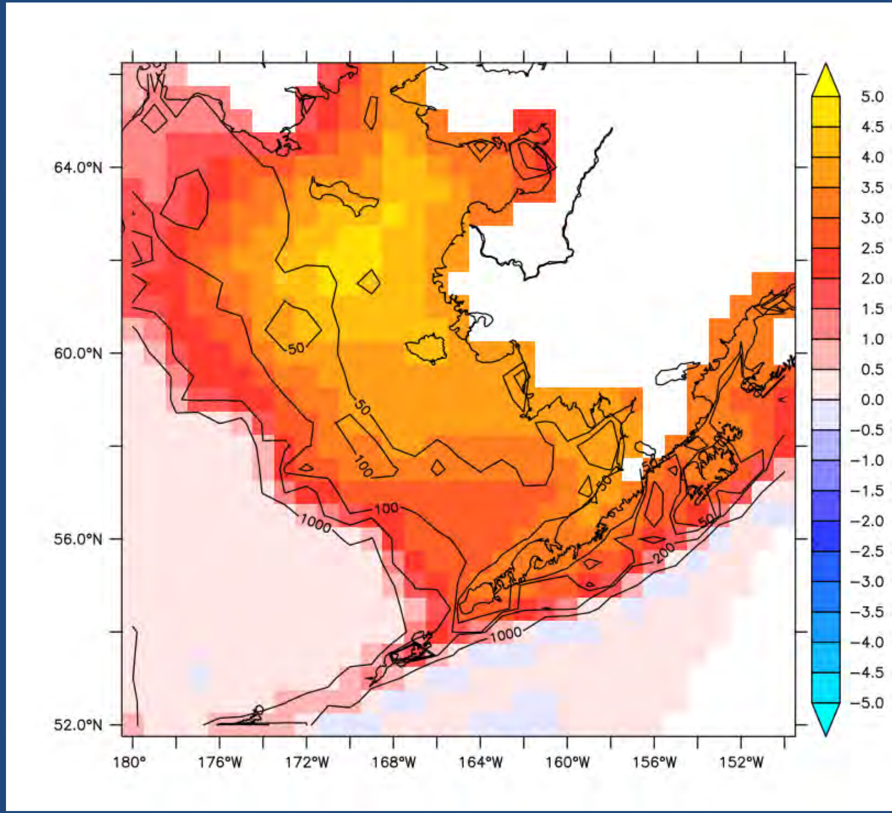
Individual realizations: spatial aves



Individual realizations: change by 2090s

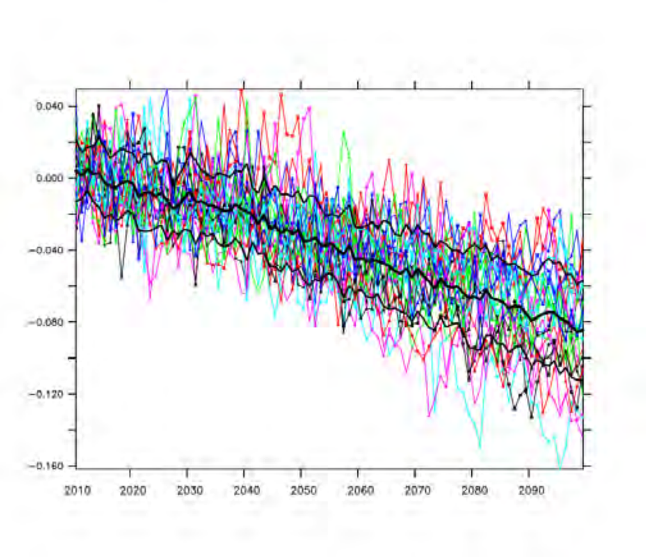


Average change by 2090s

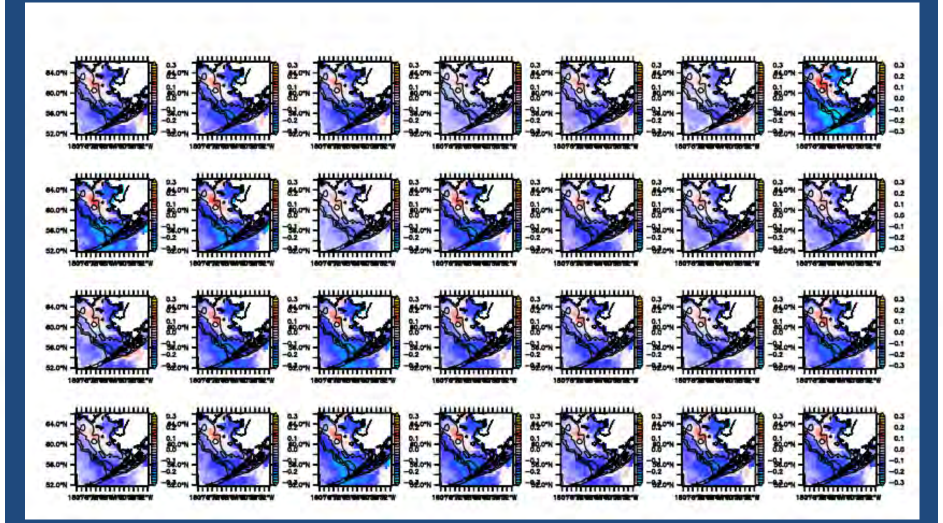


Hybrid dynamical-statistical downscaling: projected change in large crustacean zooplankton (rcp8.5)

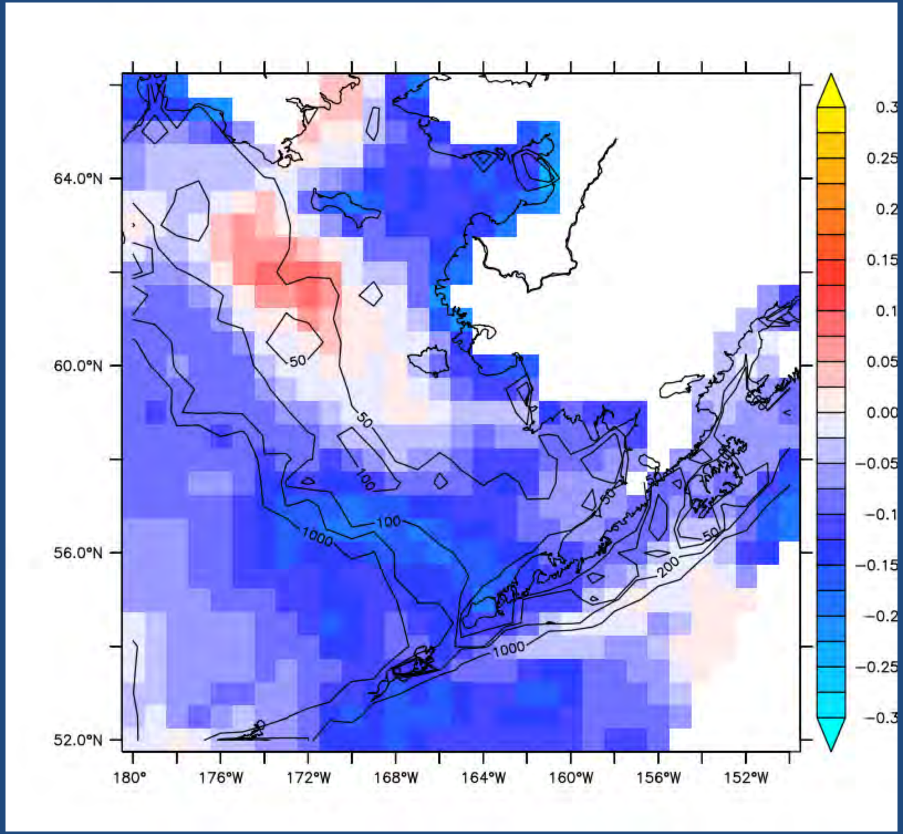
Individual realizations: spatial aves



Individual realizations: change by 2090s



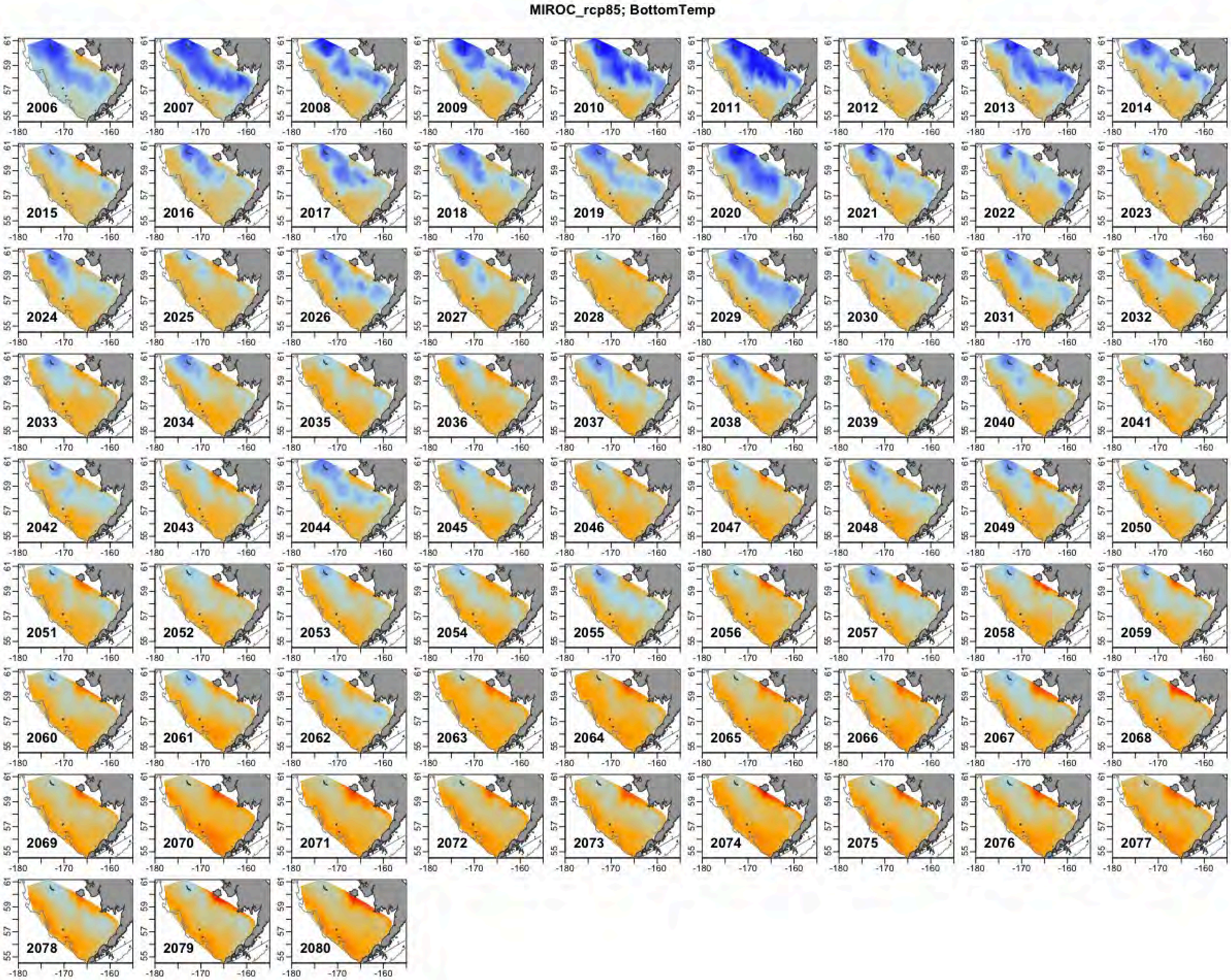
Average change by 2090s



Conclusions

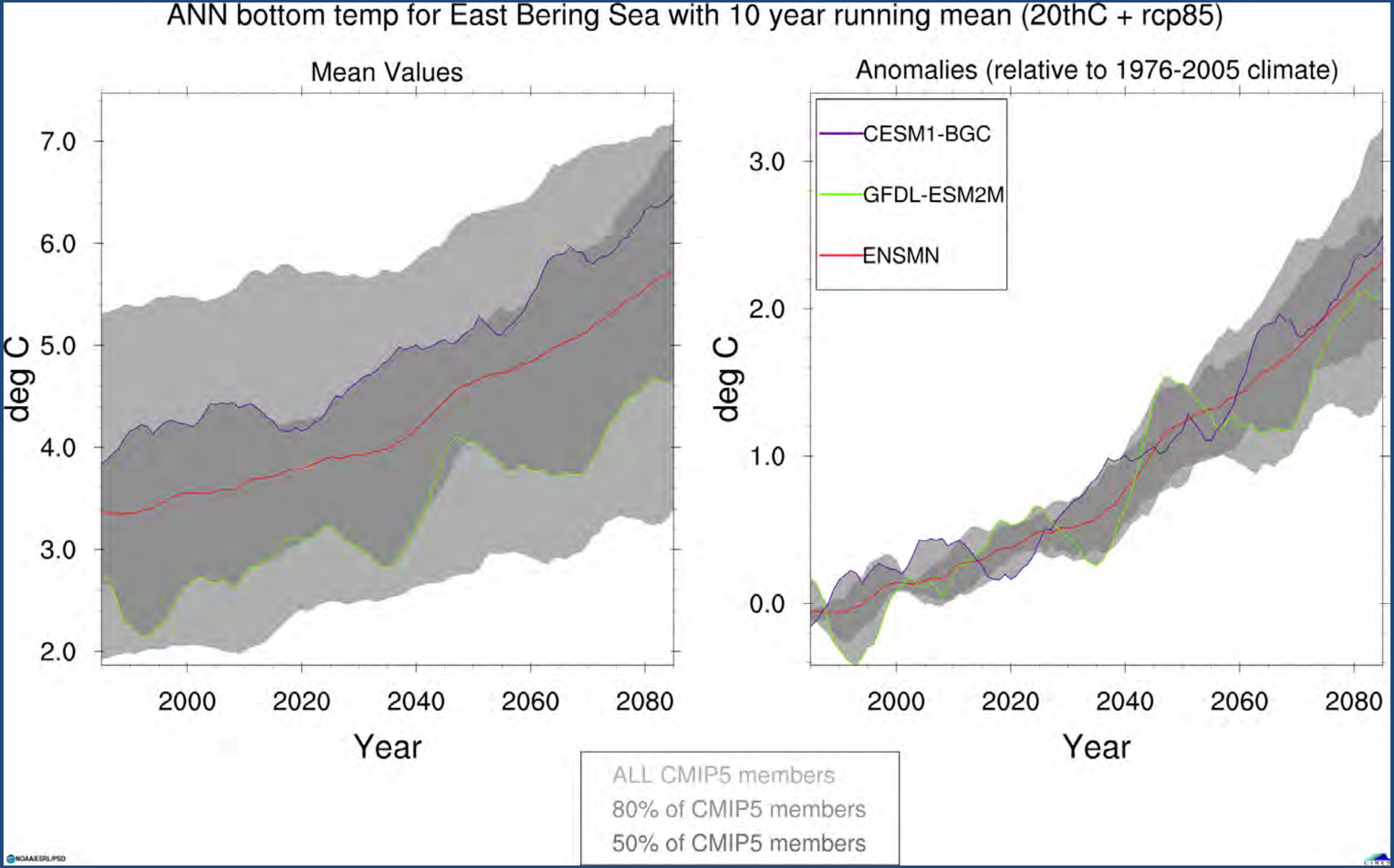
- Significant changes in physical and biological properties of the Bering Sea are underway and will accelerate in the latter half of the 21st century, especially under rcp8.5
- Sea bottom temperature will rise by up to *5 ^{o}C* by 2100
- Declines in large crustacean zooplankton (a favorite prey of economically significant species) are projected, especially on the outer shelf

One future realization of Bottom Temp



NOAA FISHERIES

CMIP5 projected Bottom Temp in the EBS (rcp8.5)

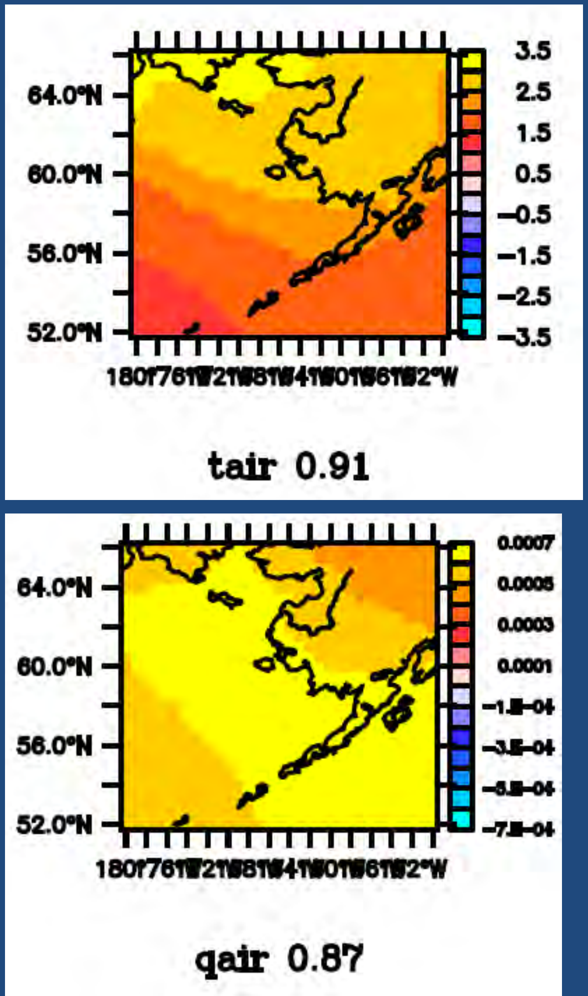


Need to summarize how global forcing drives the regional response

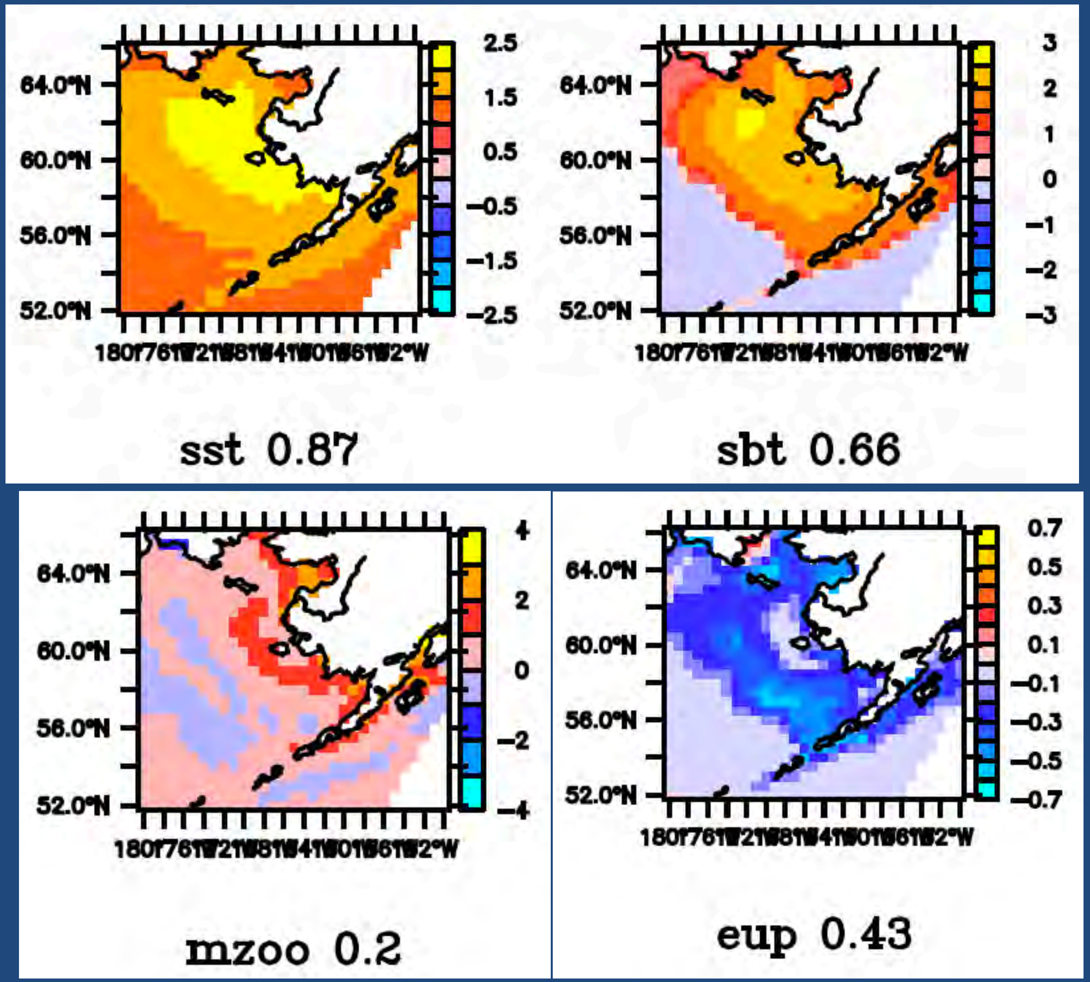
- Many possible global futures could be used to drive the regional model
- Regional model in particular has *many* variables
- Is there a way to numerically summarize both the drivers (characteristic global patterns) and the response (characteristic regional patterns)?
- Potentially could use this to *statistically* downscale from the global models

Goal: relate large-scale forcing to regional response

Large-scale forcing



Regional response



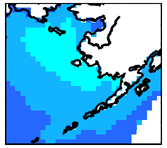
Multivariate Analysis: “Factor analysis of spatial EOFs”

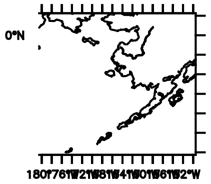
- Calculate “traditional” spatial EOFs of each variable. This yields:
  - 1) A Spatial pattern (the “EOF” in the original units of that variable)
  - 2) A time series modulating the spatial pattern (the “PC”, which has unit variance)
- Perform EOF analysis on that reduced set of time series to seek multivariate “factors” (i.e. *temporally correlated univariate spatial patterns*)

Global model variables used

Variable	Symbol	Units
Air Temperature	TAIR	Deg C
SLP	PAIR	mbar
Absolute Humidity	QAIR	kg/kg
Wind velocity	UWIND, VWIND	m/s
Downward longwave radiation	LWRAD_DOWN	W/m^2
Shortwave radiation	SWRAD	W/m^2

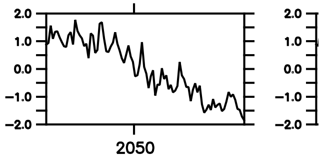
Results for CESM-rcp8.5



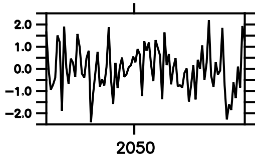


swrad 51.42

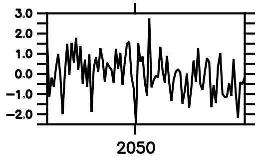
CESM-rcp8.5 univariate EOFs (mode 1)



sst 94.75

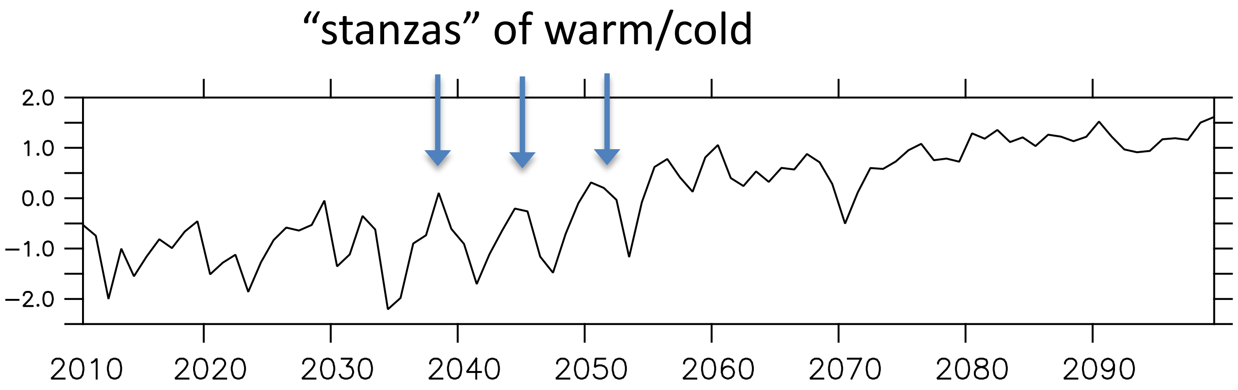


uwind 63.68



vwind 53.01

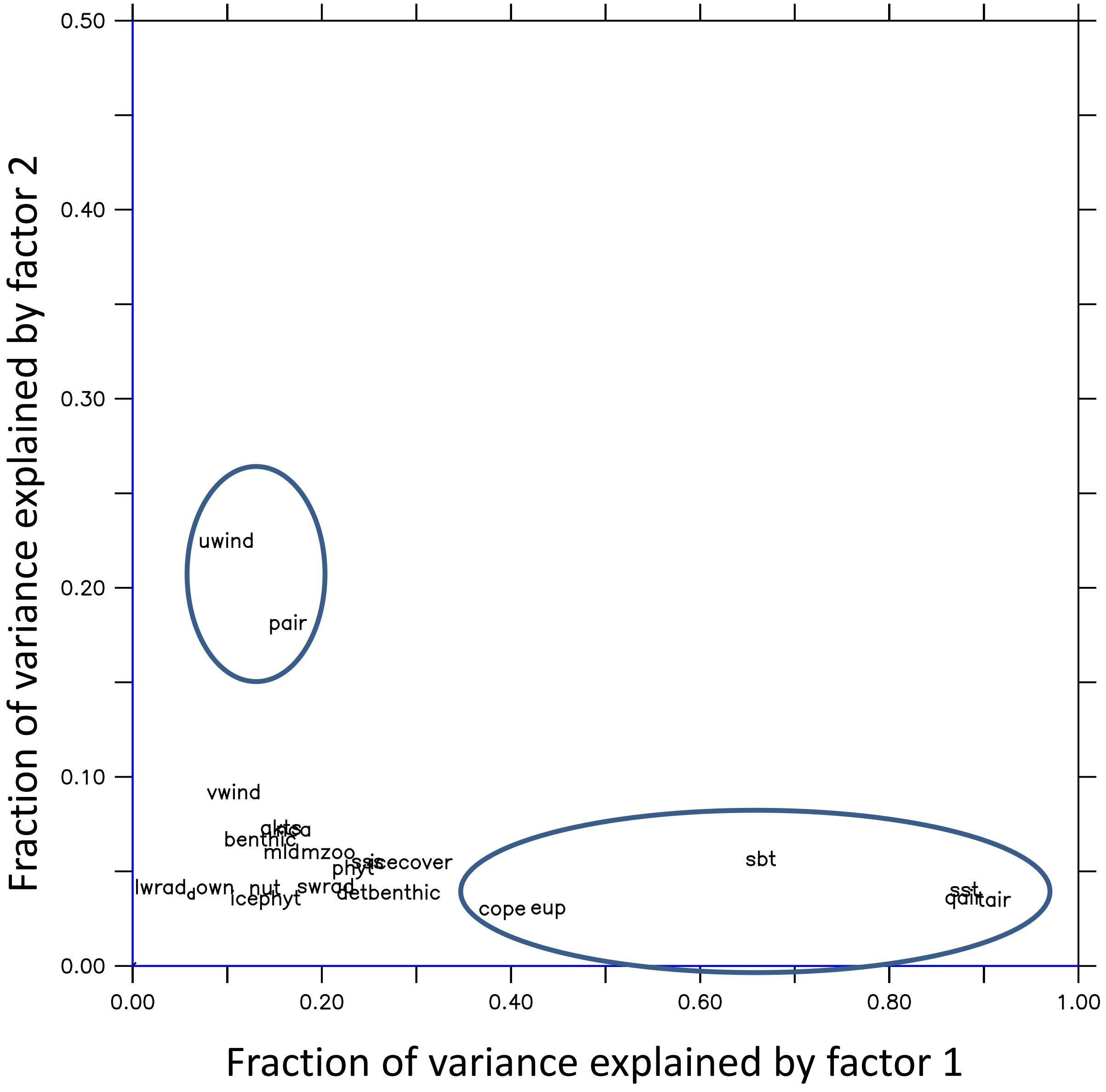
CESM-rcp8.5 univariate PCs



Time series of factor 1

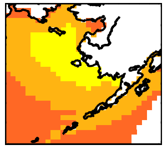
Time series of factor 2

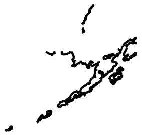
CESM-rcp8.5 multivariate PCs

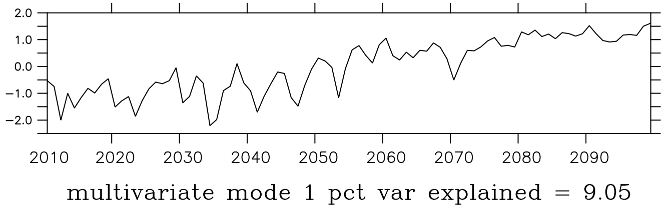


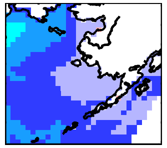
CESM-rcp8.5 variable loadings on each factor

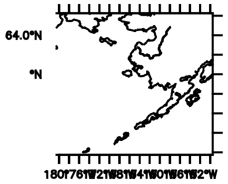
CESM-rcp8.5 multivar spatial pattern 1







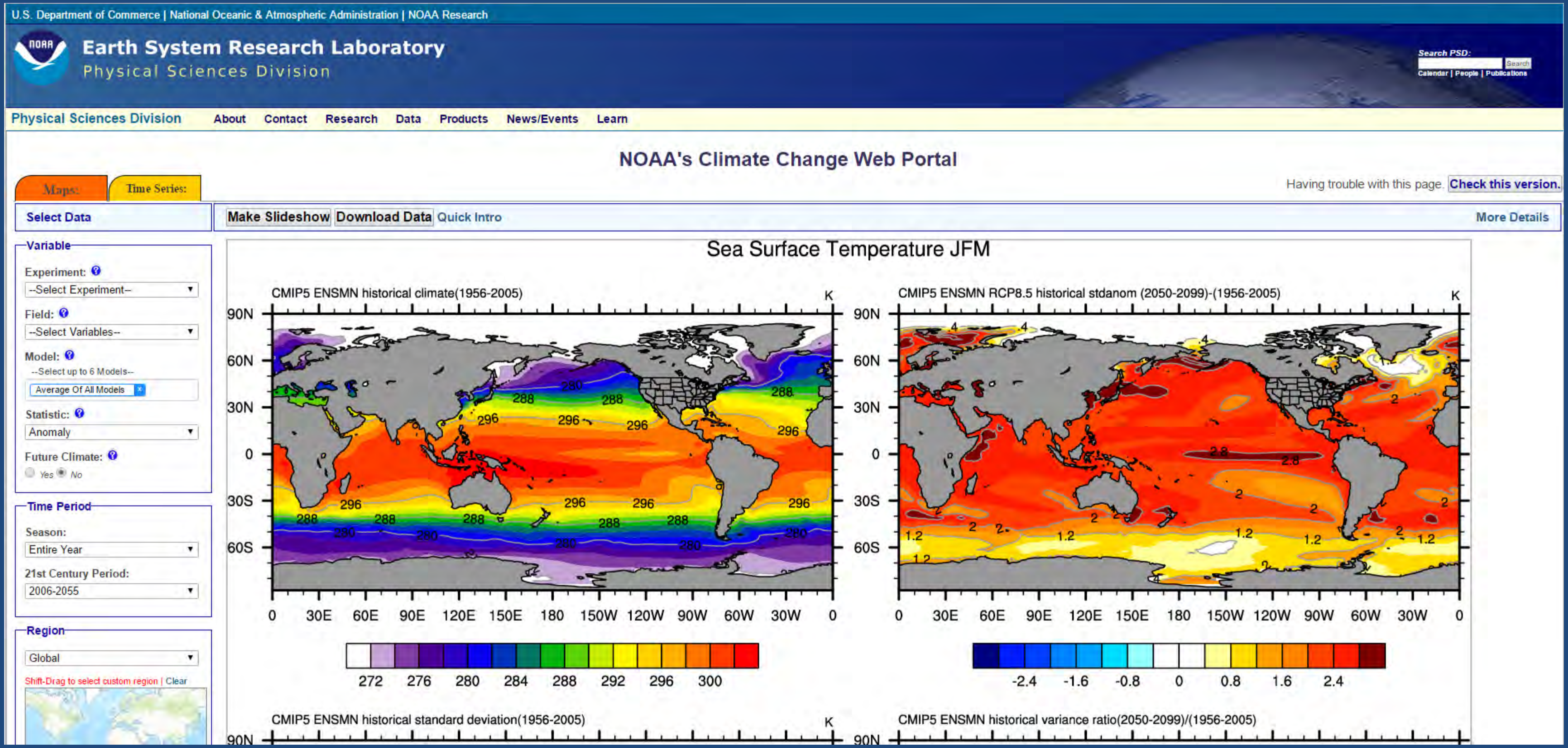




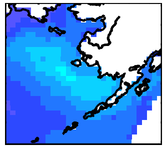
swrad 0.03

CESM-rcp8.5 multivar spatial pattern 2

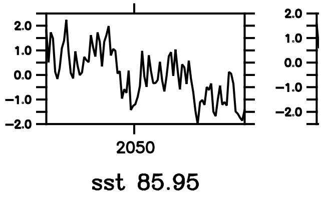
The ESRL site for exploration of CMIP5 output

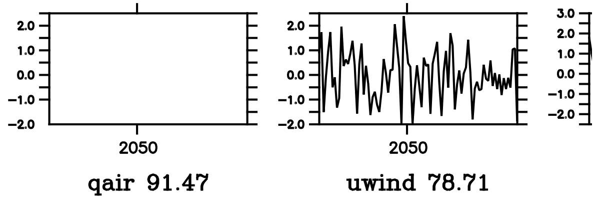


Results for GFDL-rcp8.5

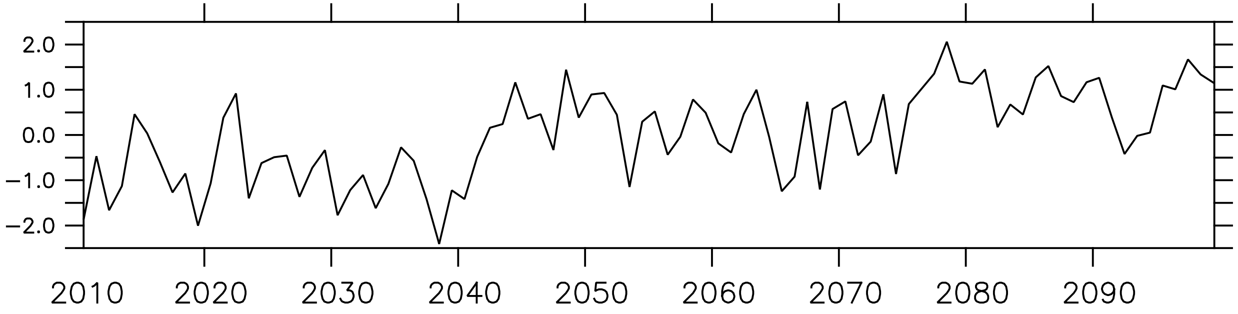


GFDL-
rcp8.5
univariate
EOFs
(mode 1)





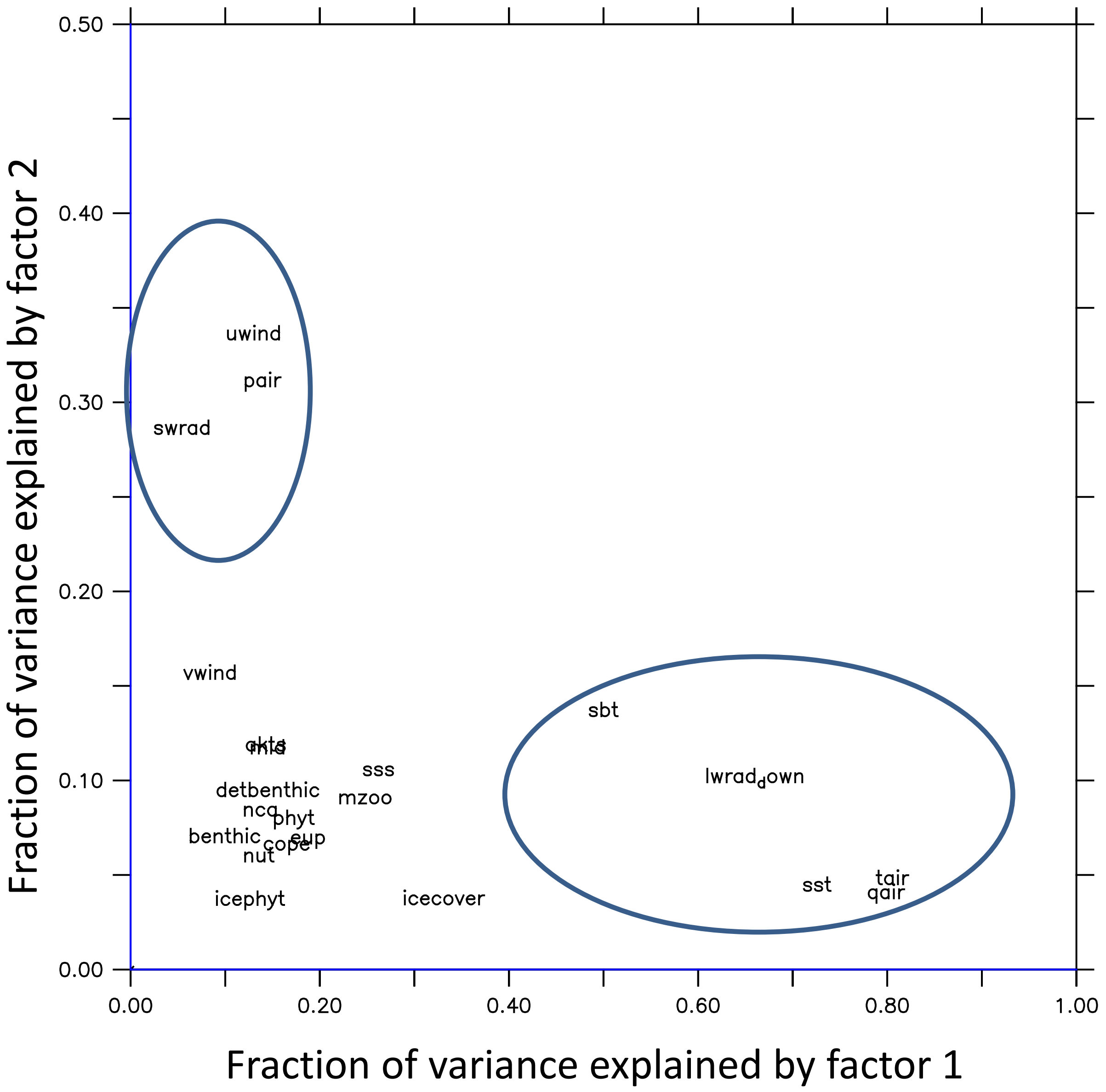
GFDL-rcp8.5 univariate PCs



Time series of factor 1

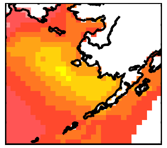
Time series of factor 2

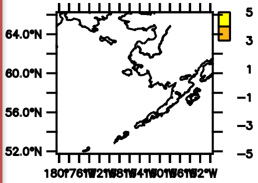
GFDL-rcp8.5 multivariate PCs



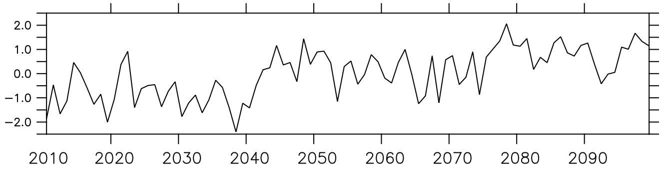
GFDL-rcp8.5 variable loadings on each factor

GFDL-rcp8.5 multivar spatial pattern 1

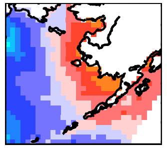




swrad 0.05



multivariate mode 1 pct var explained = 8.48



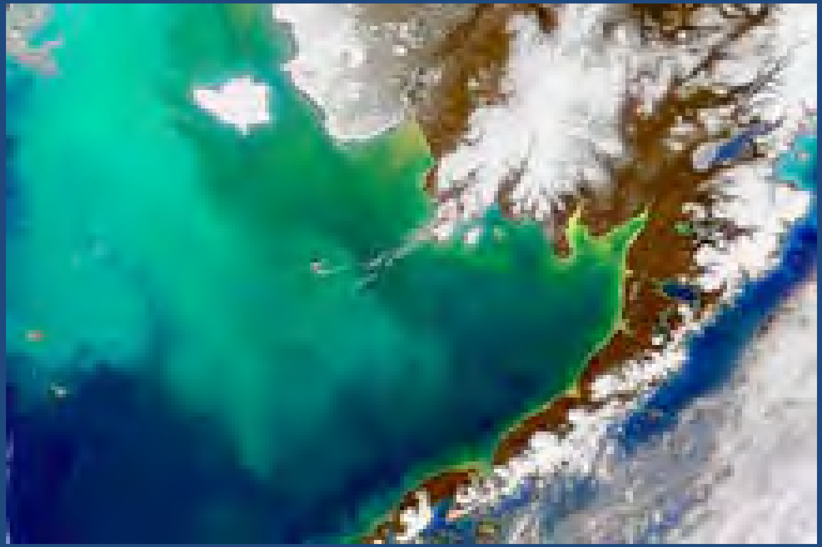
GFDL-rcp8.5 multivar spatial pattern 2

Conclusions so far

- 12 downscaling runs of global projections have been completed
- Bottom temperatures ~3 degrees C warmer by 2100, highly dependent on emissions
- Multivariate method suggests independent “heat” and “wind” modes in several models
- “heat” mode is associated with biological change (e.g. enhanced microzooplankton, reduced euphausiids) consistent with OCH

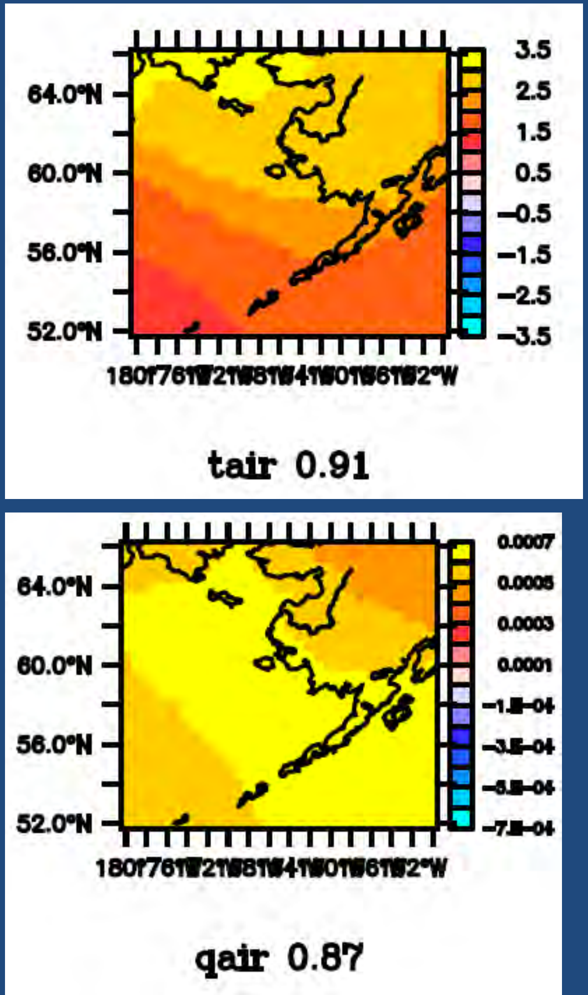
A fun idea to think about

- Coccolithophores like stratified conditions and may benefit from high CO2 levels
- They have been observed to bloom in the Bering Sea in warmer years
- Could they significantly increase future albedo?

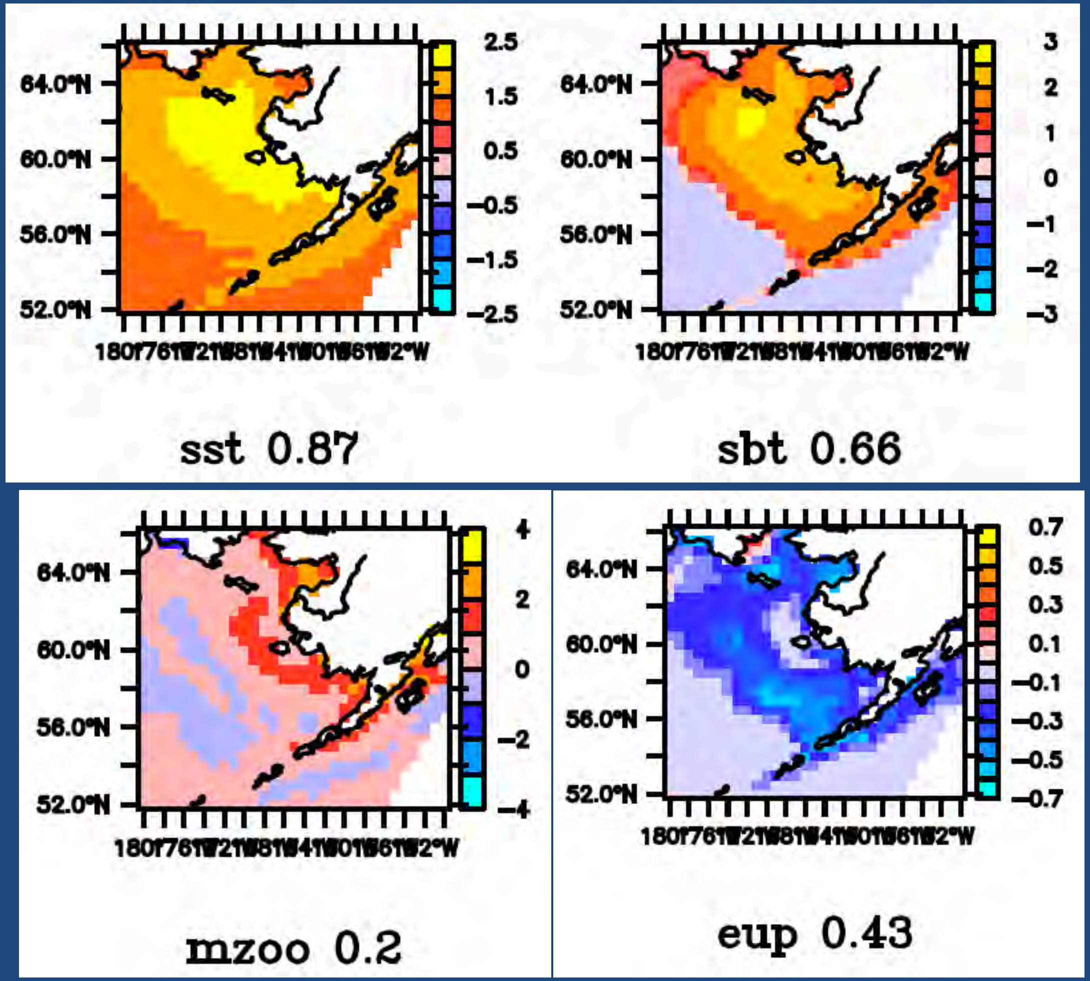


Goal: relate large-scale forcing to regional response

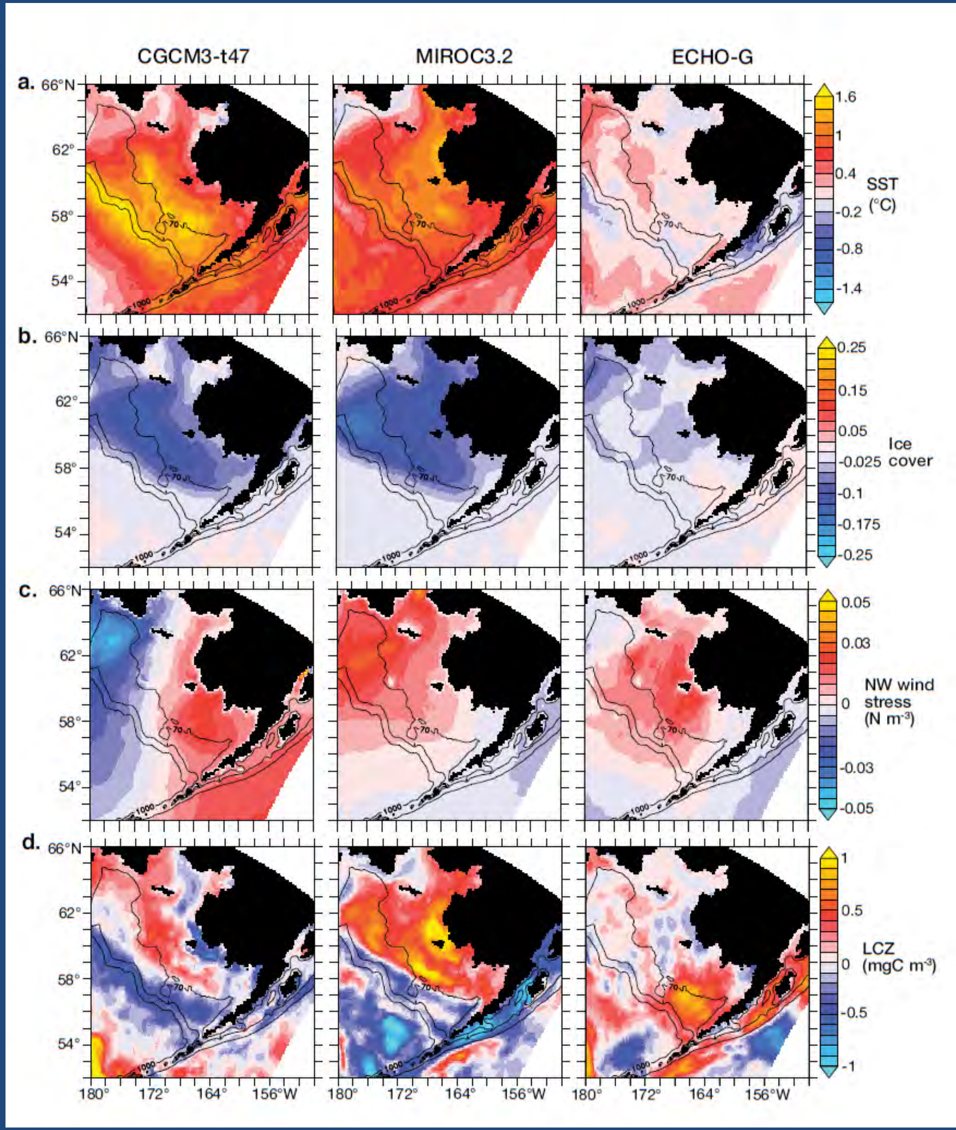
Large-scale forcing



Regional response



Predicted biophysical changes by 2030



SST

Ice cover

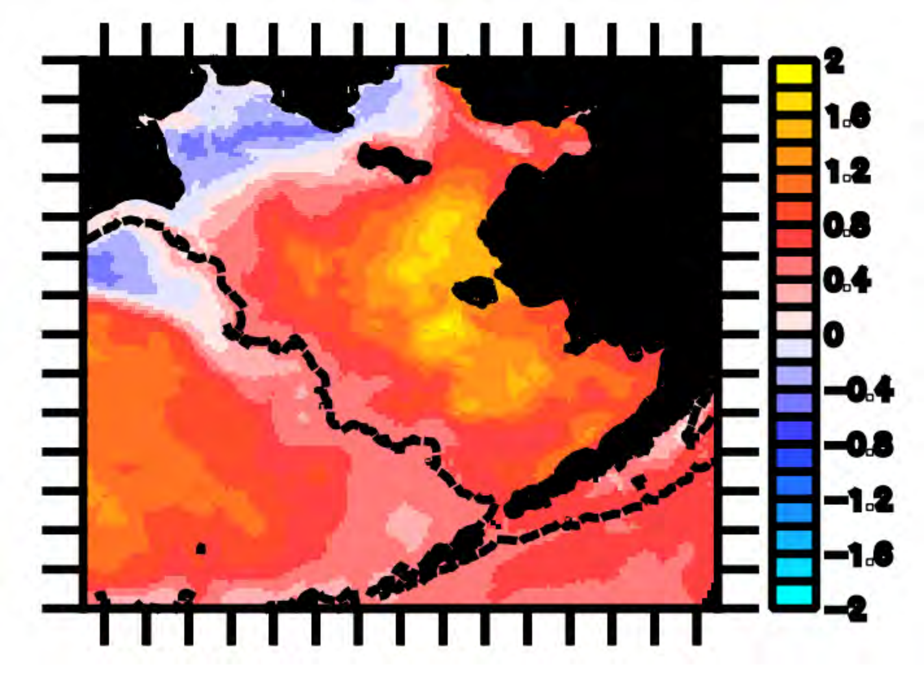
Onshelf winds

Large Crustacean Zooplankton

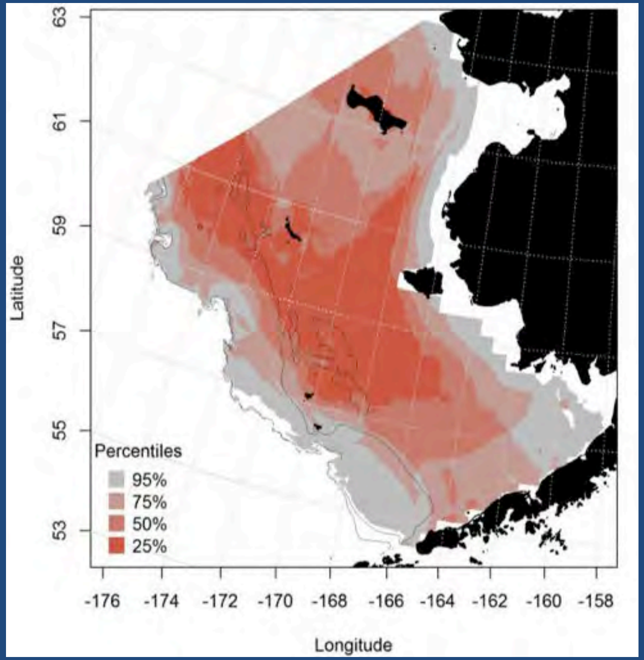
Bering Sea vulnerability analysis:

Compare present time variance and mean anticipated change with present fish distribution

Summer Bottom Temp anticipated change



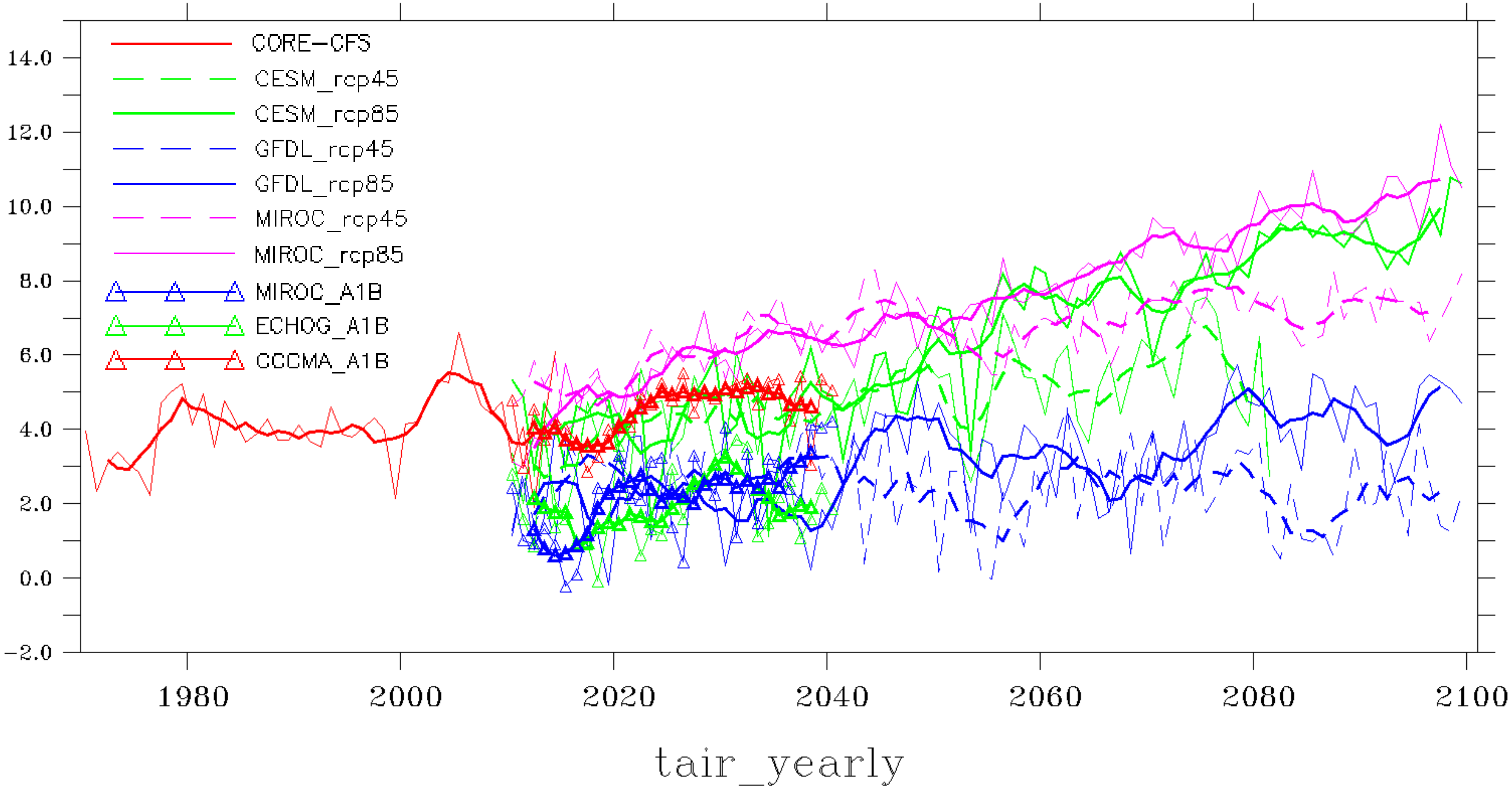
Walleye pollock Essential Fish Habitat

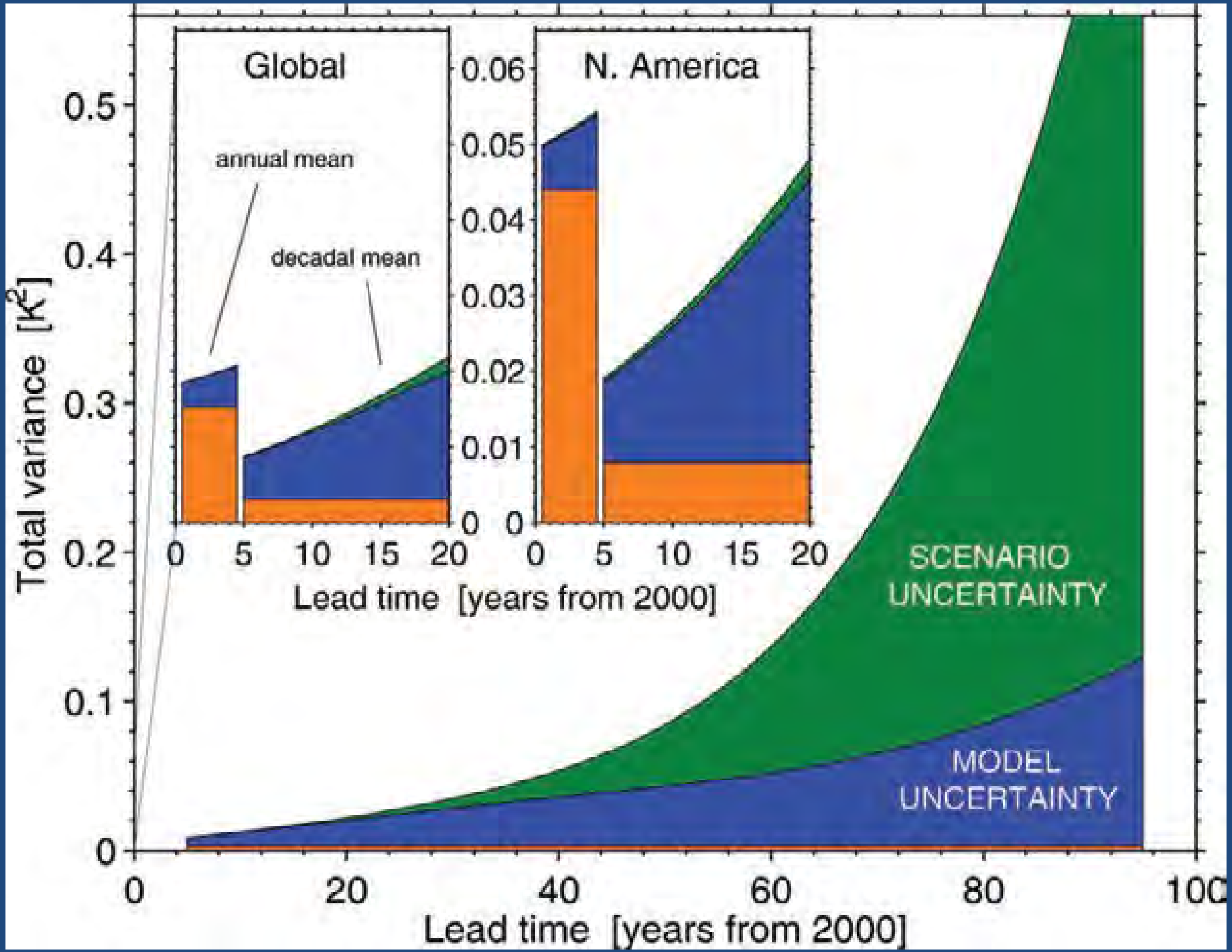


Downscaling Methods

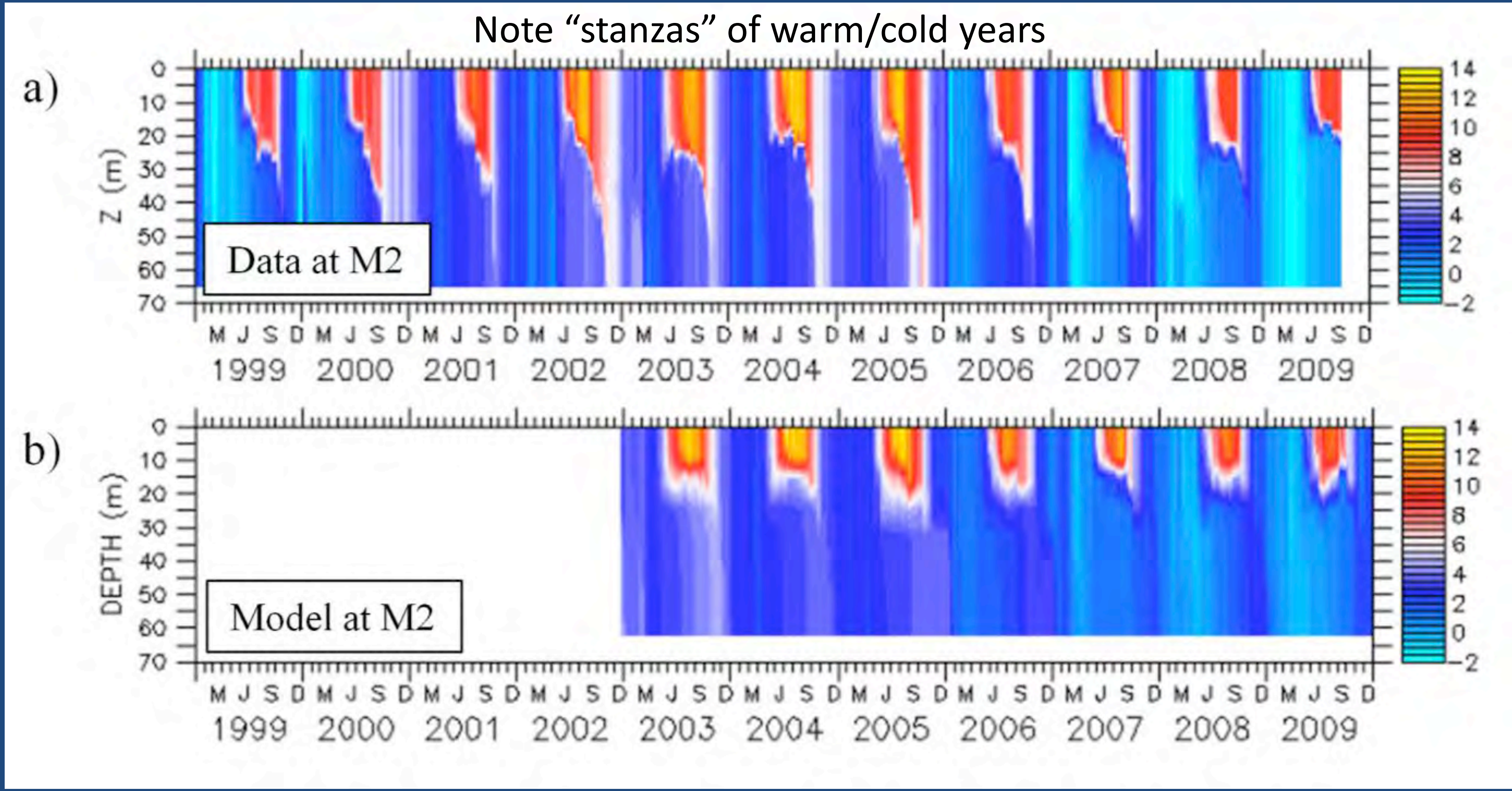
- Choose a subset of IPCC models for atmospheric forcing and oceanic boundary conditions (physical/biological) for our regional model (Bering10K)
- Model choice based on
  - Local validation (replicate present ice cover the Bering Sea)
  - Availability of needed forcing variables
  - Availability of multiple emission scenarios
  - NPZ and OA variable output (not available for all models)
- Ocean Acidification dynamics (e.g. pH, aragonite saturation) are now being added to Bering10K (D. Pilcher)

Ensemble of IPCC output: Air Temperature




Global
annual mean
decadal mean
N. America
SCENARIO UNCERTAINTY
MODEL UNCERTAINTY
Total variance [K^2]
Lead time [years from 2000]
Lead time [years from 2000]

Bering10K validation:
Modeled/Observed mid-shelf temperatures (deg C)



Vetting of IPCC models for the Arctic (Wang et al. 2012, 2015) based on monthly *ice* climatology

List Of Models And Component Of Sea Ice Model In The Coupled System

	Models	Country	Institute	Sea Ice Model	Monthly Climatology	Magnitude of seasonal cycle
1	ACCESS1.0	Australia	CISRO-BOM	CICE, v4.1	1	1
2	ACCESS1.3	Australia	CISRO-BOM	CICE, v4.1	2	2
3	BCC-CSM1.1	China	BCC	SIS		
4	BCC-CSM1.1(m)	China	BCC	SIS		
5	BNU-ESM	China	BNU	CICE, v4.1		
6	CCSM4	USA	NCAR	CICE,v4	3	3
7	CESM1(CAM5.1)	USA	NCAR	CICE,v4	4	4
8	CESM1(WACCM)	USA	NCAR-DOE	CICE.v4		5
9	CMCC-CM	Central-Europe	CERFACS	LIM		6
10	CMCC-CMS	CE	CERFACS	LIM		7
11	CNRM-CM5	CE	CNRM	GELATO v5	5	
12	CSIRO-Mk360	Australia	CSIRO-QCCCE	AGCM		
13	CanESM2	Canada	CCCMA	CanSIM1		8
14	EC-EARTH	European Center	EC-EARTH Consortinum	LM2	6	9
15	FGOALS-g2	China	LASG-CESS	CICE, v4	7	
16	FGOALS-s2	China	LASG-IAP	CSIM5		
17	FIO-ESM	China	FIO	CICE, v4	8	
18	GFDL-CM3	USA	NOAA GFDL	SISp2		10
19	GFDL-ESM2G	USA	NOAA GFDL	SISp2		
20	GFDL-ESM2M	USA	NOAA GFDL	SISp2		11
21	GSS-E2H	USA	NASA GISS	HYCOM		
22	GISS-E2R	USA	NASA GISS	Russell		
23	HadGEM2-AO	UK	NIMR/KMA	sea ice component of HadGOM2	9	12
24	HadGEM2-CC	UK	MOHC	inspired from CICE	10	13
25	HadGEM2-ES	UK	MOHC		11	14
26	INM-CM4	Russia	INM	INM-CM4	12	
27	IPSL-CM5A-LR	France	IPSL	LIM2		
28	IPSL-CM5A-MR	France	IPSL	LIM2		
29	IPSL-CM5B-LR	France	IPSL	LIM2		
30	MIROC5	Japan	AORI-NIES-JAMSTEC	COCO v4.5	13	
31	MIROC-ESM	Japan	AORI-NIES-JAMSTEC	COCO v3.4	14	15
32	MIROC-ESM-CHEM	Japan	AORI-NIES-JAMSTEC	COCO v3.4	15	16
33	MPI-ESM-LR	Germany	MPI-M	sea ice component of MPI-OM	16	17
34	MPI-ESM-MR	Germany	MPI-M	sea ice component of MPI-OM	17	18
35	MRI-CGCM3	Japan	MRI	MRI.COM3		
36	NorESM1-M	Norway	NCC	CICE, v4	18	
37	NorESM1-ME	Norway	NCC	CICE, v4		

Last two columns indicate their performance assessment.

Wang et al. 2012

CMIP5 projected Ice Cover in the EBS (rcp8.5)