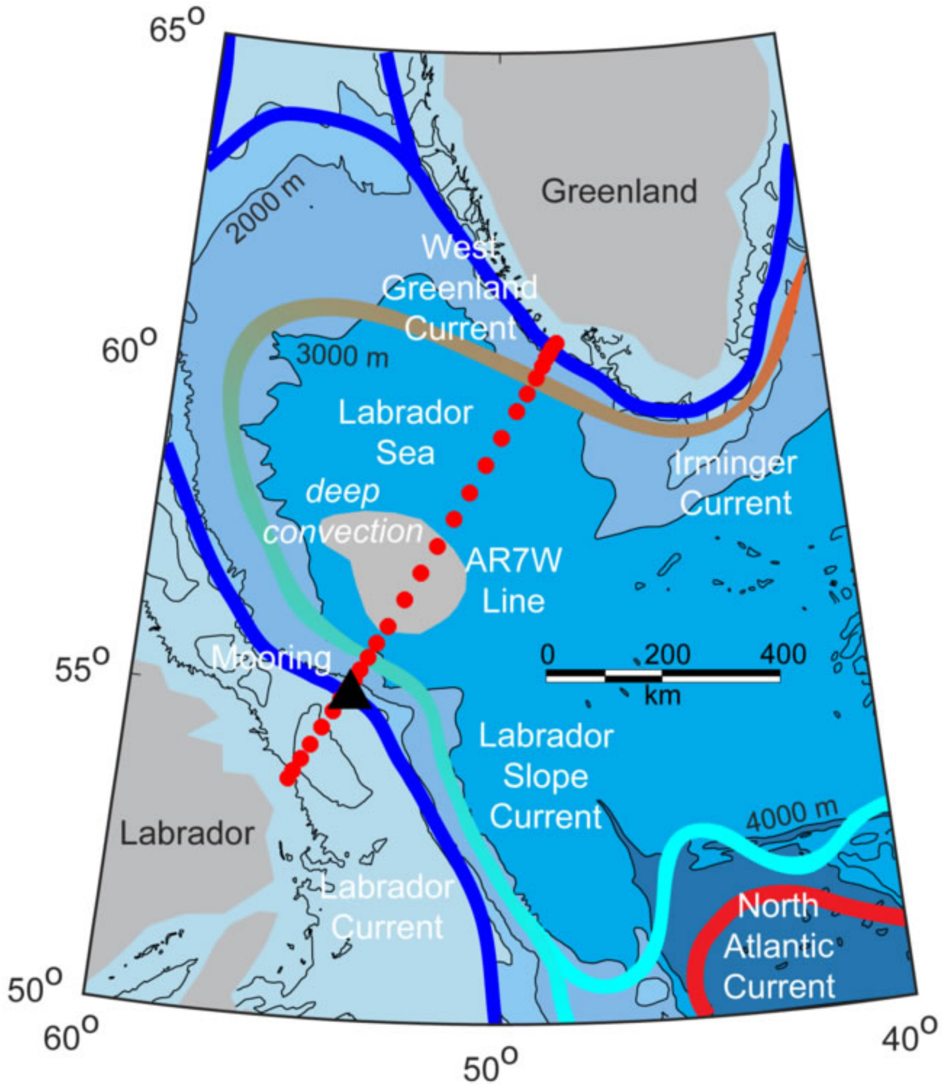
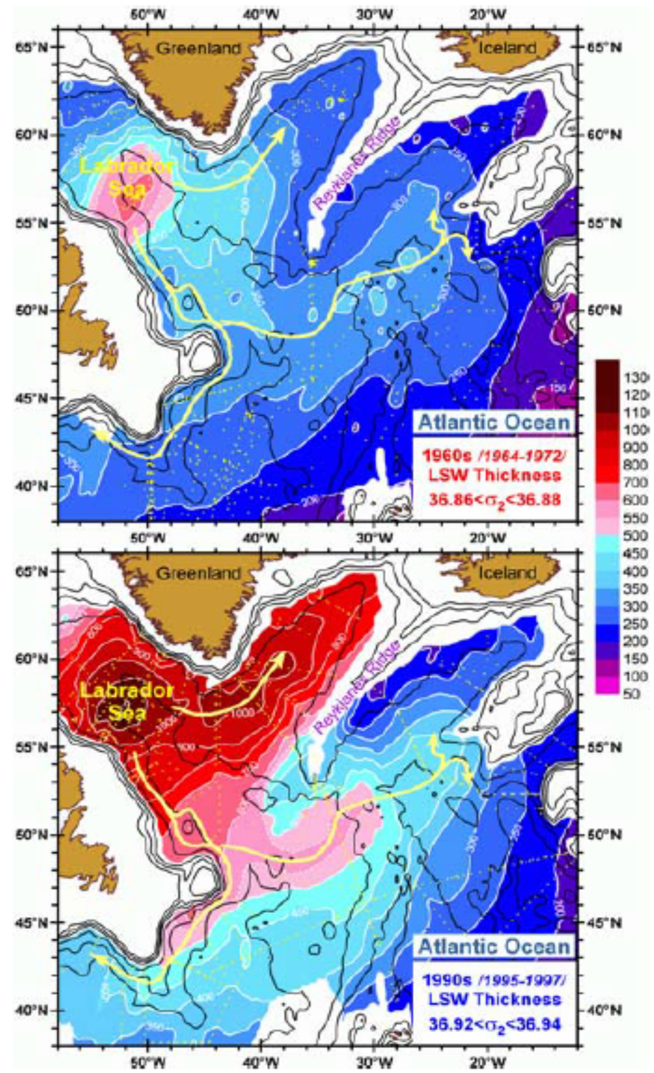
# The Labrador Sea and CMIP5 models

# GENERAL OUTLINE

- The Labrador Sea branch of the MOC
- Its representation in a regional ocean model (ROMS)
- Its representation in CMIP5 models
- The carbon cycle (present and future)
- Open challenges

- The Labrador Sea is the best observed site for deep water formation
- The Labrador Sea Water (LSW) is a dense water mass that spreads across the northwest Atlantic (Talley and McCartney, 1982) at mid-depths
- **Labrador Sea is key in controlling AMOC variability** (Yeager and Danabasoglu, 2014; Yeager 2015)
- **AMOC inter-annual signals are closely related to the variability of the Labrador Sea convection**, in turn linked to the cumulative NAO
- The highest water-column inventory of anthropogenic carbon per unit area occurs in the subpolar North Atlantic (Sabine et al., 2004; Wang et al., 2012; Khatiwala et al., 2013)




Schematic of the Labrador Sea circulation (left) and isopycnal thickness (right) during the 1960s (top) and 1990s (bottom). Huge interannual variability

Images courtesy of Igor Yashayaev and the Bedford Institute of Oceanography

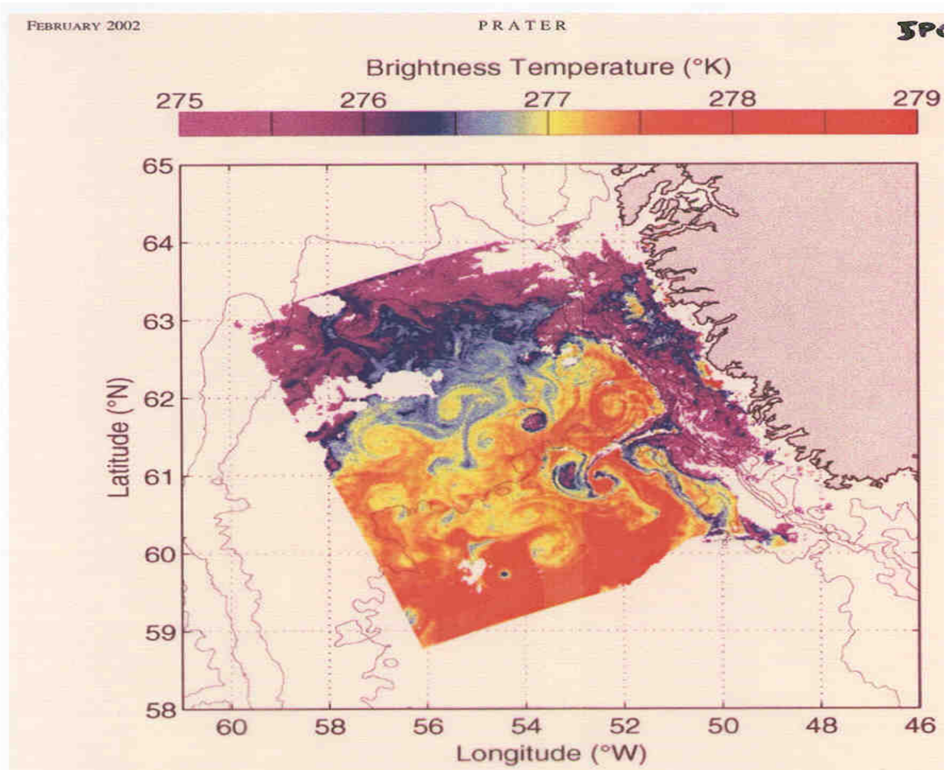
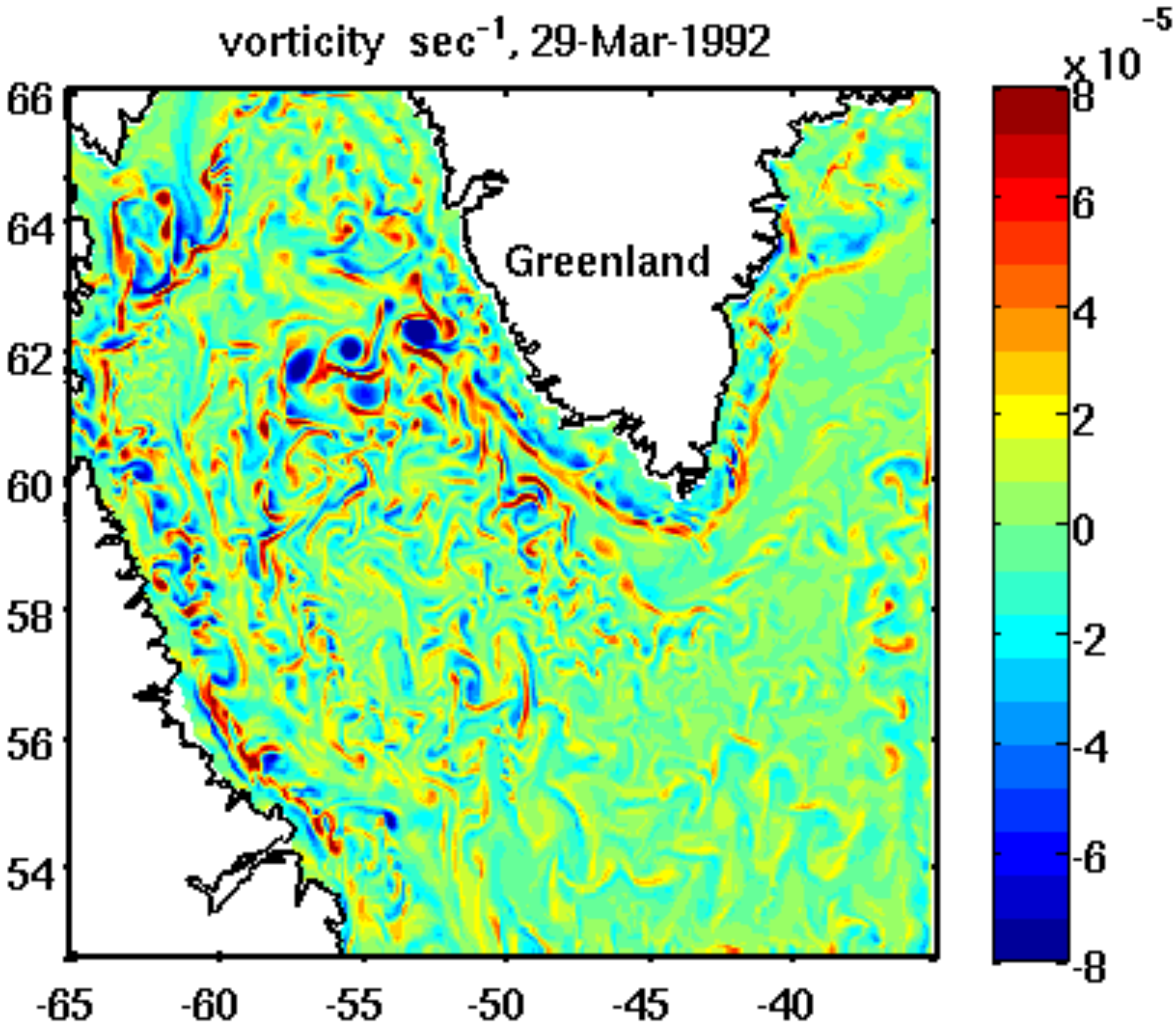



FIG. 2. Sea surface brightness temperature image of the the northern Labrador Sea from the ATSR on the *ERS-1* remote sensing satellite (from C. T. Mutlow 1999, personal communication). The image is from the 11-$\mu$m wavelength infrared sensor and shows numerous eddies near where the 3000-m isobath separates from the shelf.

Three eddy populations the LS:

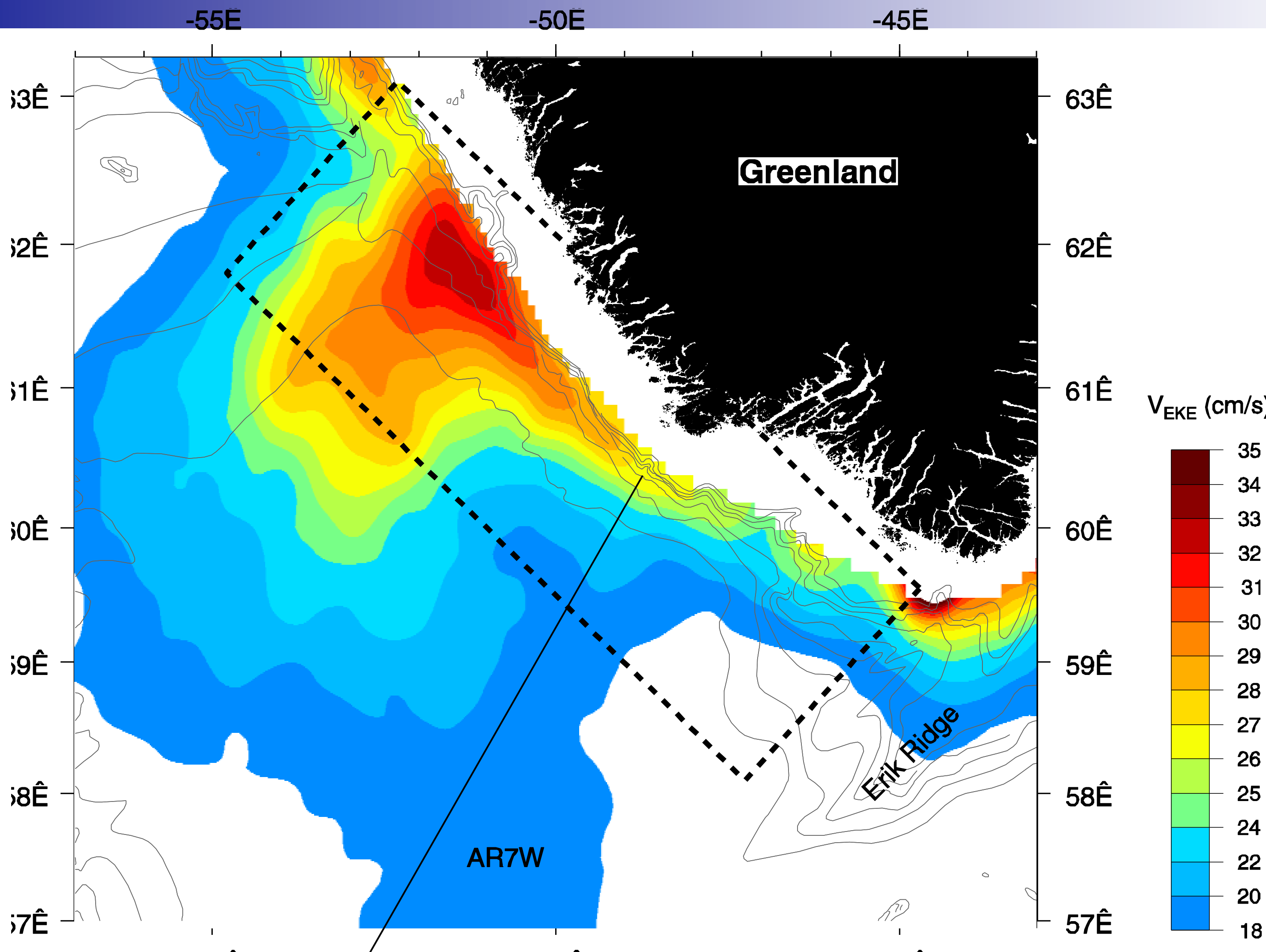
- **Irminger Rings** (IRs) formed by topographically localized baroclinic instability at about 61–62°N (Bracco and Pedlosky, 2003). They carry warmer and saltier Irminger water into the center of the Labrador Sea, where the winter-time cooling releases heat to the atmosphere (e.g. Bracco et al., 2008; Luo, Bracco and Di Lorenzo, 2011). Diameter of 40–50 km. Major source of EKE in the basin.
- **Boundary current eddies** formed along the Greenland coast by baroclinic instability of the boundary current system (Spall , 2004); smaller, diameter is close to 13 km, i.e. local Rossby deformation radius
- **Convective eddies** generated by baroclinic instability of the convective patch (Jones and Marshall, 1997); even smaller, their representation requires the use of non-hydrostatic models.


vorticity sec-1, 29-Mar-1992
Greenland
x 10-5
66
64
62
60
58
56
54
-65
-60
-55
-50
-45
-40
8
6
4
2
0
-2
-4
-6
-8

## Idealized QG experiments investigating vortex formation along the West Greenland Current

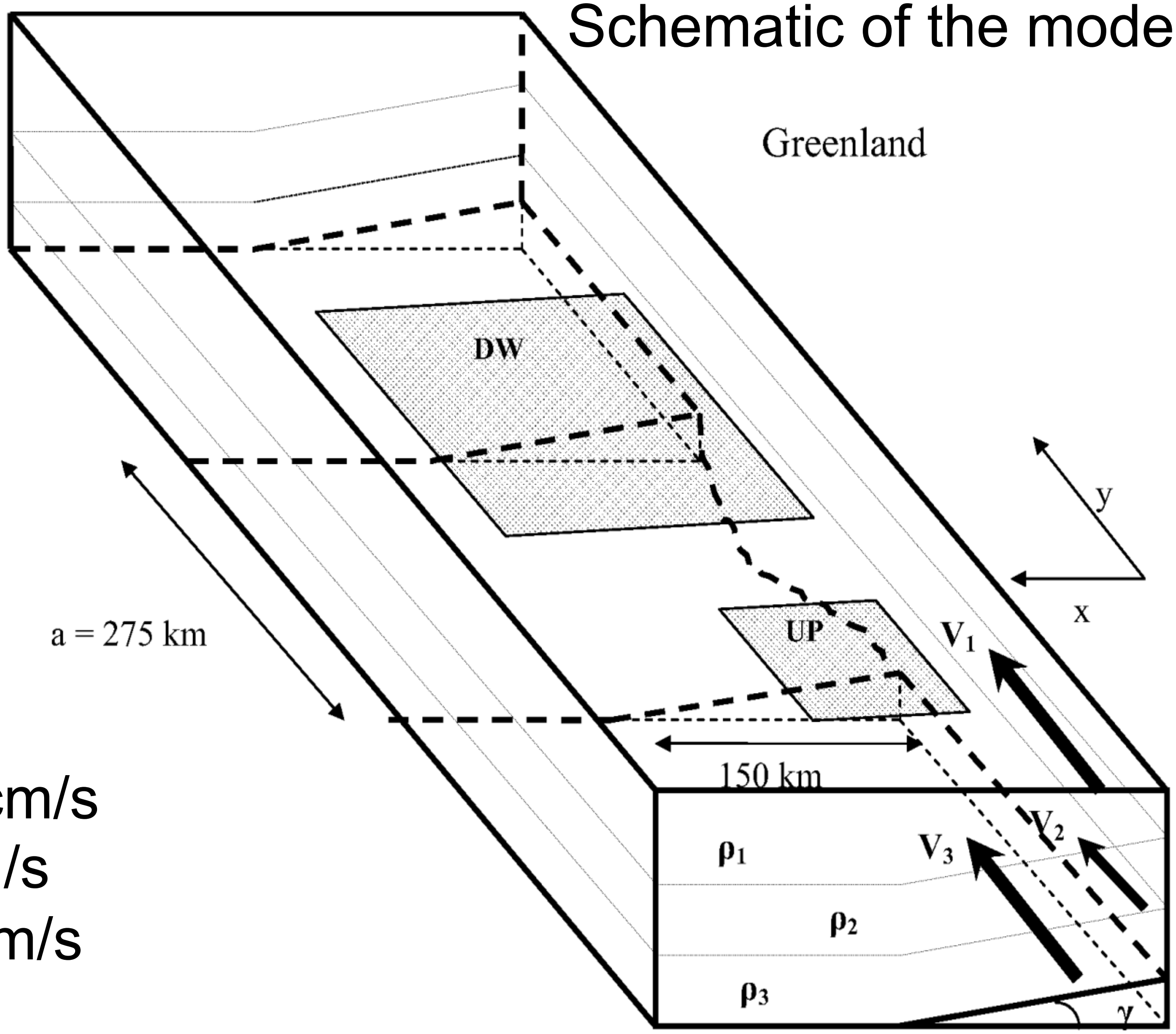
- Laterally nonuniform vertical shear → boundary confined currents in a NS channel
- Shear profile similar to the one observed in the Labrador Sea

Bracco, Pedlosky, JPO, 2003
Bracco, Pedlosky and Pickart, JPO 2008



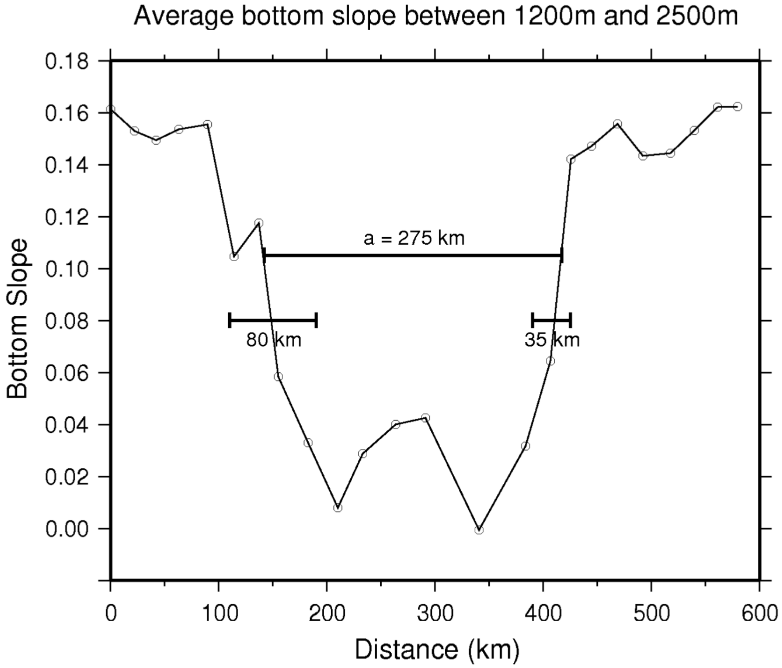

surface eddy speed + WOCE AR7W hydrography line

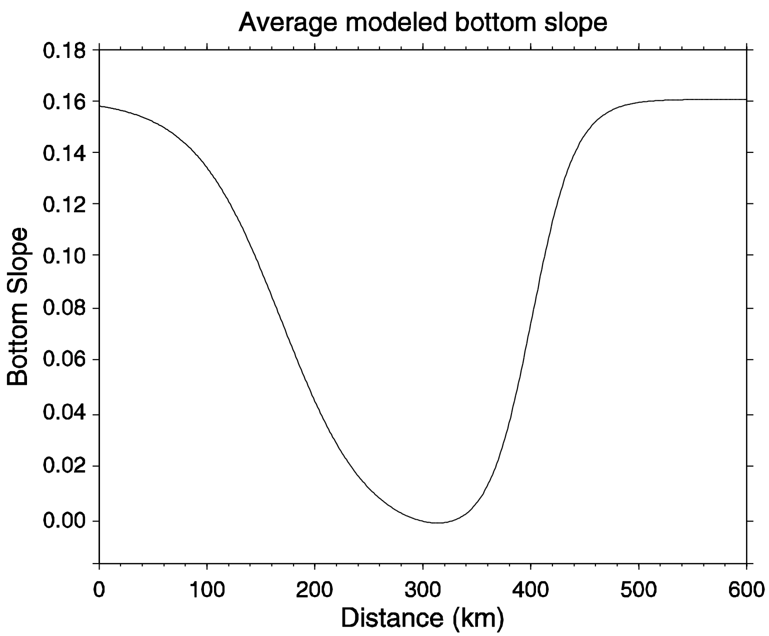
# Schematic of the model geometry

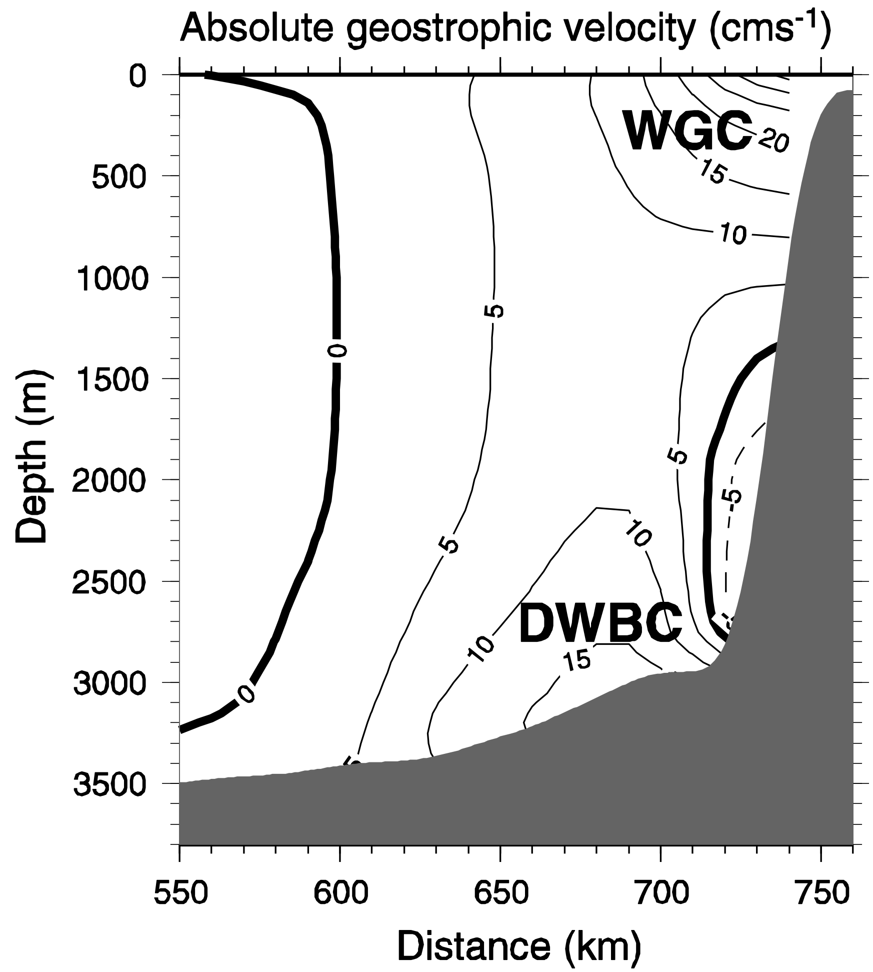



$A_1$=12 cm/s
$A_2$=6cm/s
$A_3$=10cm/s

$$\psi_i(x,y,t) = \frac{A_i}{\lambda} e^{-\lambda x} + \phi_i(x,y,t), \qquad i = 1,2,3, \qquad \lambda^{-1} = 60km$$

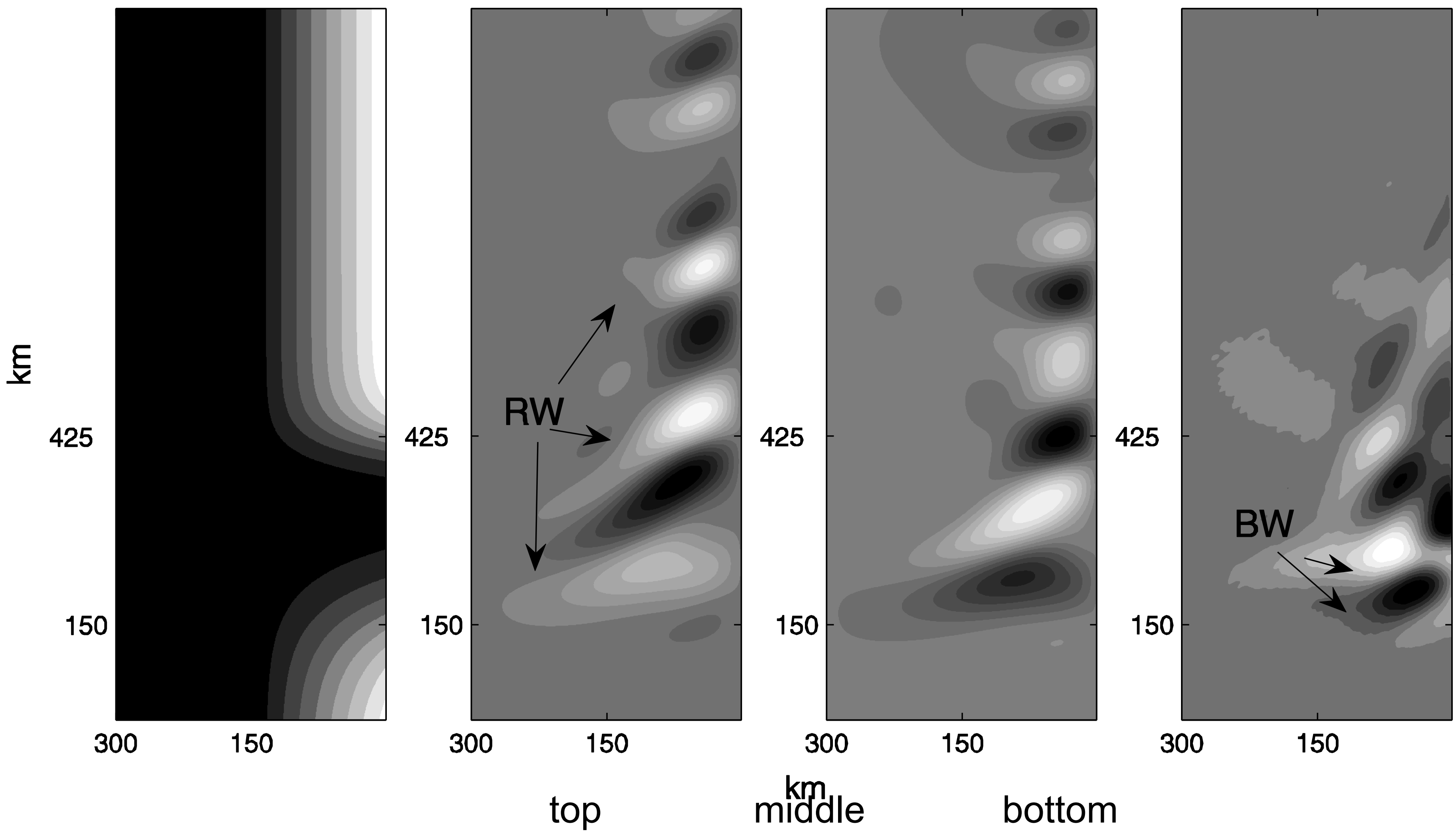



Average velocity of the BC system along the AR7W line

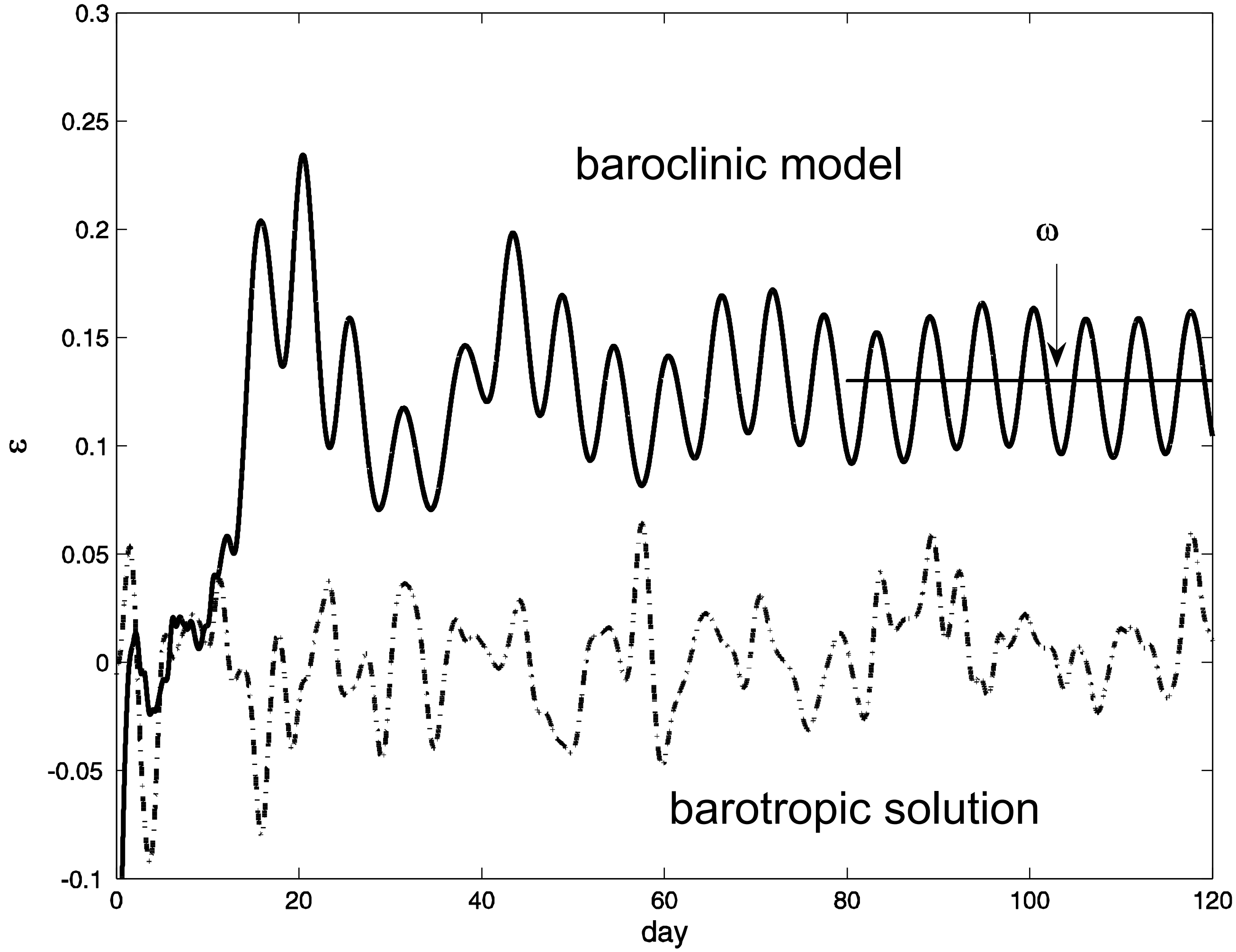
# Linear solution: Potential vorticity perturbation



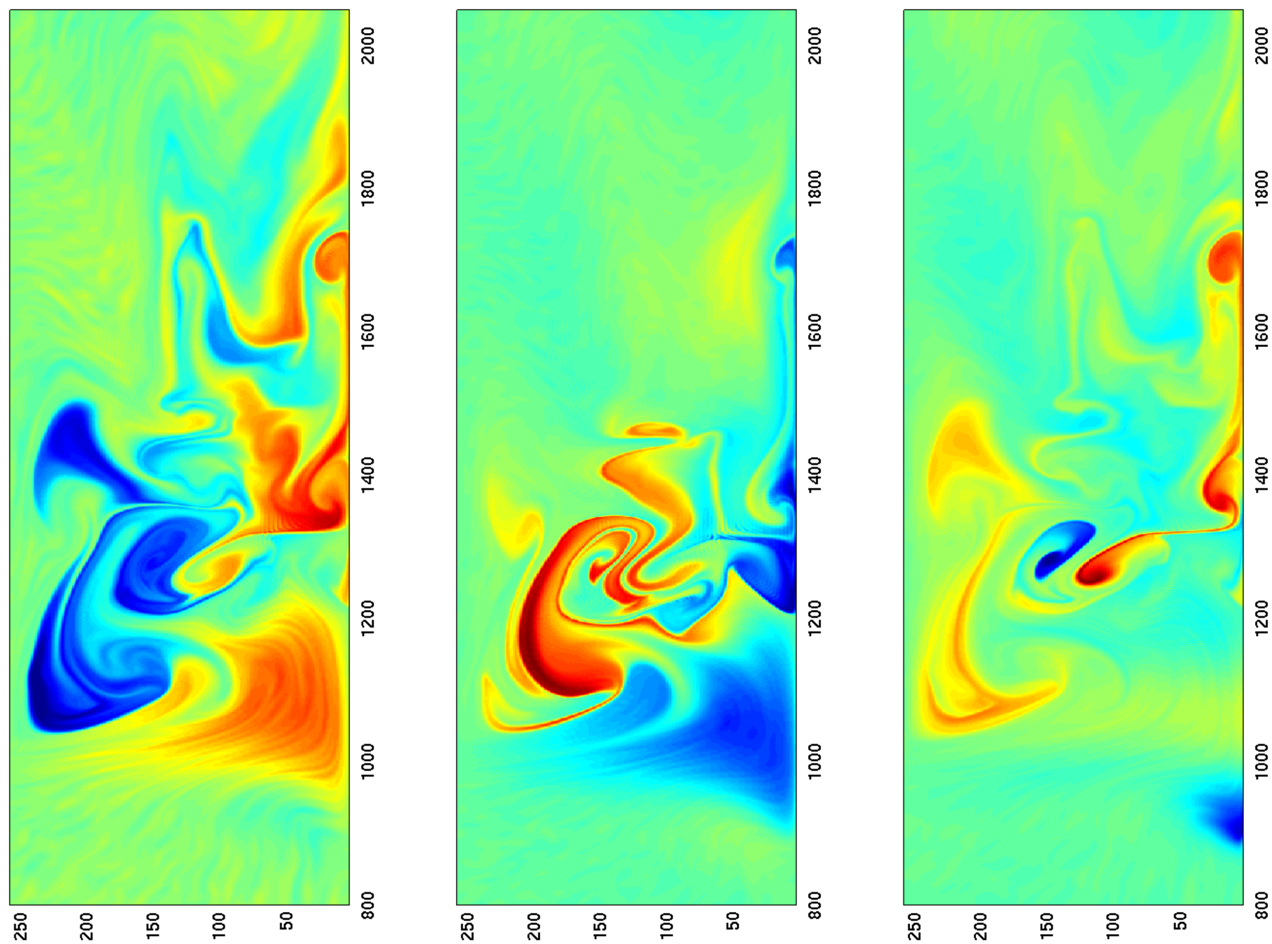
Growth rate for the linear system: 3-Layer case (solid) and barotropic model (dashed; see Carnevale et al., 1999).
Condition for BAROCLINIC instability:

$$\frac{\partial q_3}{\partial x} = \left( A_3 \lambda^2 - A_3 + A_2 \right) + \gamma(y)$$

MUST change sign from + to -



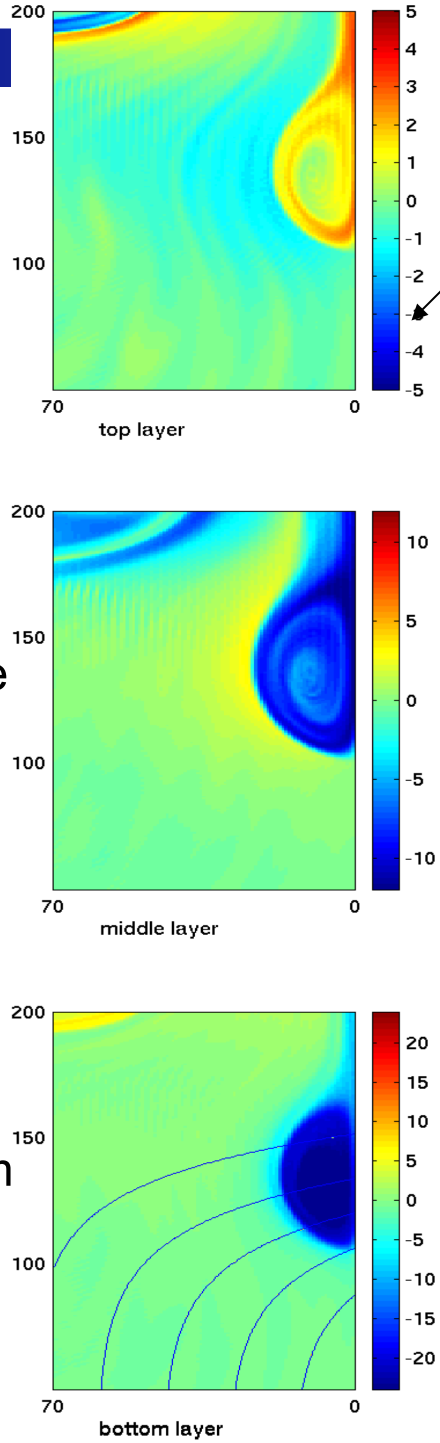
layer 1 layer 2 layer 3



top

middle

bottom



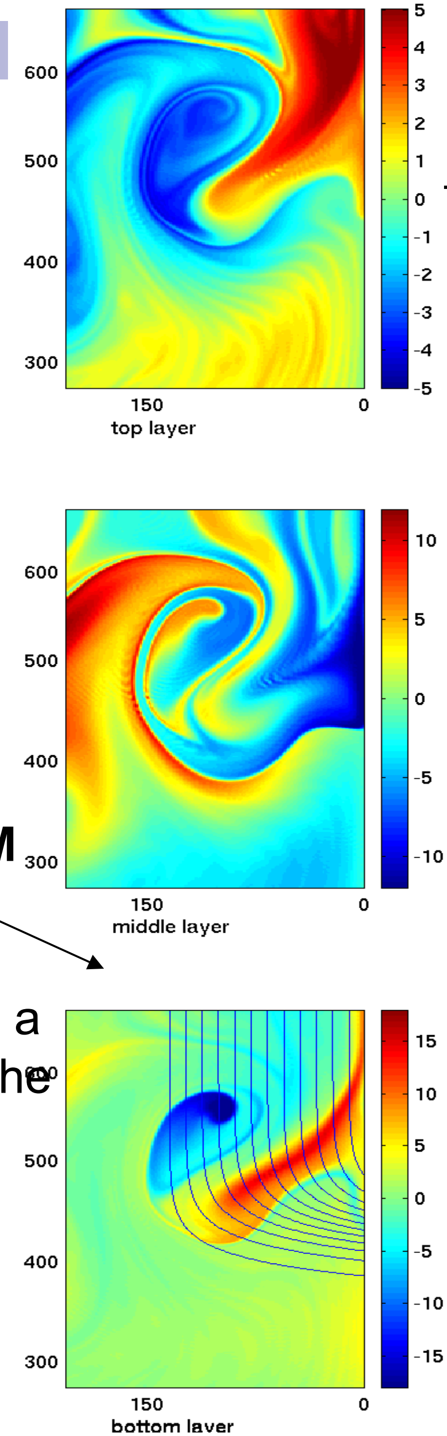

Potential vorticity perturbation:

1) **Vortices form UPSTREAM** from the equilibration of the bottom trapped wave

2) the cyclonic component is immediately destroyed by the shear of the (cyclonic) current

3) the anticyclone moves downstream under the influence of the image at the wall

4) once at the **DOWNSTREAM** step **they detach from the boundary moving towards deeper waters** and often form a dipole 'grabbing' water from the boundary current at the downstream step




top

middle

bottom

# Summary 1: why/how eddies form along the WG coast

- **The bottom-trapped disturbance grows to balance the variation in time of relative vorticity with the ambient gradient of potential vorticity. Its confinement relies on the interaction between the meridional component of the perturbation velocity and the meridional gradient of the bathymetry**

- the rate of formation: about 1 every 7 days, but likely seasonally varying. 35% of anticyclones formed at the upstream step end up in the interior. The others are re-absorbed in the current or merge

- the size (R ~ 35 km) and vertical extension of the eddies

- the asymmetry between AC and C

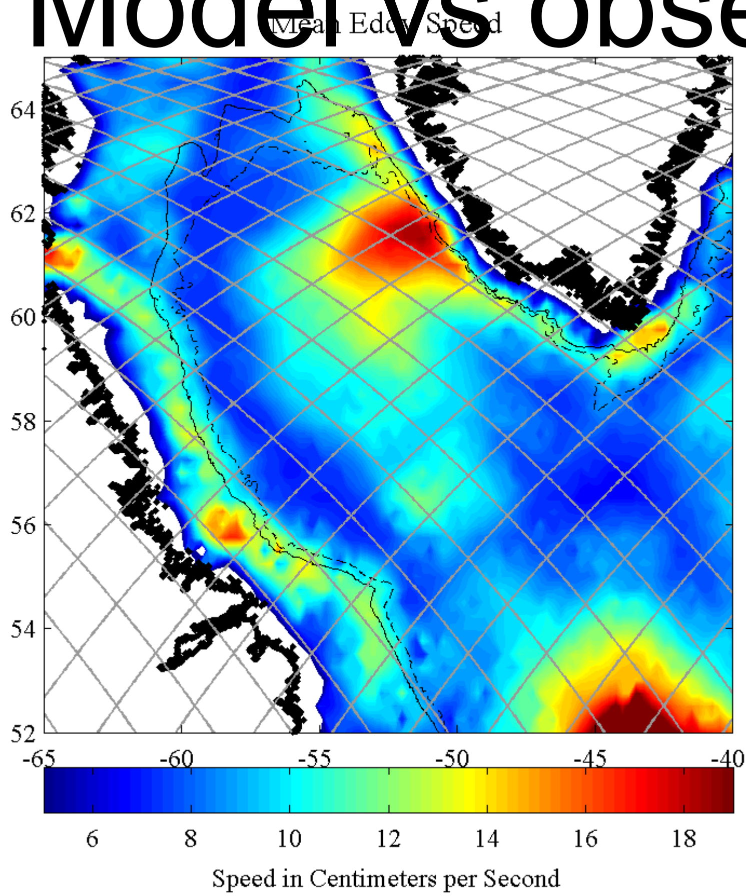
# next step
**(with Hao Luo)**

Sets of high-res ROMS experiments (7km in the horizontal) with different forcings to separate the intrinsic, locally forced, and remotely forced variability in the circulation and eddy activity of the Labrador Sea, with focus on the West Greenland boundary current:

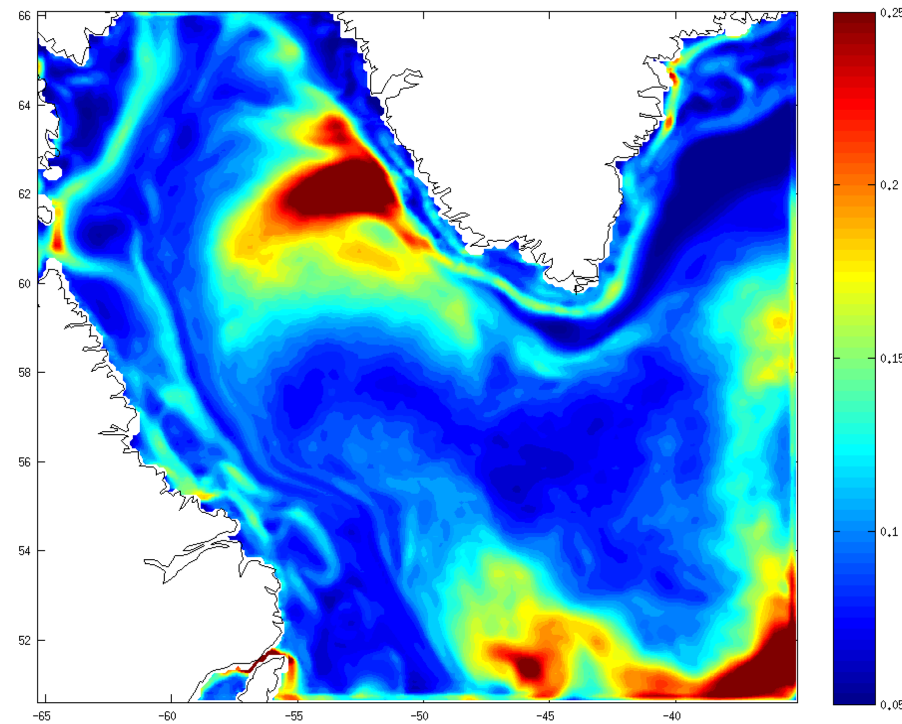
So far:

- 1. **CLIM** designed to isolate the intrinsic variability of the eddy field under a fixed annual cycle. 1 run, 50ys
- 2. **MONTHLY VARYING SURFACE FORCING (wind and heat fluxes from NCEP/NCAR)** Focus on interplay between the state of the Atlantic subpolar gyre and the atmospheric forcing; 2 runs 1980-2002
- 3. **MONTHLY VARYING BOUNDARY CONDITIONS (from SODA)** Focus on dependence of vortex formation on incoming currents strength 1 run 1980-2002/2010 (now extended: 1950-2010)

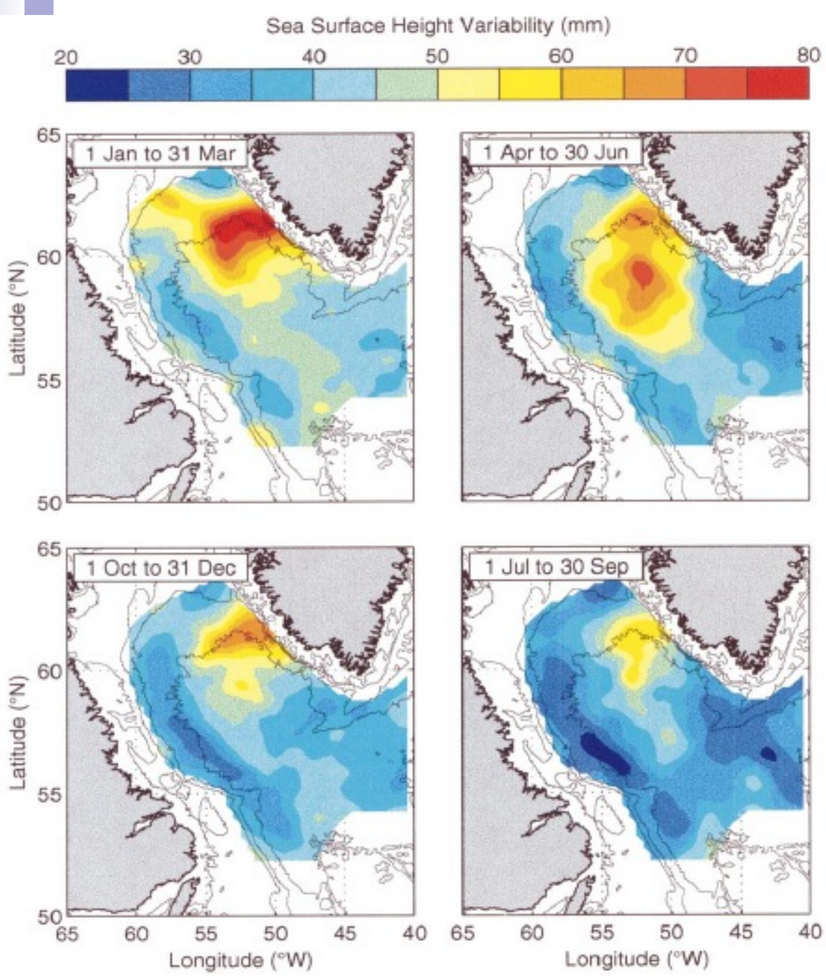
# Model vs observed EKE

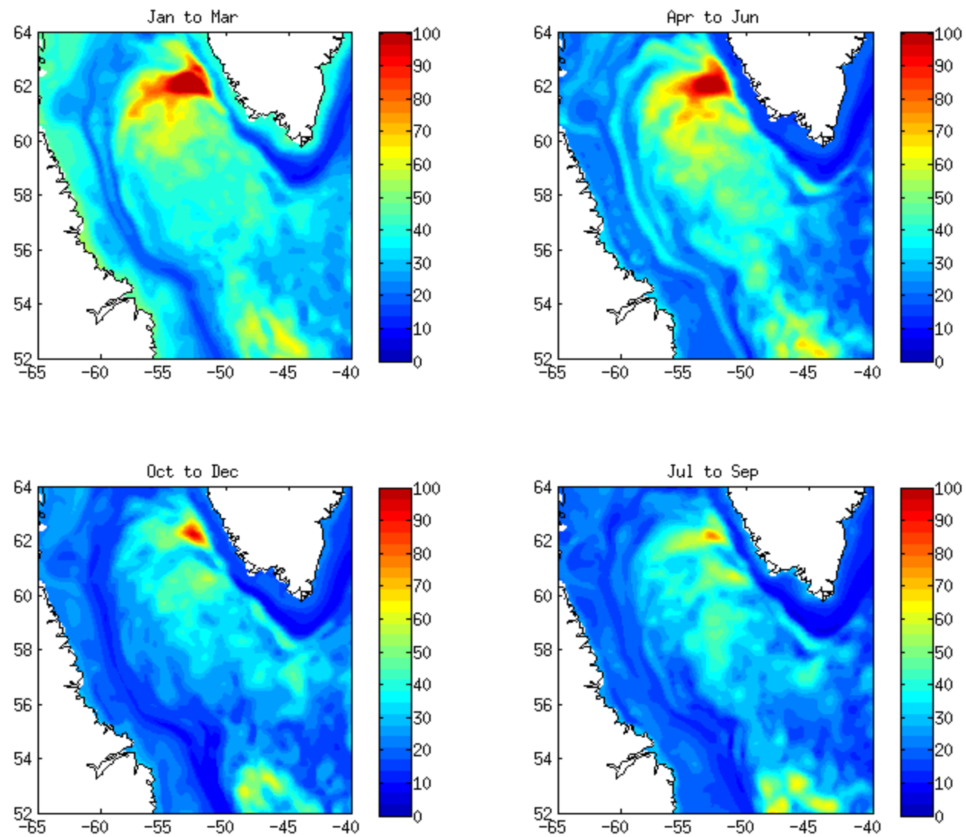



Regional climatological model runs using ROMS mean eddy speed in m/s

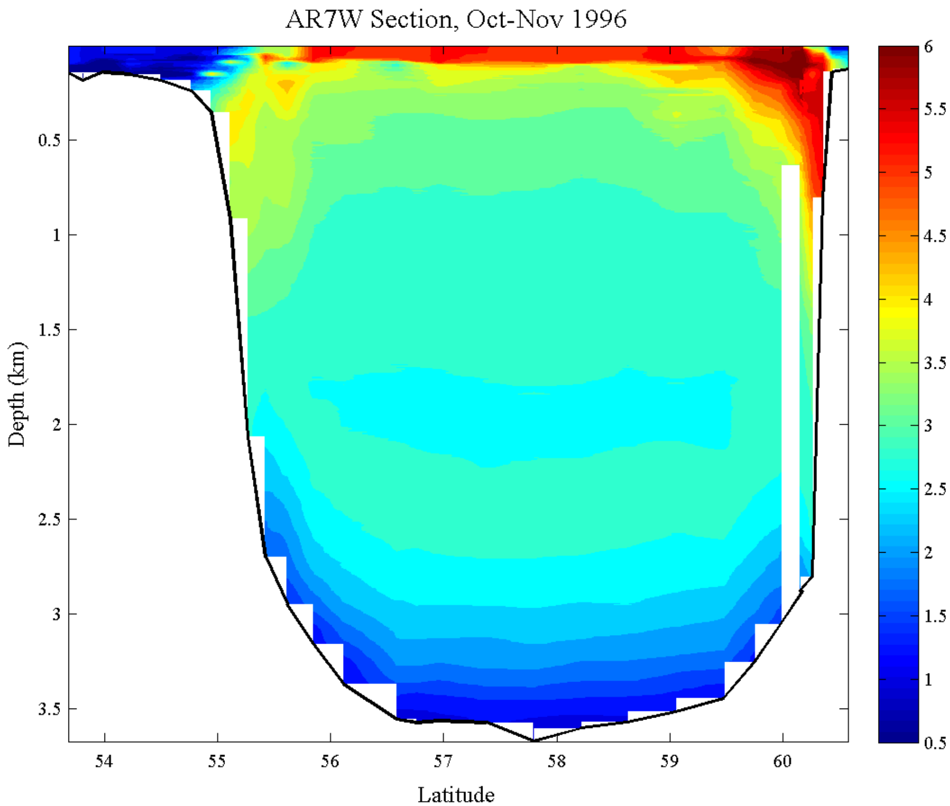



Resolving the instability over steep topography is ESSENTIAL to reproduce correct EKE distribution! Otherwise secondary peak appears



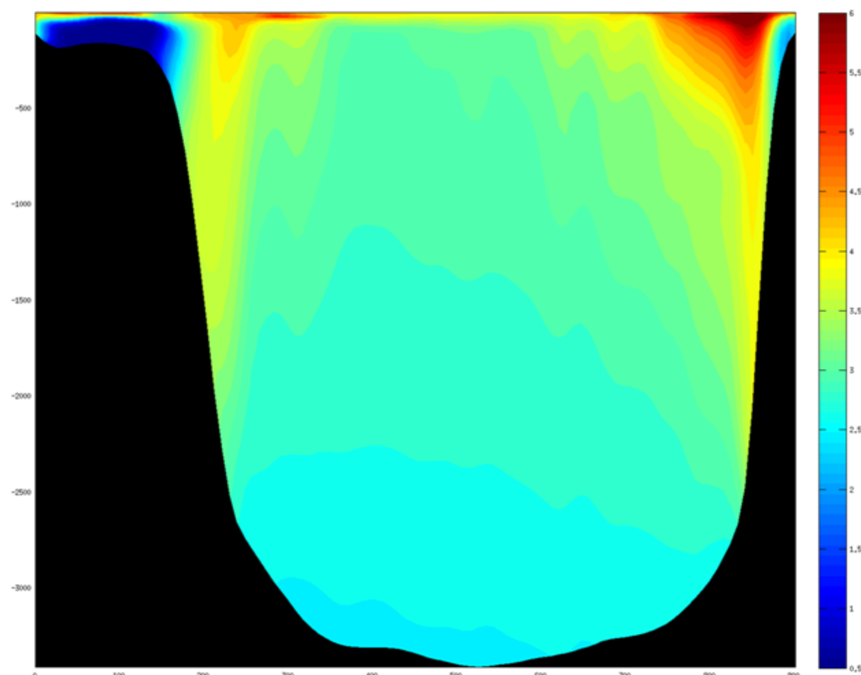




# Observed and Modeled Annual Cycle of EKE

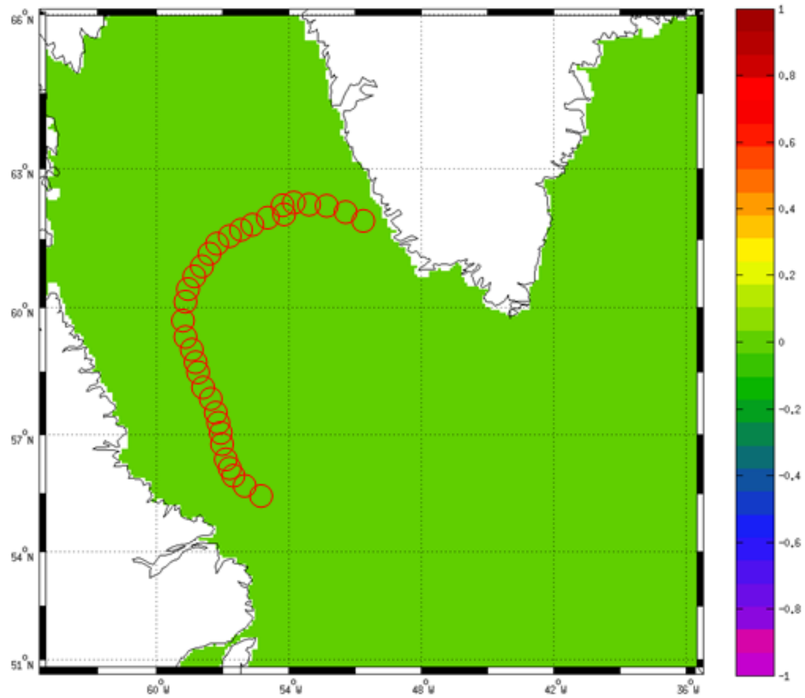



# Temperature on AR7W, Oct-Nov 1996

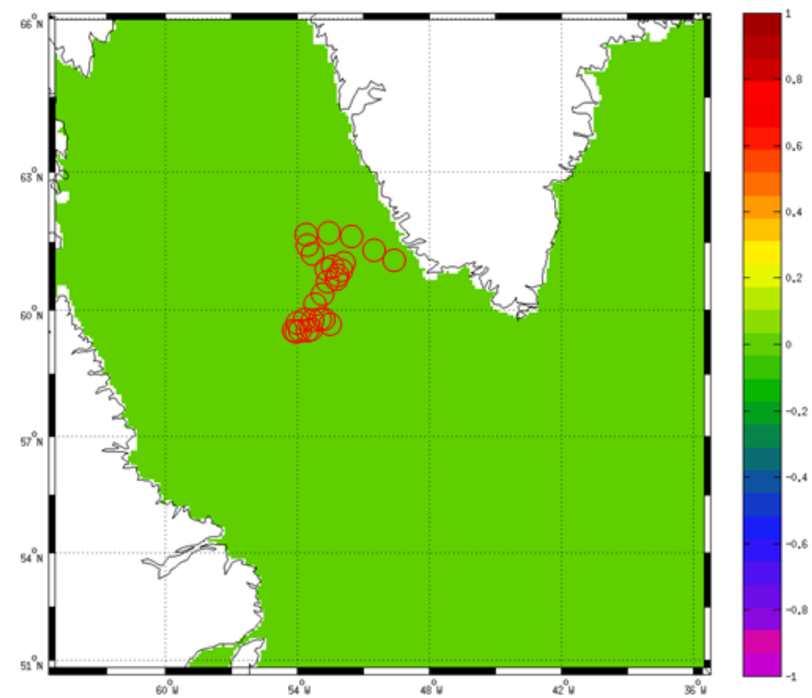
# Model Temperature for October in 1990's



# Two preferred pathways for the modeled vortices

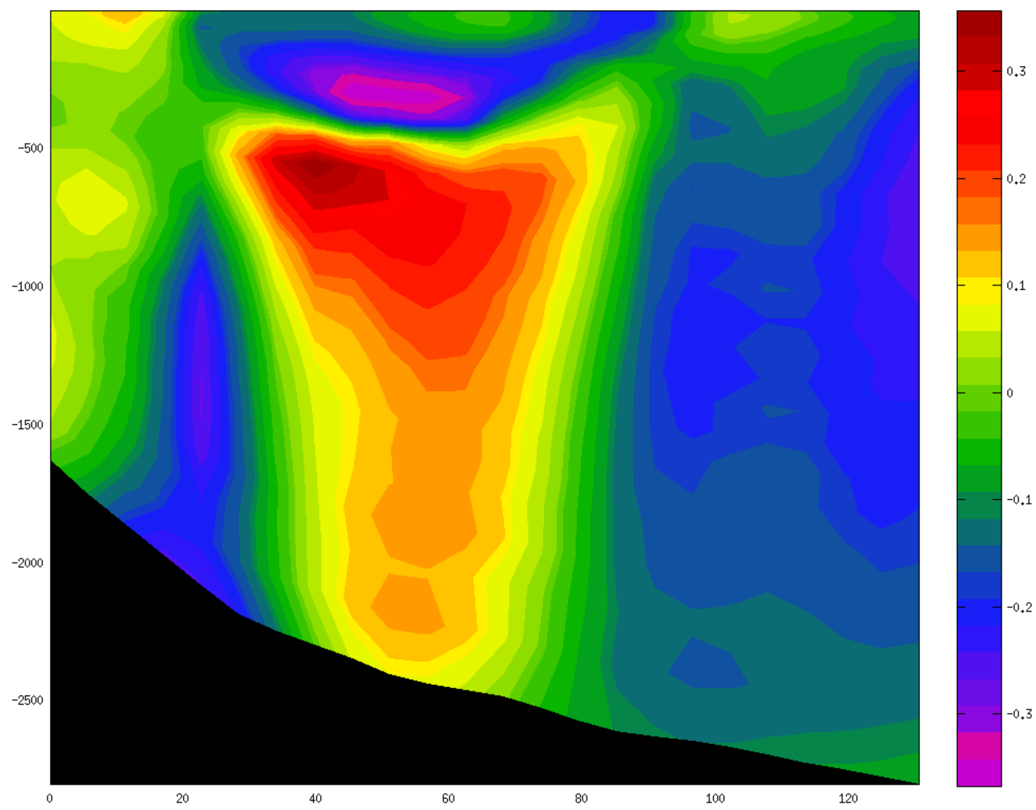


**Vortex 1 (Jan-12-1997 to Apr-06-1997)**



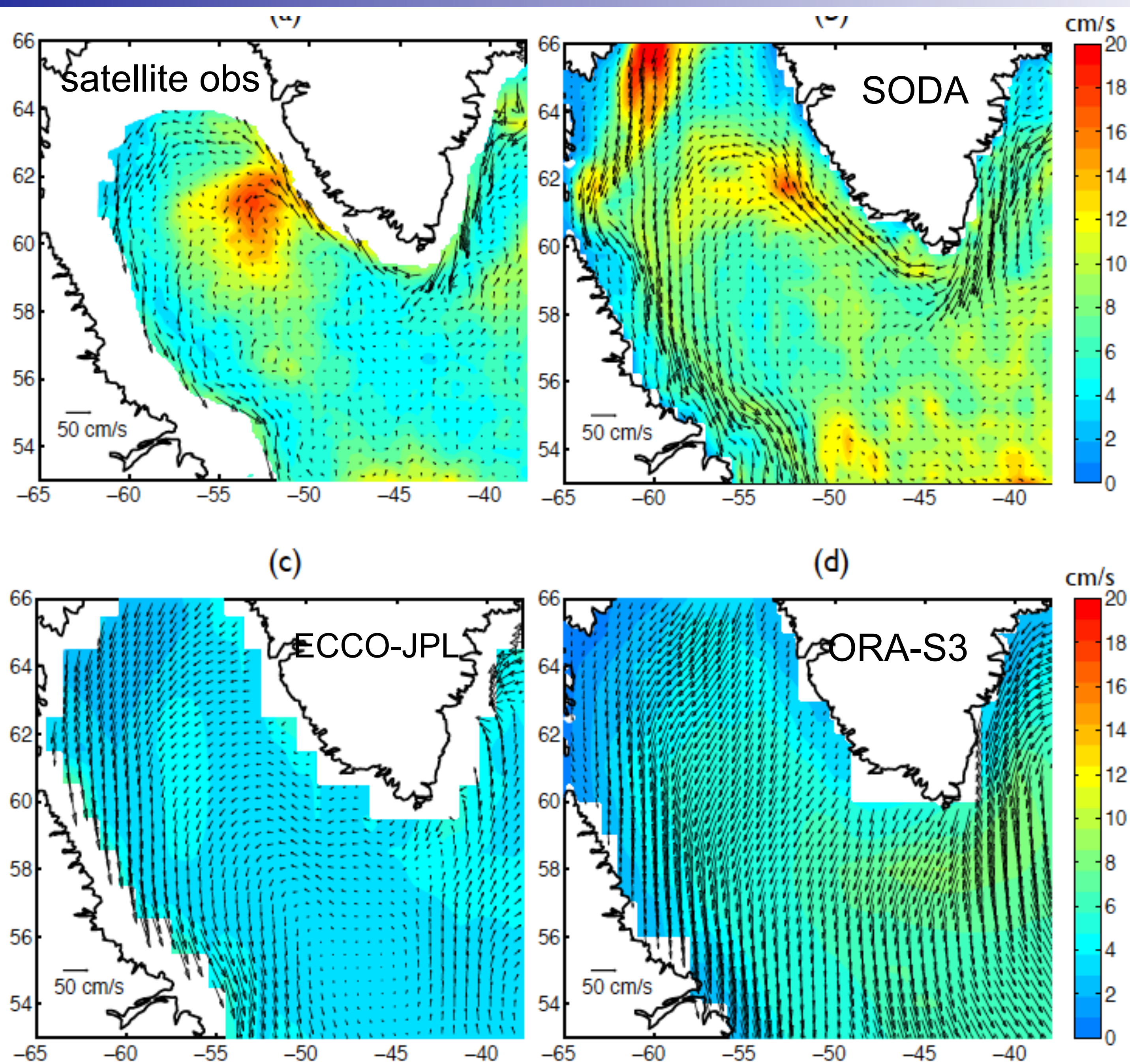
**Vortex 2 (Apr-15-1997 to Jul-06-1997)**

# Temperature structure within one of the modeled Irminger vortices



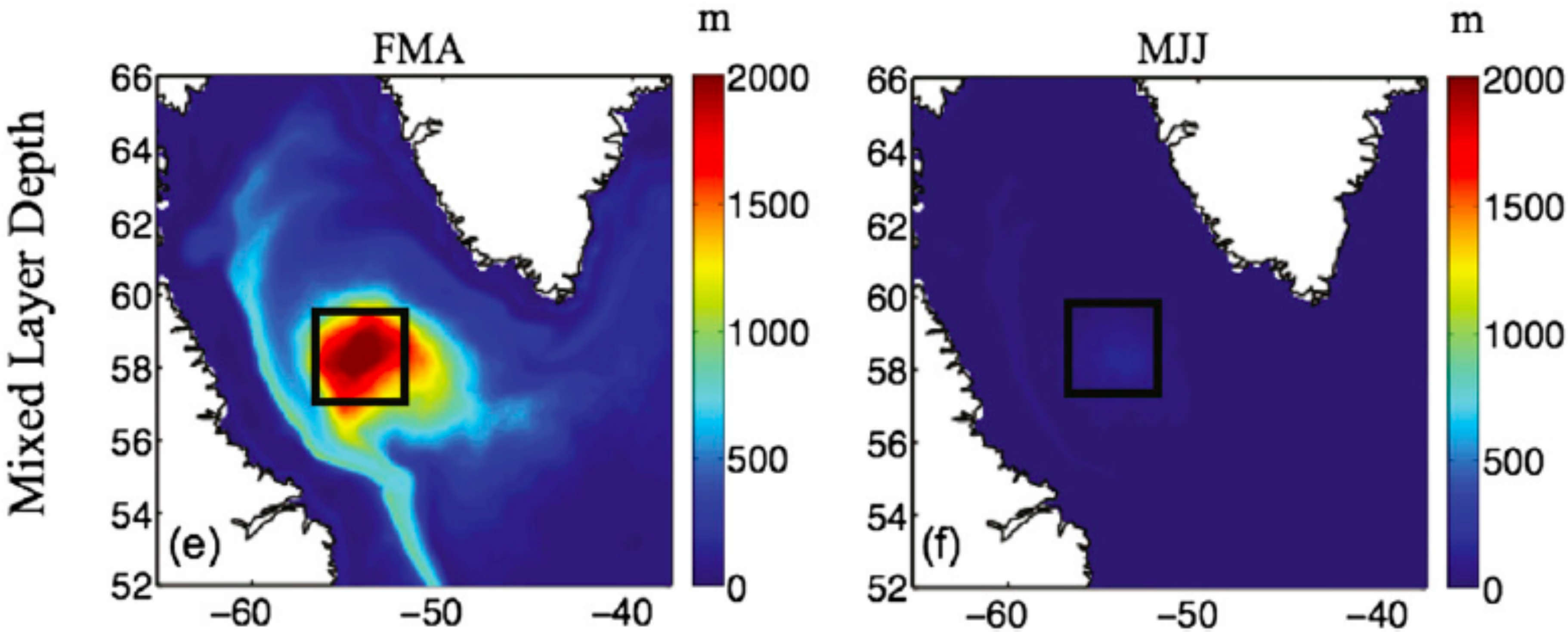

**Temperature anomaly (Mar-06)**

Surface EKE




Luo, Bracco et al, JGR 2012

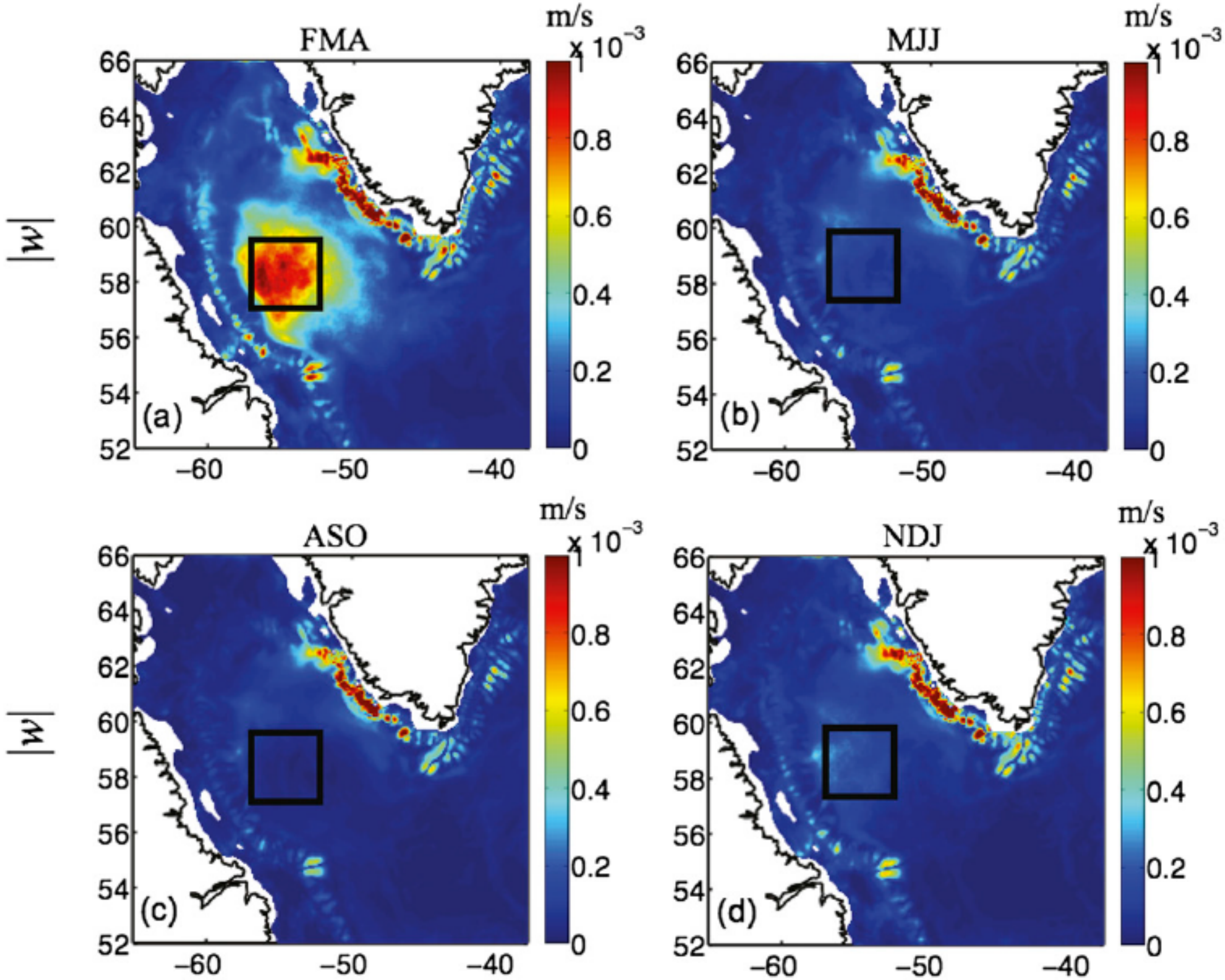
# Localization of convective activity



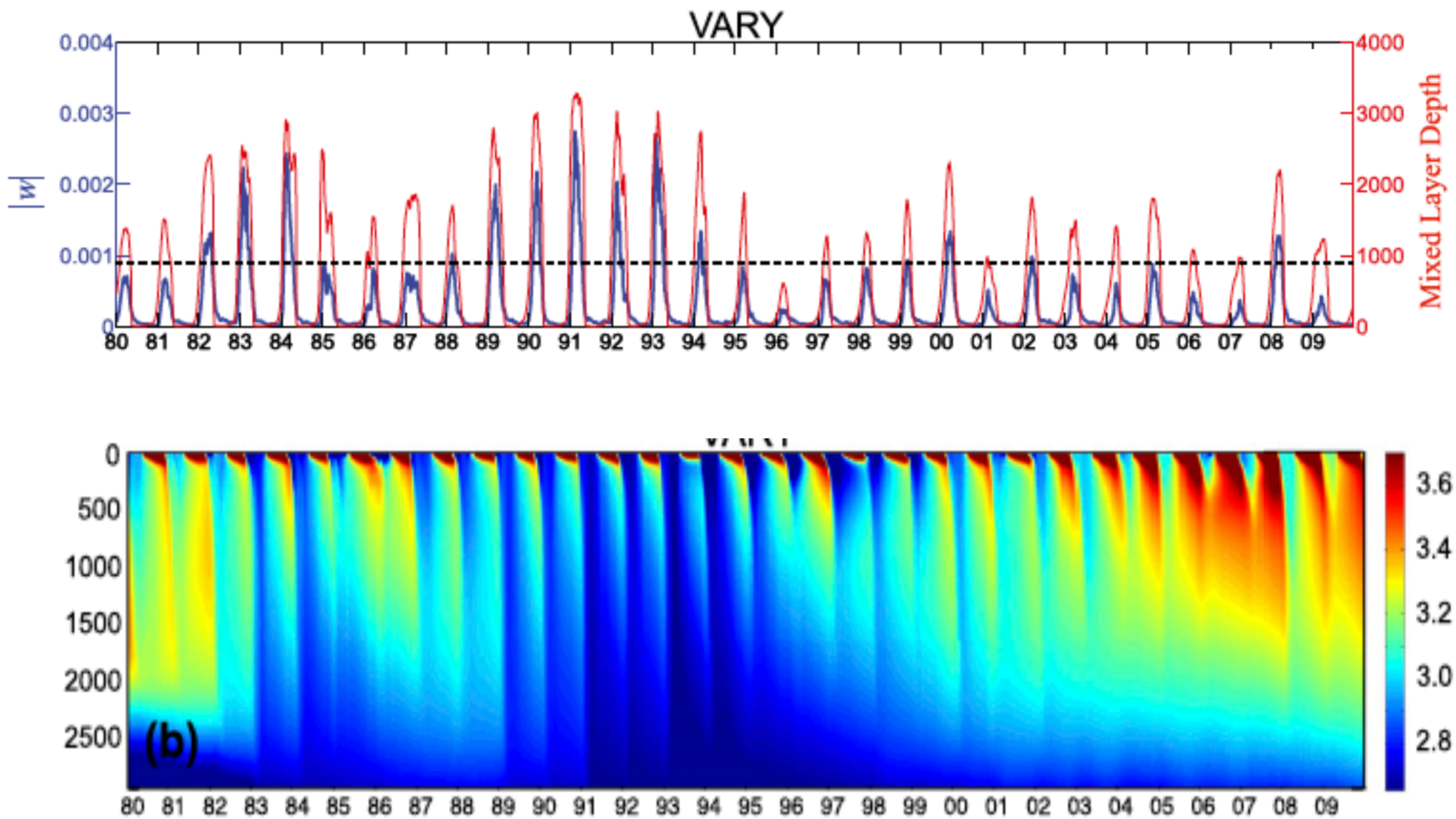

depth at which density
differences with the surface are equal to
0.008 $kgm^{-3}$.

Luo, Bracco, Zhang, J. Climate 2015

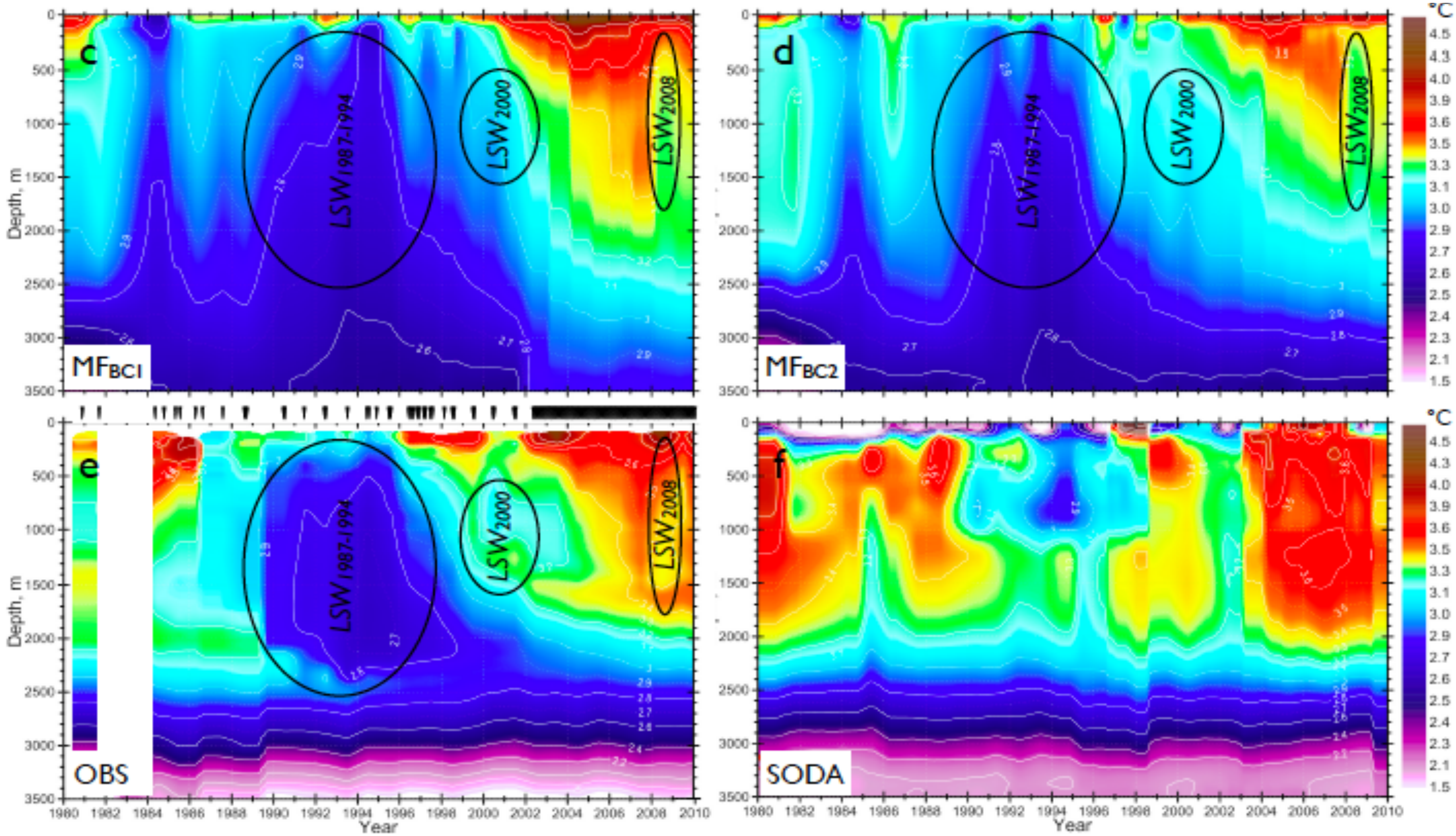
# Localization using w



# check that this works

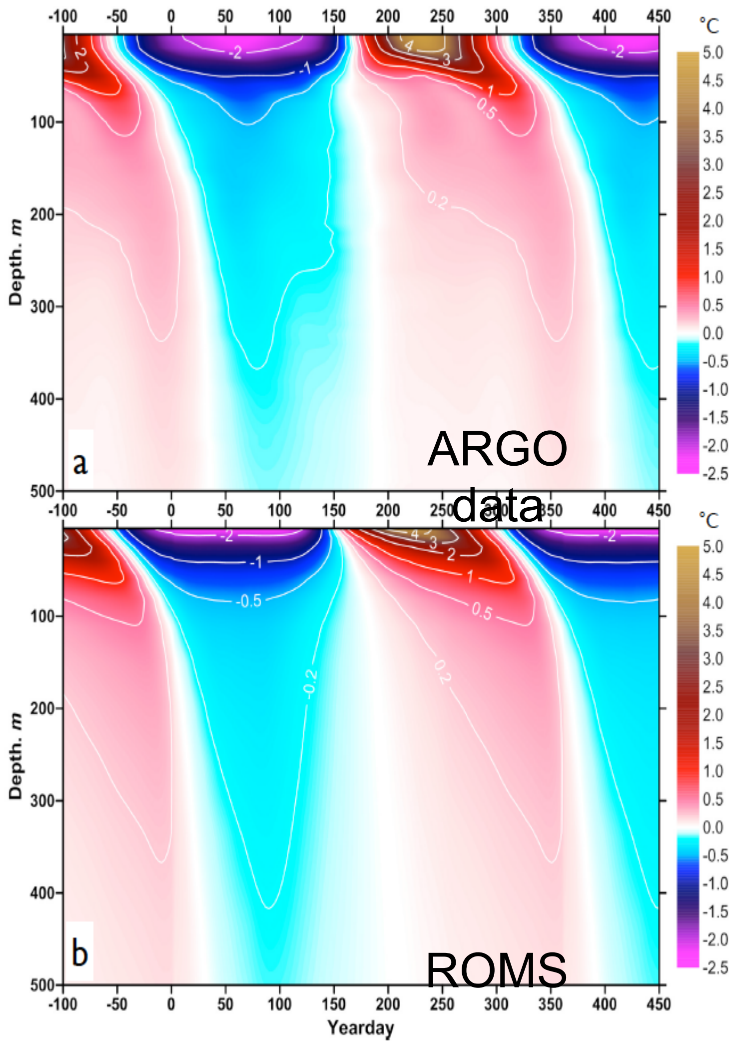


# Interannual variability (II)

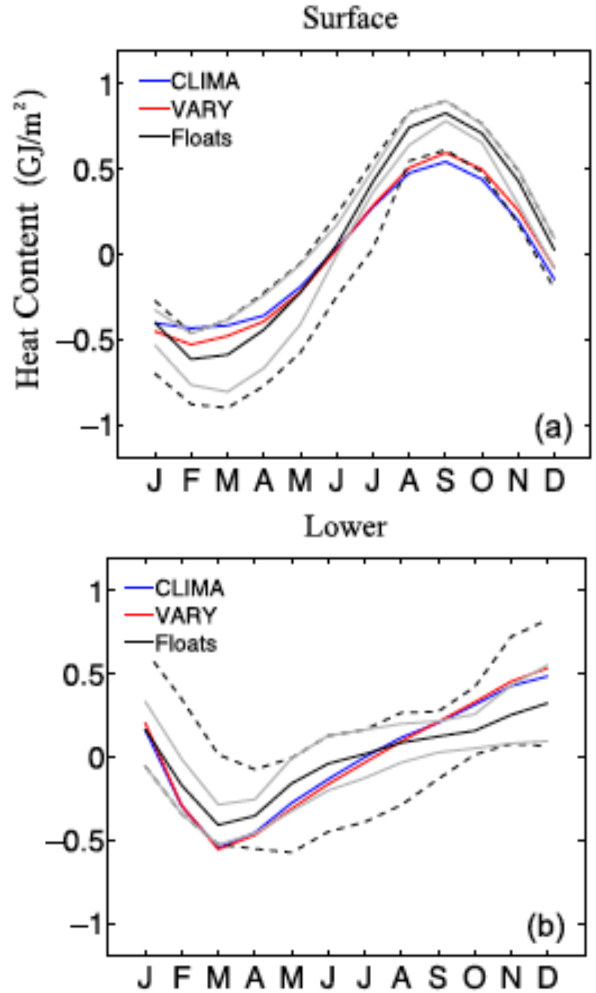



Luo, Bracco, et al., JGR 2012

# Seasonal cycle representation



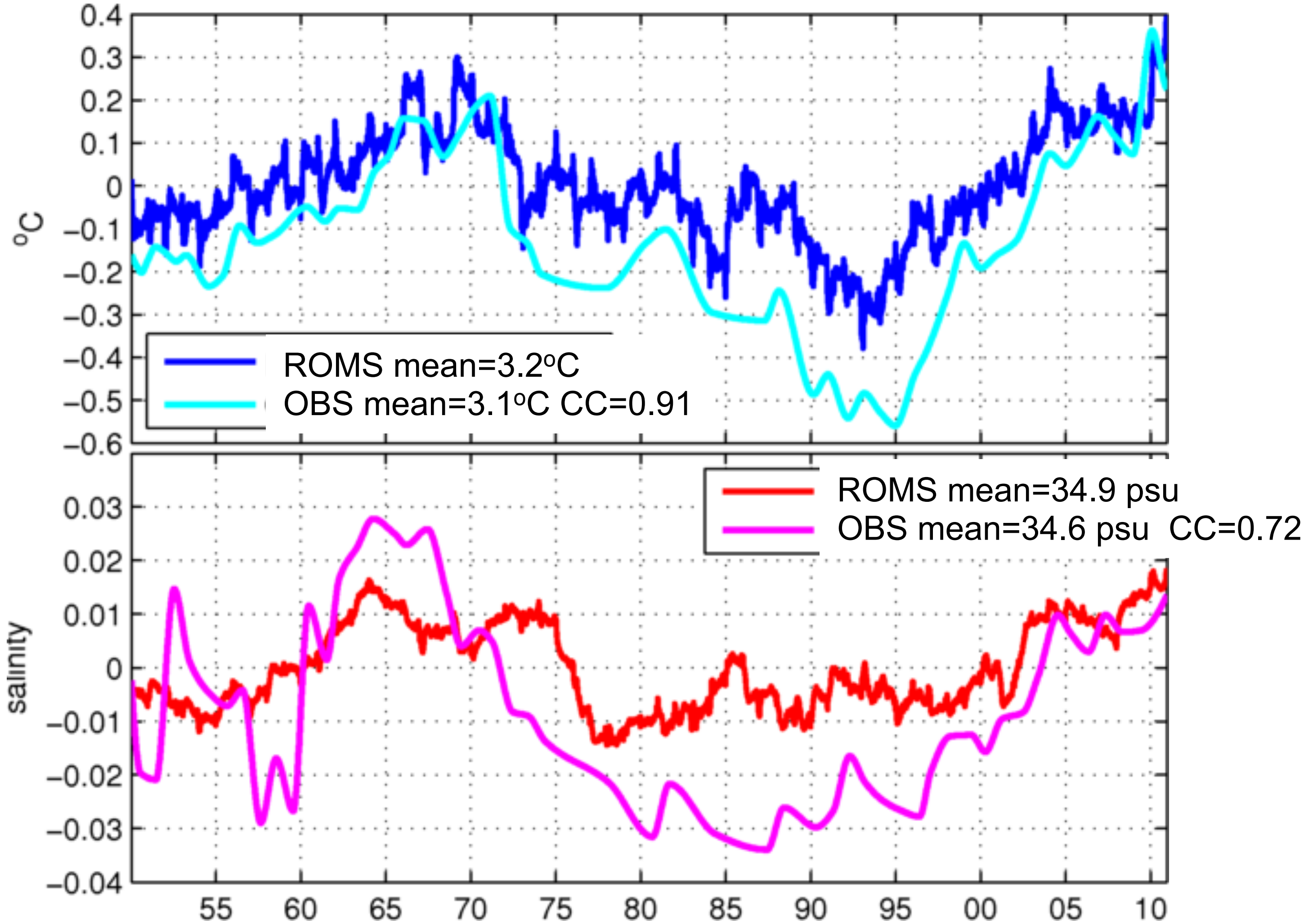

Seasonal cycle in convective region in ARGO data and model time mean 2002-2010 (weak convection) Luo, Bracco et al., 2012




Seasonal cycle of heat content) in convective region in the top 200m (surface) and between 200 and 1300m (Lower) in the model (blue and red lines) and in the observations presented in Straneo (2006) (black and gray lines). The model and the P-ALACE float data cover the period 1996–2000 (strong convection)

Luo, Bracco, Zhang, 2015

# Interannual variability



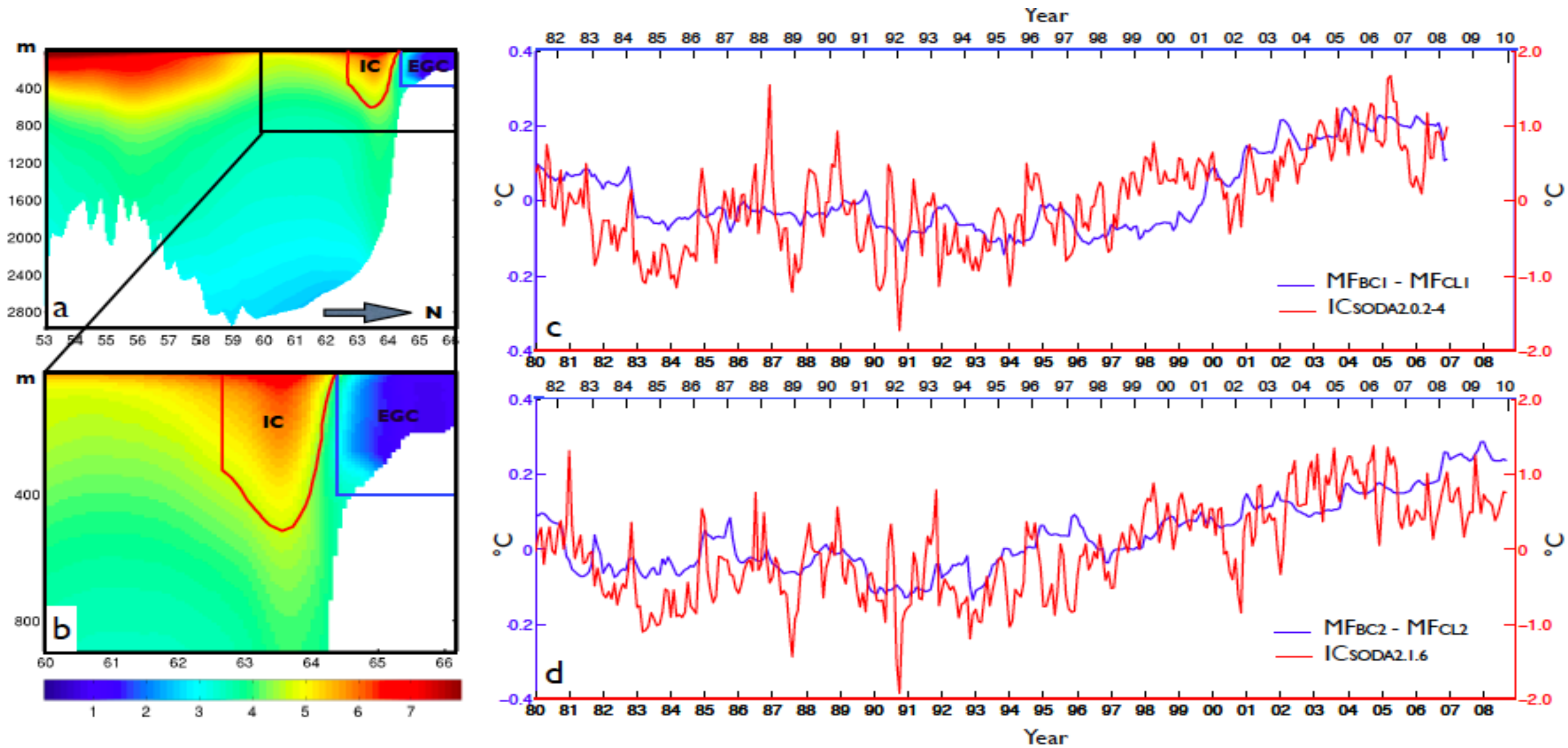

Tagklis, Bracco et al., in Prep

# In summary with ROMS

- Excellent representation of convective activity localization
- Very good representation of water column stratification from surface to ~ 2200m (below too well mixed compared to observations)
- Excellent representation of interannual variability of potential temperature (good for salinity)
- Excellent representation of seasonal cycle in both strong and weak convective periods

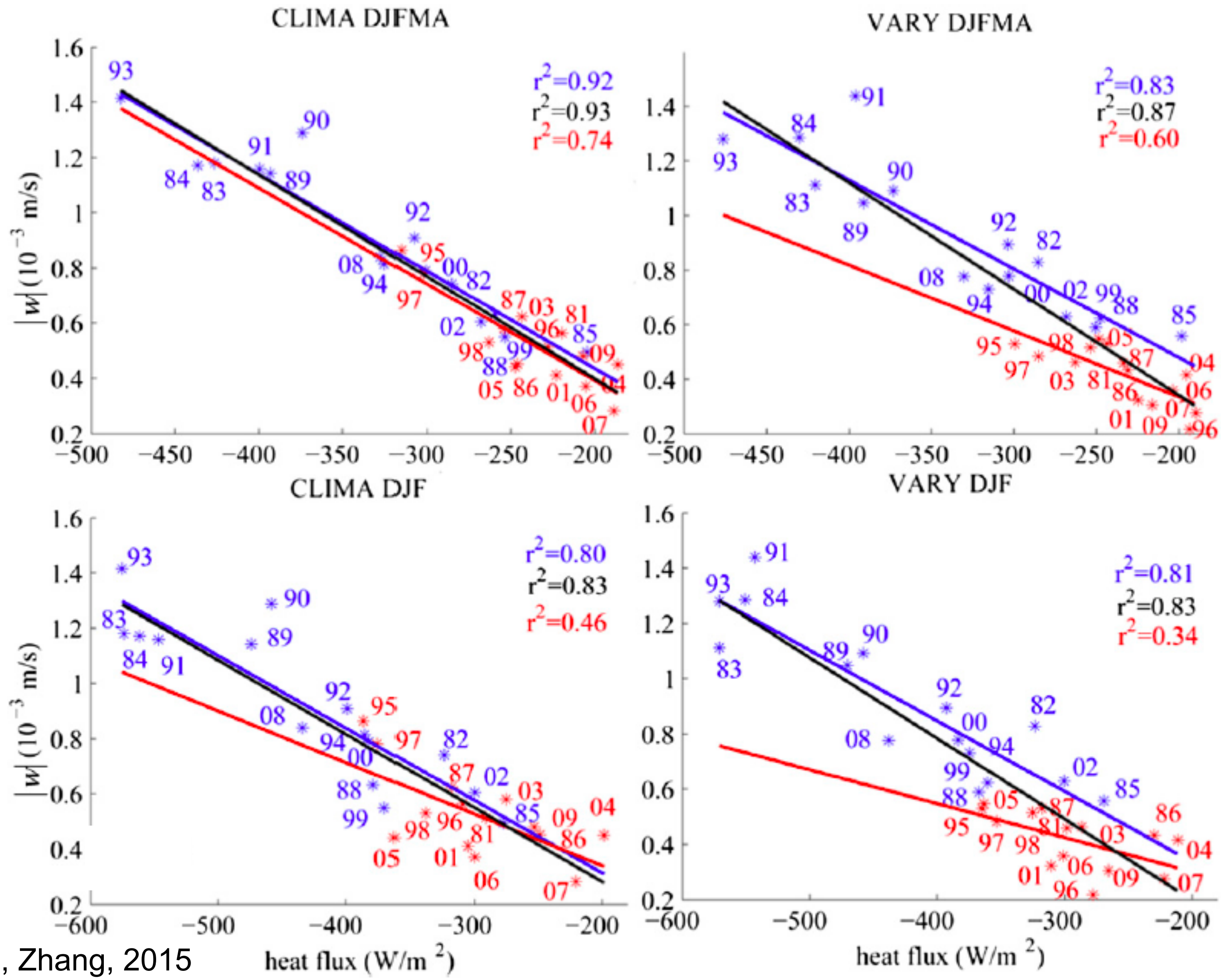
Time to use those skills for sensitivity investigations

**Sensitivity runs:** comparisons between using a climatological Irminger Current at boundary vs interannual varying (role of boundary current in recent trends)

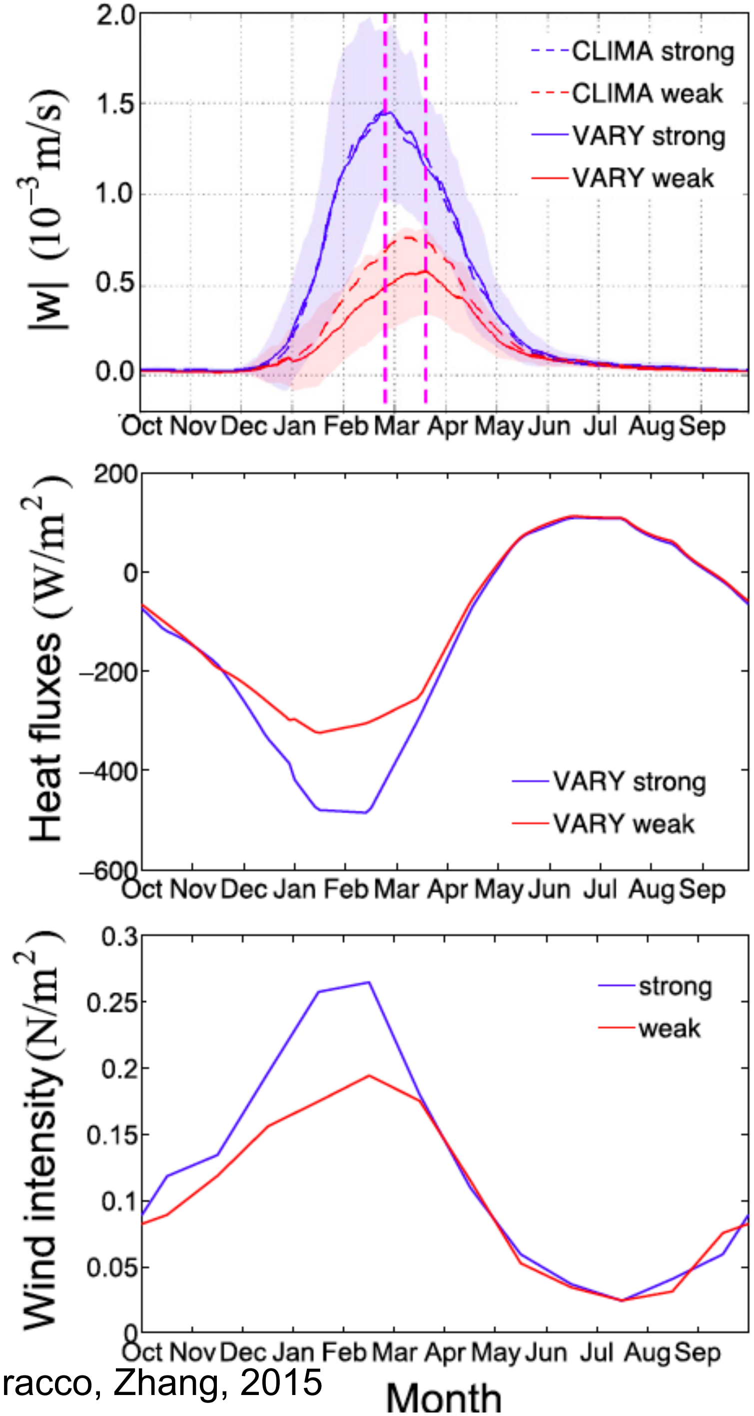



Luo, Bracco, et al., JGR 2012

# **Role of heat fluxes:** Integrated atmospheric fluxes dominate




Luo, Bracco, Zhang, 2015




Luo, Bracco, Zhang, 2015

**Strength of convection determined by atmospheric fluxes** with IC modulation (25% at most) – different from SO!

Different seasonal cycle for weak and strong events; different initiation and termination (overall: the convective season is one month shorter during weak years)

Reduced atmospheric cooling between December and April but not over the rest of the year

(Integrated quantities matter, not so much resolving each mesoscale atmospheric events)

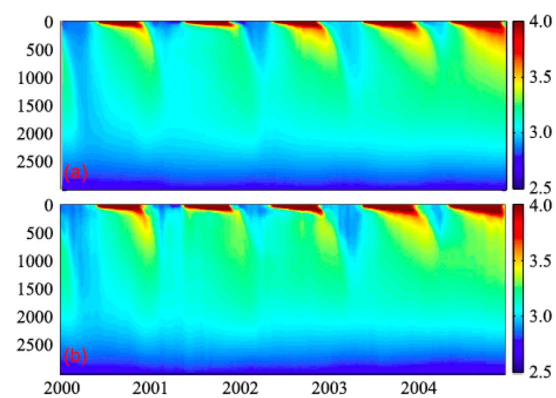



FIG. A3. Evolution of PT (°C) in the CR from 2000 to 2004: (a) VARY and (b) VARY-HF. The plot is obtained using 3-day averages of PT.

# CMIP5 models

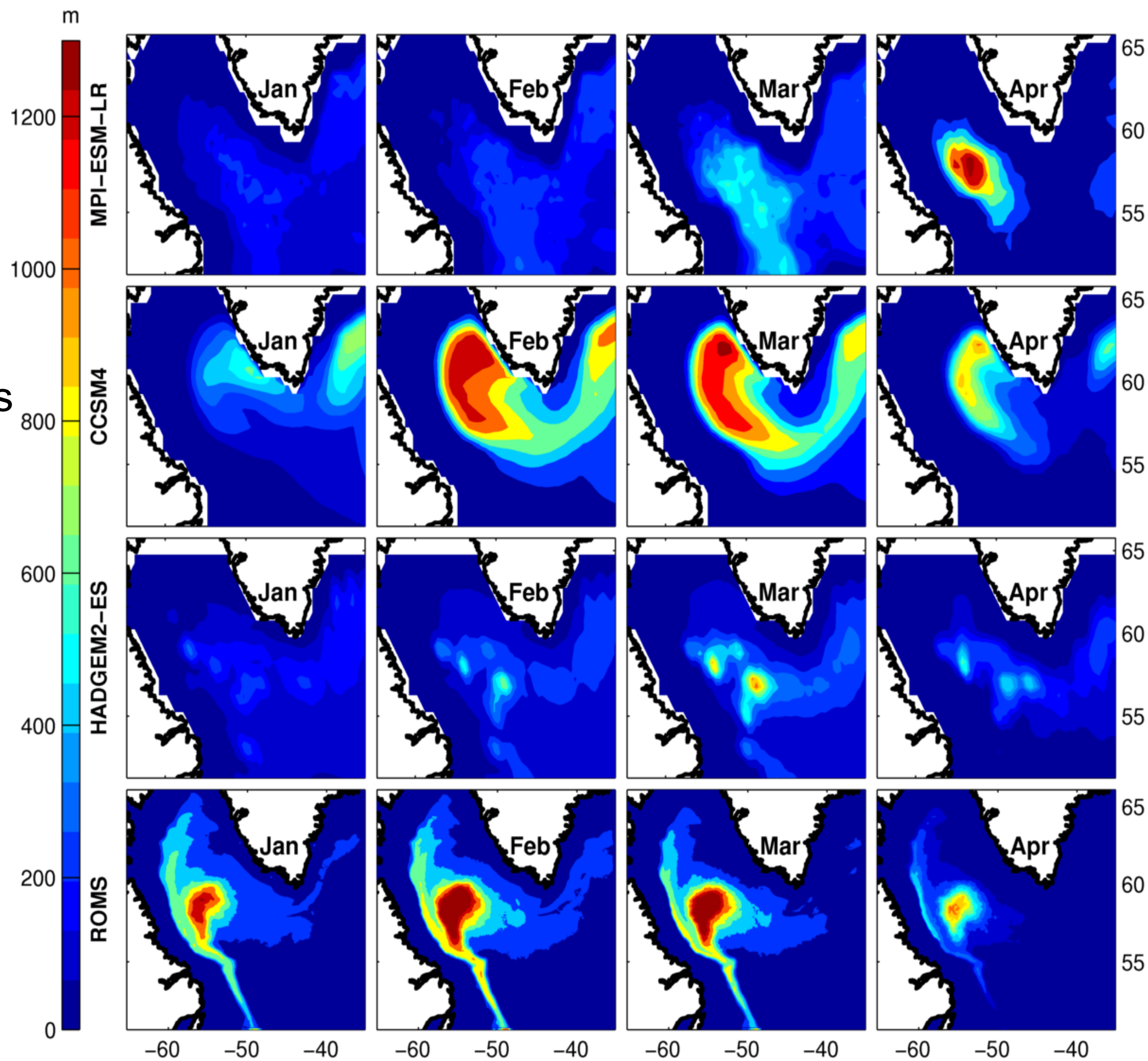
- As in the SO we have eddies (resolution issue)
- We need to verify **localization, strength of convection, seasonality, convection drivers, interannual variability** (using ROMS in lieu of obs)

| Modeling group/center | Institute ID | Model Name |
|---|---|---|
| NOAA Geophysical Fluid Dynamics Laboratory | NOAA GFDL | GFDL ESM2M<br>GFDL ESM2G |
| Institut Pierre-Simon Laplace | IPSL | IPSL CM5A LR<br>IPSL CM5B LR |
| Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais) | MOHC (additional realizations by INPE) | HadGEM2-ES<br>HadGEM2-ES_his |
| Max-Planck-Institut fur Meteorologie (Max Planck Institute for Meteorology) | MPI-M | MPI-ESM-LR<br>MPI-ESM-MR |
| Community Earth System Model Contributors | NSF-DOE-NCAR | CCSM4<br>CESM1(BGC) |

# Localization and seasonal cycle

MLD
mean over
1950-2010

Historical
CMIP5 runs
and ROMS




Tagklis,
Bracco et al.,
In Prep

## Common problems among models

- Convection is too weak (CCSM is an exception: sea-ice is poorly simulated; too much sea-ice forms and melts; heat flux maximum into the ocean nearby sea-ice edge)
- For majority of models seasonal cycle is delayed and shortened

Two possible explanations:

- ✓ heat fluxes are weak
- ✓ ocean mean state is too warm (requires more cooling for convection to start)

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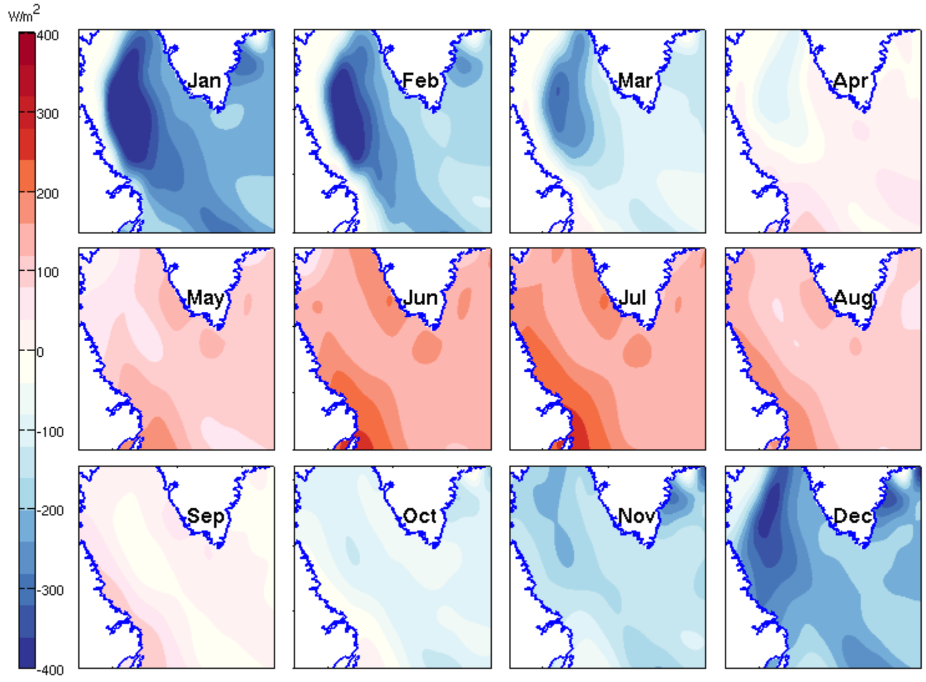
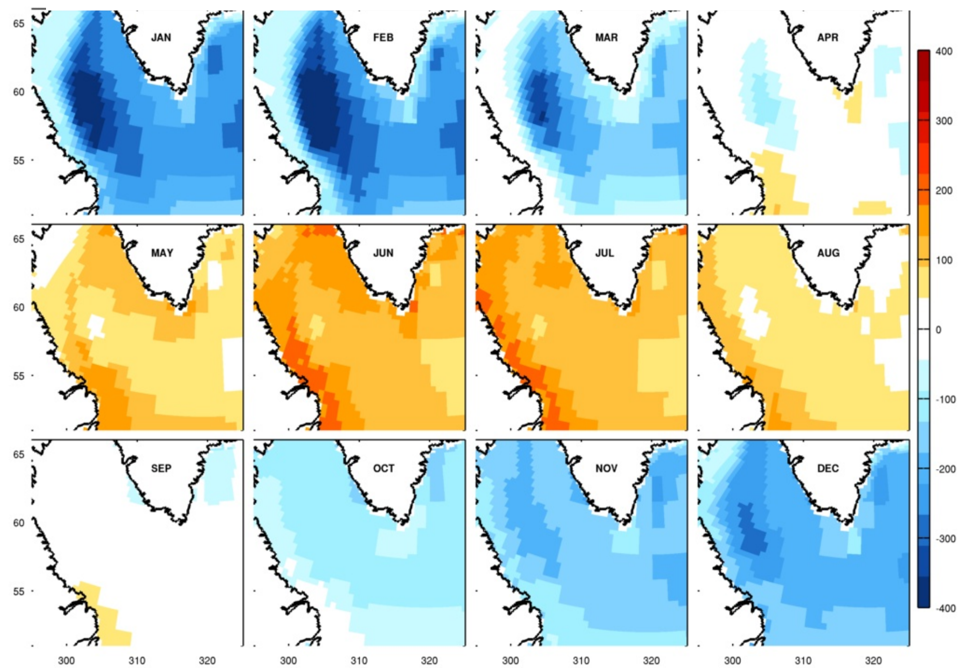


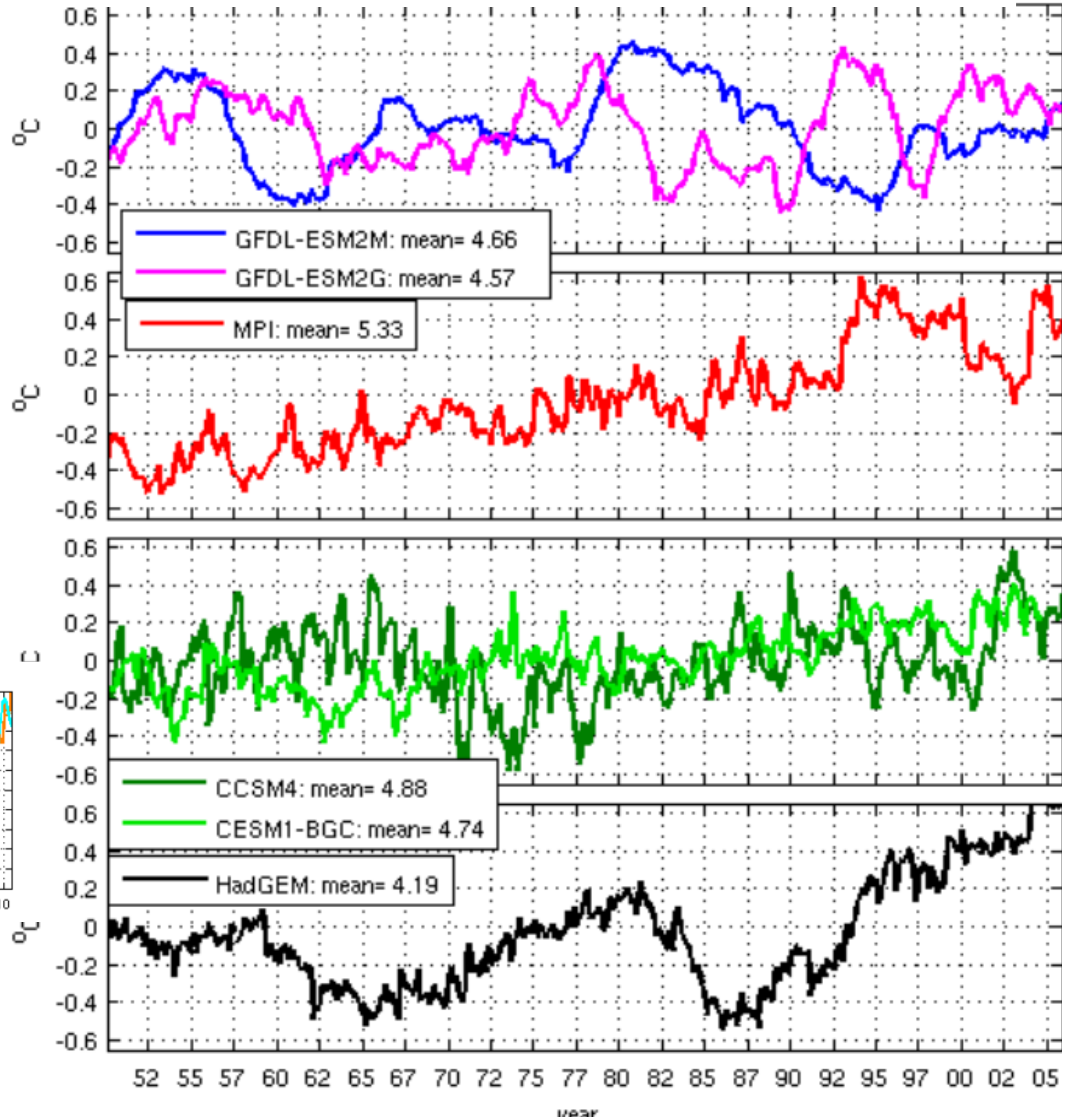

Heat fluxes, NCEP (CORE-2)

Heat fluxes, MPI-ESM-LR



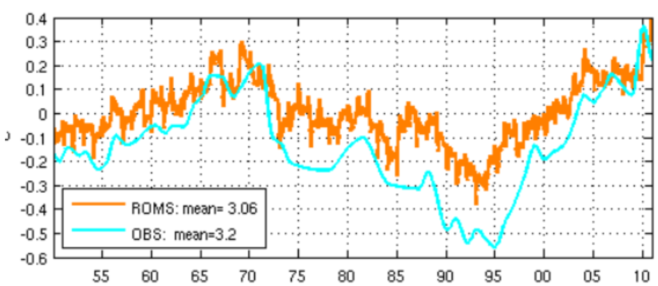

Hypothesis 1 is wrong

Temperature anomaly, convective region, 150-2000m



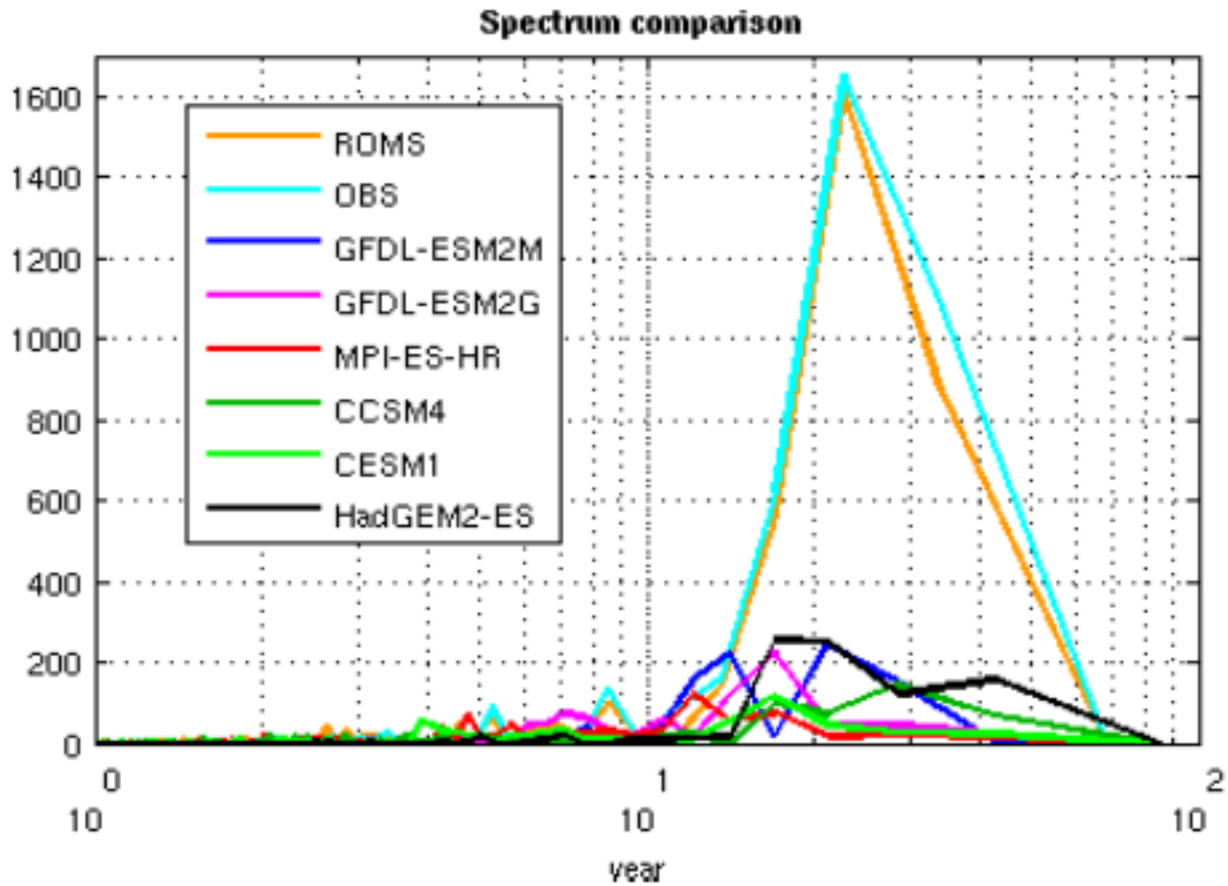

Majority of CMIP5 models is 1-2 °C too warm!

Problem is oceanic mean state




Tagklis, Bracco et al., In Prep

# Interannual variability




Power spectra show substantial underestimation at decadal scales in models

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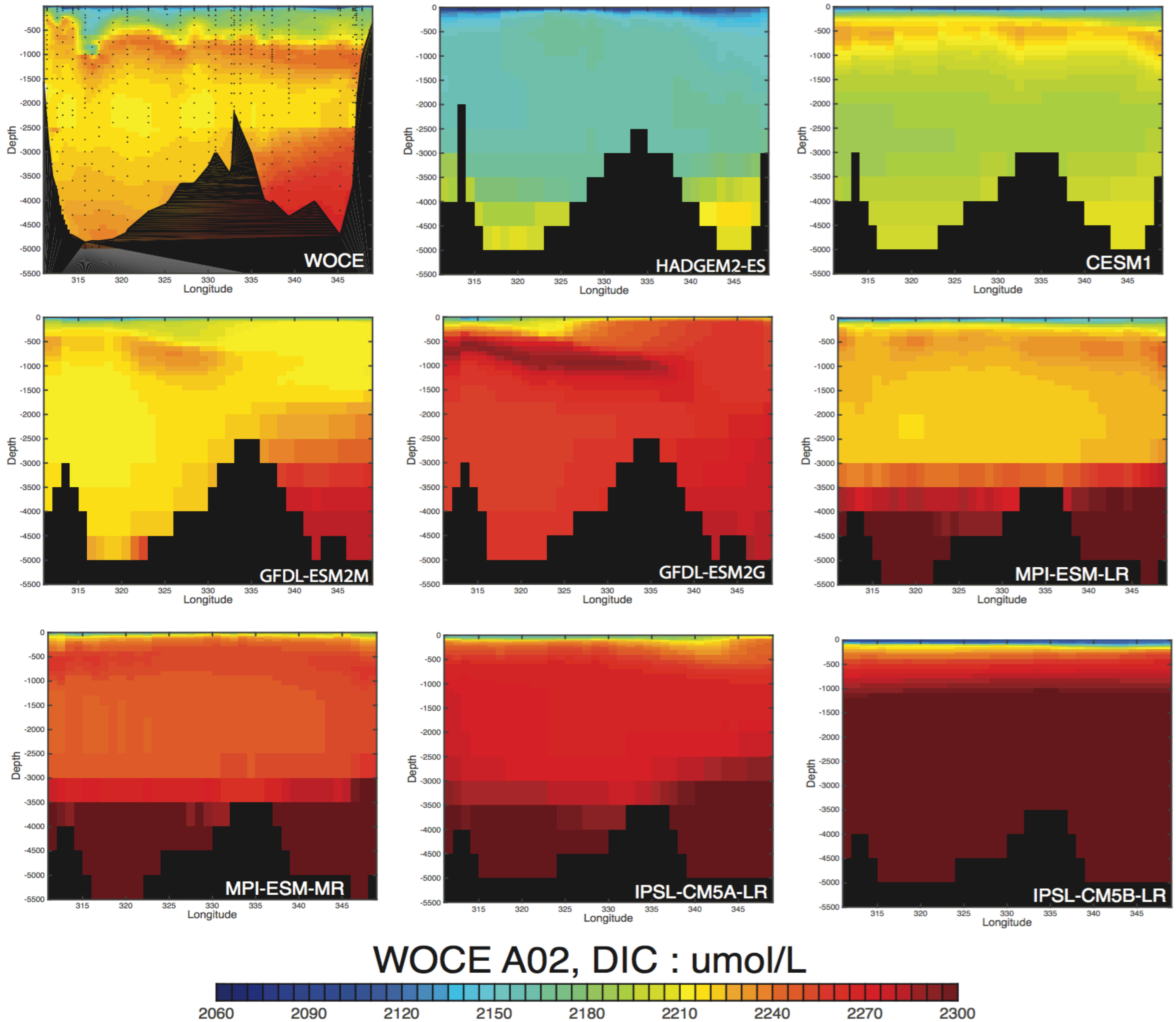
# Physics biases and carbon cycle representation




model-model differences are O $(100 mmolL^{-1})$, larger than the anthropogenic carbon concentration.

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# Is it the physics or the biology?

| Correlation | CESM1 (BGC) | GFDL-ESM2M | GFDL ESM2G | HadGEM2-ES | IPSL-CM5A-LR | IPSL-CM5B-LR | MPI-ESM-LR | MPI-ESM-MR |
|---|---|---|---|---|---|---|---|---|
| **S, T** | 0.79 | 0.90 | 0.96 | 0.80 | 0.30 | 0.61 | 0.84 | 0.73 |
| **S, O2** | -0.87 | -0.94 | -0.97 | -0.85 | -0.43 | -0.65 | -0.90 | -0.83 |
| **T, sDIC** | -0.52 | -0.88 | -0.92 | -0.88 | -0.21 | -0.43 | -0.75 | -0.67 |
| **T, O2** | -0.95 | -0.98 | -0.98 | -0.99 | -0.88 | -0.93 | -0.98 | -0.96 |
| **sDIC, O2** | 0.54 | 0.85 | 0.92 | 0.91 | 0.32 | 0.47 | 0.78 | 0.71 |

Comparing correlations and differences between models from same center (same biology, differences only in physics) the answer is clear:

**The physical representation of T, S and circulation drives the biases in the DIC one**

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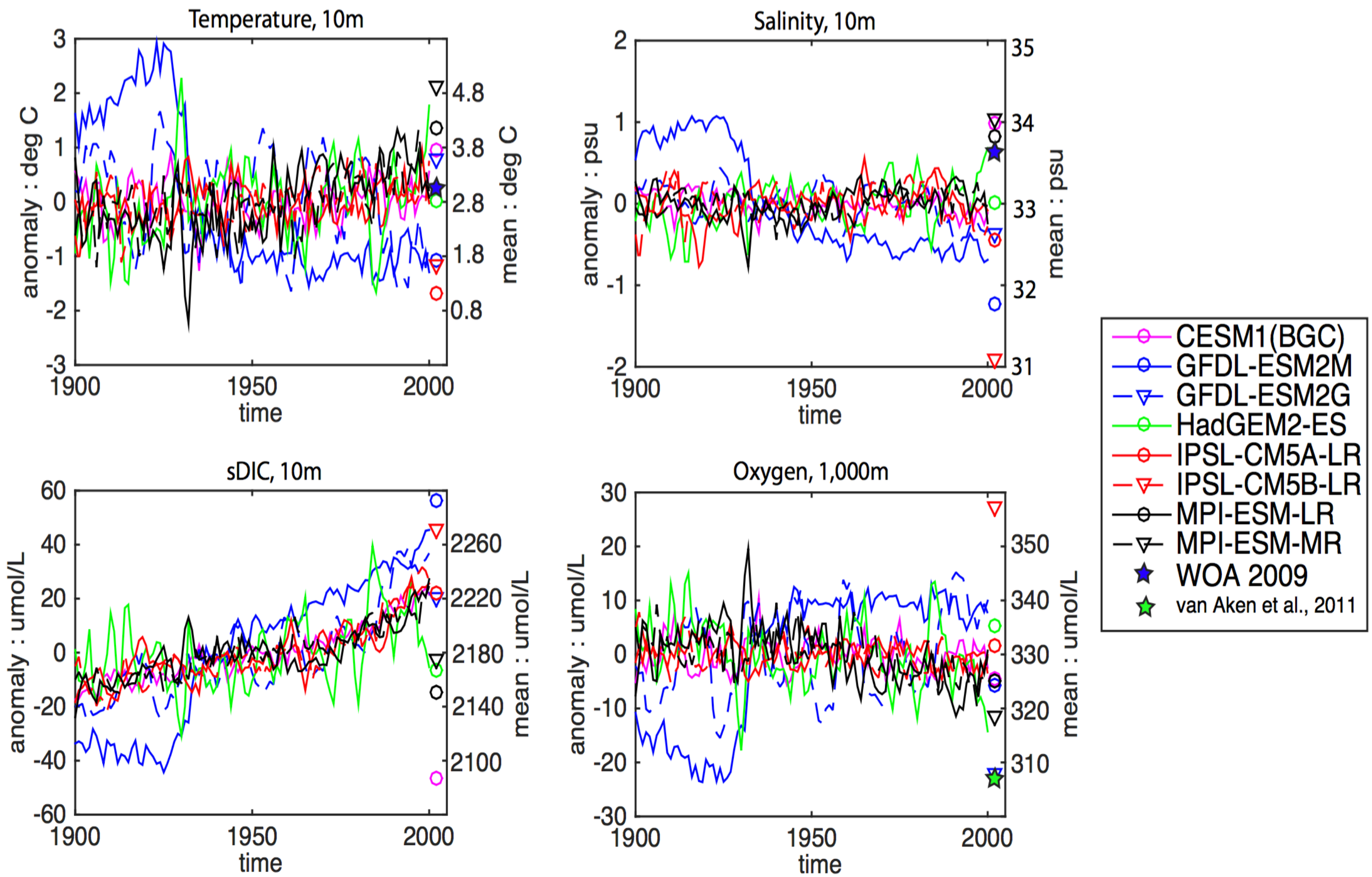


Trends in T and S (here surface only) and limited interannual variability are reflected in DIC and $O_2$

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# Challenges

- Simulating drivers of interannual variability (atmosphere/ coupled problem)
- Eddies! What is the impact of parameterizing them for high latitudes circulation and variability?
- Mean state: why generally so warm? (IPSL being the exception)
- We have looked at two of the most difficult –but important – regions: yes, models have large biases but it is not a lost cause!
- Nested techniques?
- Attribution problem! Can we detect and attribute changes associated with global warming at high latitudes? Not really in observations. Different answer from models.