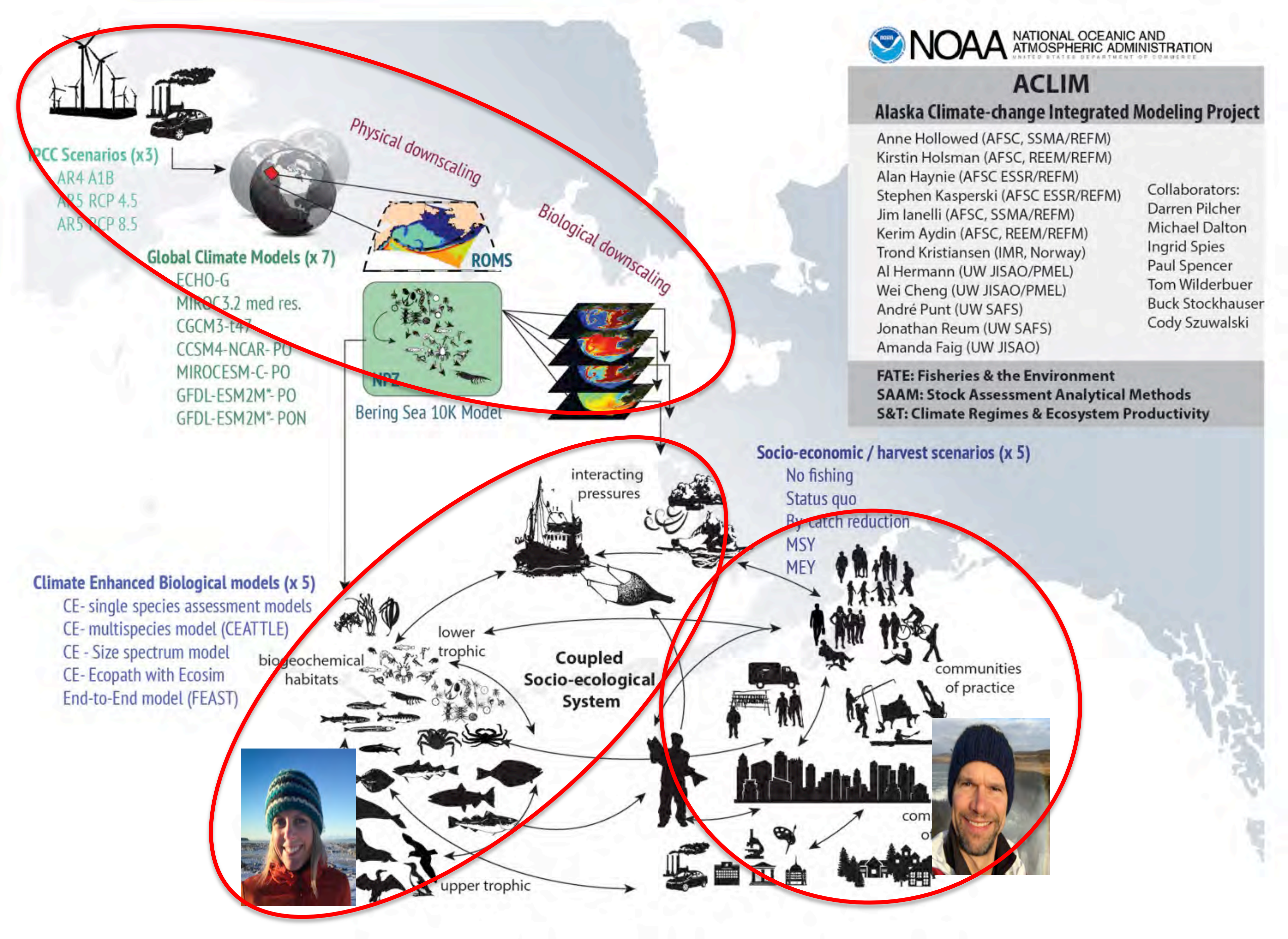
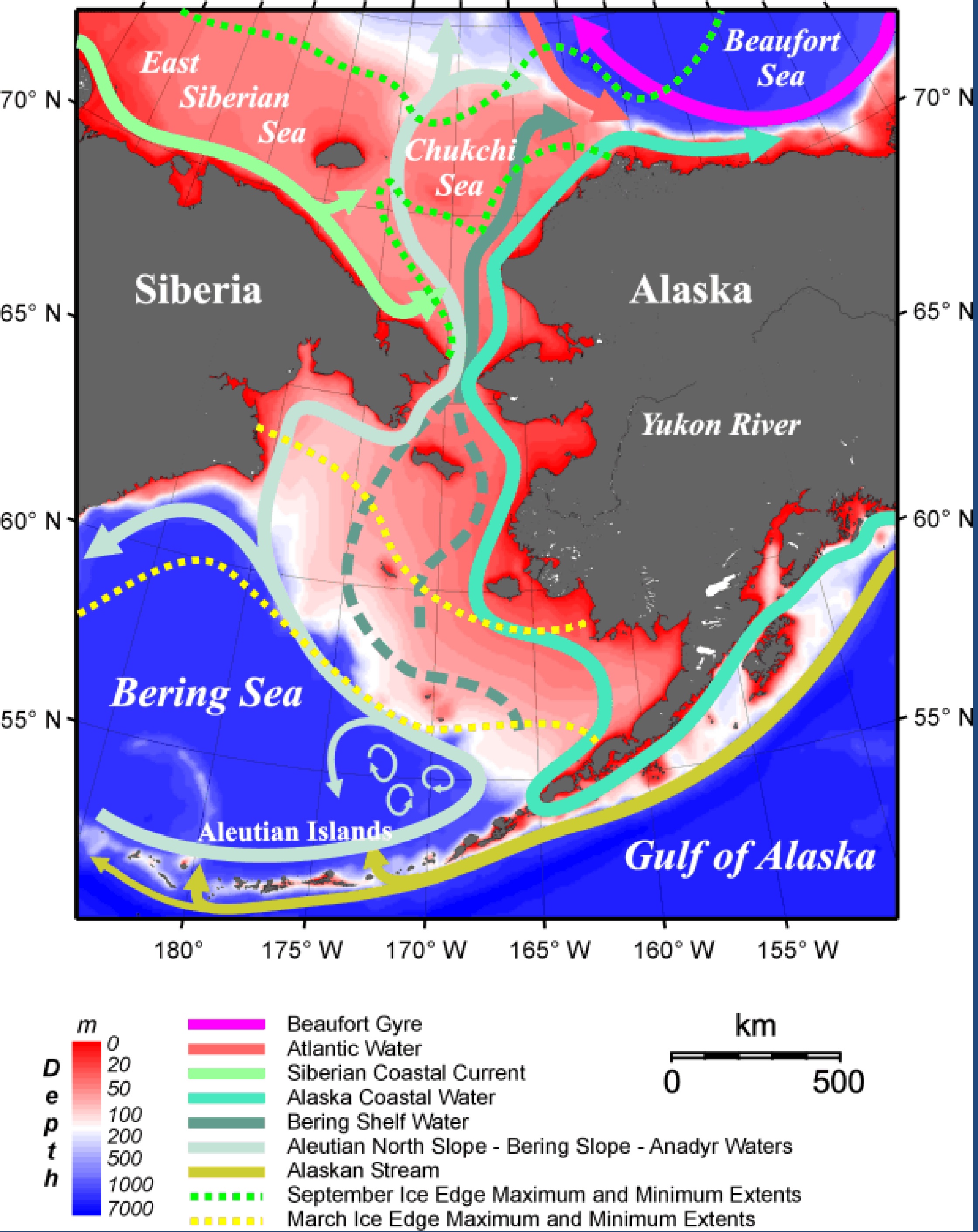
Linking global to regional ocean forecsts: a hybrid dynamical-statistical approach

Albert J. Hermann[1]

Wei Cheng[1], Georgina A. Gibson[2], Ivonne Ortiz[1], Kerim Aydin[3], Samantha Siedlecki[4]

[1]Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle, WA, USA. E-mail: albert.j.hermann@noaa.gov
[2]International Arctic Research Center, University of Alaska Fairbanks, Fairbanks, AK, USA.
[3]NOAA/Alaska Fisheries Science Center, Seattle, WA, USA.
[4]University of Connecticut, Groton, CT, USA.


NOAA NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
UNITED STATES DEPARTMENT OF COMMERCE
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)
Wei Cheng (UW JISAO/PMEL)
André Punt (UW SAFS)
Jonathan Reum (UW SAFS)
Amanda Faig (UW JISAO)
Collaborators:
Darren Pilcher
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
Physical downscaling
Biological downscaling
ROMS
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
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
upper trophic



What is unique about the Bering Sea?

Physical

- Seasonal ice with advection to the south
- Tidal mixing sets up distinct biophysical regimes

Biological

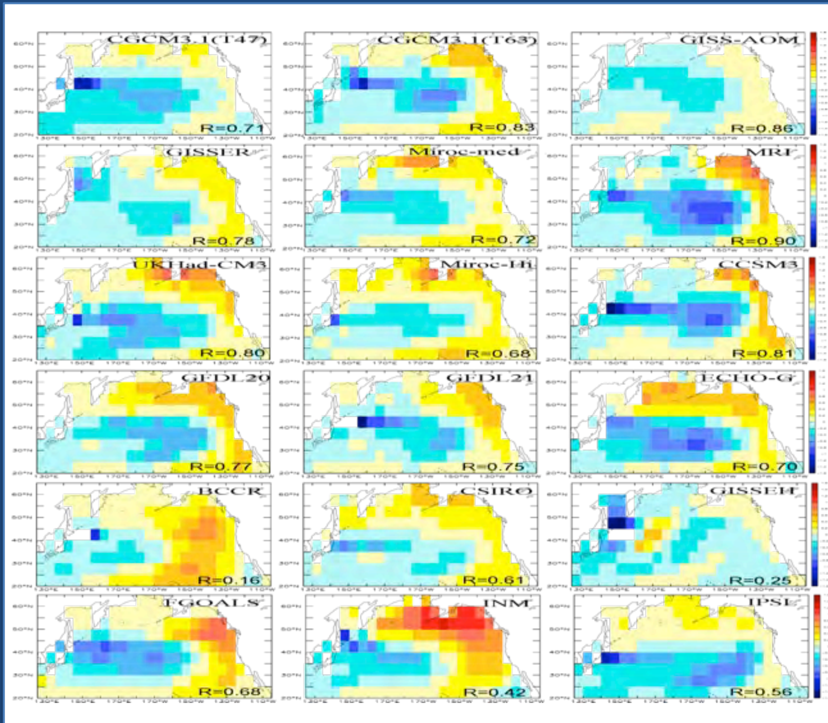
- Ice plankton may be a major food source to higher trophic levels
- Benthic food chain is a major player

BERING SEA ECOSYSTEM
walrus
fur seal
bearded seal
kittiwakes
murres
Coast Guard Cutter *Healy*
crab boat
walrus
humans
longliner
NOAA Ship *Oscar Dyson* fish assessment
kittiwakes
fur seals
bowhead whales
plankton bloom
ice algae
murres
micro-zooplankton
phytoplankton
copepod
capelin
fur seals
cod
zooplankton
phytoplankton
pollock
ichthyoplankton
pollock
murres
fin whales
polychaetes
cod
euphasiids
bivalves
arrowtooth flounder
arrowtooth flounder
myctophids
snow crabs
snow crabs
gastropods
bivalves
ICE EXTENT &
NATIVE SUBSISTENCE

One prevailing paradigm: cold years are good for walleye pollock

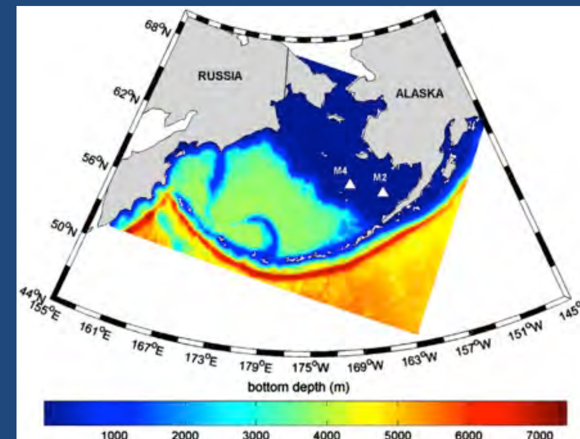
Duffy-Anderson et al., 2014

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

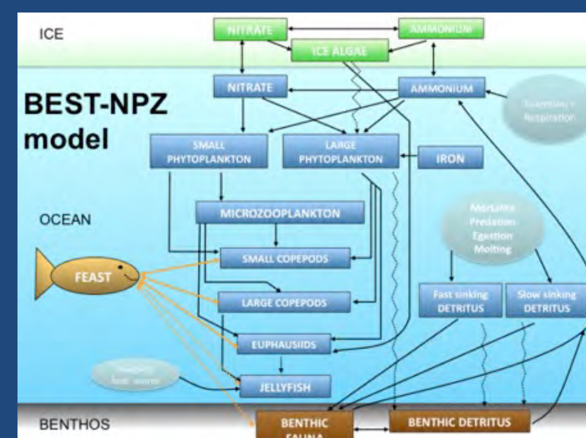


ensemble of runs

Bering10K



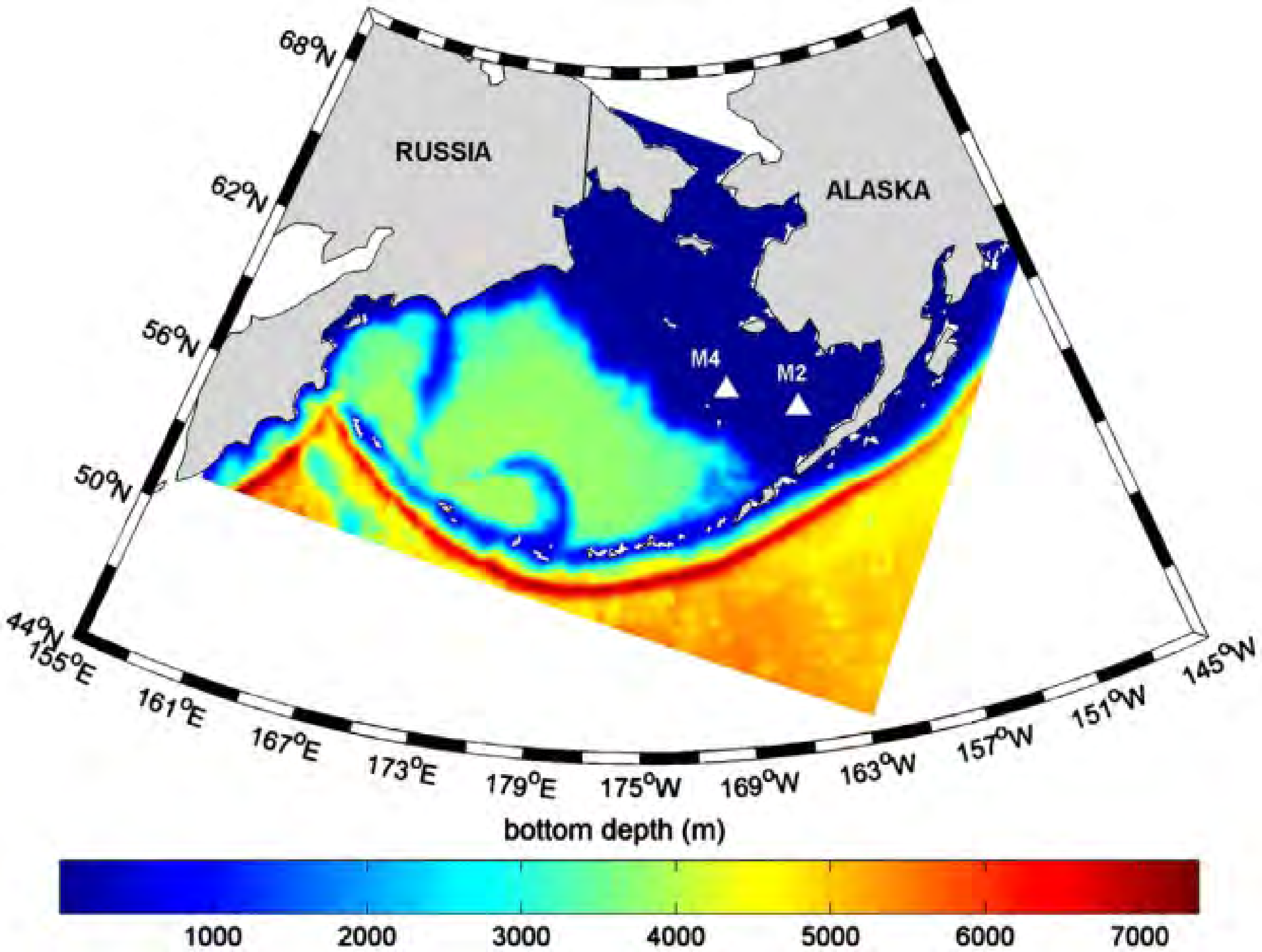
NPZ



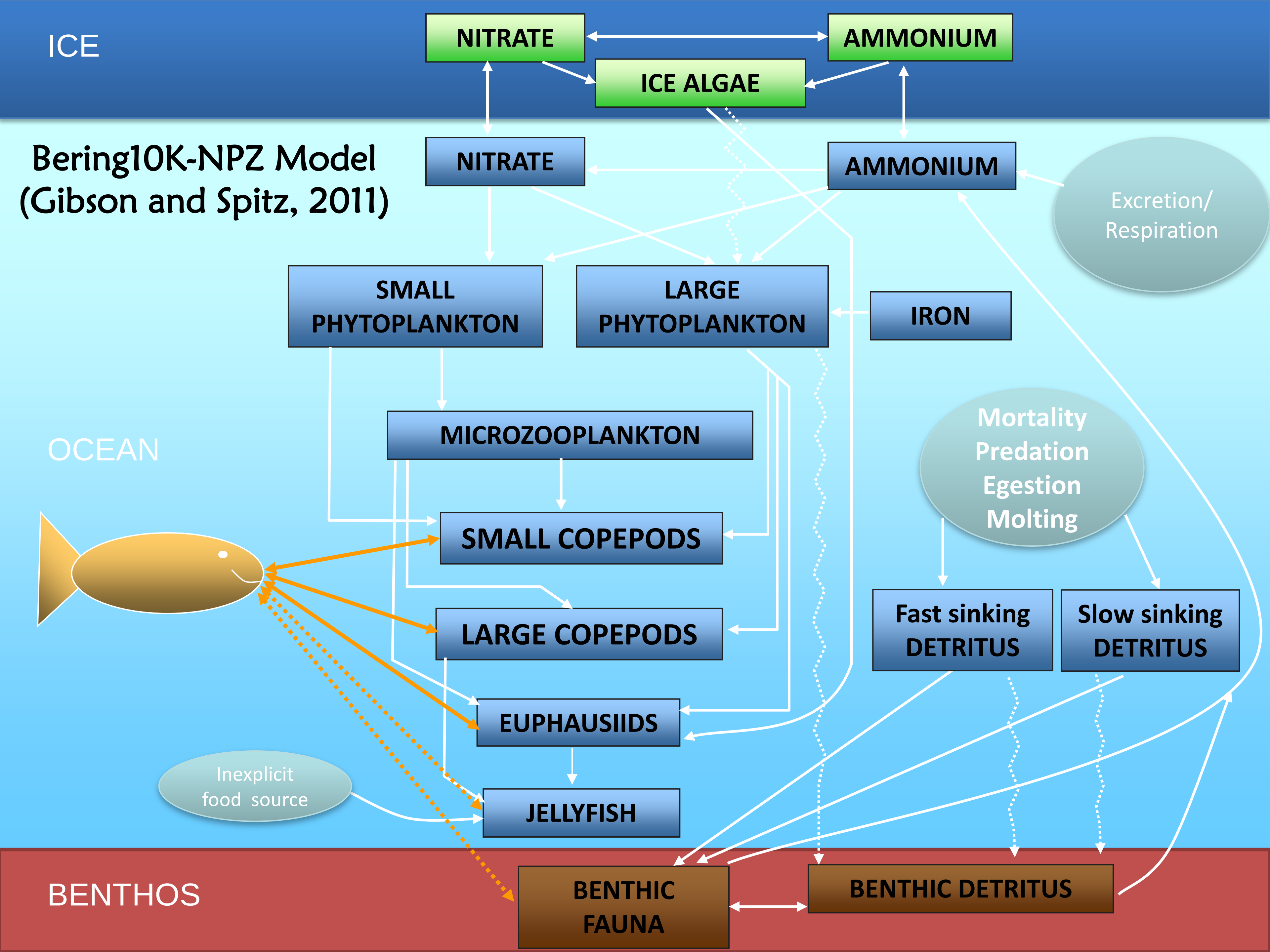
ensemble of projected futures

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

Bering10K model

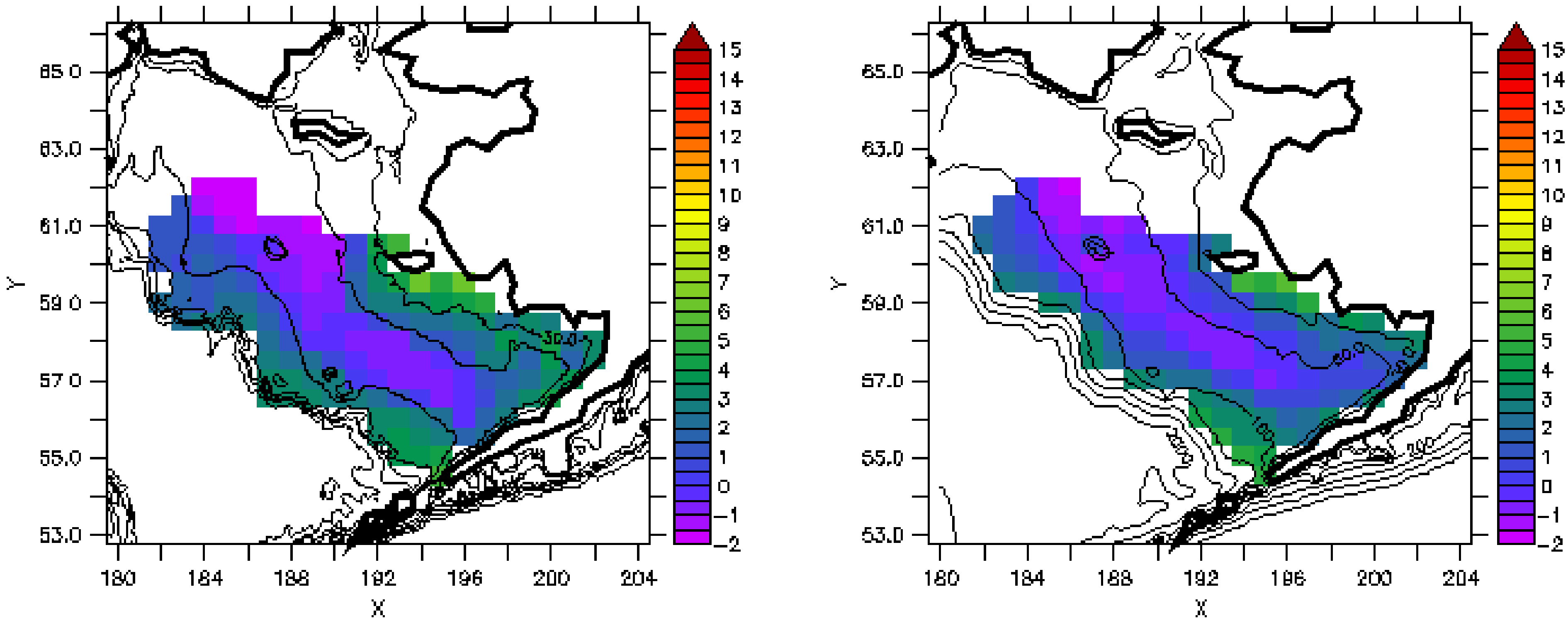


- Regional Ocean Modeling System (ROMS)
- Descendent of NEP5 (Danielson et al. 2012)
- 10 layers, 10-km grid
- Includes ice and tides
- CCSM bulk flux
- Details in Hermann et al. (DSR2, 2013, 2016)


ICE
NITRATE
AMMONIUM
ICE ALGAE
Bering10K-NPZ Model
(Gibson and Spitz, 2011)
NITRATE
AMMONIUM
Excretion/
Respiration
SMALL PHYTOPLANKTON
LARGE PHYTOPLANKTON
IRON
MICROZOOPLANKTON
OCEAN
Mortality
Predation
Egestion
Molting
SMALL COPEPODS
LARGE COPEPODS
Fast sinking DETRITUS
Slow sinking DETRITUS
EUPHAUSIIDS
Inexplicit food source
JELLYFISH
BENTHOS
BENTHIC FAUNA
BENTHIC DETRITUS

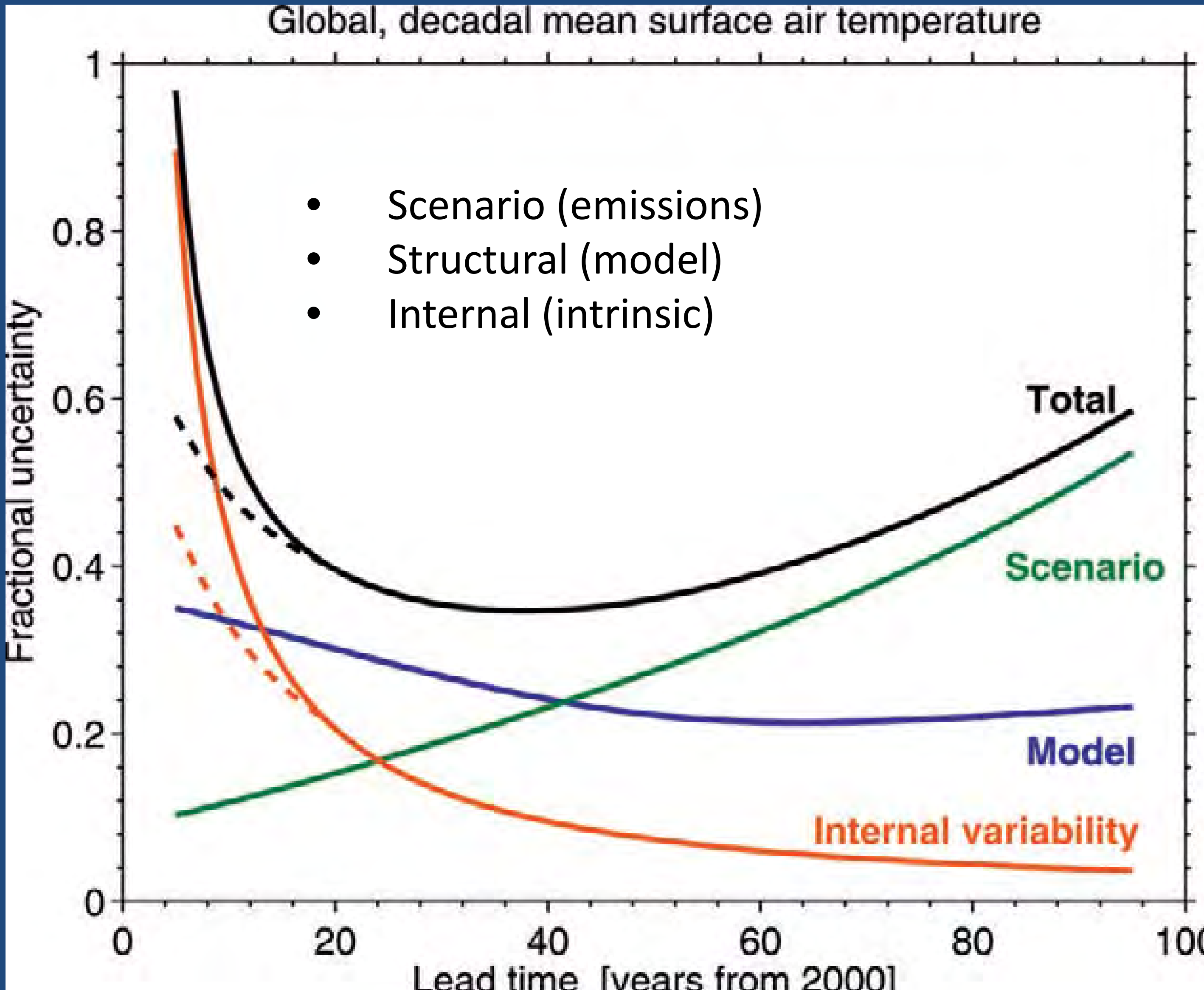
Bering10K validation: the "Cold Pool"

DATA MODEL



Bottom Temp in deg C, summer 2009

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



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

Downscaling Methods

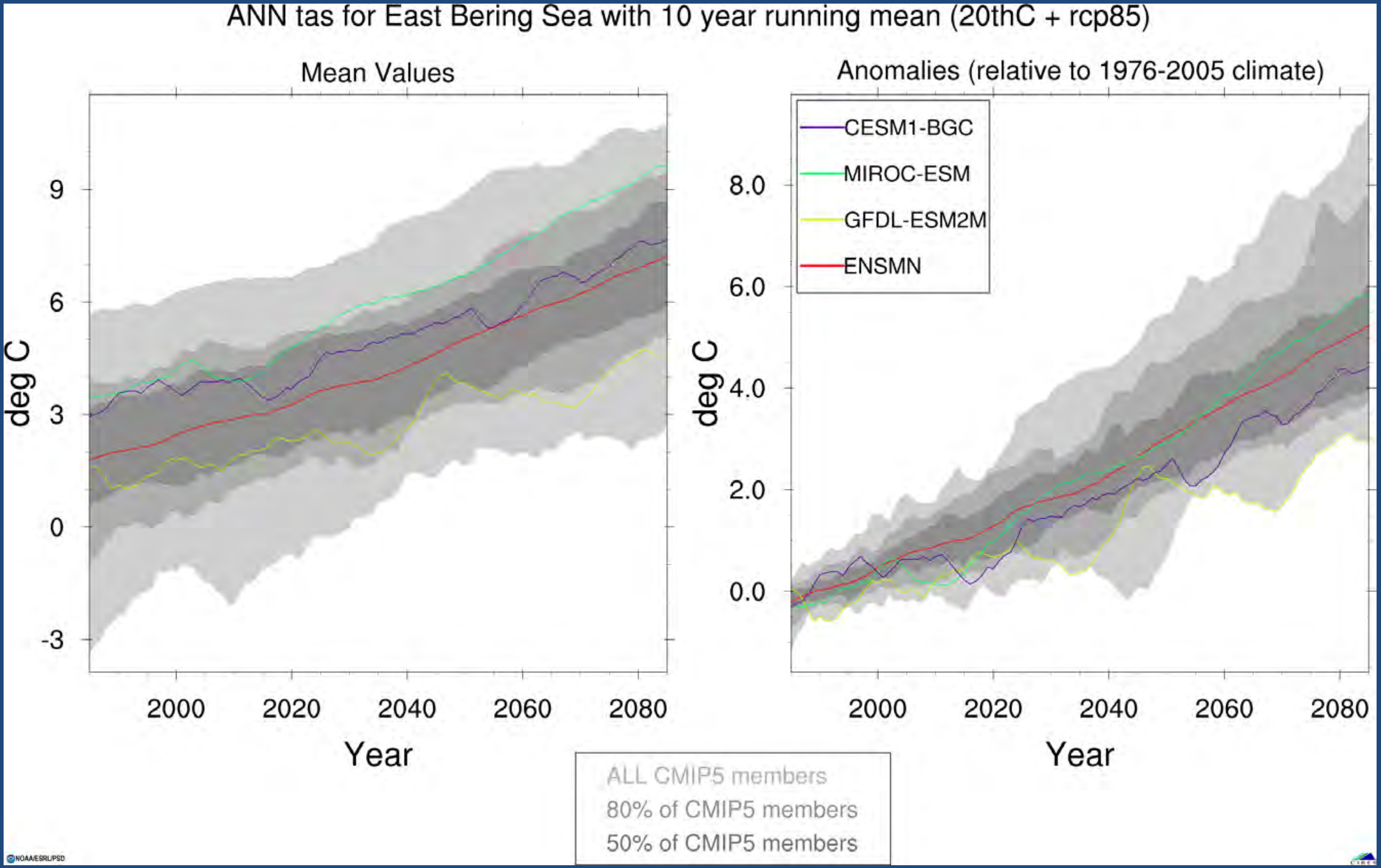
- Choose a subset of IPCC models for atmospheric forcing and oceanic boundary conditions (physical/biological) for our regional model (Bering10K)
- Model choice based on
  - Local validation (replicate present ice cover the Bering Sea)
  - Availability of needed forcing variables
  - Availability of 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)

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

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



(from NOAA climate change web portal)

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

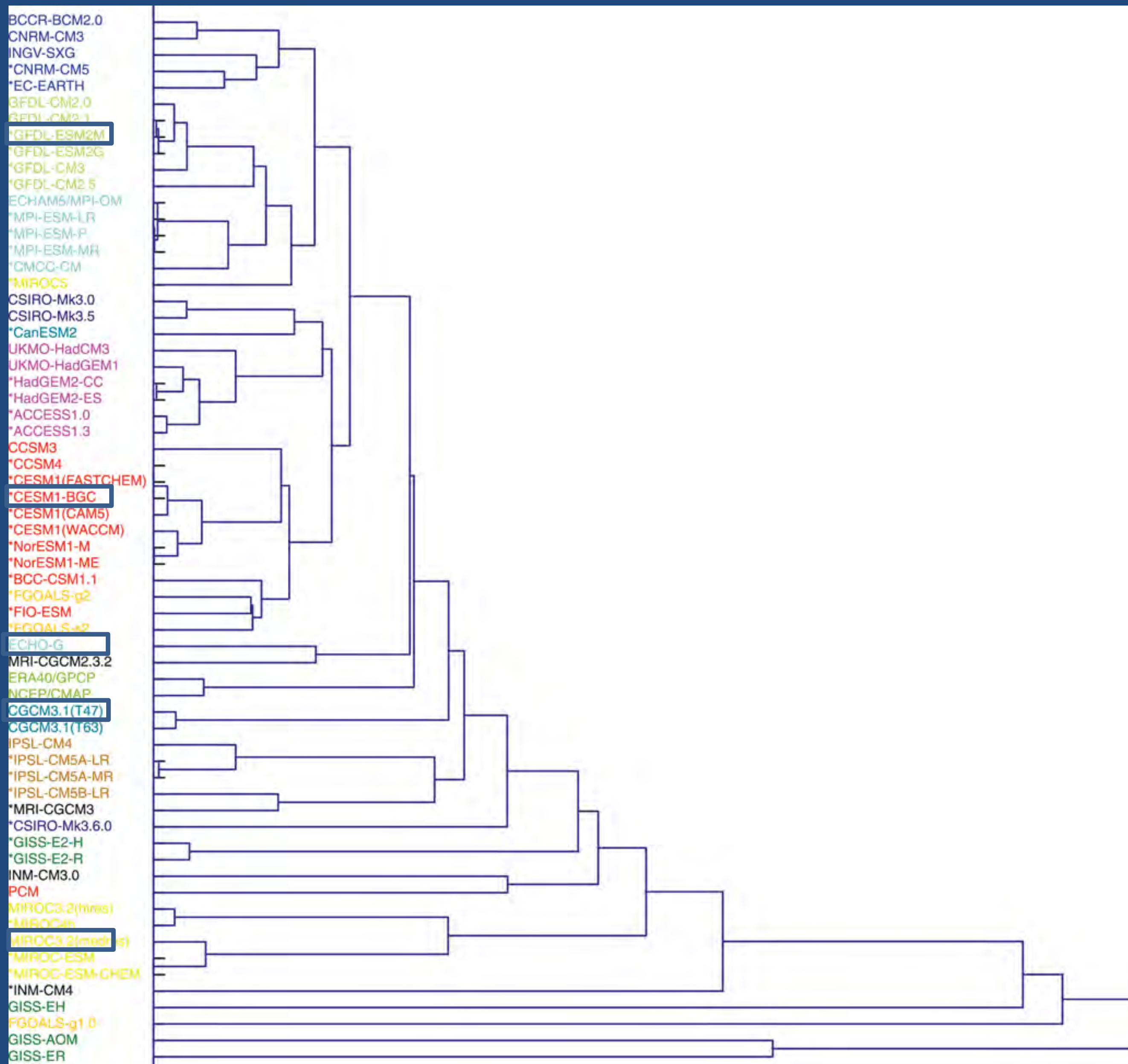
GFDL

CESM

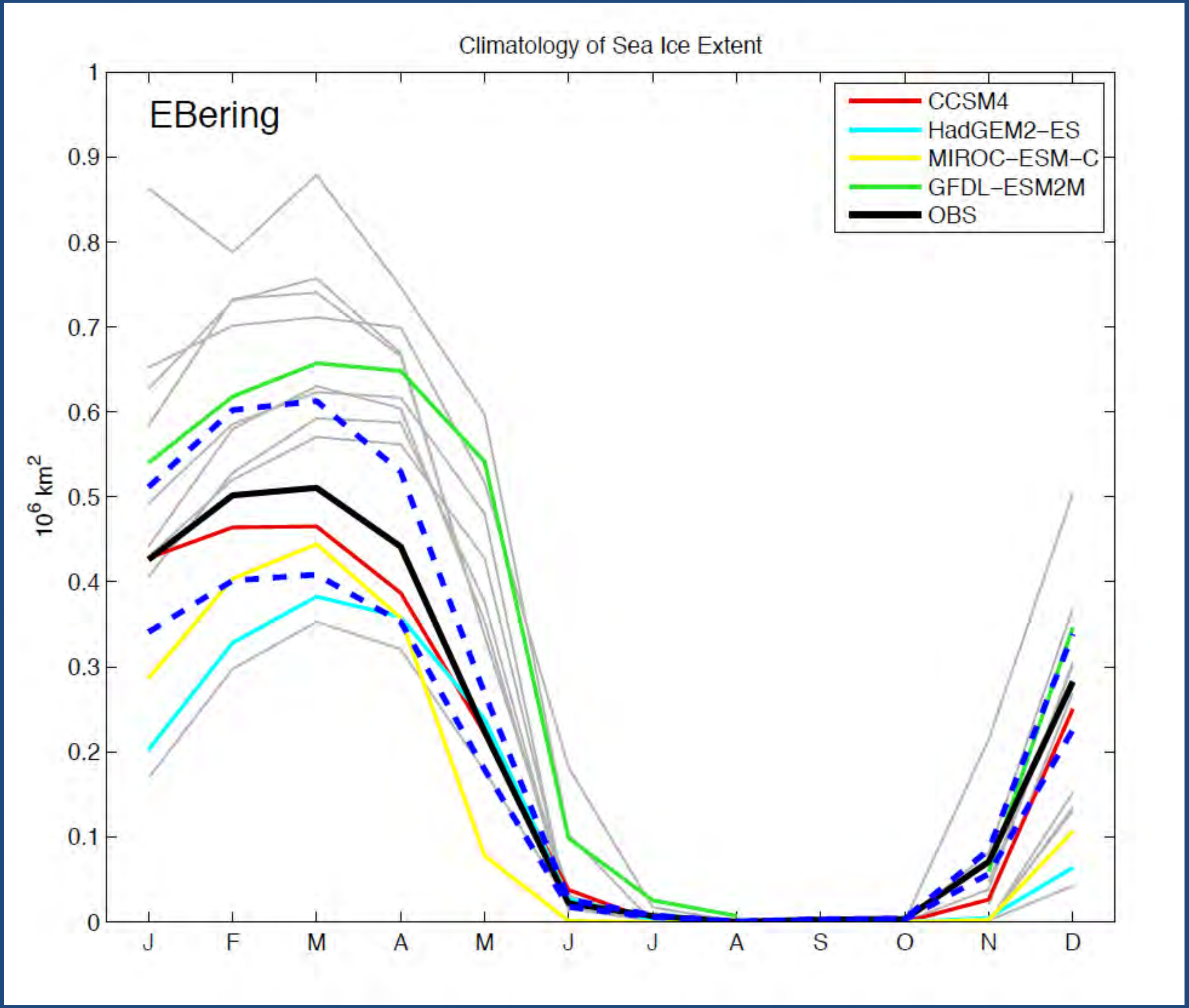
ECHOG

CGCM3.1-t47

MIROC



Our chosen global models replicate ice climatology for the Eastern Bering Sea (M. Wang)

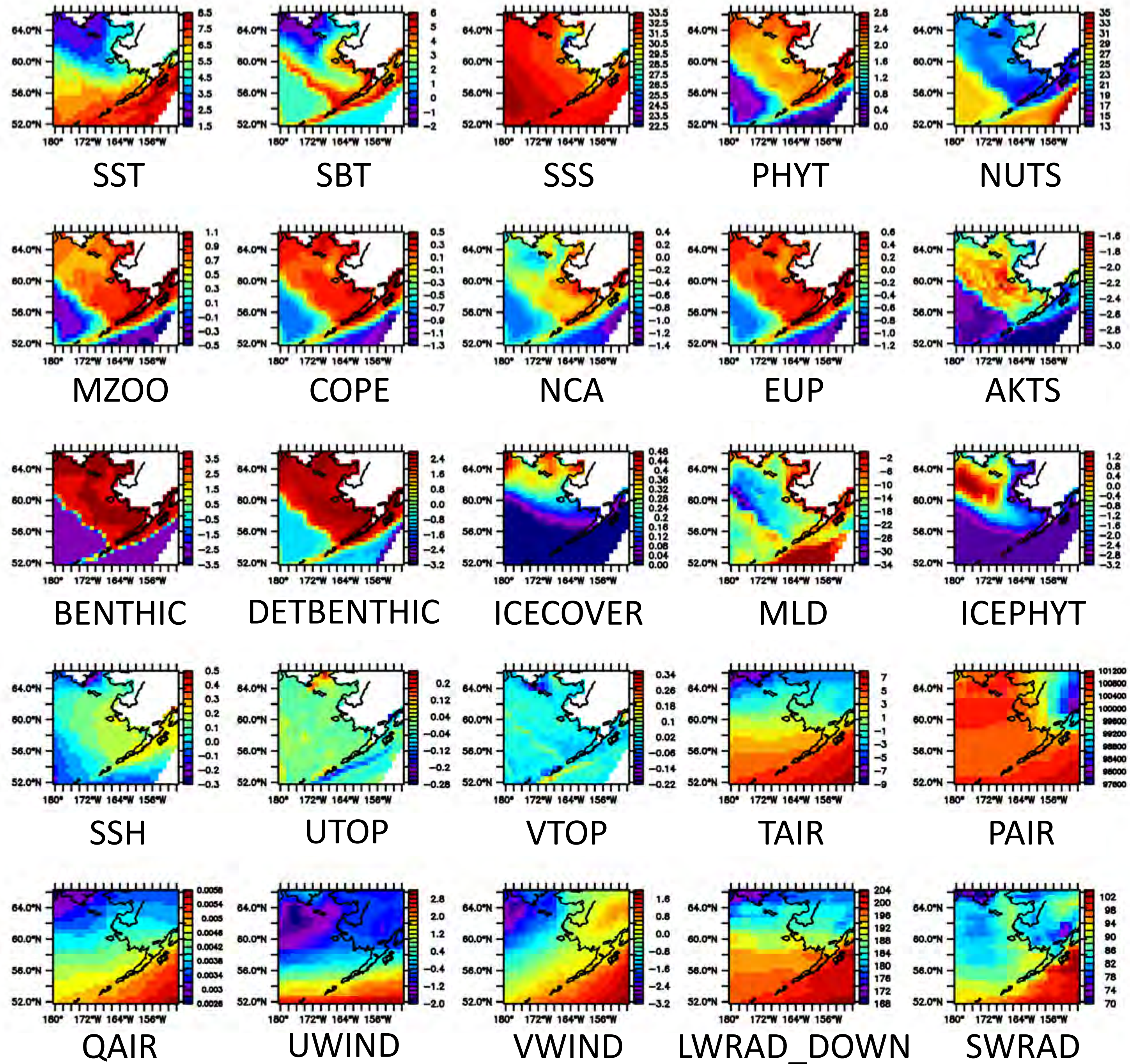


SBT — Bottom Temperature

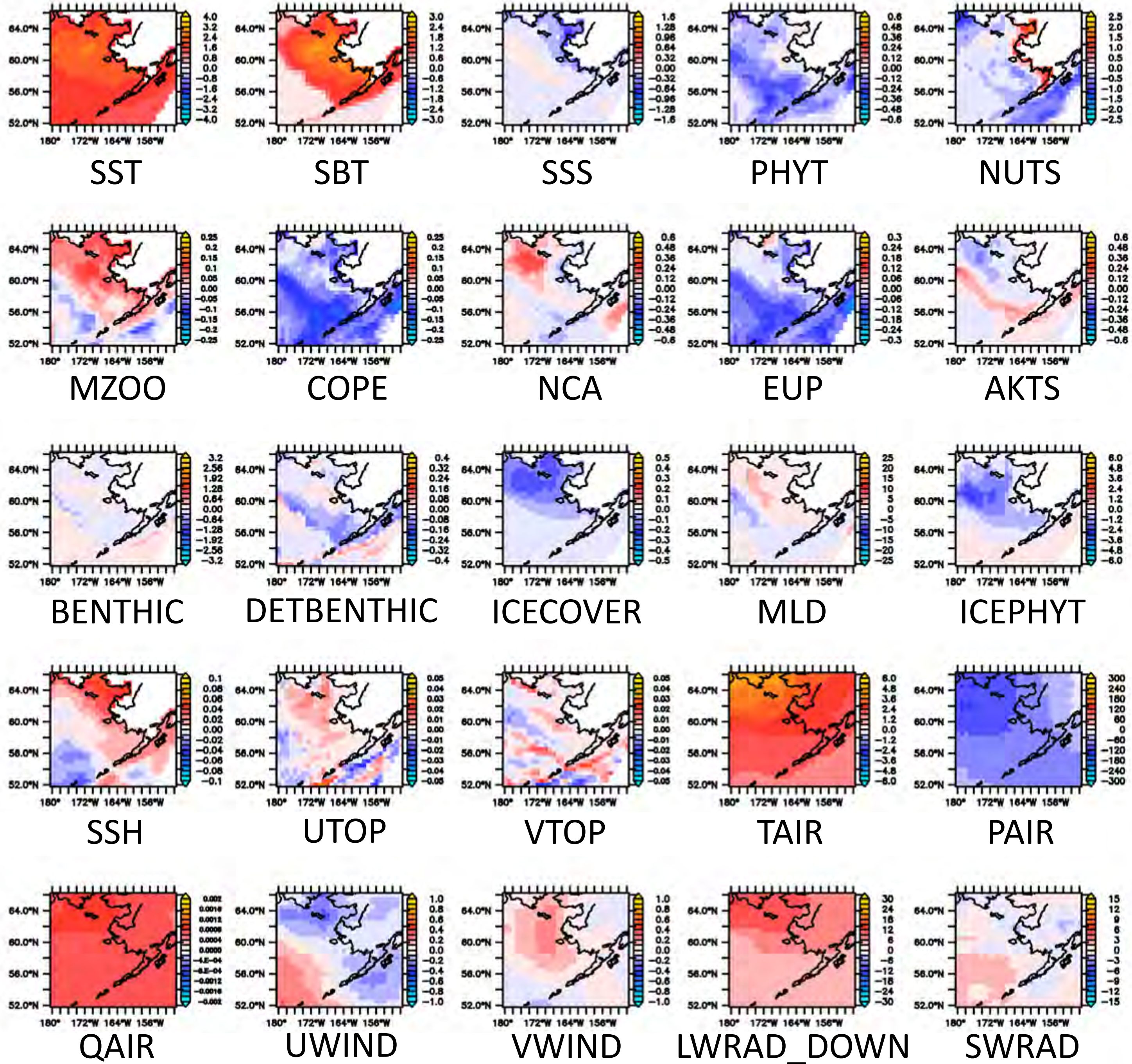
LCZ — Small Copepods (depth ave), Neocalanus (depth ave), Euphausiids (depth ave)

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}

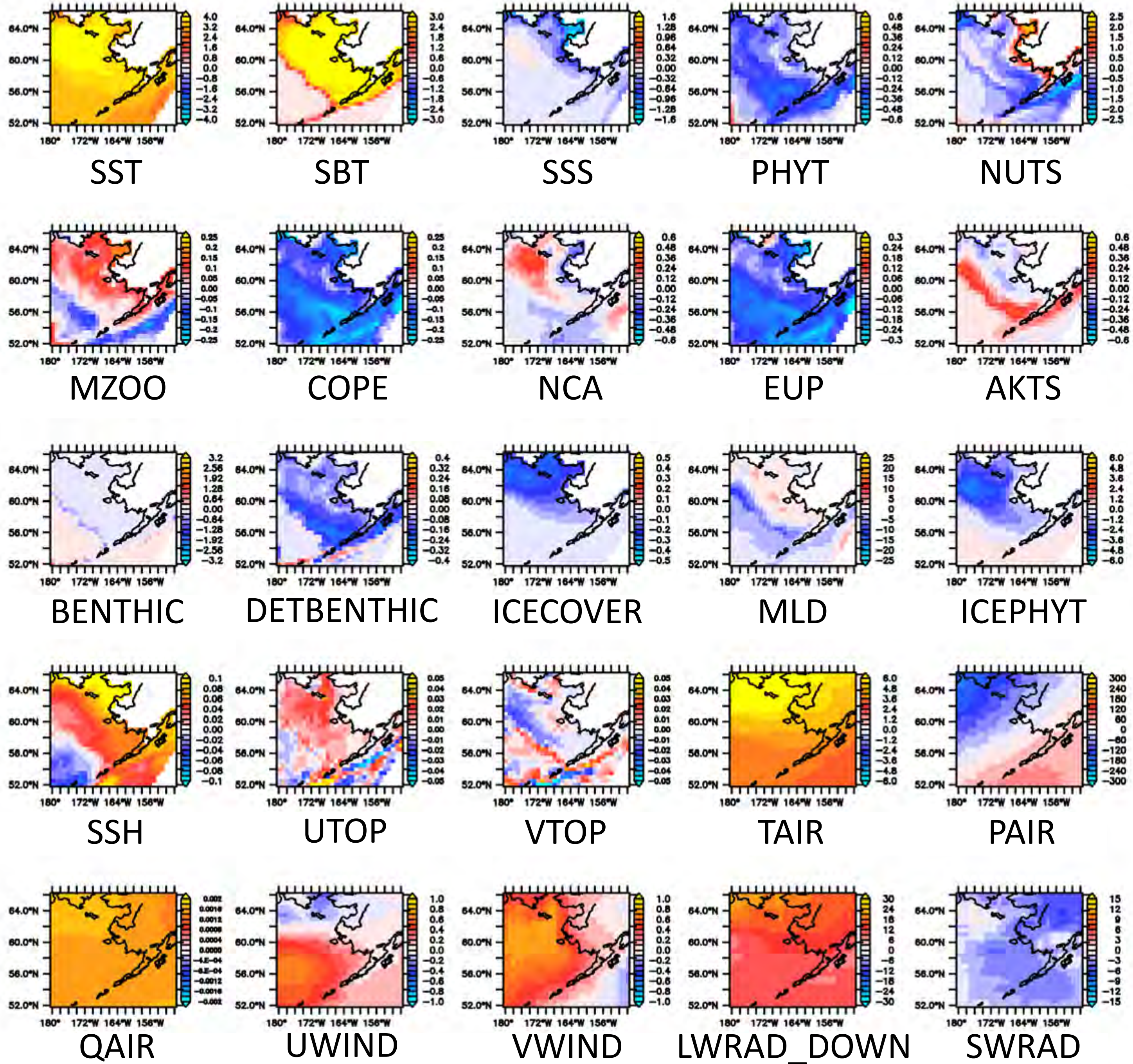
Average present conditions



Change by 2050s (rcp8.5)



Change by 2090s (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

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*)
- *Project* atmospheric forcing from more CMIP5 members onto the multivariate patterns obtained from the mini-ensemble
- Get a much bigger ensemble of regional estimates!

The mathematical procedure

1. Decompose each variable into univariate EOF
2. Perform PC analysis on the multivariate collection of time series
3. This now forms a new basis set explaining the original data
4. Calculate the spatial patterns corresponding to that basis set
5. Project any new forcing data onto that basis set to get the corresponding time function

$$V_{ilt} = \sum_j X_{jil} T_{jit}$$

$$T_{jit} = \sum_k M_{kji} \Gamma_{kt}$$

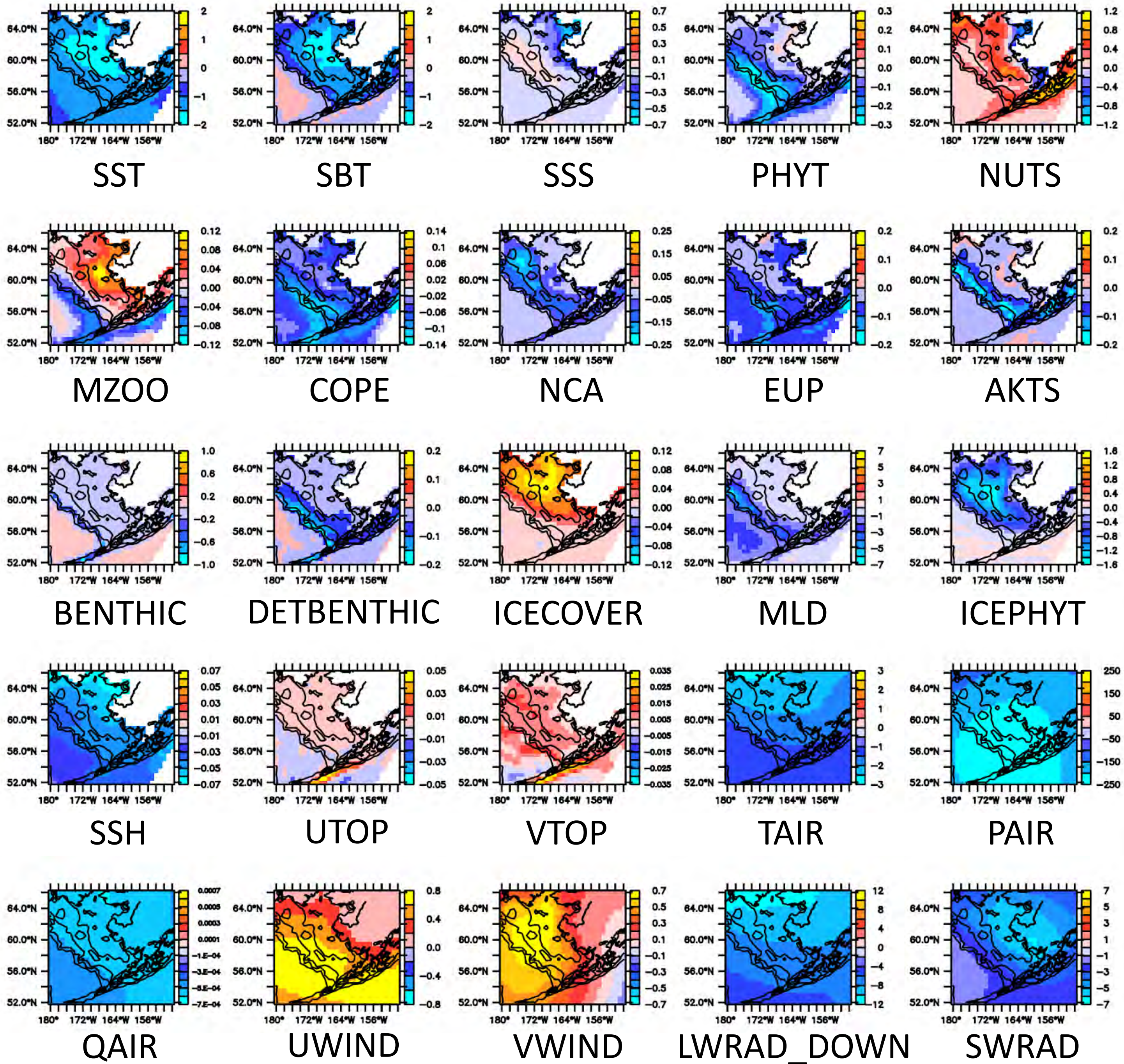
$$V_{ilt} = \sum_k C_{kil} \Gamma_{kt}$$

$$C_{kil} = \sum_t \Gamma_{kt} V_{ilt}$$

$$\Gamma^*_{ikt} = [\sum_l (V_{ilt} C_{kil})] / [\sum_l (C_{kil} C_{kil})]$$

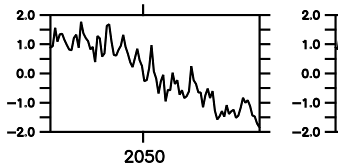
univariate EOF (mode 1)

$$V_{ilt} = \sum_j X_{jil} T_{jit}$$



CESM-rcp8.5 univariate PCs

$$V_{ilt} = \sum_j X_{jil} T_{jit}$$



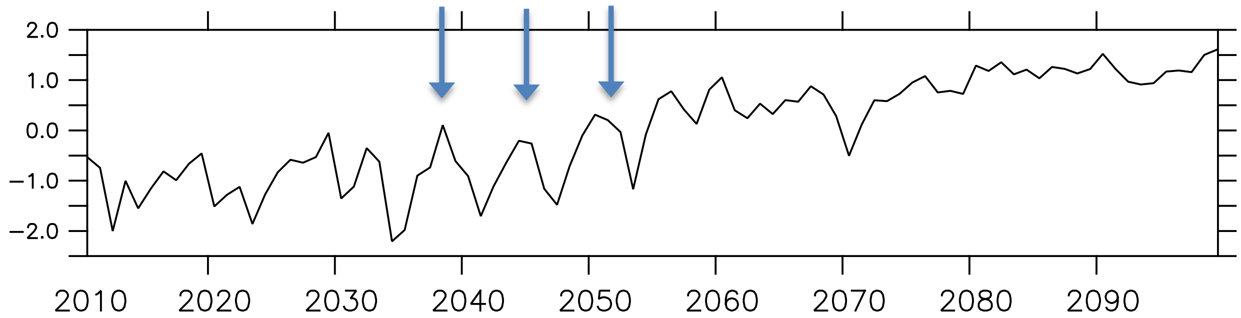
SST	SBT	SSS	PHYT	NUTS
MZOO	COPE	NCA	EUP	AKTS
BENTHIC	DETBENTHIC	ICECOVER	MLD	ICEPHYT

- Next step is to perform PC analysis on this set of univariate time series *Tjit*
- this yields a time series modulating all variables, with associated spatial patterns (multivariate modes) emphasizing covariance among variables

CESM-rcp8.5 multivariate PCs

$$T_{jit} = \sum_k M_{kji} \Gamma_{kt}$$

“stanzas” of warm/cold

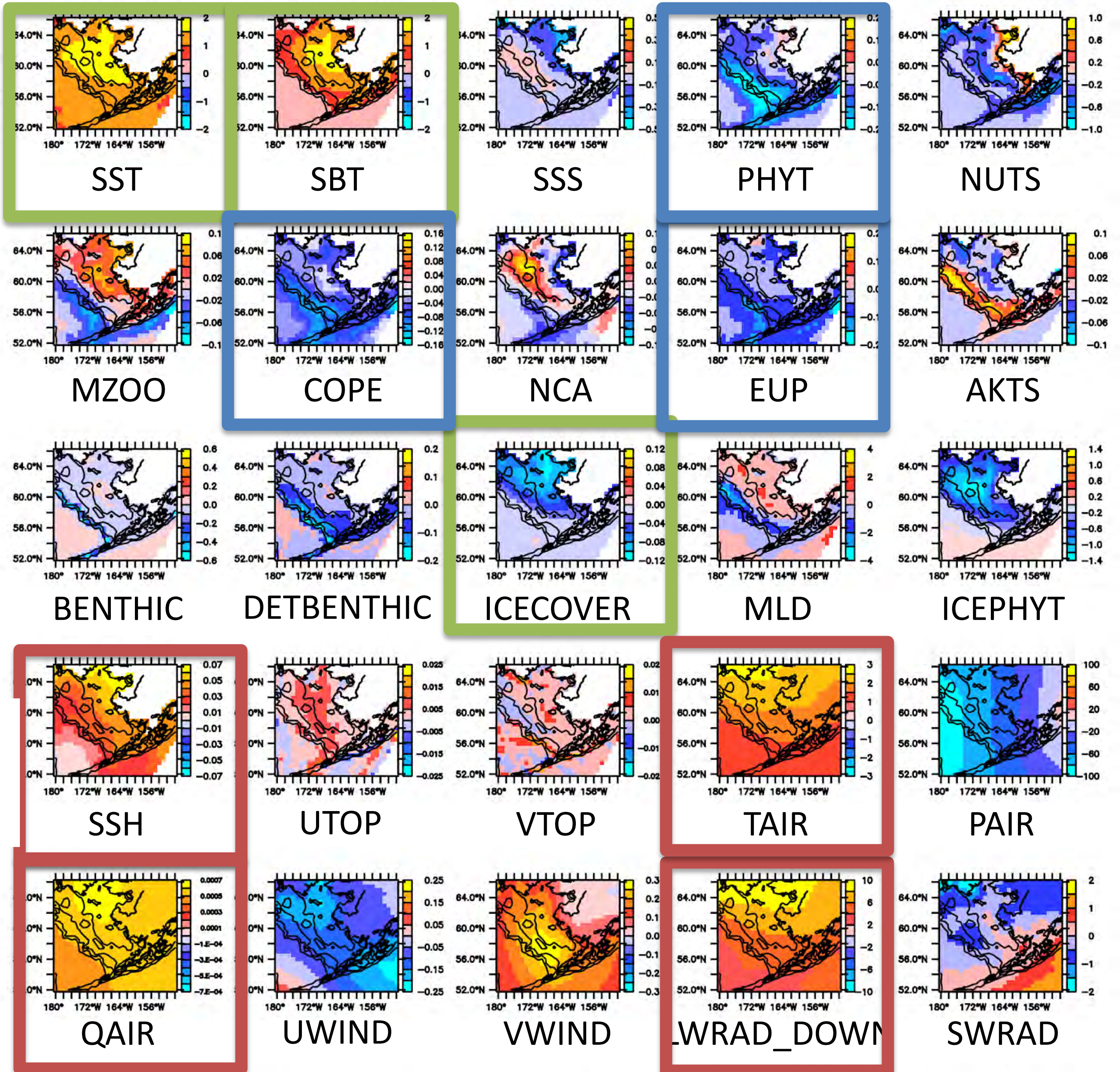


Time series of factor 1

Time series of factor 2

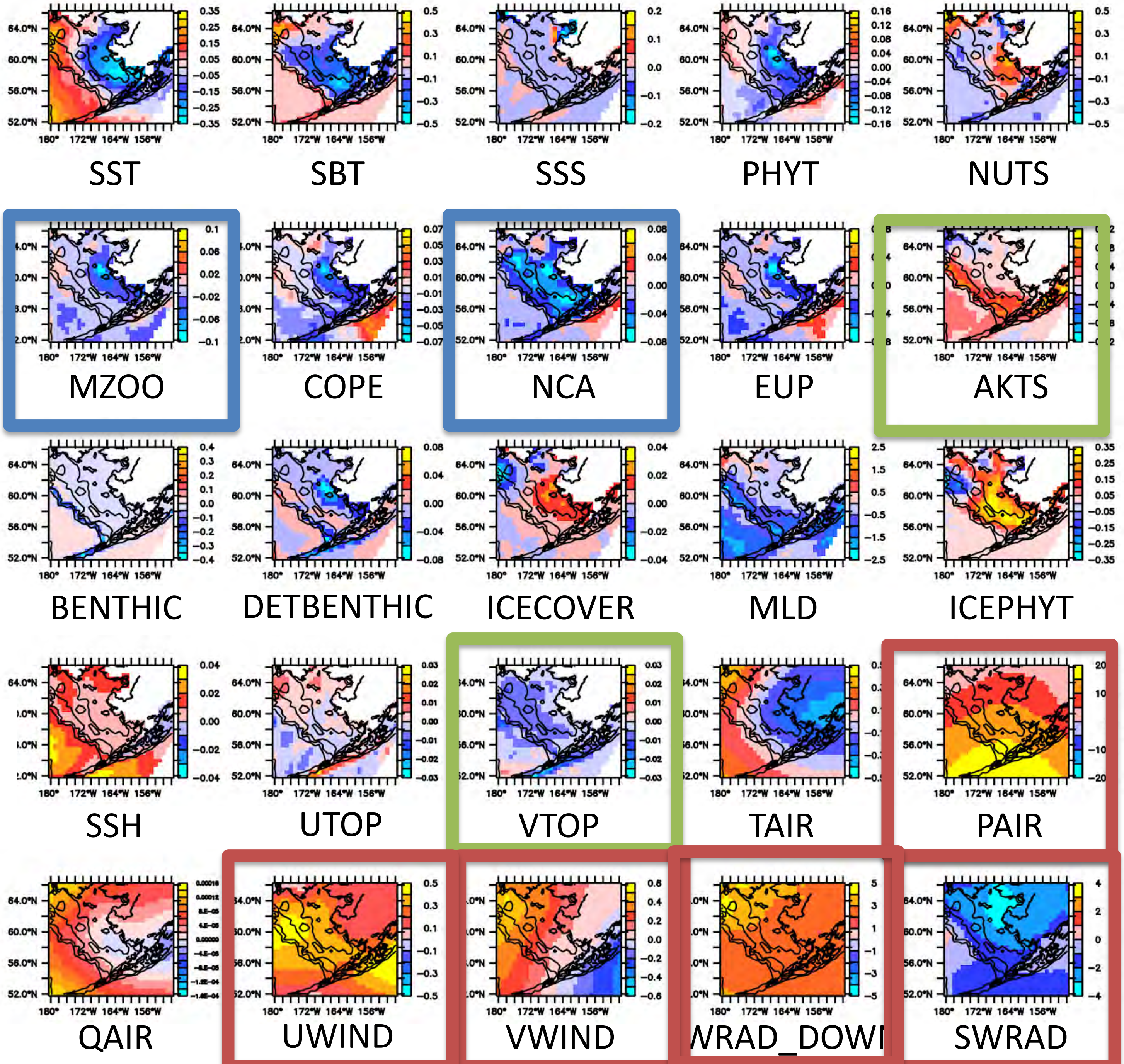
multivariate EOF (mode 1)

$$C_{kil} = \sum_{t} \Gamma_{kt} V_{ilt}$$

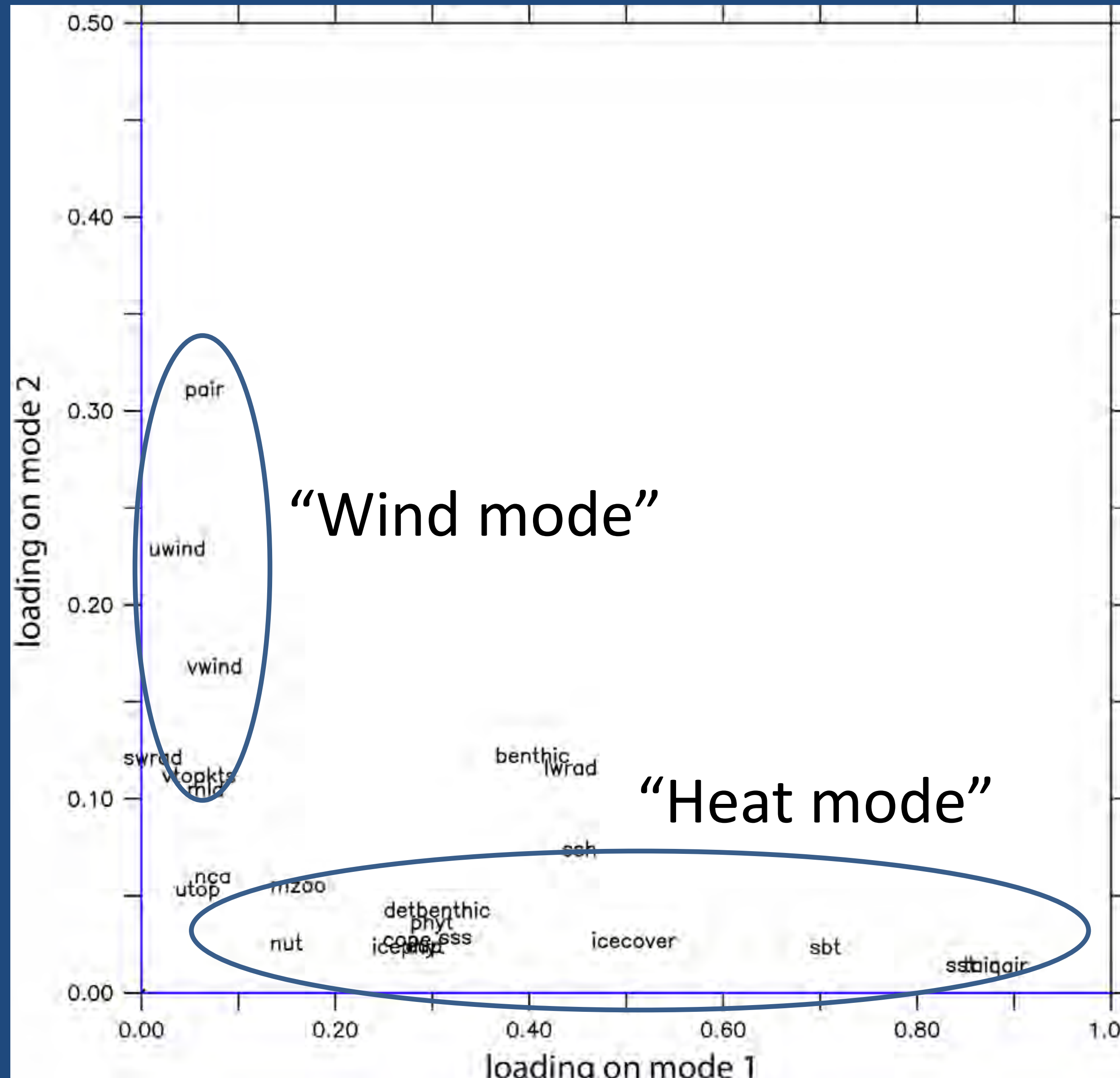


multivariate EOF (mode 2)

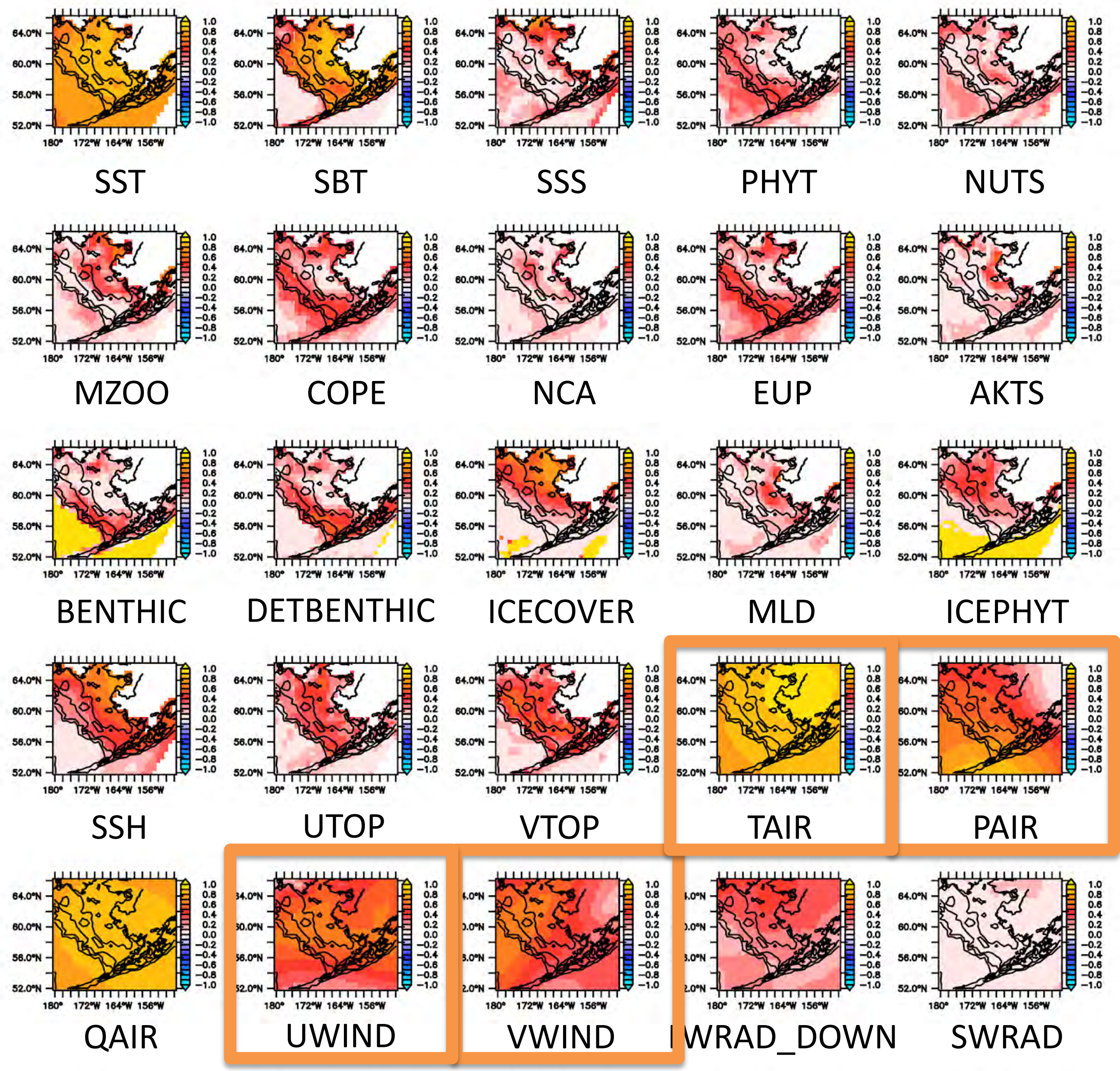
$$C_{kil} = \sum_t \Gamma_{kt} V_{ilt}$$



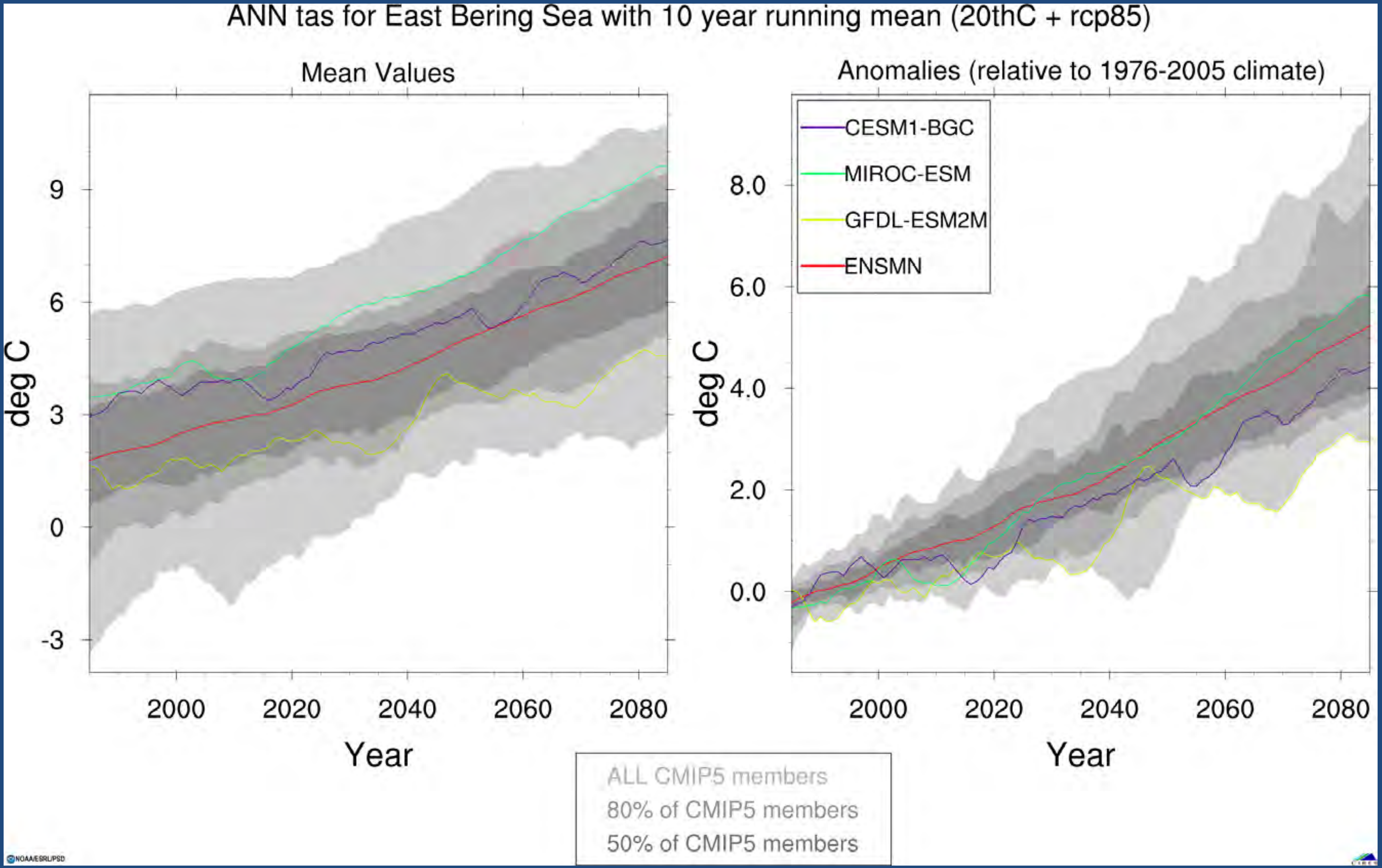
variable loadings suggest separate "heat" and "wind" modes



Large % Variance of training data explained using ONLY
TAIR
PAIR
UWIND
VWIND
as "predictors"



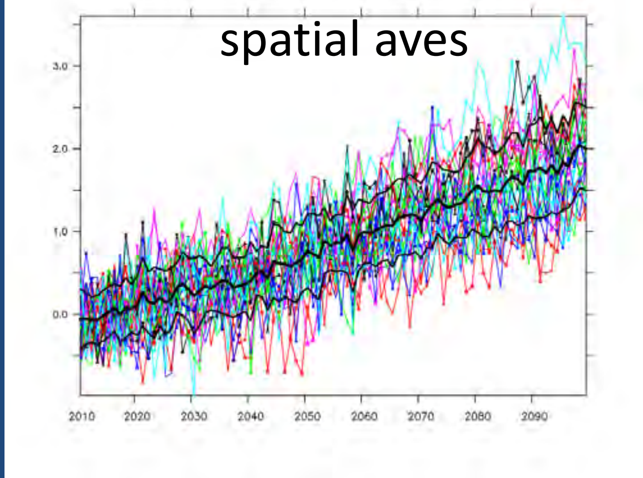
CMIP5 projected air temperature in the EBS (rcp8.5)



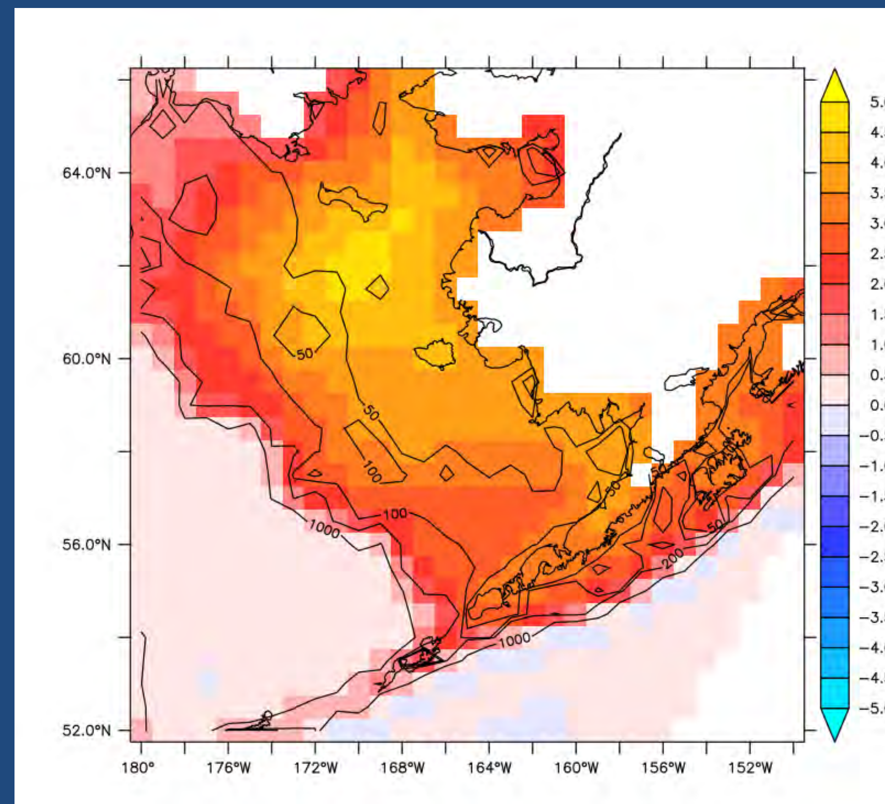
(from NOAA climate change web portal)

Project CMIP5 output onto multivaraite modes to estimate change in sea bottom temperature (rcp8.5)

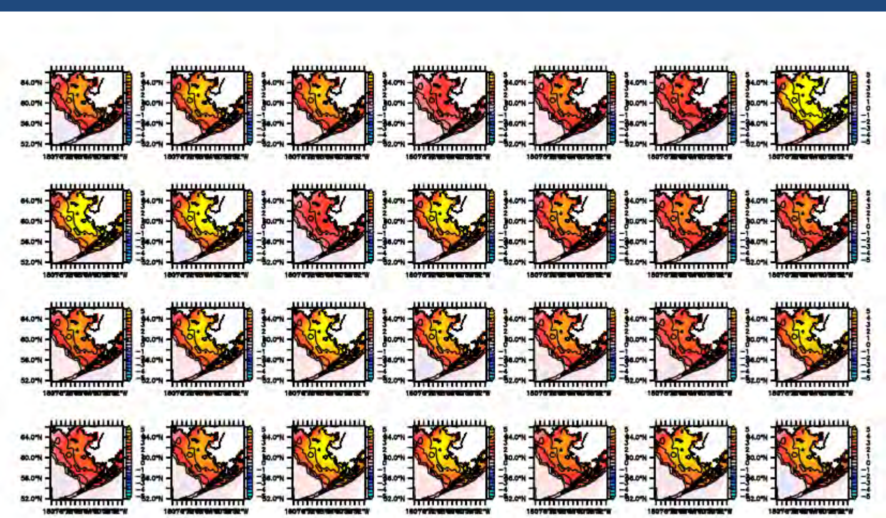
Individual realizations: spatial aves



Average change by 2090s

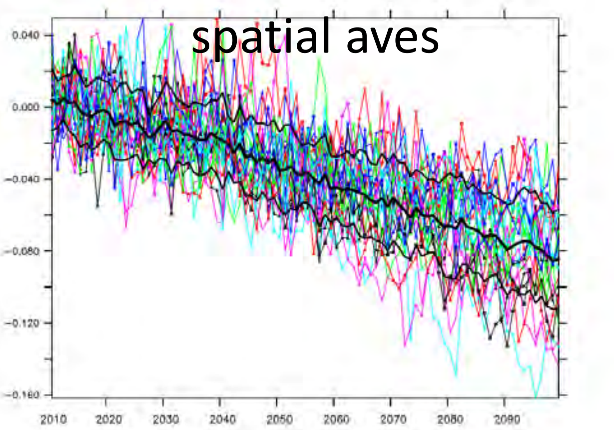


Individual realizations: change by 2090s

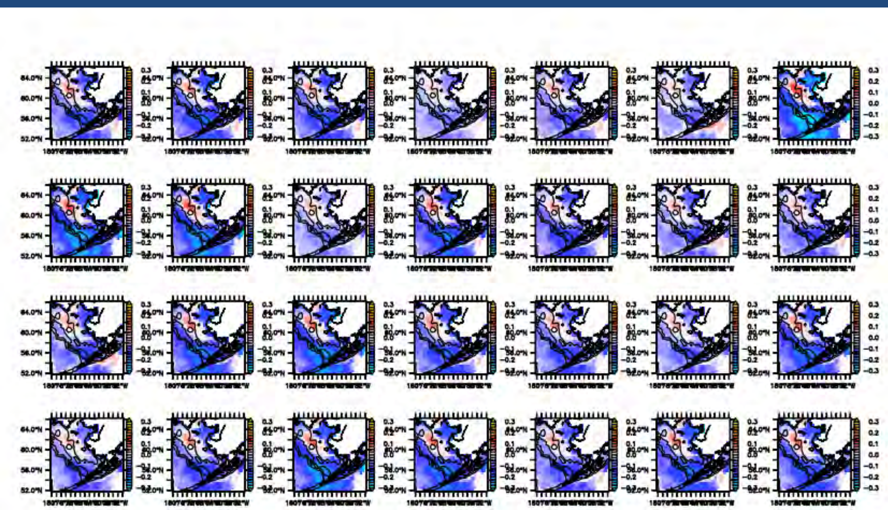


Project CMIP5 output onto multivariate modes to estimate change in large crustacean zooplankton (rcp8.5)

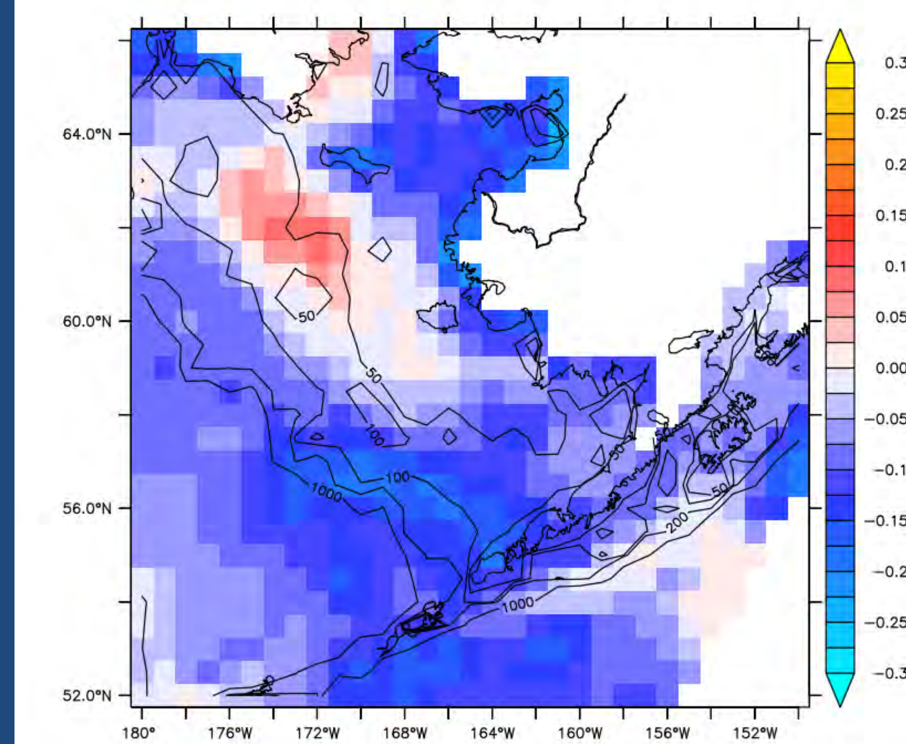
Individual realizations: spatial aves



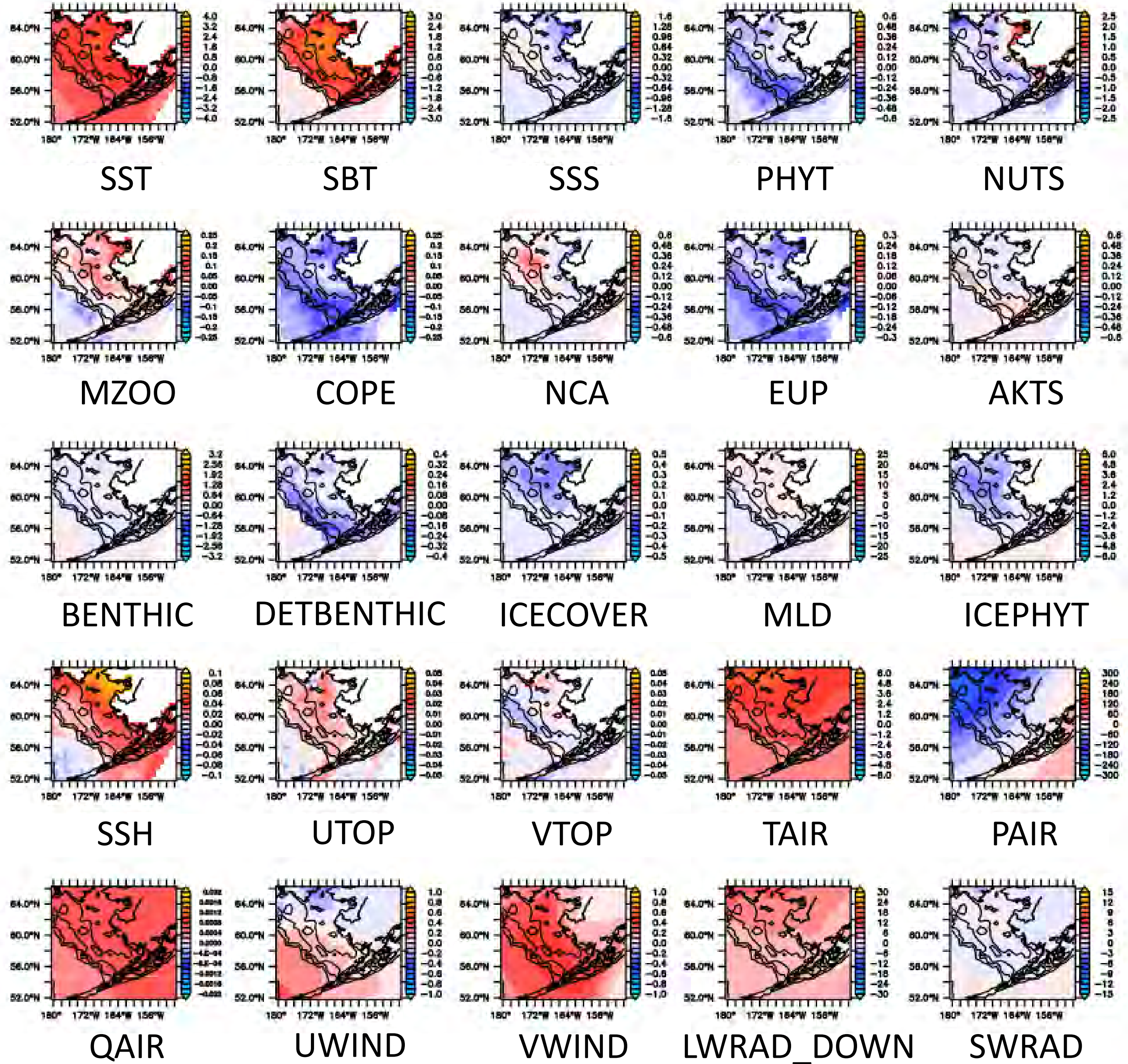
Individual realizations: change by 2090s



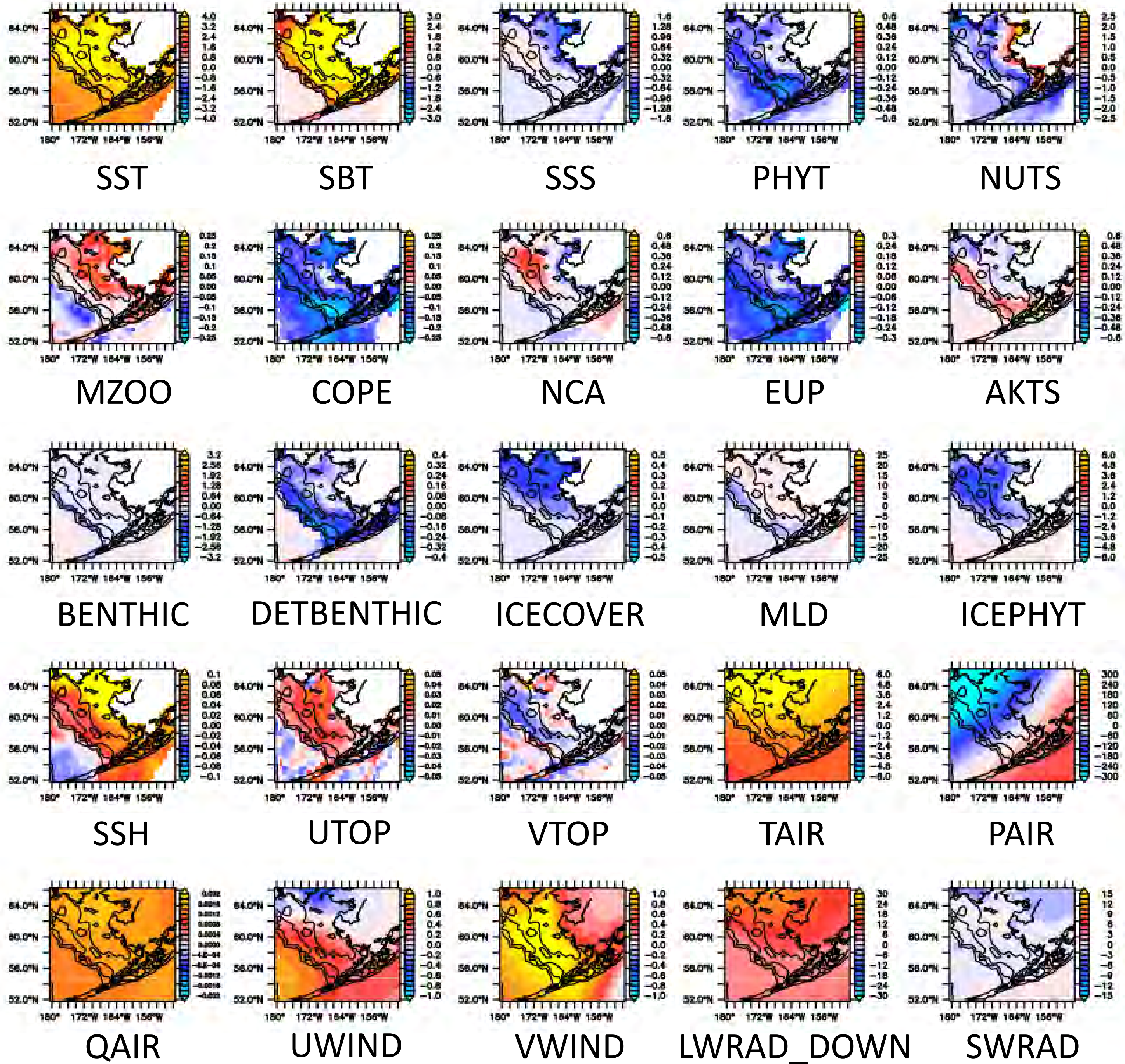
Average change by 2090s



mean change rcp 4.5



mean change rcp 8.5



Conclusions

- 12 downscaling runs of global projections have been completed
- Bottom temperatures up to 5 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)
- Projection of “large ensemble” of forcings onto these modes yields a much bigger regional ensemble
- This method could (potentially) be used for other regions and time scales!