State estimation of Atlantic Ocean circulation at the Last Glacial Maximum

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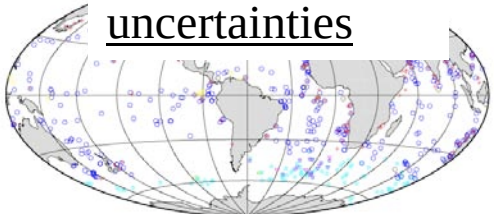
|INTRO| The Last Glacial Maximum

- LGM is a key period in our evolving climate understanding
  - relatively high quality and quantity of data
  - used by modelers to test models, infer climate sensitivity
- For understanding ocean circulation changes, LGM data remain sparse
  - disparate data records difficult to synthesize as a whole
- Best practice coupled climate models do not agree with best practice proxies

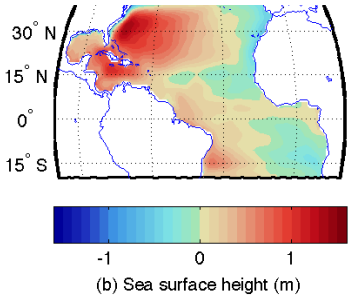
|INTRO| State estimation

- Seek ocean state estimate that is dynamically consistent and in agreement with data, given error estimates
- Least squares solved with method of Lagrange multipliers
- Cost: any function one can write in terms of model variables and/or data
- Controls: uncertain model parameters or boundary conditions

Measurements + uncertainties



Numerical model & its adjoint



Cost function

$$\sum_i [\,\text{model}_i(\vec{u}) - \text{data}_i\,]^2$$

Control vector

e.g. zonal wind speed

|INTRO| LGM state estimation

- Study how ocean circulation may have been different at LGM
- Treat LGM N. Atlantic circulation as seasonal steady-state
- Incorporate as many proxy records as possible
  - Uncertainty estimates provide relative weighting
- Initial version is working and preliminary results available

|EXP DESIGN| Model configuration

General setup

- Model
  - MIT GCM coupled ocean / sea ice model
  - Prescribed atmosphere
  - Stresses, evaporation, & heat fluxes via bulk formulas
- Domain
  - N. Atlantic 33°S to 75°N
  - 1 degree, 23 levels
  - Closed Med., N. and S. boundaries

Modern reference case

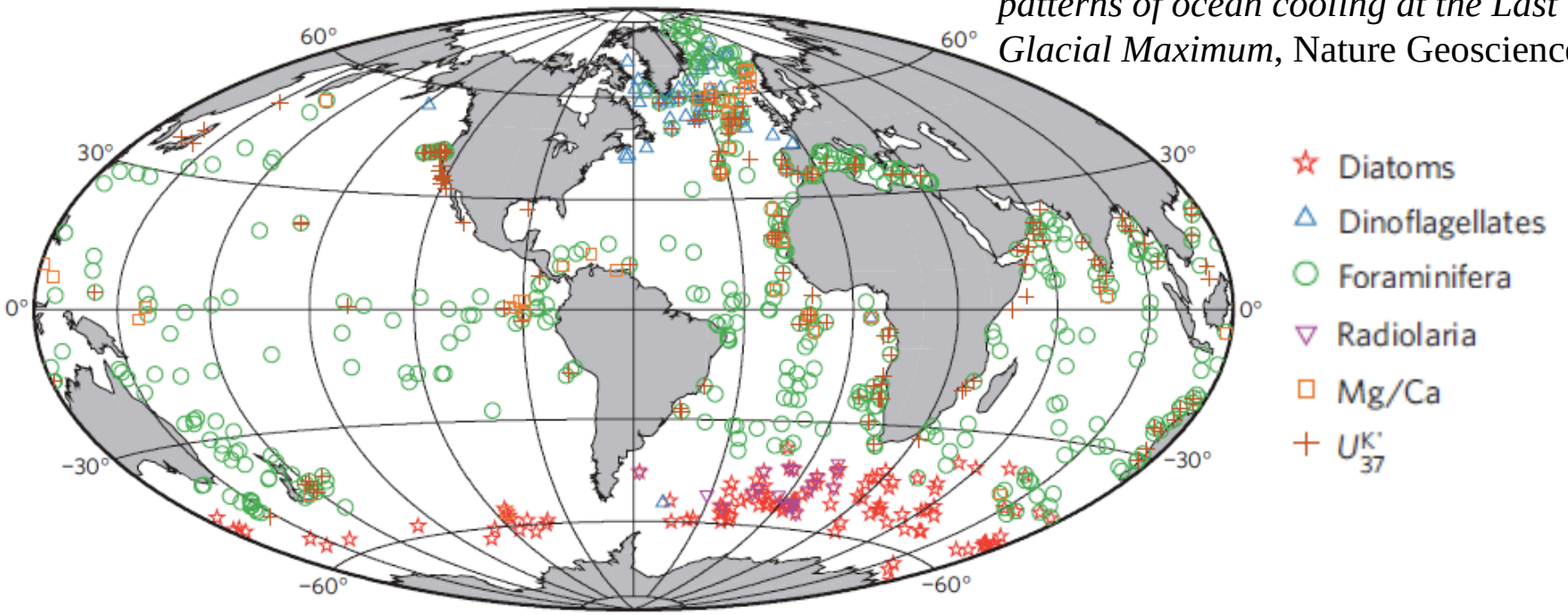
- 1st guess boundary conditions
  - ECCO bathymetry
  - Initial conditions: OCCA T/S[1]
  - Atmospheric forcing: 6-hr NCEP 2006
- Cost function:
  - Misfit to OCCA T/S
  - Forget & Wunsch[2] data error
- Controls:

- Initial T/S	- Relative humidity
- U/V wind speed	- Shortwave radiation
- Atm. temp	- Precipitation

1. **Forget (to appear)**, *Mapping ocean observations in a dynamical framework: a 2004-2006 ocean atlas*, JPO.
2. **Forget & Wunsch (2007)**, *Estimated Global Hydrographic Variability*, JPO, 37.

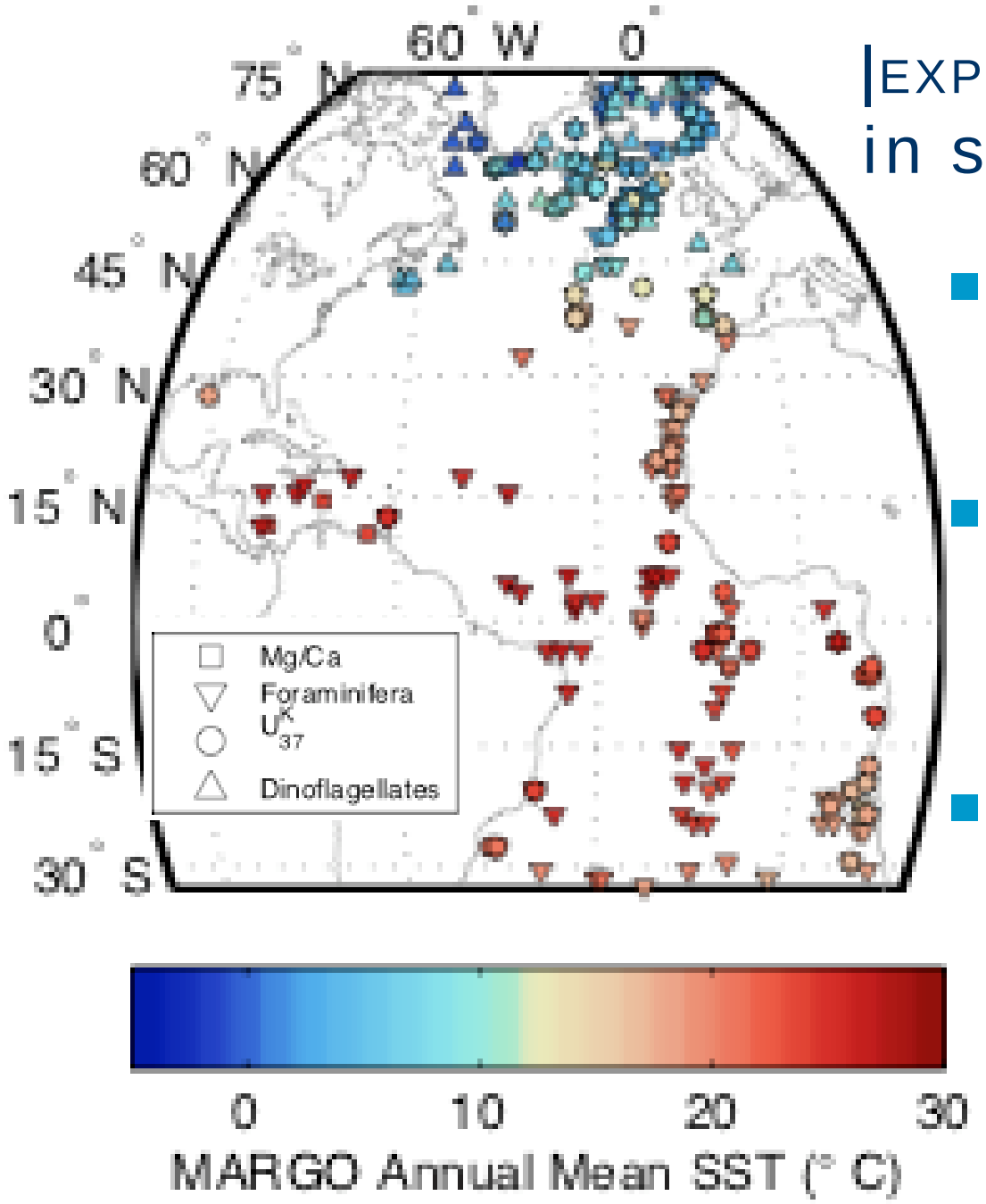
MARGO

From **MARGO Project Members (2009)**, *Constraints on the magnitude and patterns of ocean cooling at the Last Glacial Maximum*, Nature Geoscience.



- Multi-proxy approach
  - 8 SST reconstructions
  - N/S sea ice reconstructions
- LGM 19-23 cal kyr BP
- Common calibration reference temperatures
- Consistent uncertainty criteria
  - age assignment
  - # samples
  - reliability

|EXP DESIGN| Data used in state estimate



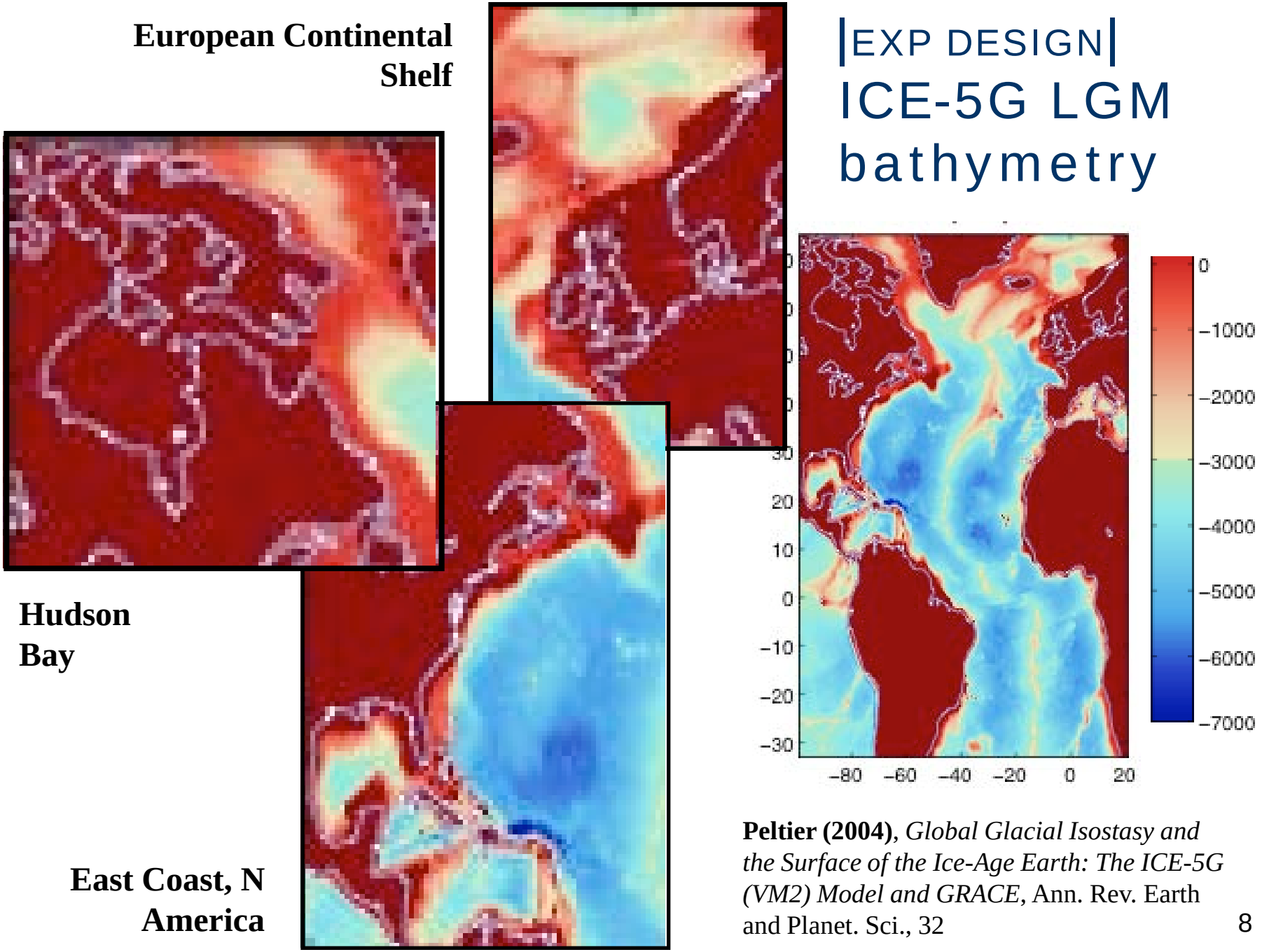
- Use reconstructions w/ some coverage in domain
- Geochemical SST proxies
  - [46] Alkenones U_k^{37}
  - [31] Foraminifera Mg/Ca
- Assemblage based SSTs
  - [136] Planktonic foraminifera
  - [49] Dinoflagellate cysts

|EXP DESIGN|
ICE-5G LGM bathymetry

European Continental Shelf

Hudson Bay

East Coast, N America



Peltier (2004), *Global Glacial Isostasy and the Surface of the Ice-Age Earth: The ICE-5G (VM2) Model and GRACE*, Ann. Rev. Earth and Planet. Sci., 32

|EXP DESIGN| Modeled LGM Cases

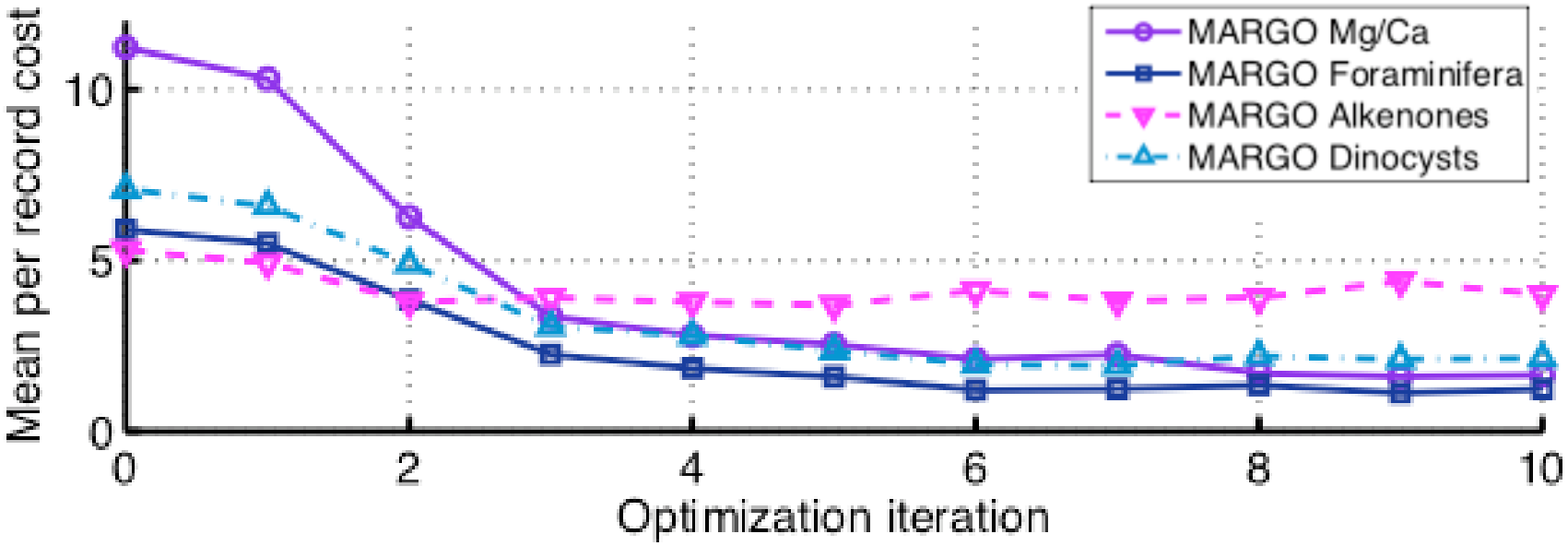
- All cases:
  - Bathymetry: ICE-5G 21k estimate
  - Initial condition: OCCA T/S
  - Estimation cost: misfit to MARGO SST estimates
  - Data uncertainties: semi-quantitative mean reliability index [MARGO 2009]
    - number of samples, age model, reconstruction reliability
- MLGM 1:
  - 1st guess atmospheric forcing: NCEP 2006, 6-hr averages
- MLGM 2:
  - 1st guess atmospheric forcing: CCSM3 coupled LGM runs, monthly averages

Otto-Bliesner & Esther Brady (2006), *Last Glacial Maximum and Holocene Climate in CCSM3*, Journal of Climate, 19 (11).

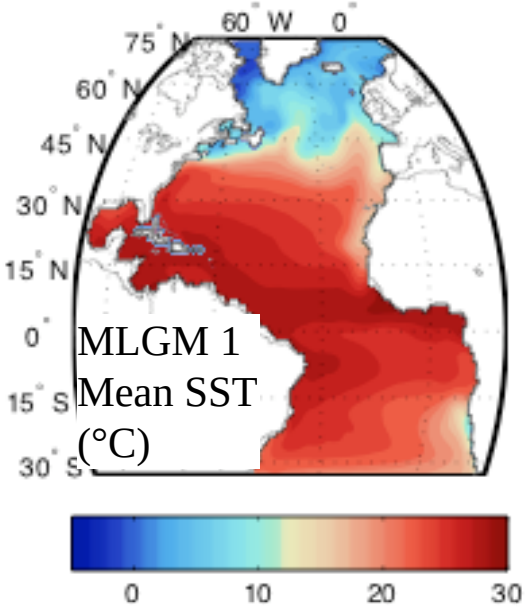
|RESULTS| MLGM 1 model-data misfits

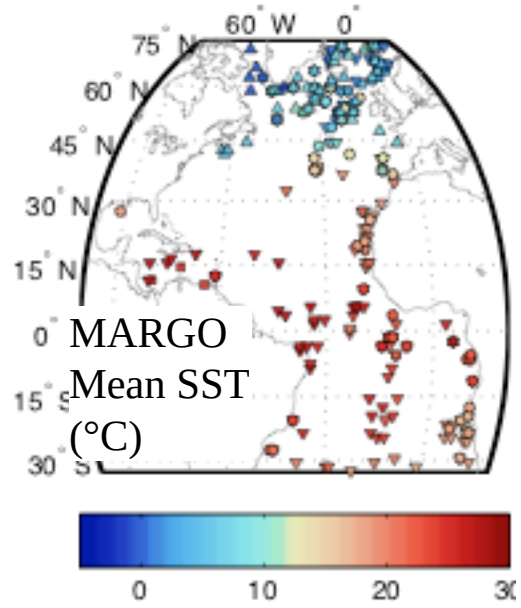
- Per proxy record cost:

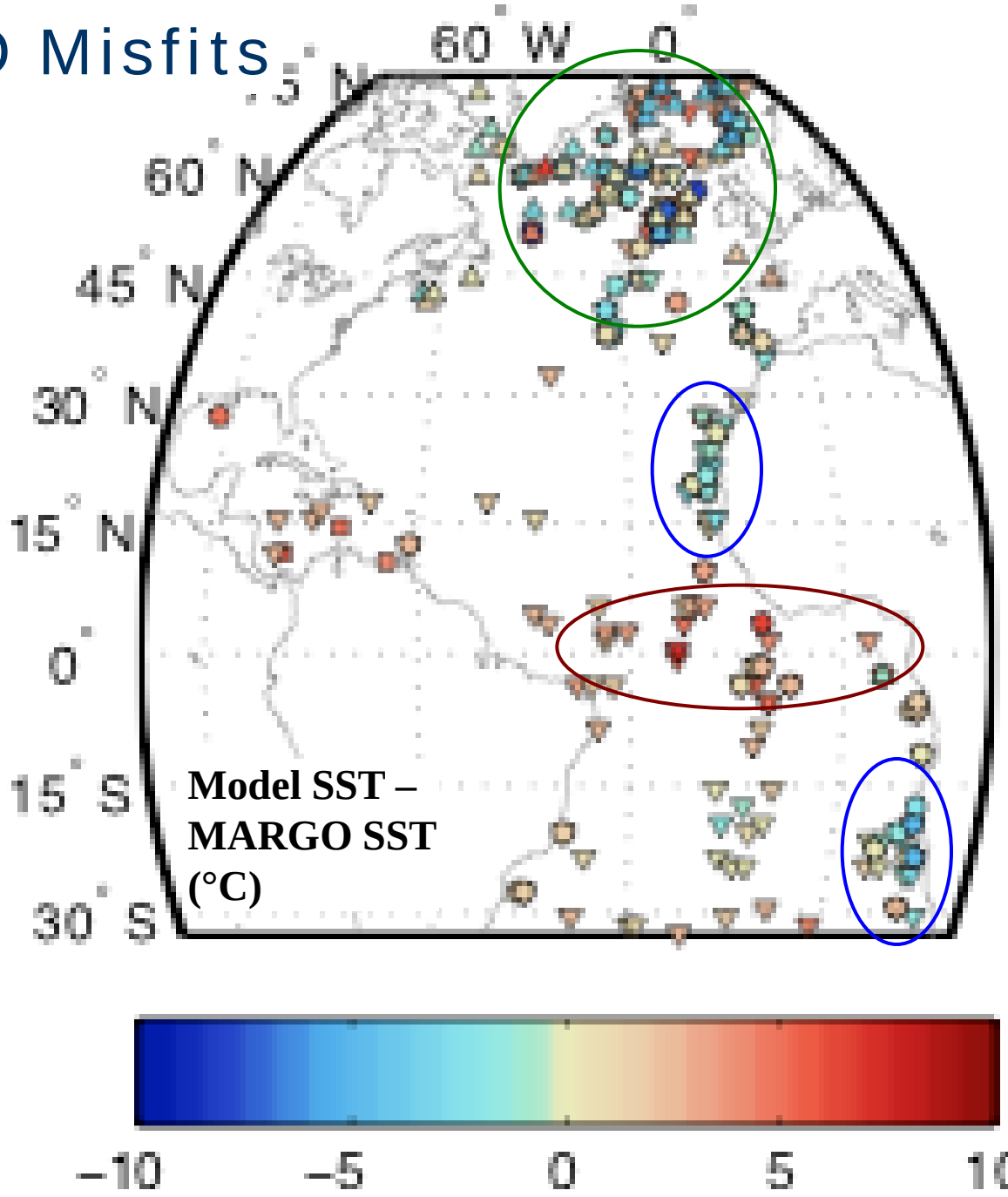
$$cost(record\ r) = \frac{[SST(r) - \overline{MSST(location(r), season(r)}]^2}{uncertainty(r)^2}$$

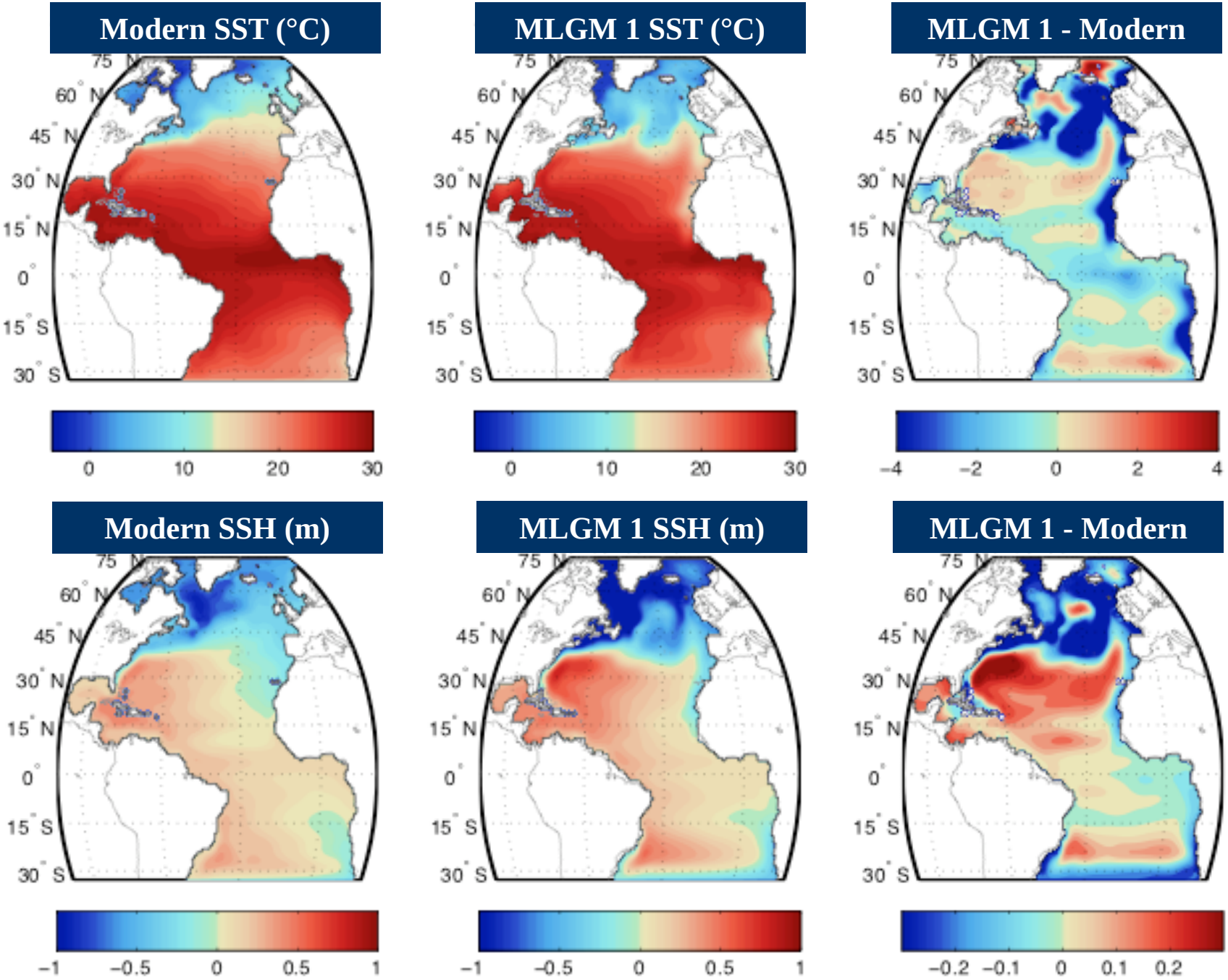


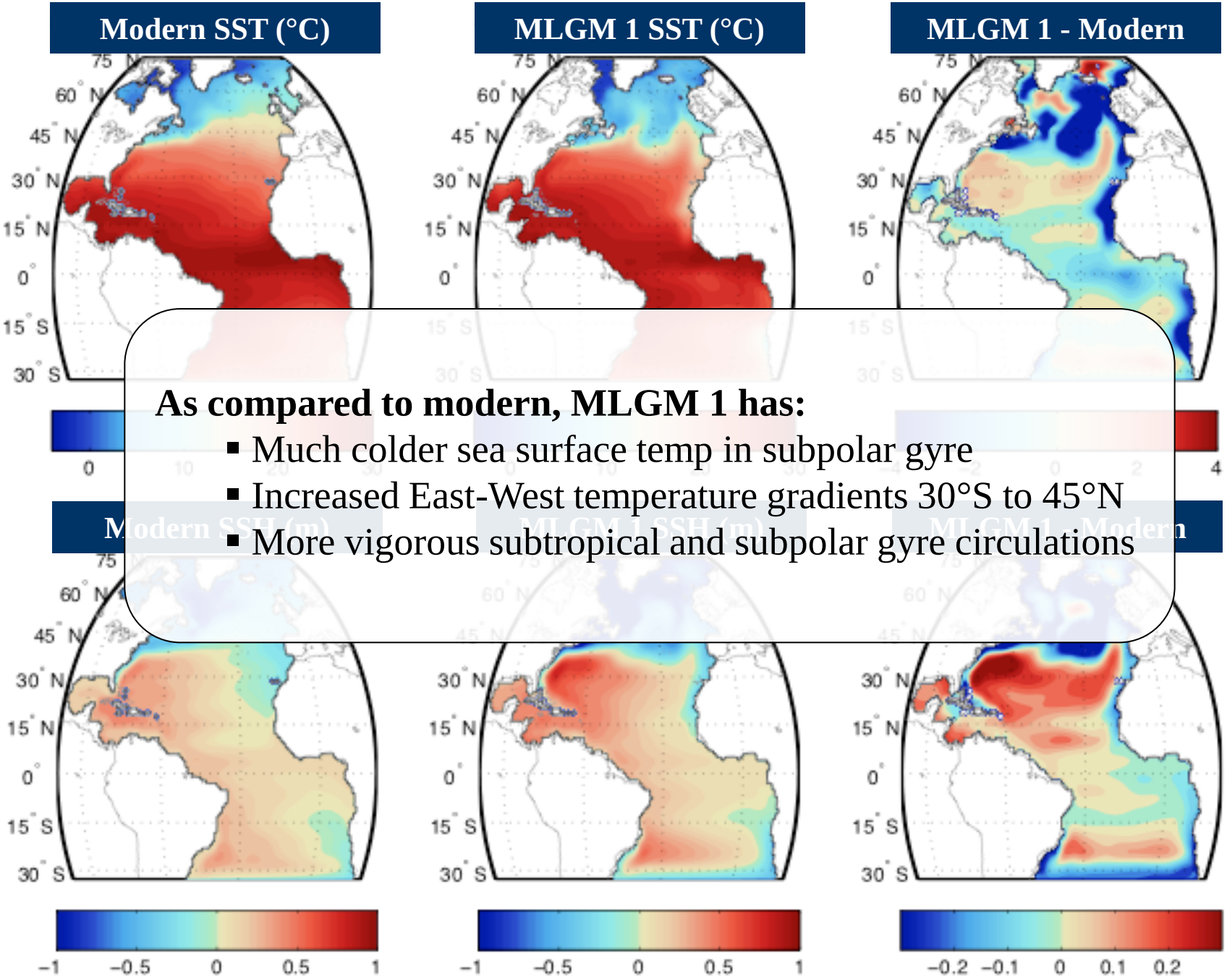
|RESULTS| MARGO Misfits



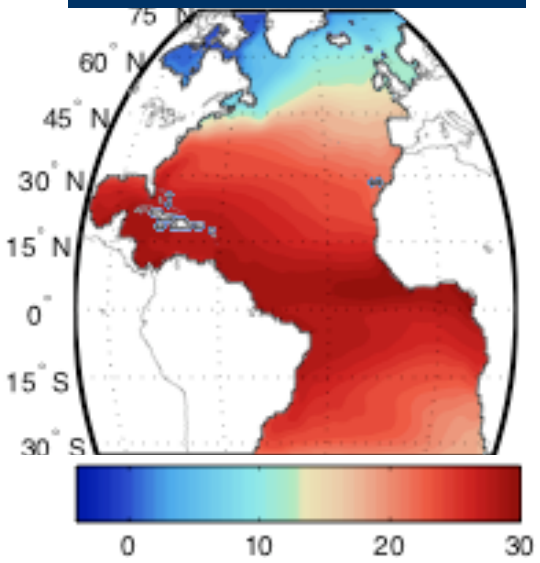




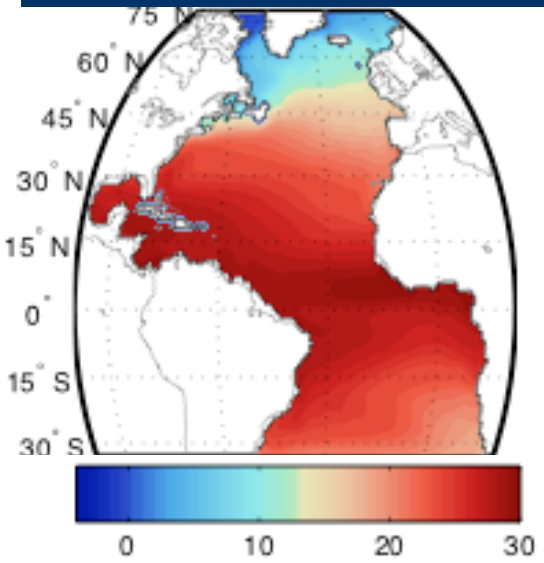

Modern SST (°C)
MLGM 1 SST (°C)
MLGM 1 - Modern
Modern SSH (m)
MLGM 1 SSH (m)
MLGM 1 - Modern
75 N
60 N
45 N
30 N
15 N
0
15 S
30 S
0 10 20 30
0 10 20 30
−4 −2 0 2 4
−1 −0.5 0 0.5 1
−1 −0.5 0 0.5 1
−0.2 −0.1 0 0.1 0.2


Modern SST (°C)
MLGM 1 SST (°C)
MLGM 1 - Modern
Modern SSH (m)
MLGM 1 SSH (m)
MLGM 1 - Modern
As compared to modern, MLGM 1 has:
Much colder sea surface temp in subpolar gyre
Increased East-West temperature gradients 30°S to 45°N
More vigorous subtropical and subpolar gyre circulations

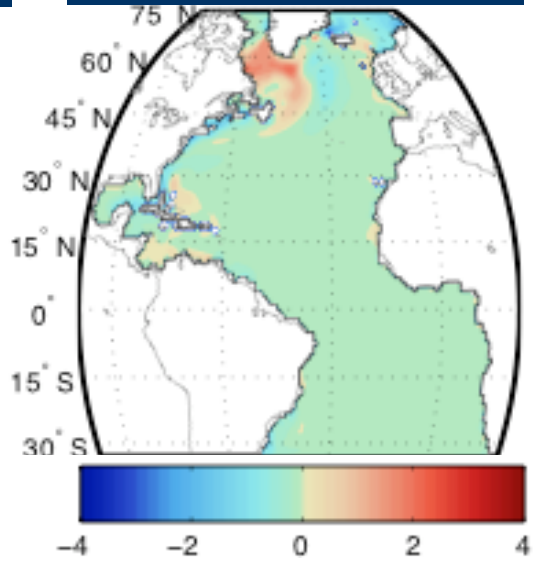
Modern bathymetry SST (°C)



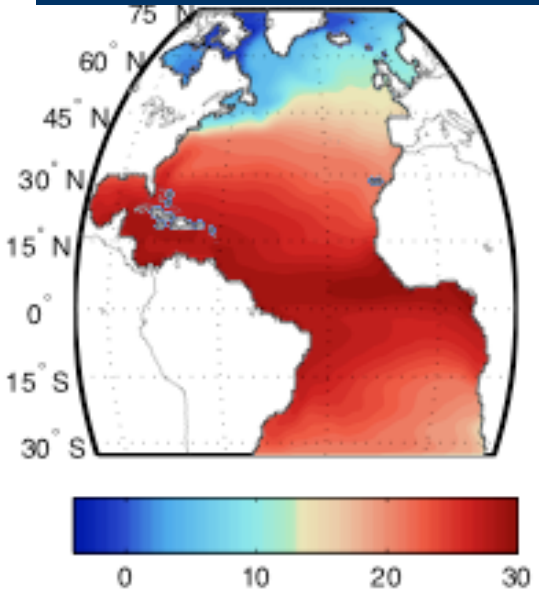
ICE-5G LGM bathymetry SST (°C)



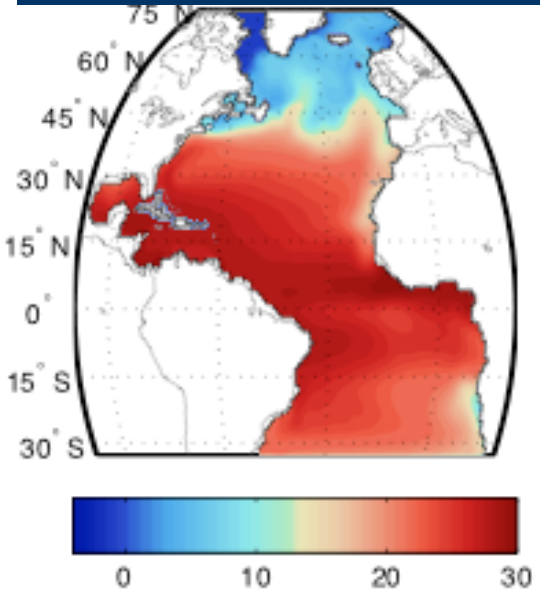
SST change associated with LGM bathymetry



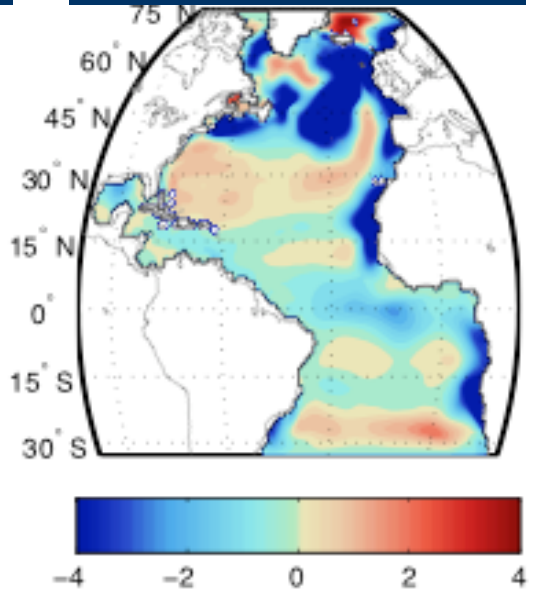
+ Modern data SST (°C)

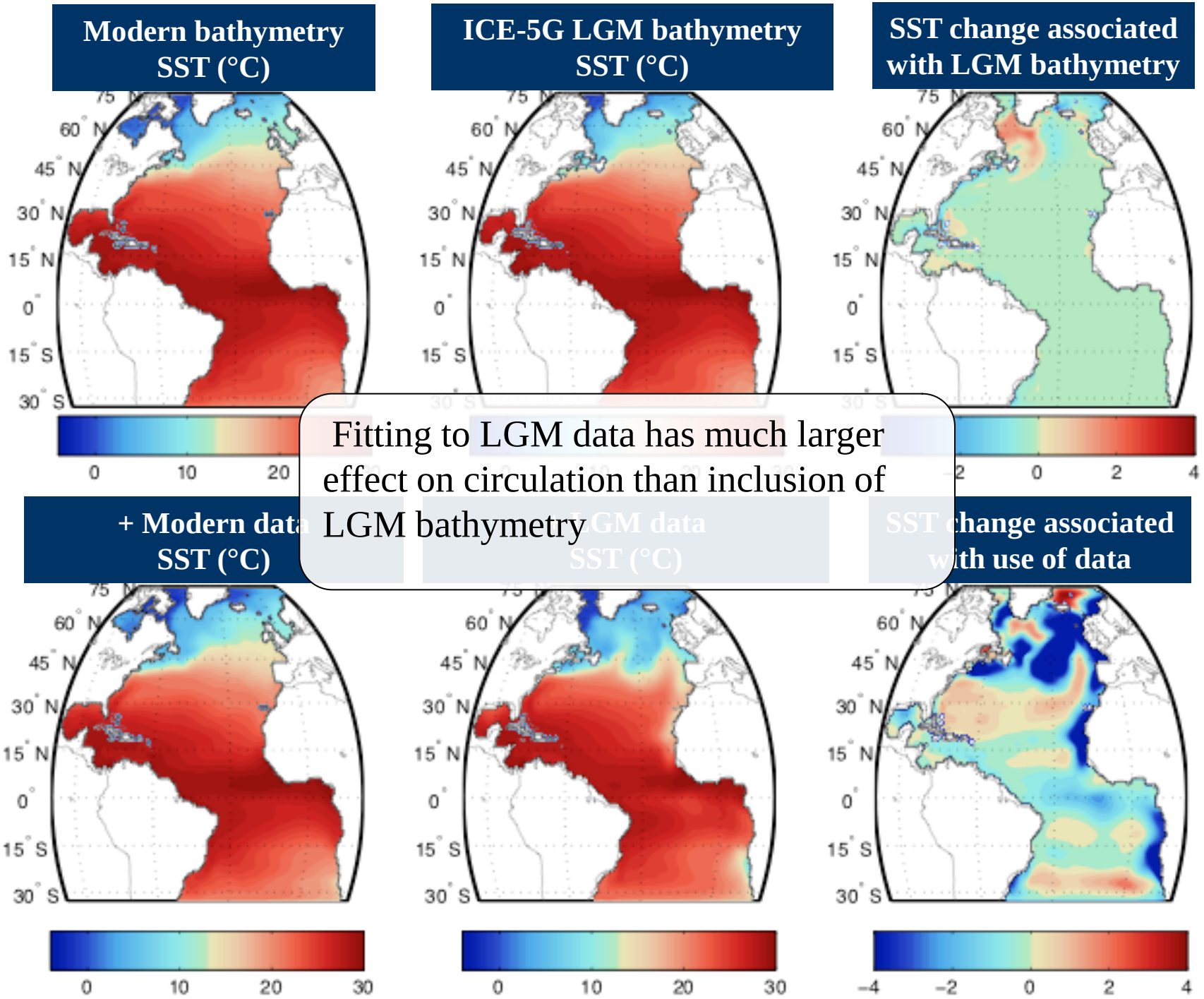


+ LGM data SST (°C)



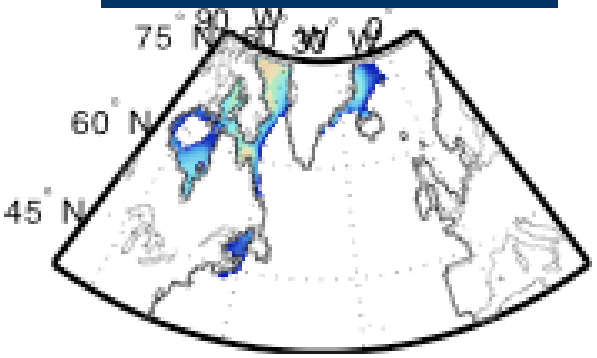
SST change associated with use of data



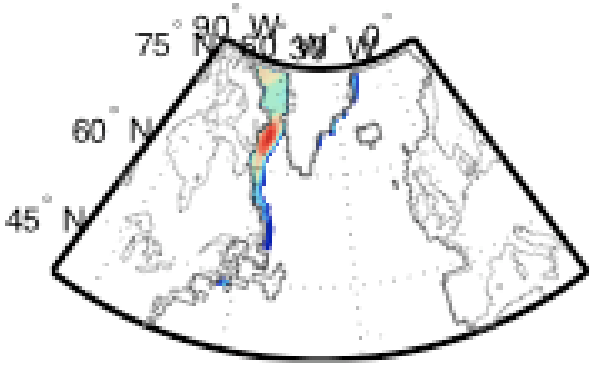

Modern bathymetry
SST (°C)
ICE-5G LGM bathymetry
SST (°C)
SST change associated with LGM bathymetry
Fitting to LGM data has much larger effect on circulation than inclusion of LGM bathymetry
+ Modern data
SST (°C)
LGM data
SST (°C)
SST change associated with use of data
75 N
60 N
45 N
30 N
15 N
0
15 S
30 S
0
10
20
30
−4
−2
0
2
4

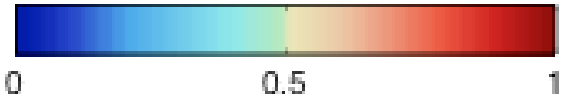
|RESULTS| Fractional sea ice area

Modern fractional sea ice area

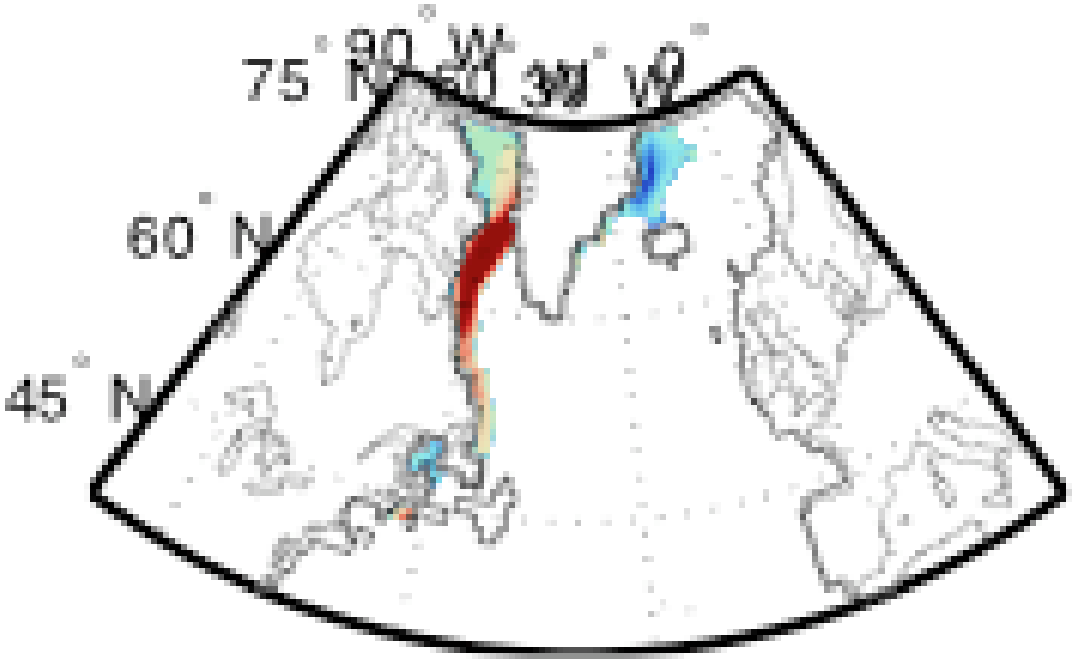


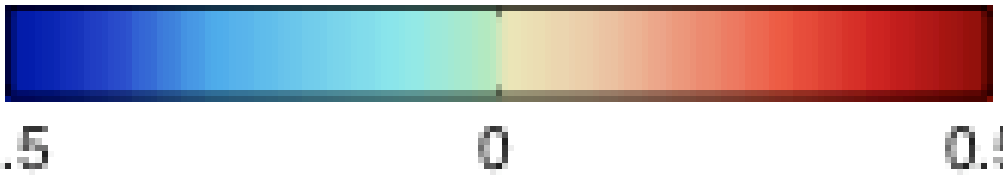
MLGM 1 fractional sea ice area



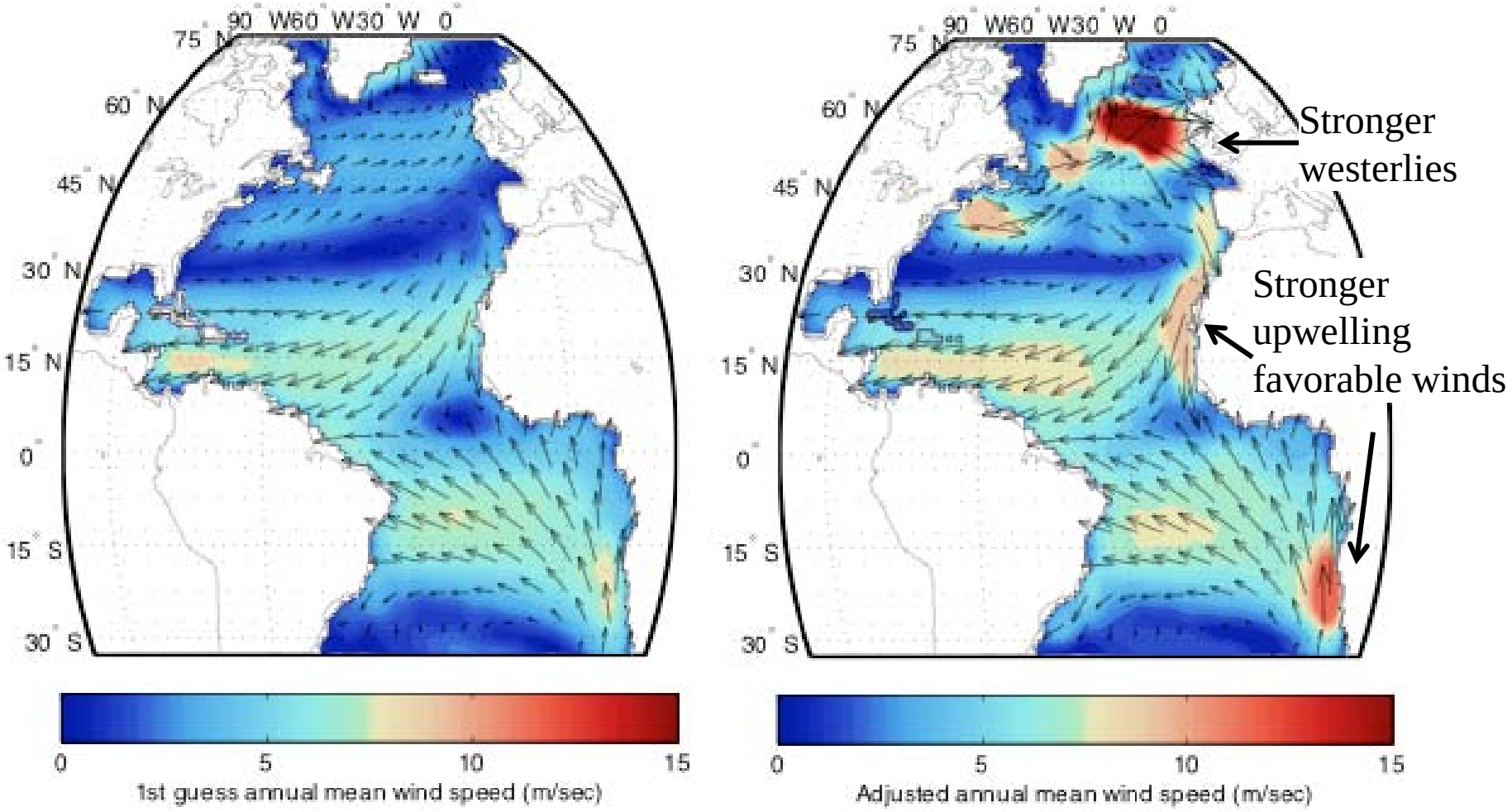


MLGM 1 – Modern





|RESULTS| MLGM 1 Wind speeds before and after adjustment



Discussion

- LGM N. Atlantic ocean state estimation system working
  - Seasonal steady-state assumption
  - Constrain to multiple proxy types
  - Per observation uncertainty assignment
  - Model misfit at variety of timescales (e.g. monthly mean)
  - Preliminary results using 4 MARGO SST compilations

- Future work
  - Experiment more with CCSM3 as 1st guess atmosphere
  - Use open boundaries in south, possibly north and Med.
  - Incorporate additional LGM datasets with uncertainties
    - Next up: sea ice extent & benthic records

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