Ocean heat content and Earth's energy imbalance: insights from climate models

Matt Palmer[1], Chris Roberts[1], Doug McNeall[1], Freya Garry[2], Roberto Fernandez-Bilbao[3], Jonathan Gregory[1,3]

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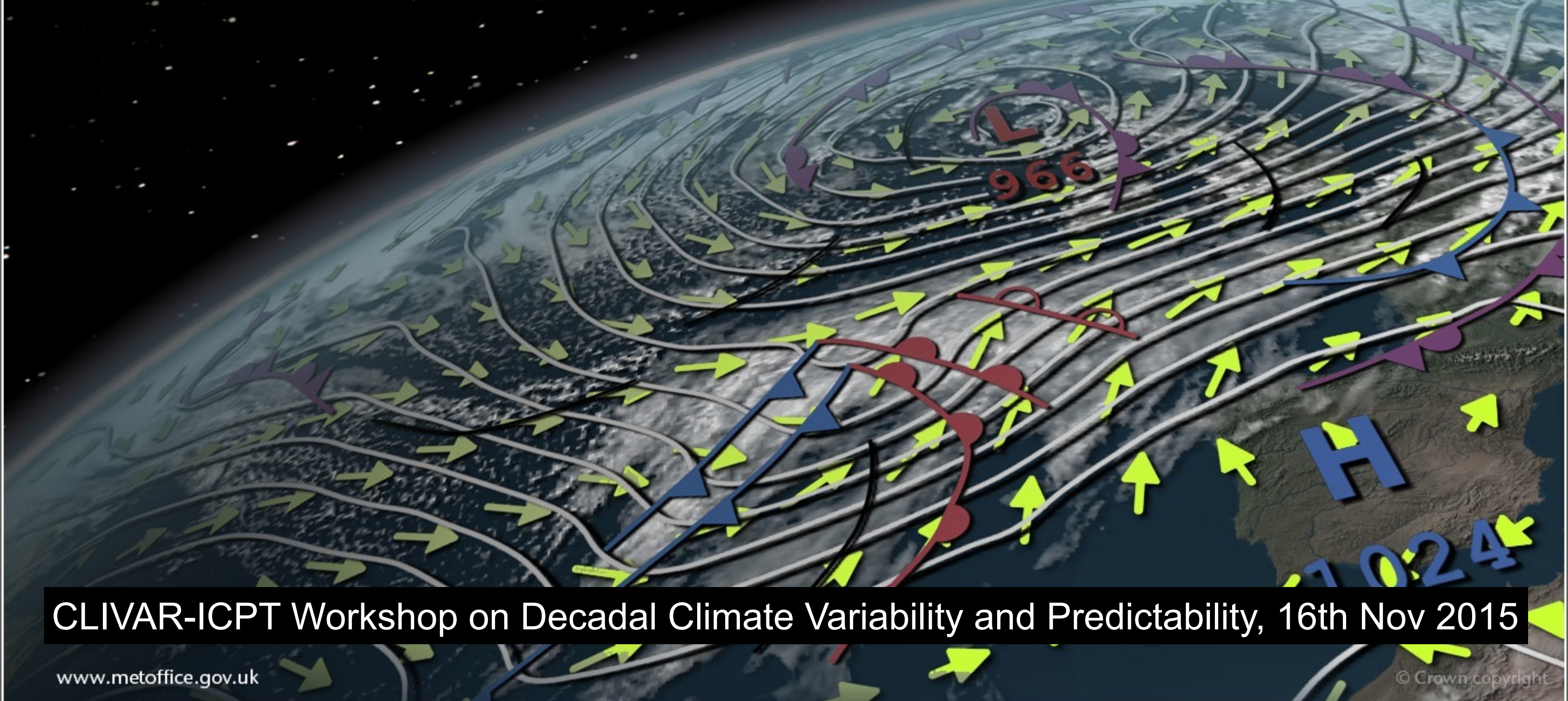
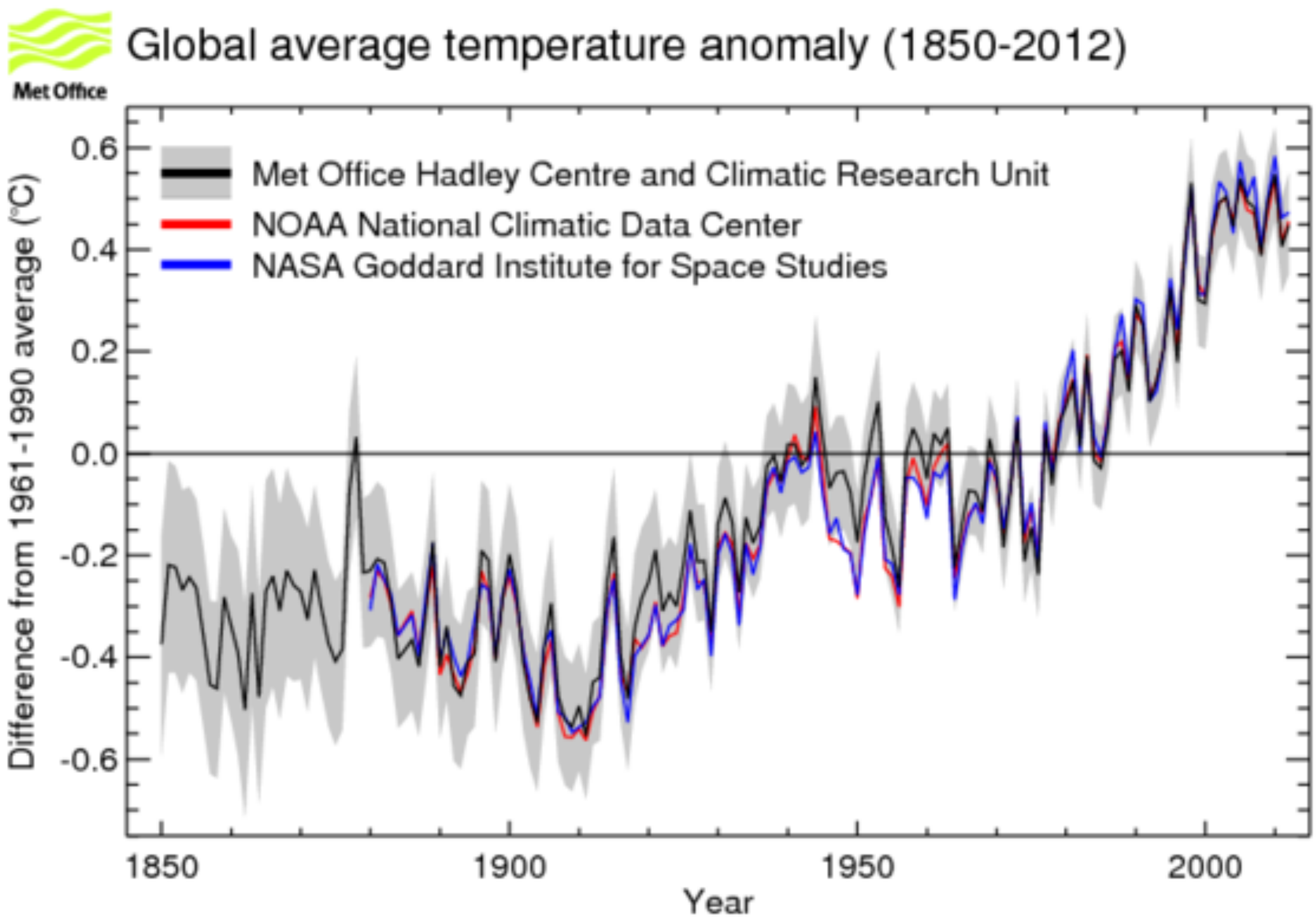


CLIVAR-ICPT Workshop on Decadal Climate Variability and Predictability, 16th Nov 2015

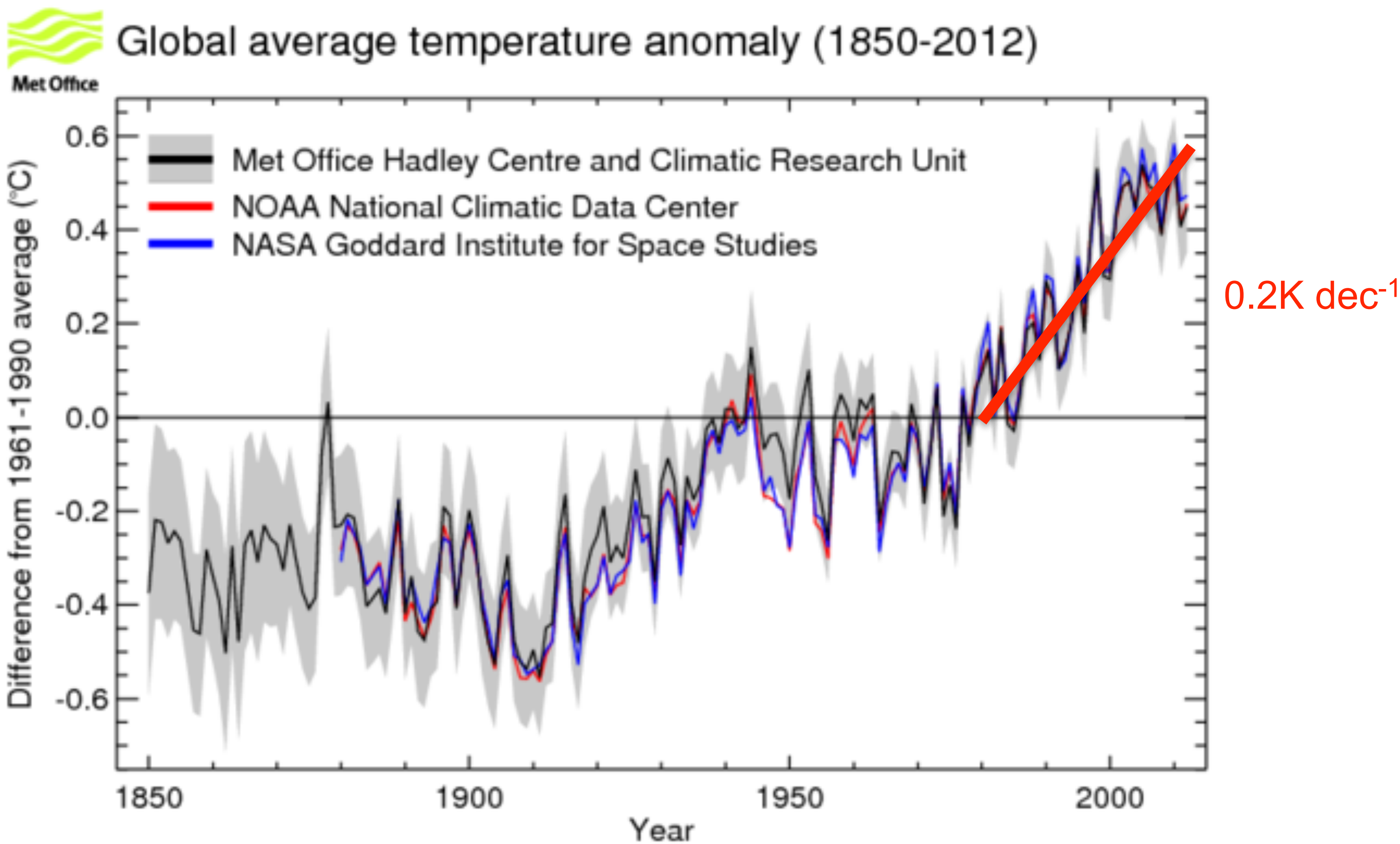
Outline

- Some context: the global warming "hiatus"
- CMIP5 models - unforced simulations (piControl)
- CMIP5 models - forced simulations (historical + RCP8.5)
- Summary + open questions..

Some context: the global warming "hiatus"



Some context: the global warming "hiatus"



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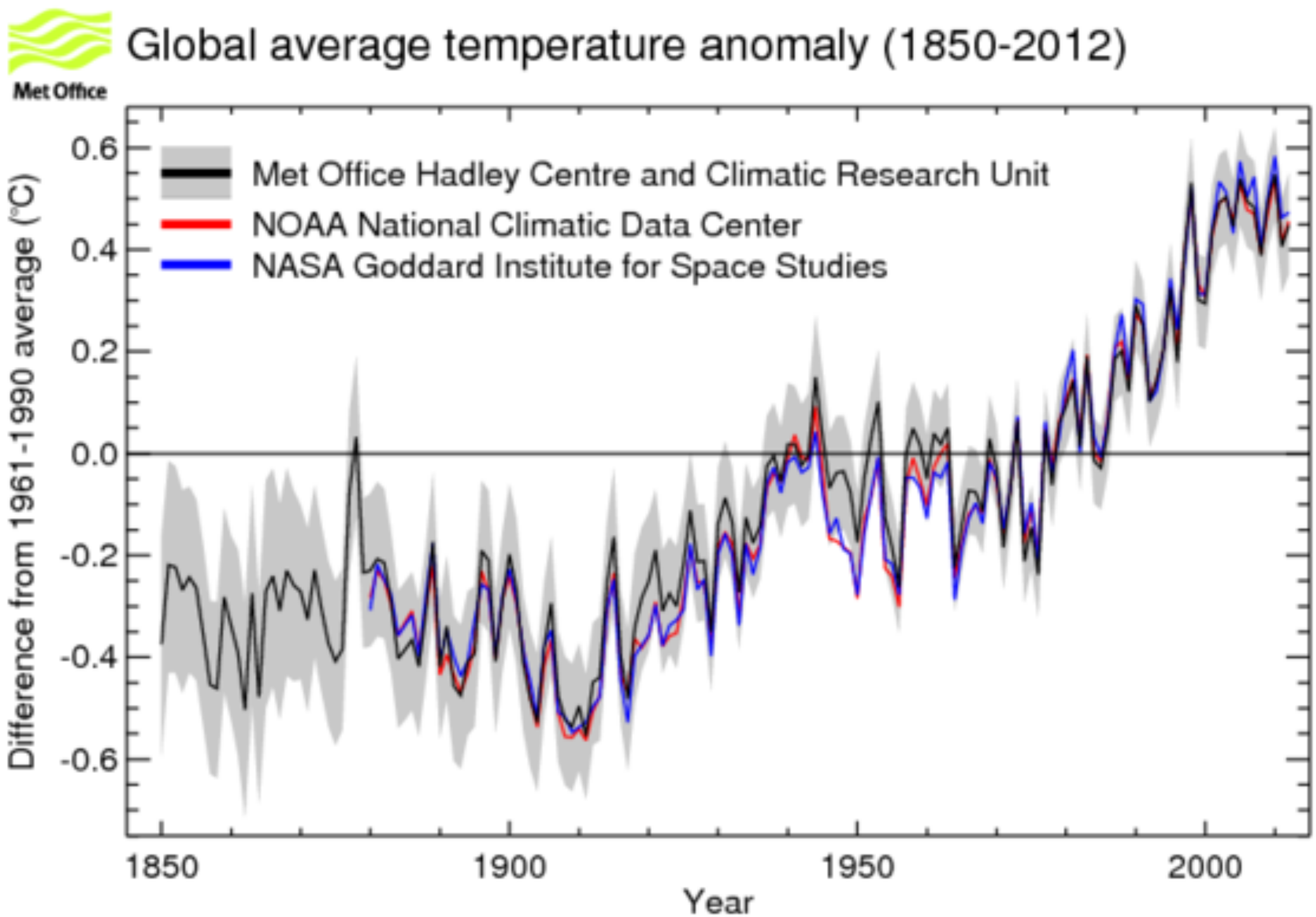
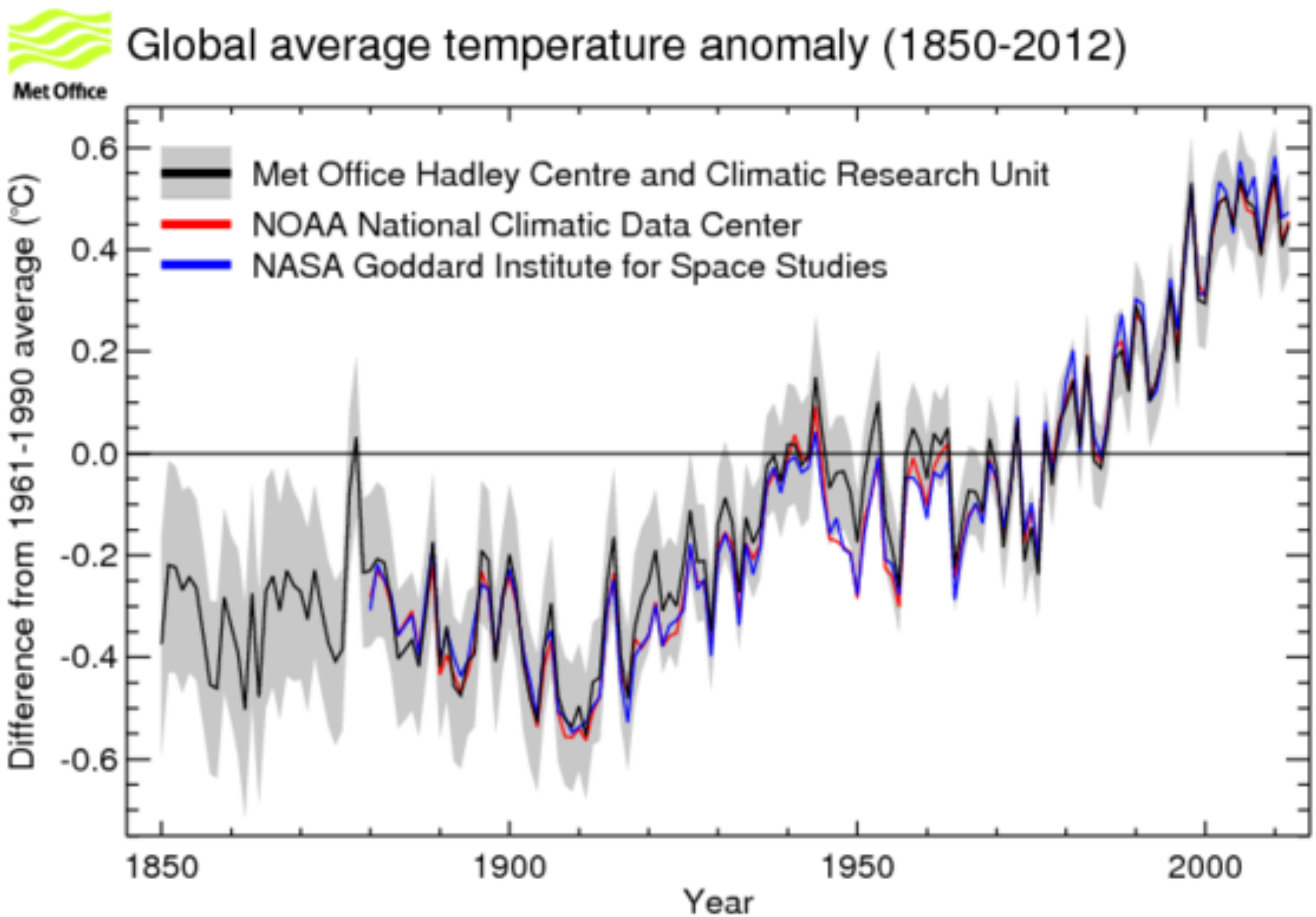


1. A change in net radiation at top-of-atmosphere (netTOA) ? [0.6 Wm^{-2}]

Some context: the global warming "hiatus"



1. A change in net radiation at top-of-atmosphere (netTOA) ? [0.6 Wm^{-2}]
2. A rearrangement of ocean heat content (OHC) ?

CMIP5 unforced "piControl" simulations

Approach

Assume a linear combination of forcings and internal variability in the real world

=> Analyse multi-century CMIP5 preindustrial control simulations to address the following questions:

(i) On what timescale does netTOA come into balance with changes in total OHC?

(ii) What is the potential role of internal variability in netTOA for the recent pause in surface warming?

(iii) What is the potential role of ocean heat redistribution for the recent pause in surface warming?

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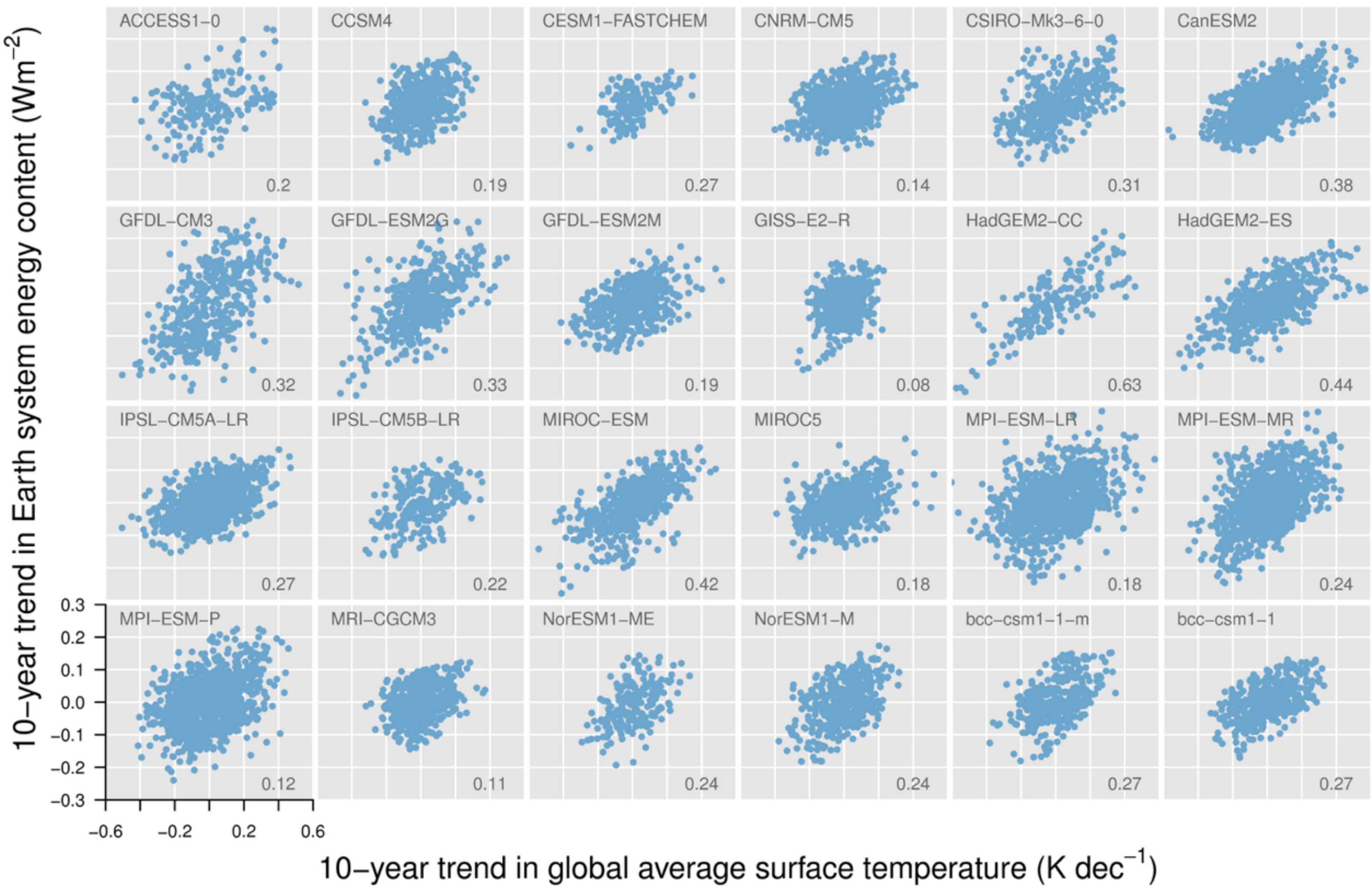
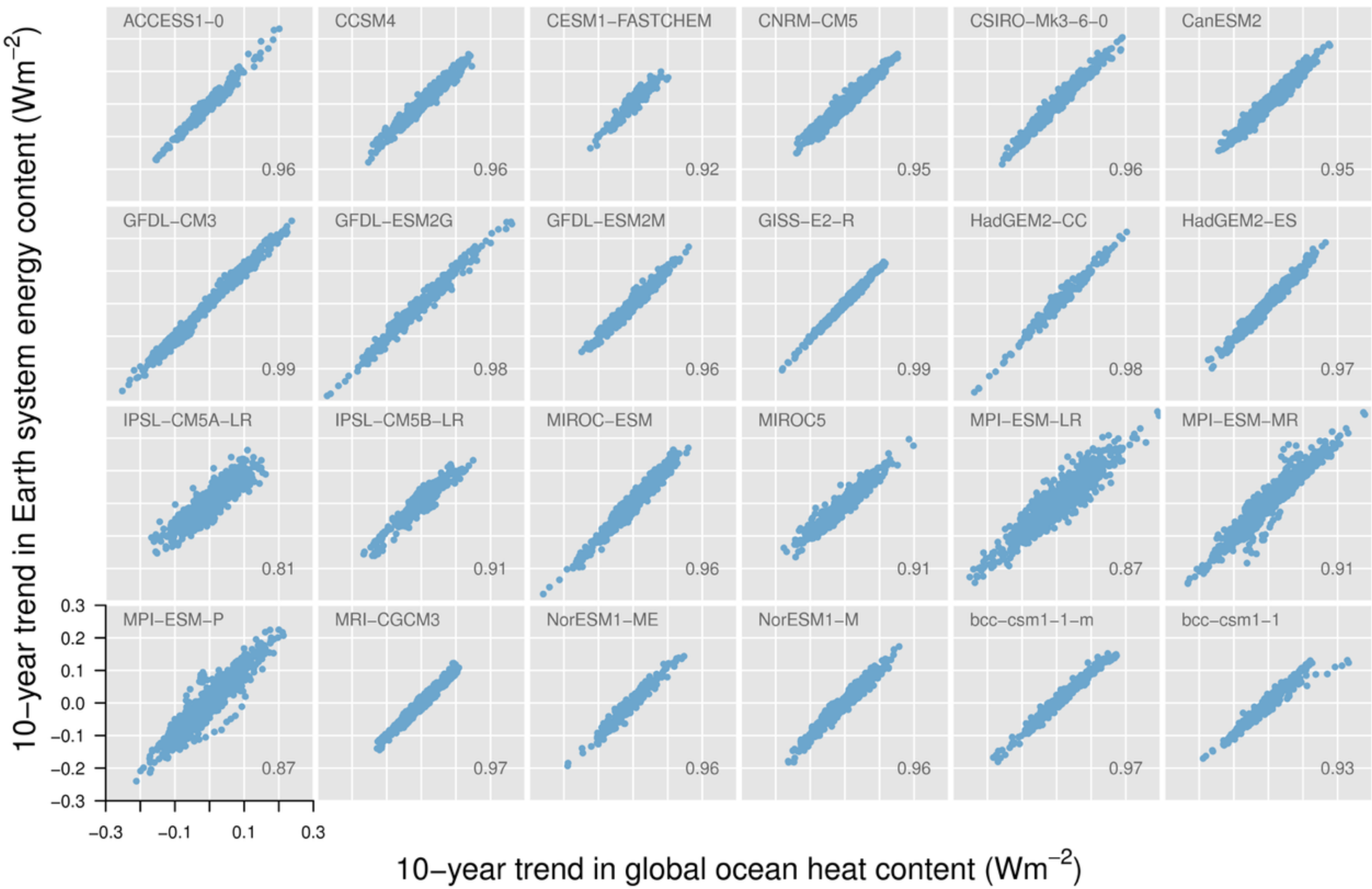
Note: the analyses presented are idealised studies, where there is no attempt to account for realistic observational sampling

10-yr trends in surface temperature are NOT a robust indicator of trends in Earth System energy



Palmer, M.D. and D.J. McNeall (2014) "Internal variability of Earth's energy budget simulated by CMIP5 climate models", Env. Res. Lett., doi:10.1088/1748-9326/9/3/034016

10-yr trends in global OHC changes ARE a robust indicator of trends in Earth System energy



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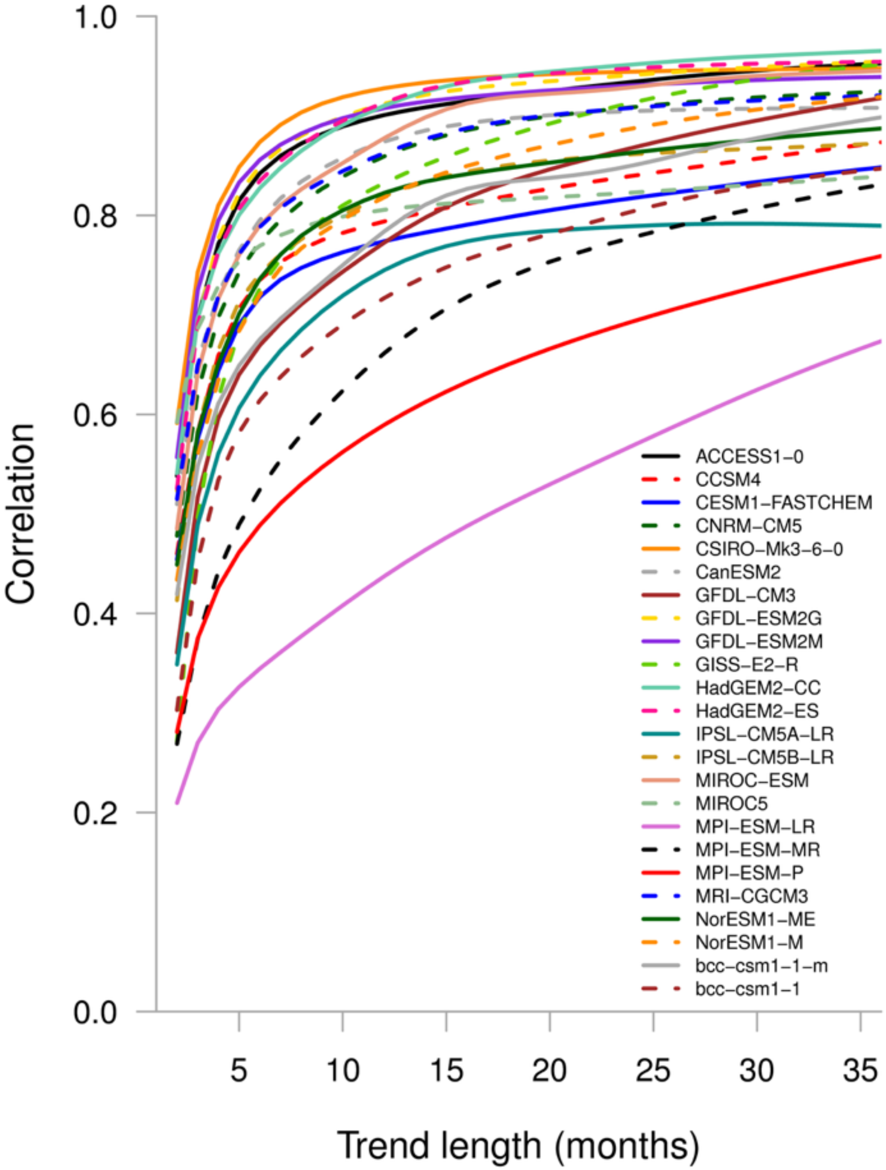

The ocean becomes the dominant term in Earth's energy budget on a typical time scale of ~ 12 months

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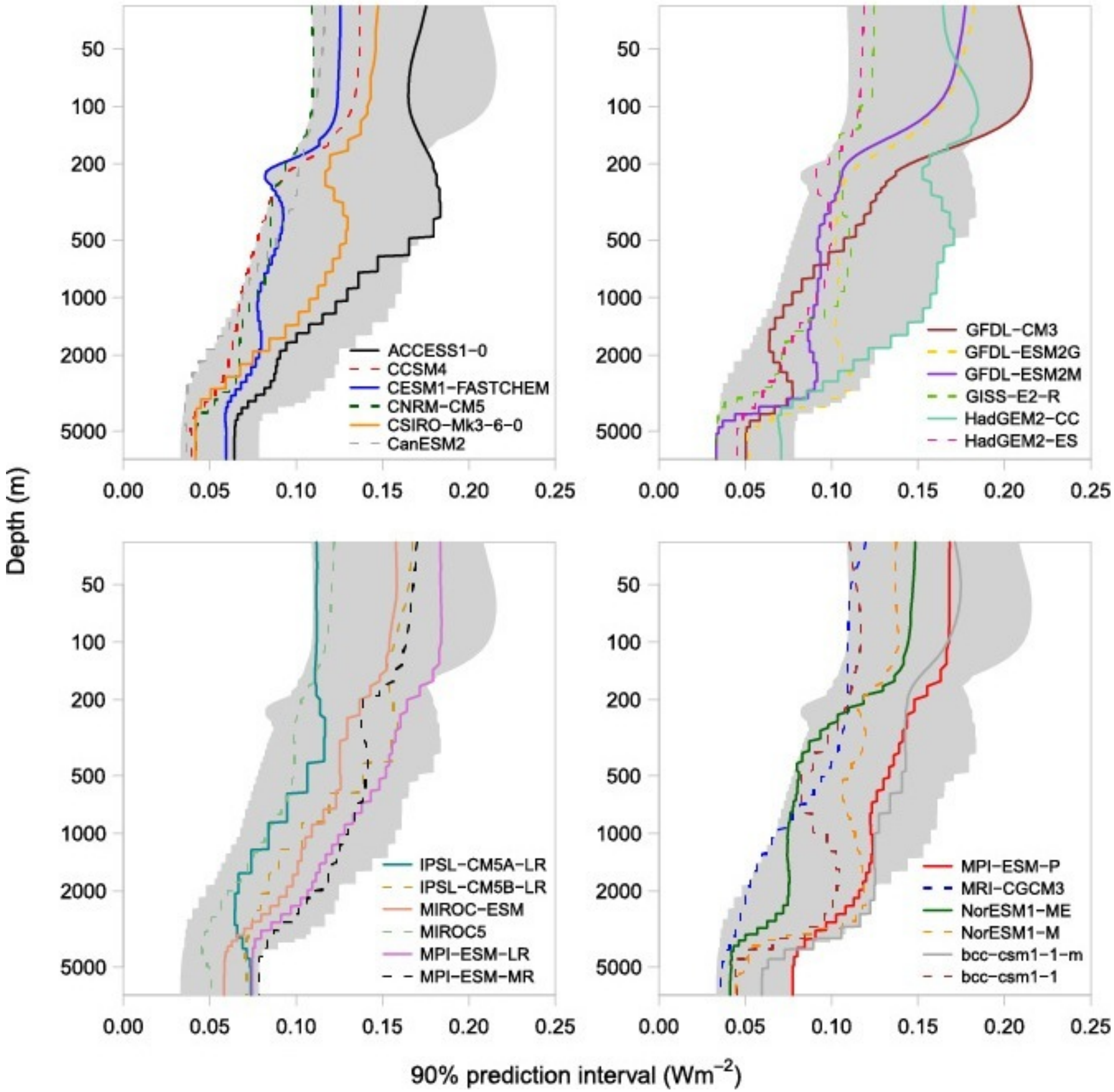

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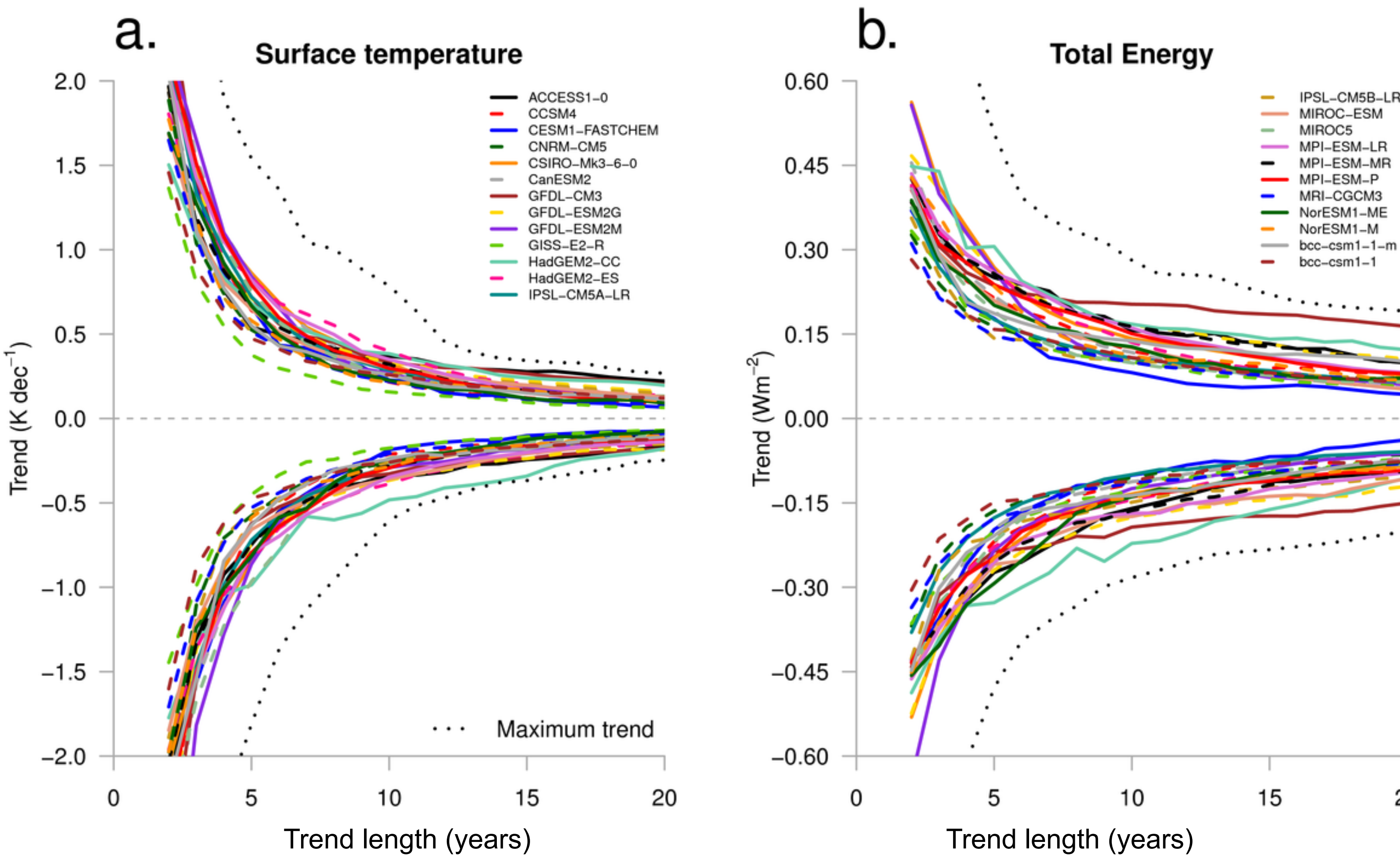
Internal variability => trends in GST and netTOA that are large compared to "background" warming/heating rates (2.5th and 97.5th centiles)



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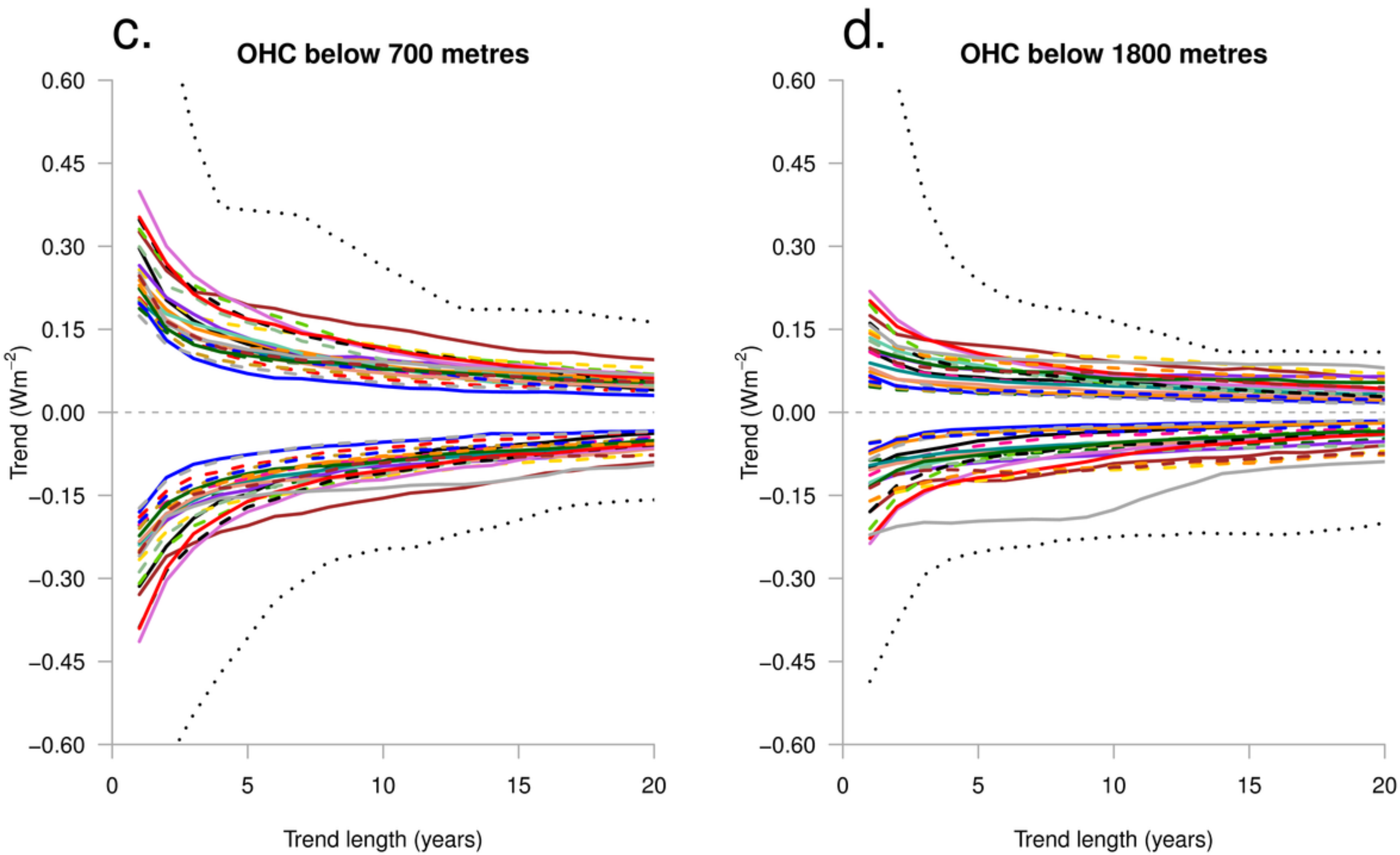
Internal variability => substantial ocean heat re-arrangement compared to "background" heating rates (2.5th and 97.5th centiles)



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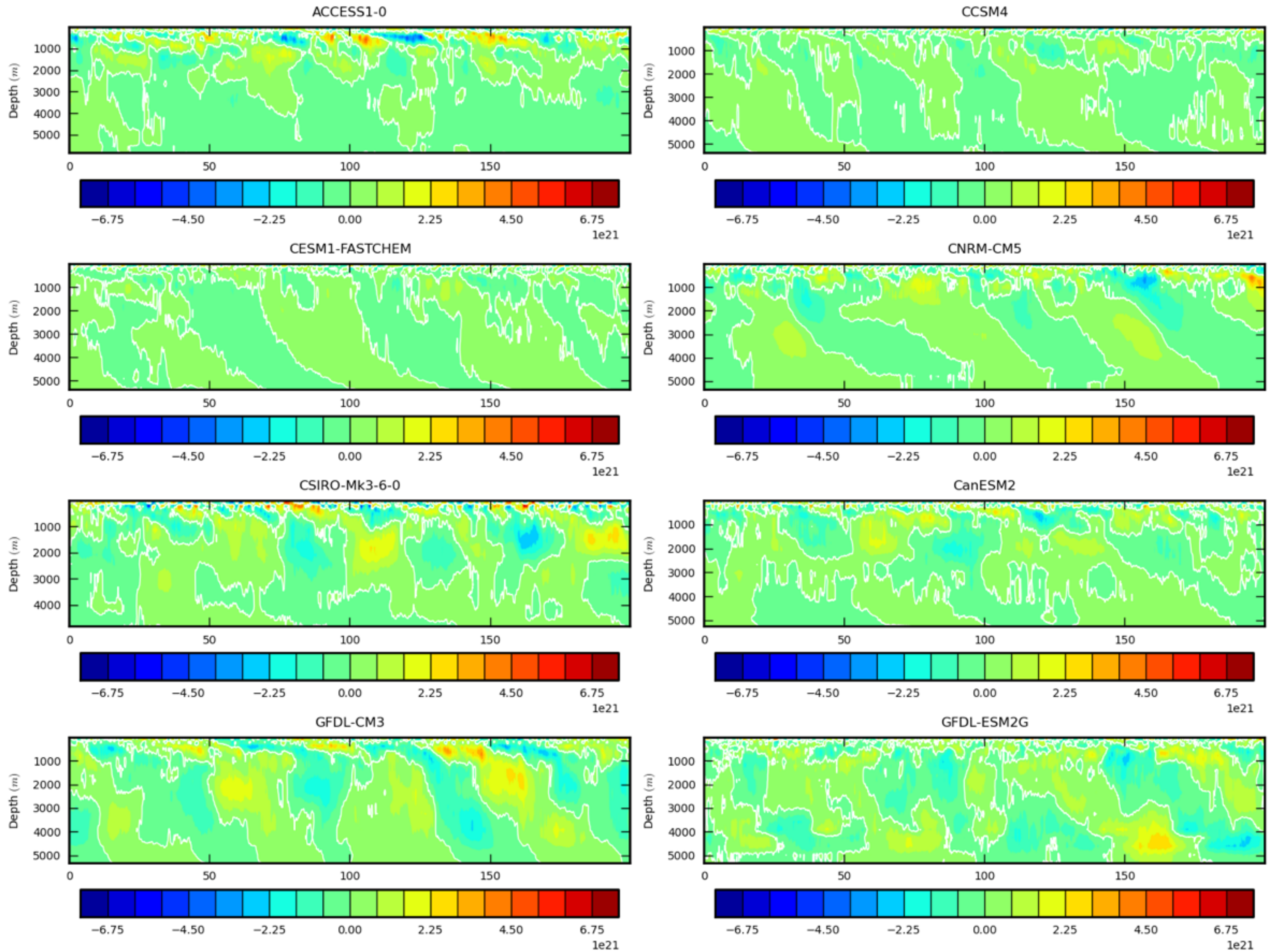
The character and magnitude of ocean heat re-arrangement varies substantially among CMIP5 models (hovmoller plots of OHC over 200 years)



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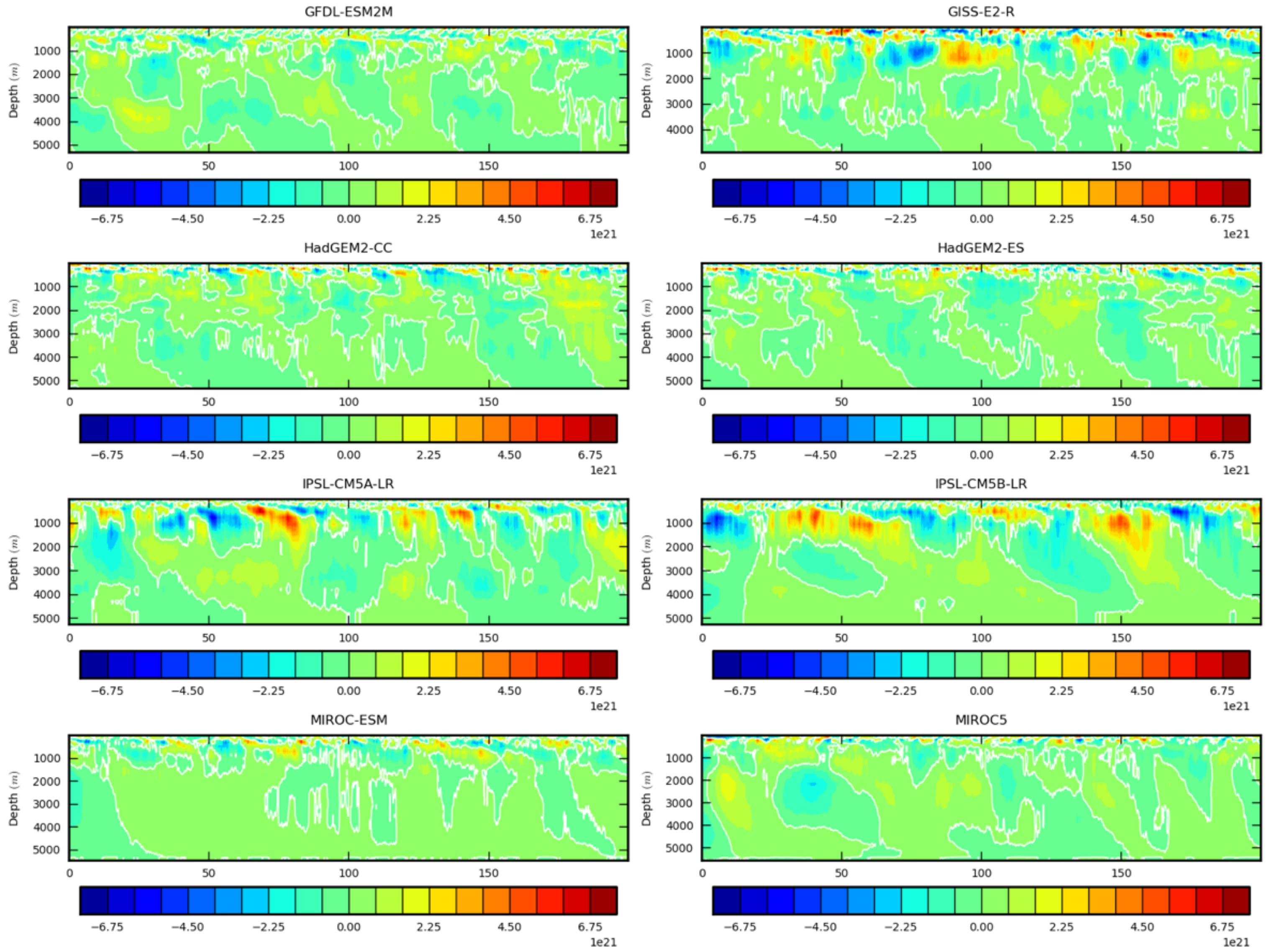

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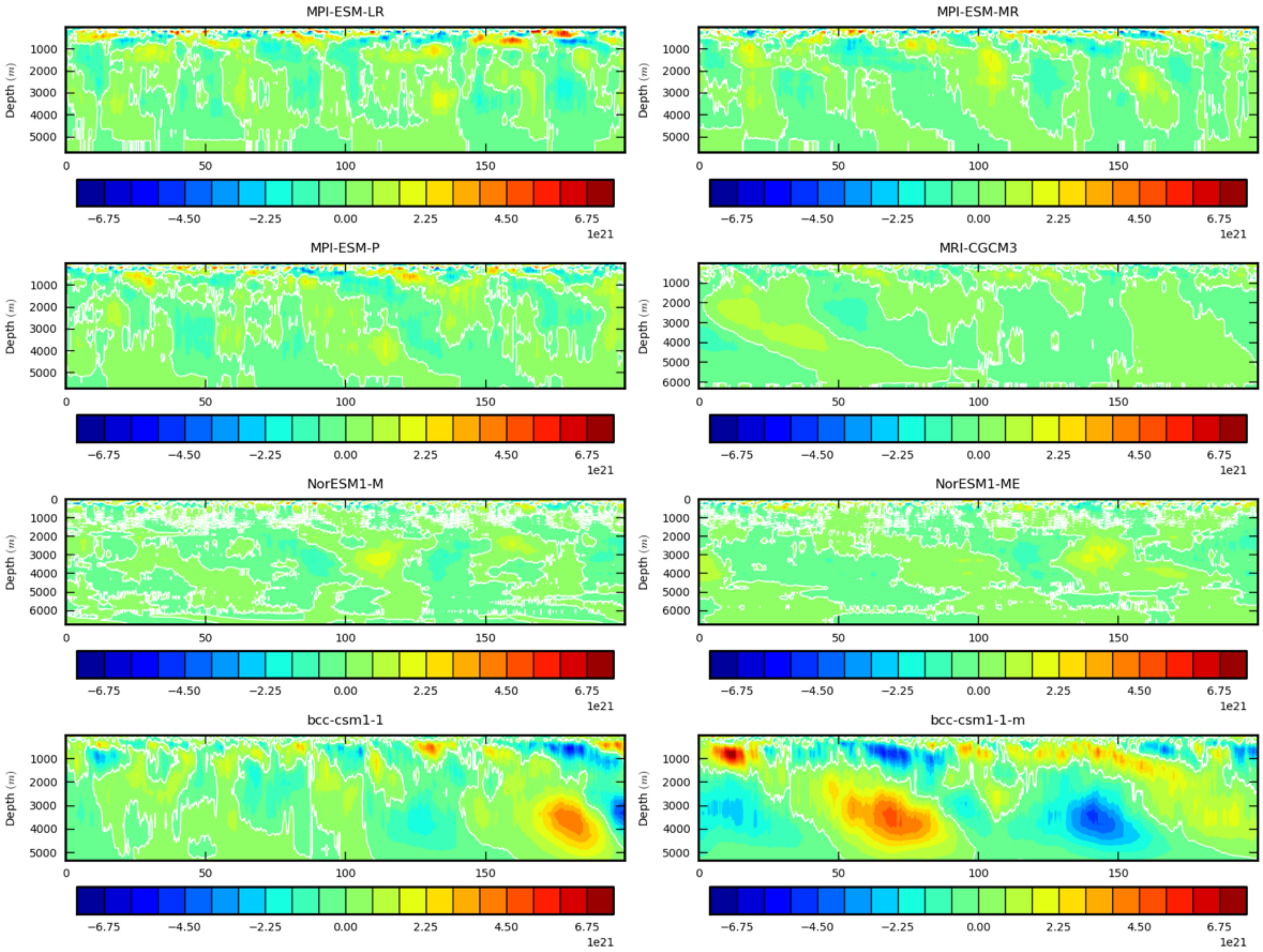

Summary of CMIP5 piControl simulations

(i) The ocean becomes the dominant term in Earth's energy budget on a timescale of about 1 year

(ii) Changes in netTOA associated with internal variability of order 0.1-0.3 Wm^{-2} on decadal timescales [c.f. 0.6 Wm^{-2}]

(iii) Ocean heat rearrangement across 700m (1800m) isobath is of order 0.1-0.2 (0.5-0.15) Wm^{-2} [c.f. 0.6 Wm^{-2}]

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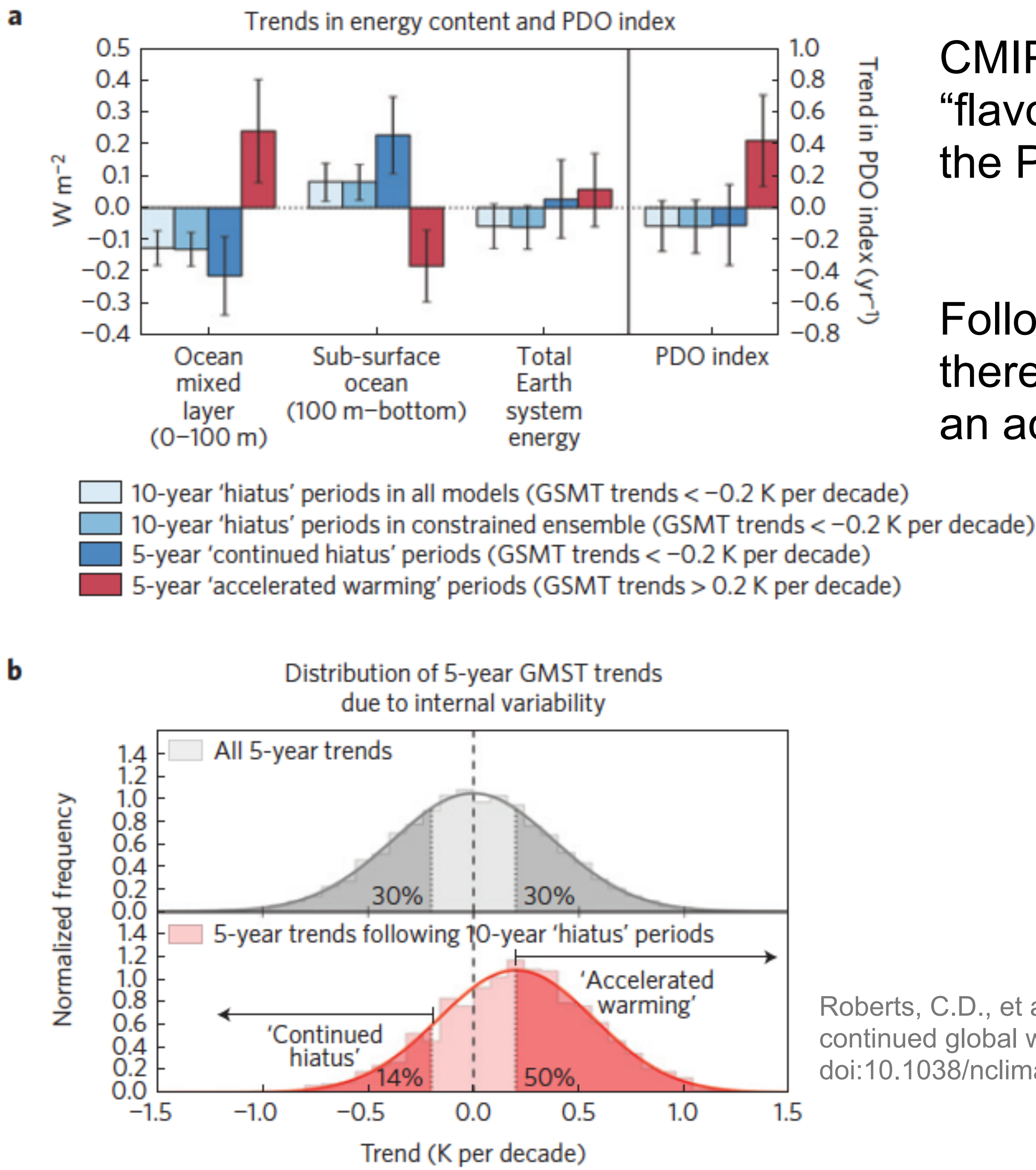
And..

(iv) 10-15 year "hiatus" in surface temperature rise could be explained by internal variability alone => see Roberts et al [2015, next 2 slides]

(v) Surface temperature trends are NOT a reliable reliable indicator of changes in Earth System energy (and hence global warming) on decadal timescales

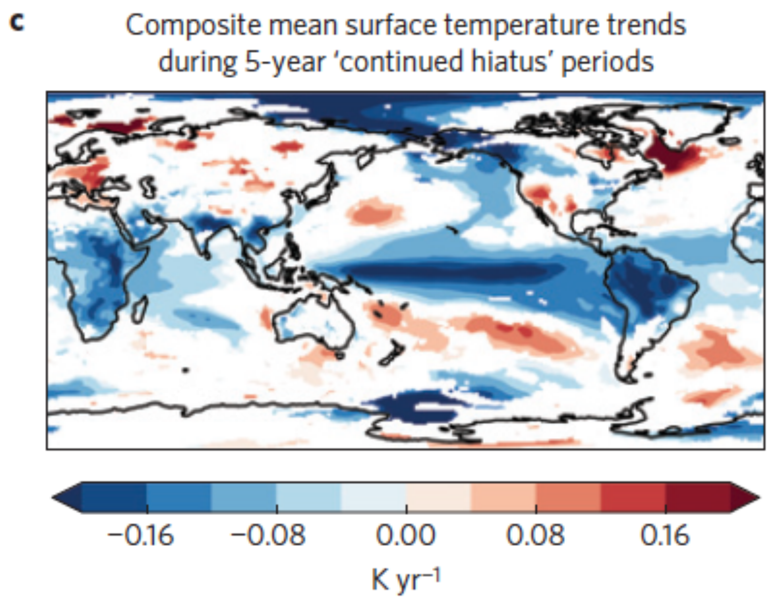
(vi) Representation of internal variability varies considerably among CMIP5 models



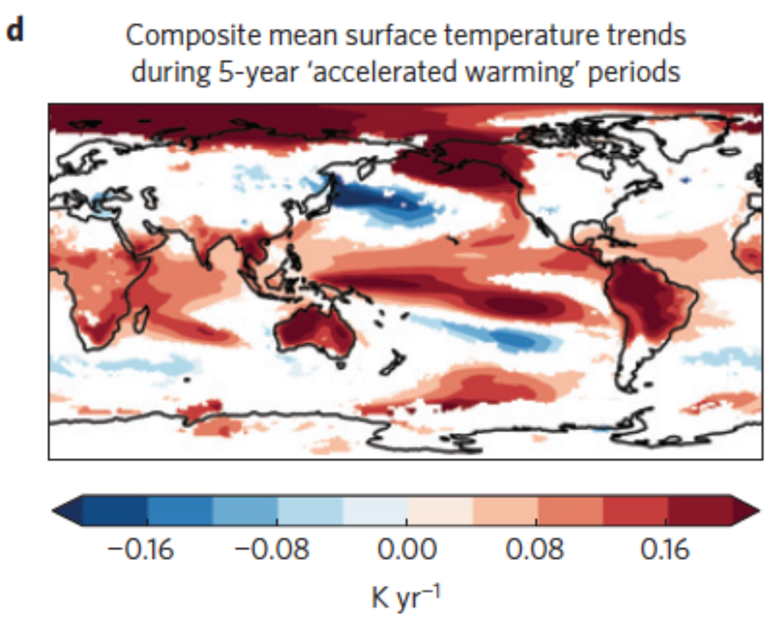
CMIP5 models show different "flavours" of hiatus event, but the Pacific is a key region

Following a hiatus decade there is a greater change of an accelerated warming

Roberts, C.D., et al. (2015) "Quantifying the likelihood of a continued global warming hiatus", *Nature Climate Change*, doi:10.1038/nclimate2531



CMIP5 hiatus multi-model composite dominated by PDO-like pattern

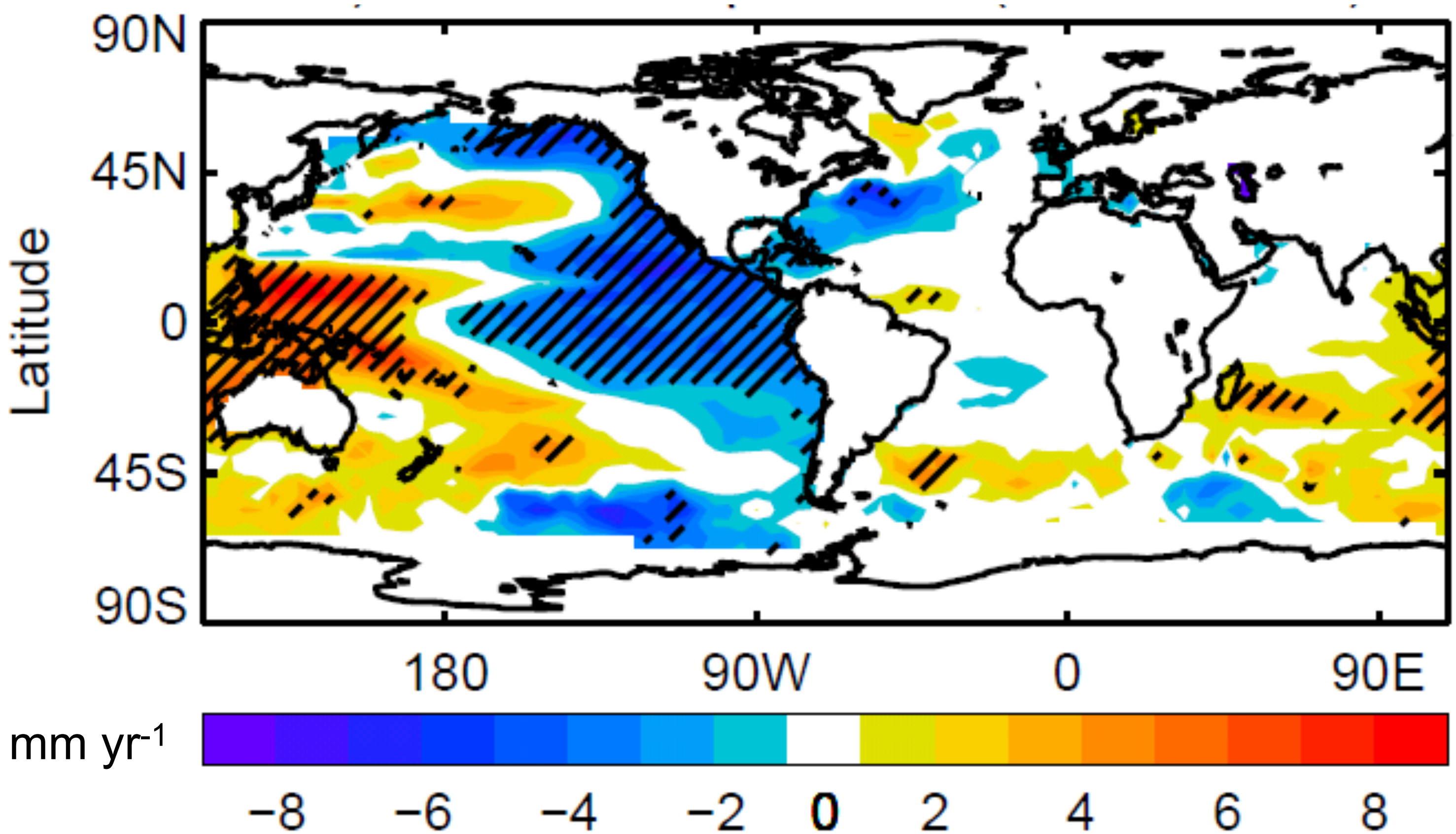


CMIP5 accelerated warming composite also dominated by PDO-like pattern

Roberts, C.D., et al. (2015) "Quantifying the likelihood of a continued global warming hiatus", *Nature Climate Change*, doi:10.1038/nclimate2531

A role for external forcings during the hiatus?

Observed rate of sea level change 1993-2012 (relative to GMSLR)

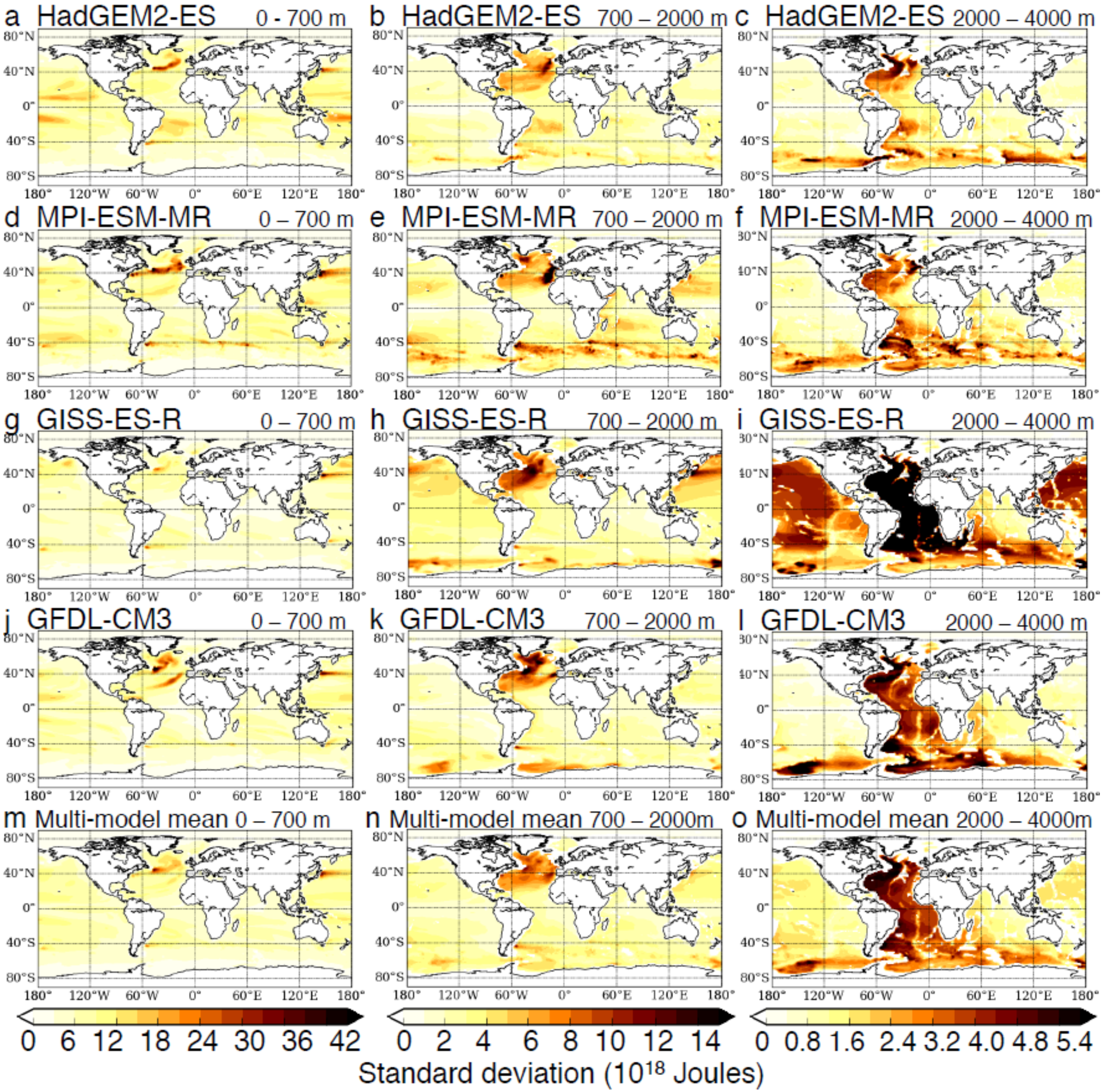


Hatched regions are inconsistent with unforced variability in at least 2/3 of models

Bilbao et al [2015]

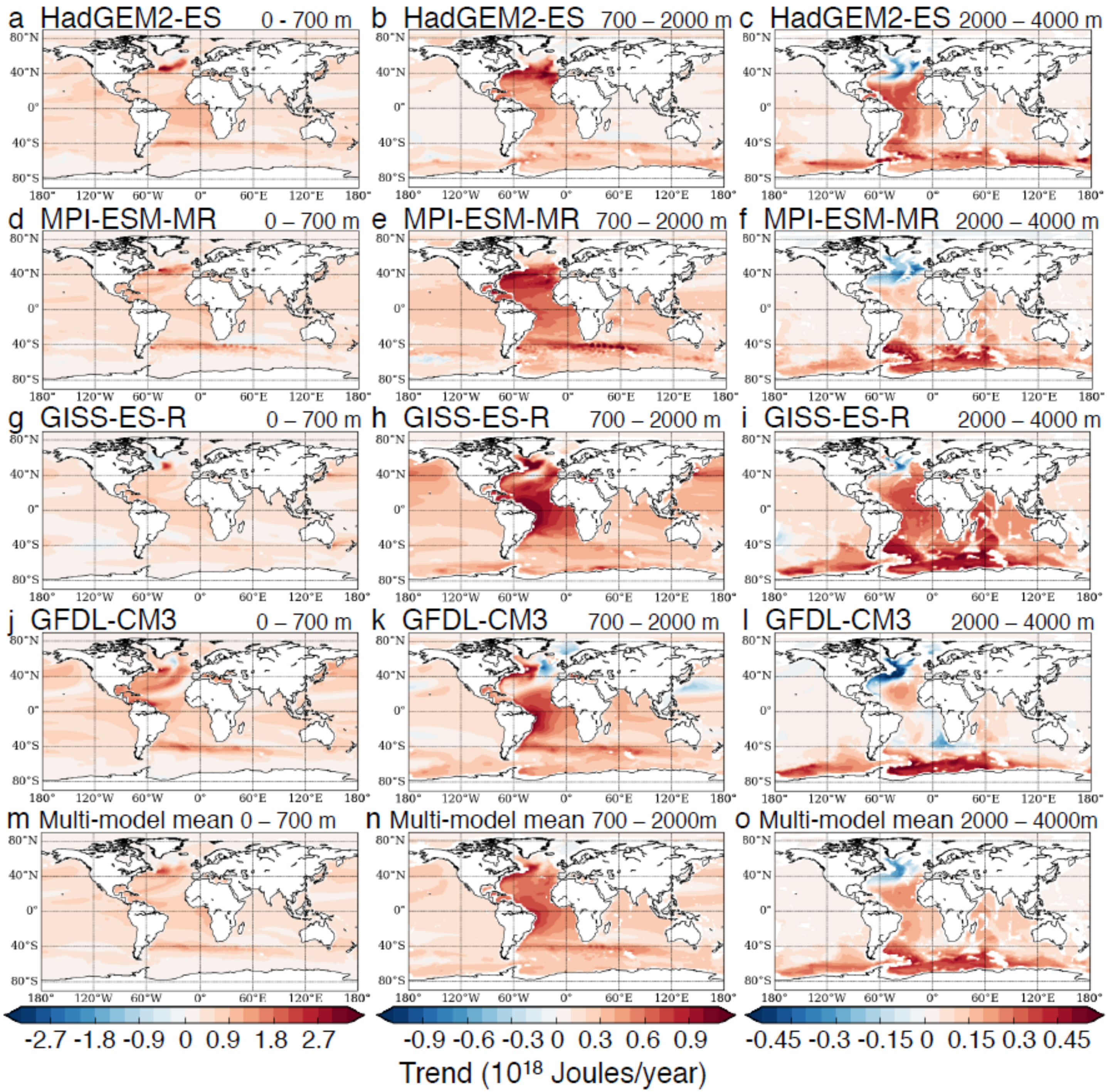
CMIP5 forced simulations “historical” and “RCP8.5”

Internal variability of OHC by layer (piControl)



Standard deviation of the column integrated OHC between 0-700 m, 700-2000 m or 2000-4000 m in the control simulation of the CMIP5 models HadGEM2-ES, MPI-ESM-MR, GISS-E2-R and GFDL-CM3. The multi-model means of the standard deviation in these four models are also shown for each depth range.

Garry et al [submitted]



Trends in OHC by depth layer (RCP8.5)

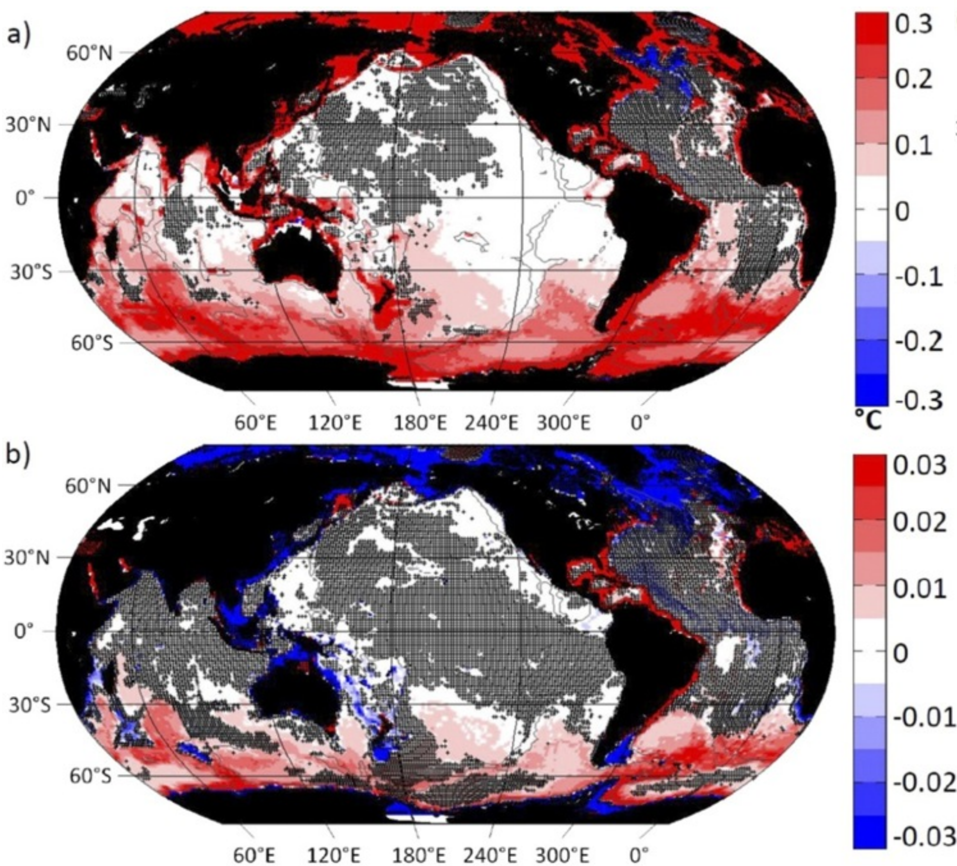
Linear trend from column integrated OHC during the period 2010 – 2100 (RCP 8.5 simulations). Calculated for the depth ranges 0-700 m, 700-2000 m or 2000-4000 m for the CMIP5 models HadGEM2-ES, MPI-ESM-MR, GISS-E2-R and GFDL-CM3. The multi-model means of the trends in these four models are also shown for each depth range.

Garry et al [submitted]

CMIP5 bottom water property changes under RCP8.5

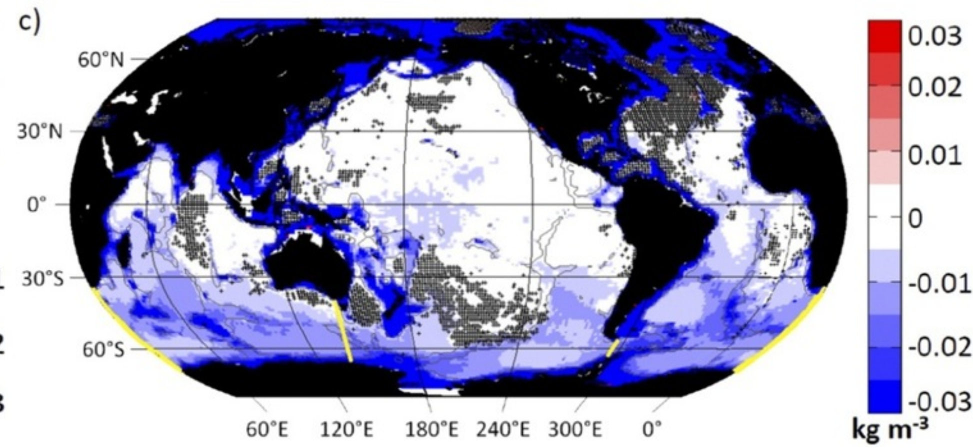
Based on 25 models

Bottom temperature



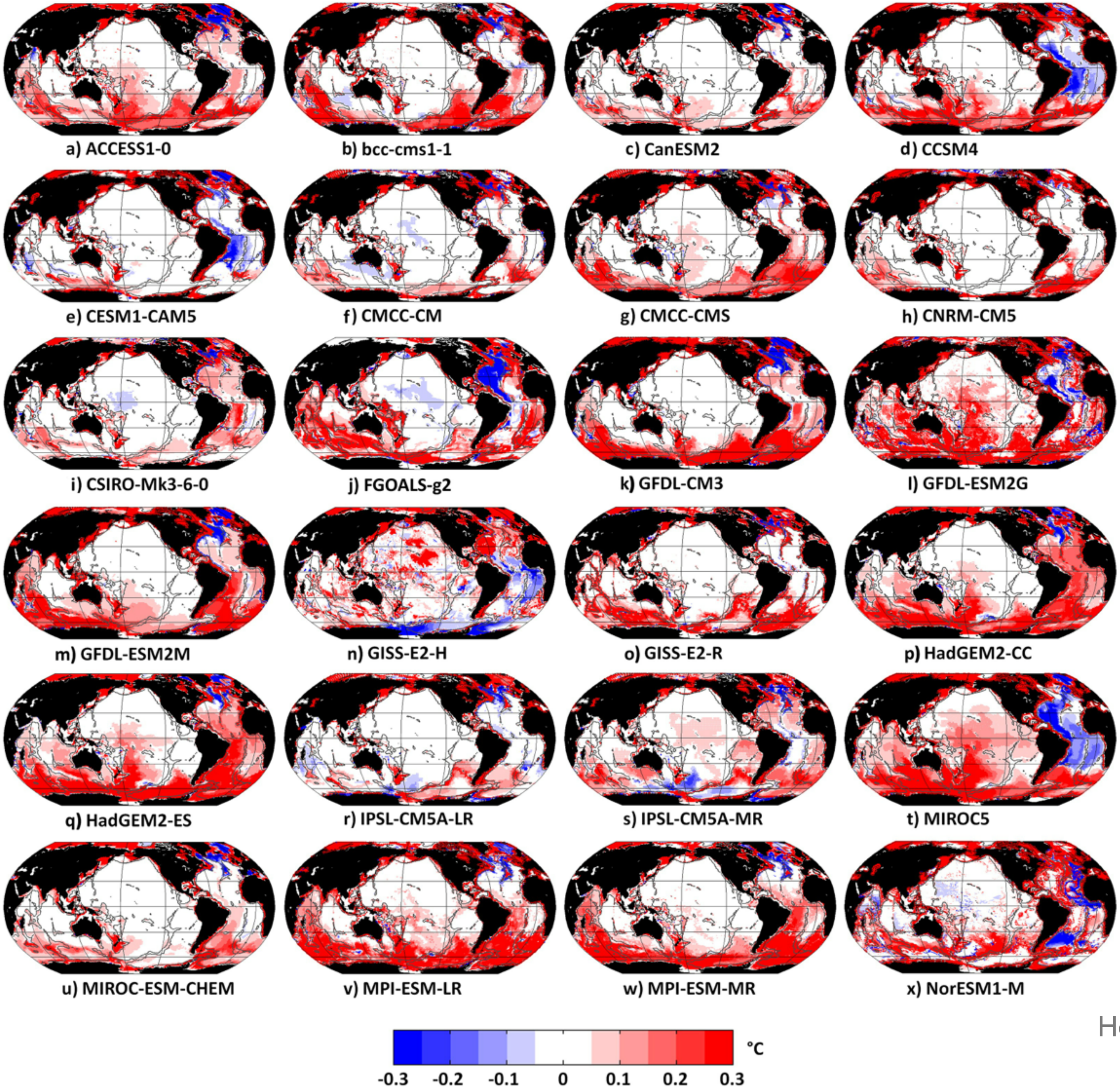
Bottom salinity

Bottom density σ_2



RCP8.5 multimodel mean change (2081–2100 minus 1986–2005) in (a) bottom temperature, (b) bottom salinity, and (c) bottom density σ_2. Control drift has been removed. Black stippling indicates areas where fewer than 16 models agree on the sign of the change. Gray contour indicates the 3000-m isobath. Yellow lines in (c) indicate the study boundaries for the three ocean basins in the Southern Ocean.

Heuzé et al [2015]



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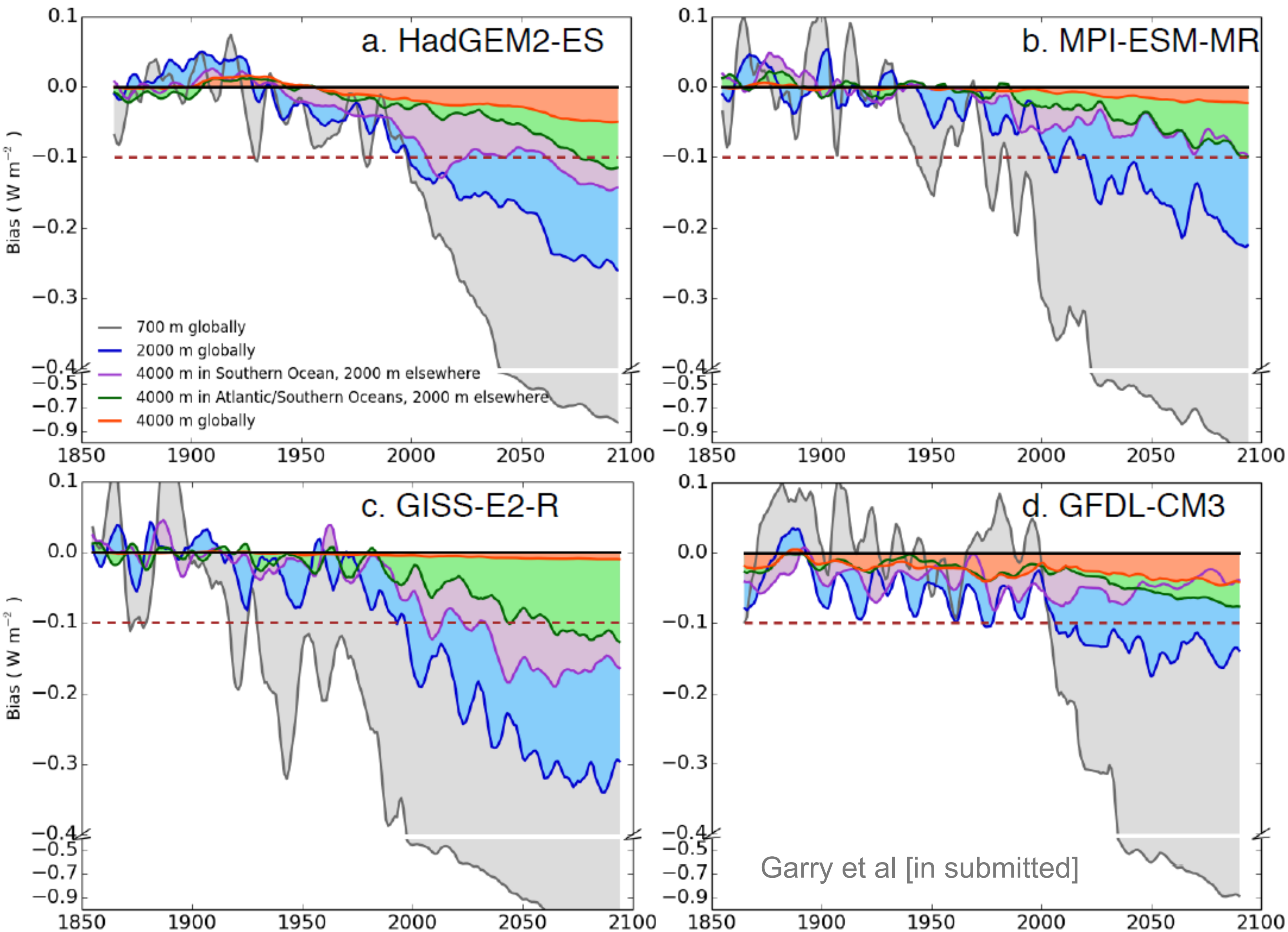


Bias in estimate of netTOA based on d(OHC)/dt for "historical" and "RCP8.5" simulations

Summary of CMIP5 historical and RCP8.5 simulations

(i) The Atlantic and Southern Oceans are key regions for OHC variability and the response to anthropogenic warming

(ii) The climate change signal extends over the full depth of the water column

(iii) Argo-like observations are adequate to monitor Earth's energy imbalance historically, but deeper observations are required over the 21st Century

(iv) The patterns and magnitudes of OHC variability and change vary by CMIP5 model

Some open questions..

1. How might realistic sampling of the ocean affect the results presented here?

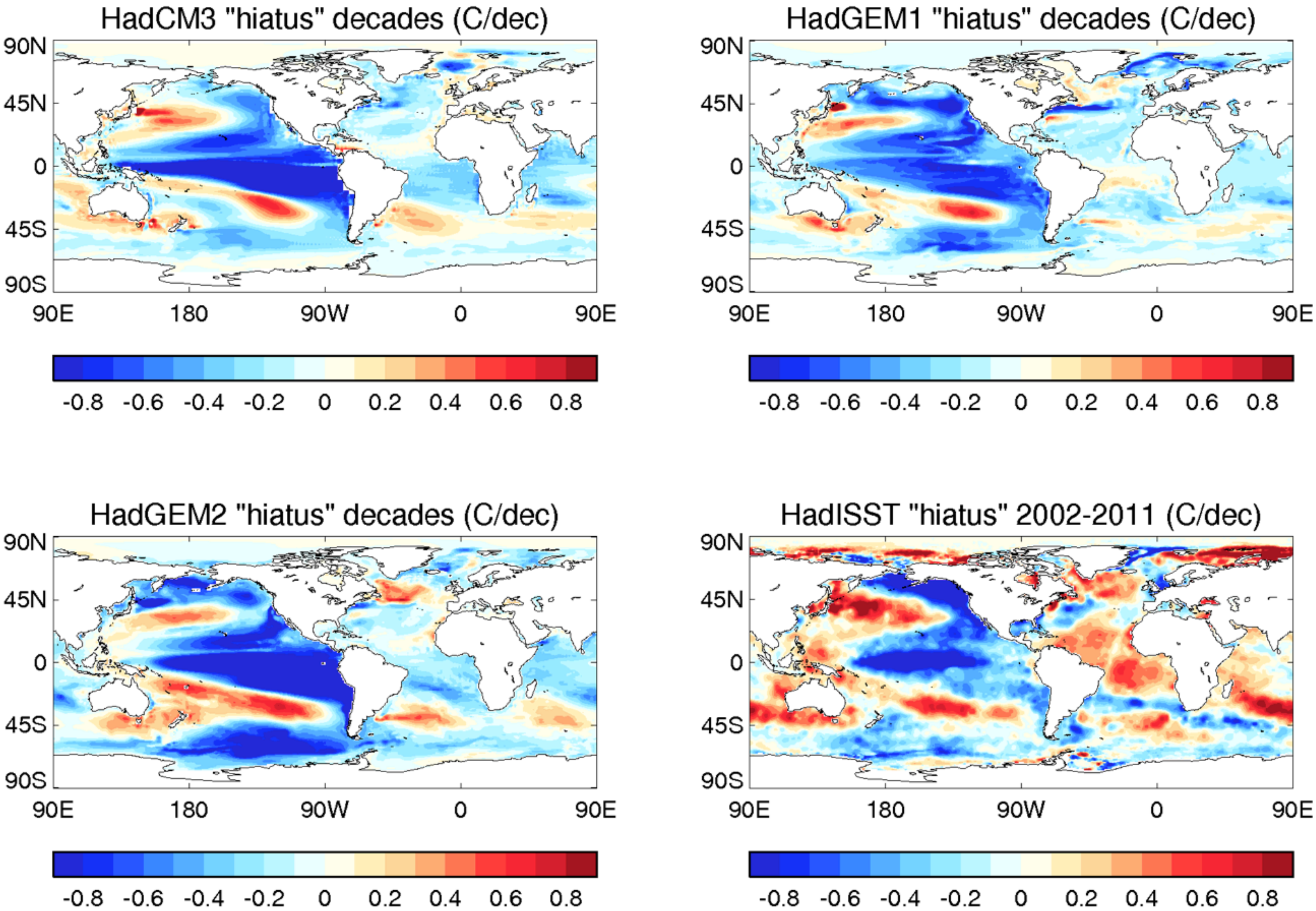
2. What is the relative importance of the deep ocean, ice covered regions and marginal seas for estimating netTOA from d(OHC)/dt?

3. What important processes for OHC variability and change are poorly represented or missing from CMIP5 models? (e.g. AABW formation)

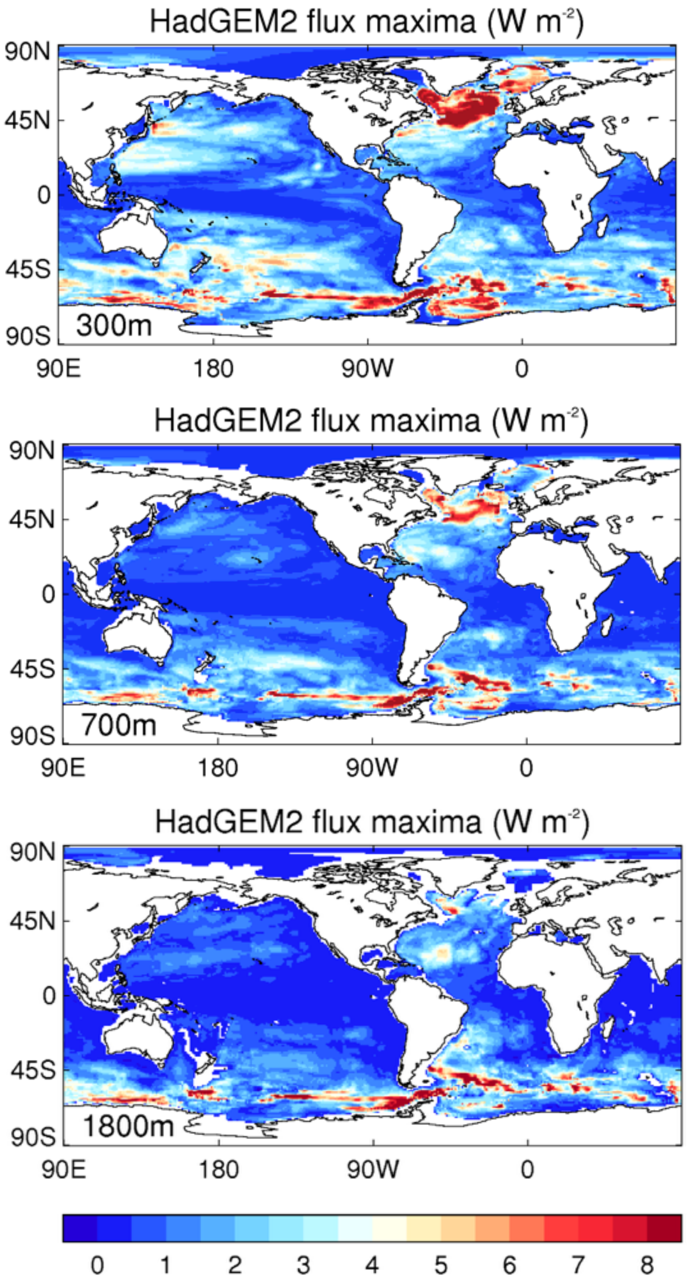
4. How might the balance of processes change in the presence of eddies? (how would these results change for high(er)-resolution models?)

5. How can we determine which models are most like reality? => need for process-based constraints on climate model projections (?)

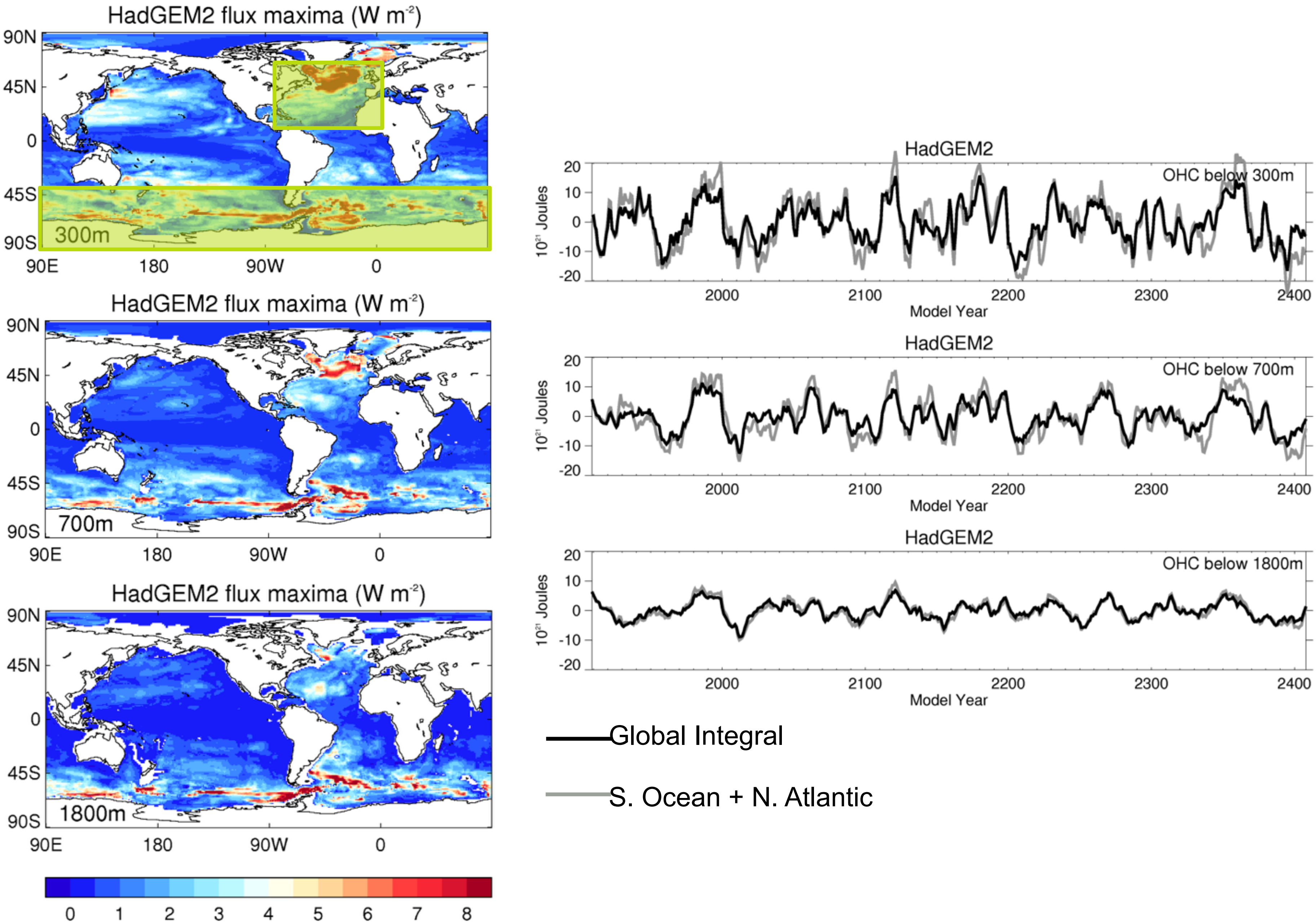
Questions and discussion..

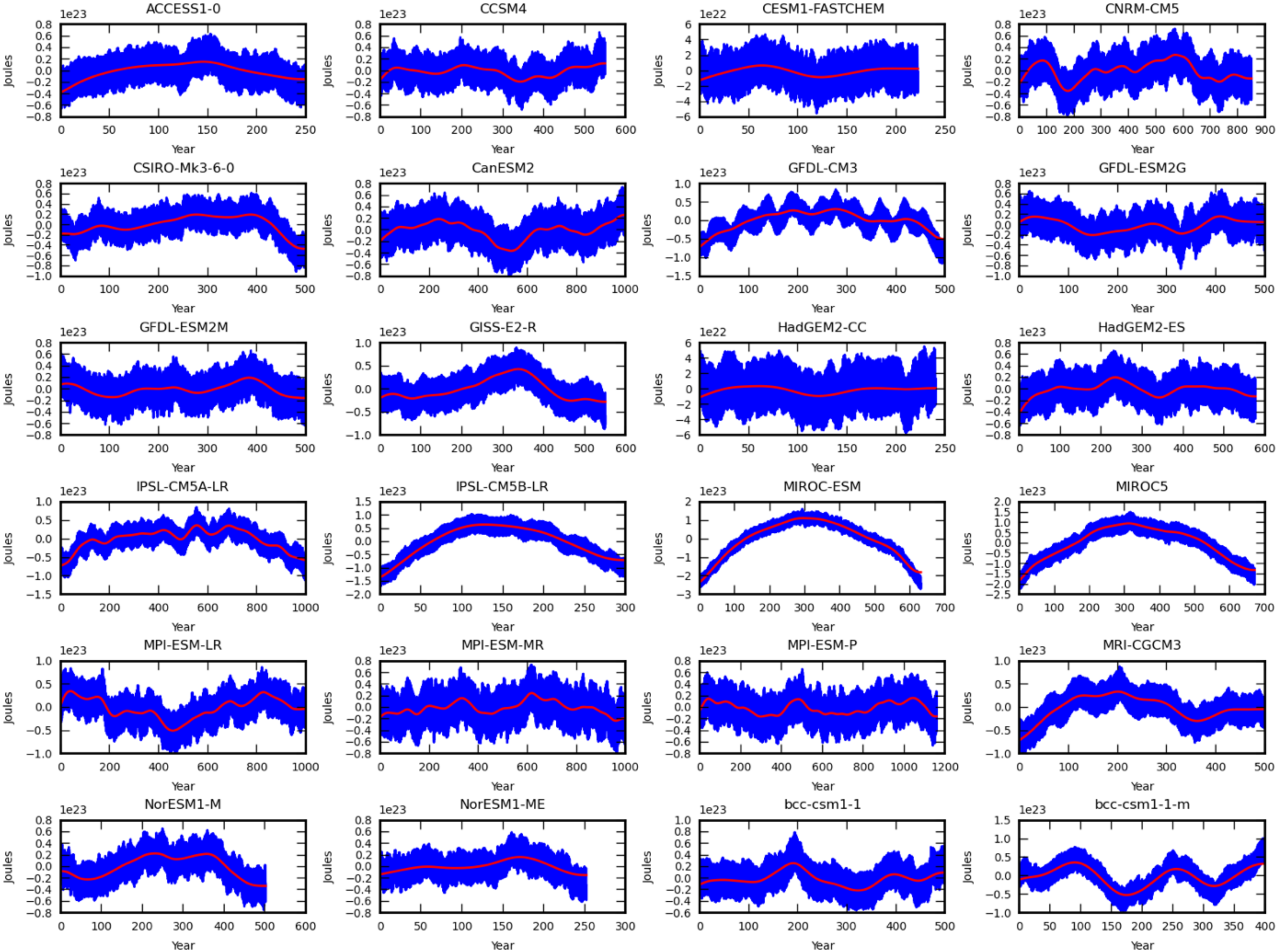


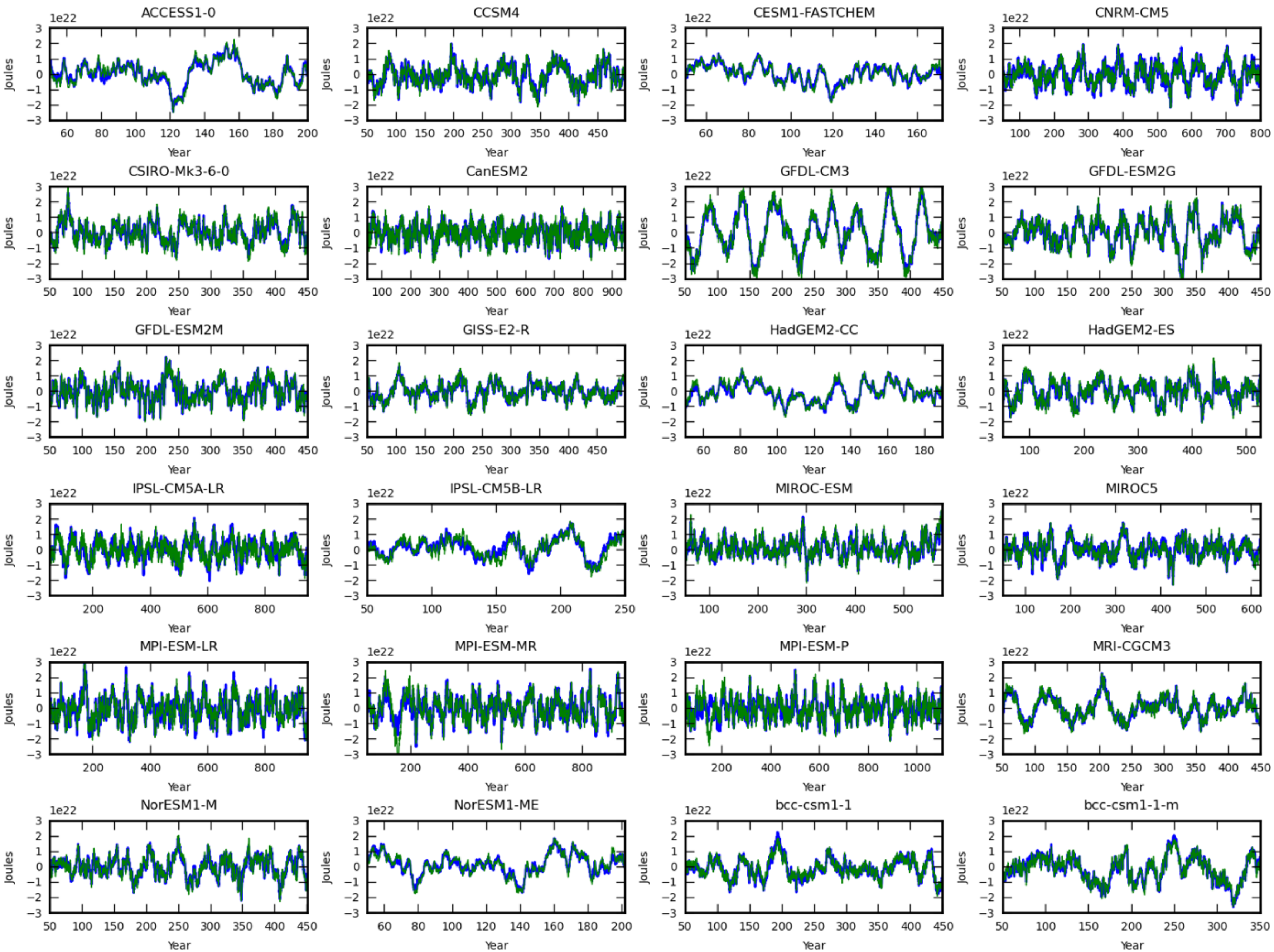
HadCM3 "hiatus" decades (C/dec)
HadGEM1 "hiatus" decades (C/dec)
HadGEM2 "hiatus" decades (C/dec)
HadISST "hiatus" 2002-2011 (C/dec)
90N
45N
0
45S
90S
90E
180
90W
0
90E
-0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8



HadGEM2 flux maxima (W m-2)
90N
45N
0
45S
90S
300m
90E
180
90W
0
HadGEM2 flux maxima (W m-2)
90N
45N
0
45S
90S
700m
90E
180
90W
0
HadGEM2 flux maxima (W m-2)
90N
45N
0
45S
90S
1800m
90E
180
90W
0
0
1
2
3
4
5
6
7
8


HadGEM2 flux maxima (W m⁻²)
300m
HadGEM2 flux maxima (W m⁻²)
700m
HadGEM2 flux maxima (W m⁻²)
1800m
90N
45N
0
45S
90S
90E
180
90W
0
1
2
3
4
5
6
7
8
HadGEM2
OHC below 300m
HadGEM2
OHC below 700m
HadGEM2
OHC below 1800m
10²¹ Joules
Model Year
2000
2100
2200
2300
2400
Global Integral
S. Ocean + N. Atlantic


ACCESS1-0
1e23
CCSM4
1e23
CESM1-FASTCHEM
1e22
CNRM-CM5
1e23
CSIRO-Mk3-6-0
1e23
CanESM2
1e23
GFDL-CM3
1e23
GFDL-ESM2G
1e23
GFDL-ESM2M
1e23
GISS-E2-R
1e23
HadGEM2-CC
1e22
HadGEM2-ES
1e23
IPSL-CM5A-LR
1e23
IPSL-CM5B-LR
1e23
MIROC-ESM
1e23
MIROC5
1e23
MPI-ESM-LR
1e23
MPI-ESM-MR
1e23
MPI-ESM-P
1e23
MRI-CGCM3
1e23
NorESM1-M
1e23
NorESM1-ME
1e23
bcc-csm1-1
1e23
bcc-csm1-1-m
1e23
Joules
Year


ACCESS1-0
CCSM4
CESM1-FASTCHEM
CNRM-CM5
CSIRO-Mk3-6-0
CanESM2
GFDL-CM3
GFDL-ESM2G
GFDL-ESM2M
GISS-E2-R
HadGEM2-CC
HadGEM2-ES
IPSL-CM5A-LR
IPSL-CM5B-LR
MIROC-ESM
MIROC5
MPI-ESM-LR
MPI-ESM-MR
MPI-ESM-P
MRI-CGCM3
NorESM1-M
NorESM1-ME
bcc-csm1-1
bcc-csm1-1-m
1e22
Joules
Year