

# Southern Ocean response to climate change in the CMIP5 models: Linking biology to physics

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7<sup>th</sup> August 2013, Carbon-Climate Connections in the Earth System, NCAR

## AR 5 Models studied: (scenario RCP8.5)

**CanESM2:** (Canadian Earth System Model)

**HadGEM2-ES:** Hadley coupled Earth System Model, with dynamic terrestrial vegetation and carbon, ocean biology and carbonate chemistry, tropospheric chemistry

**HadGEM2-CC:** same as above but no tropospheric chemistry

**IPSL-CM5A-LR & IPSL-CM5A-MR** (Institut Pierre Simon Laplace): atmosphere with low and medium resolution. LMDZ atmospheric model; NEMO ocean model

**IPSL-CM5B-LR:** same as above but new set of physical parametrizations

**MIROC-ESM & MIROC-ESM-CHEM:** Japanese Earth System Model with an NPZD ocean ecosystem model, and dynamic vegetation on land

**MPI-ESM-LR & MPI-ESM-MR:** The Max Planck Earth System Model: marine biogeochemistry and land biosphere, fully coupled carbon cycle

**GFDL-ESM2G:** ocean module depth-based vertical coordinate MOM

**GFDL-ESM2M:** sigma coordinate mixed layer and density-based vertical coordinate in the interior GOLD

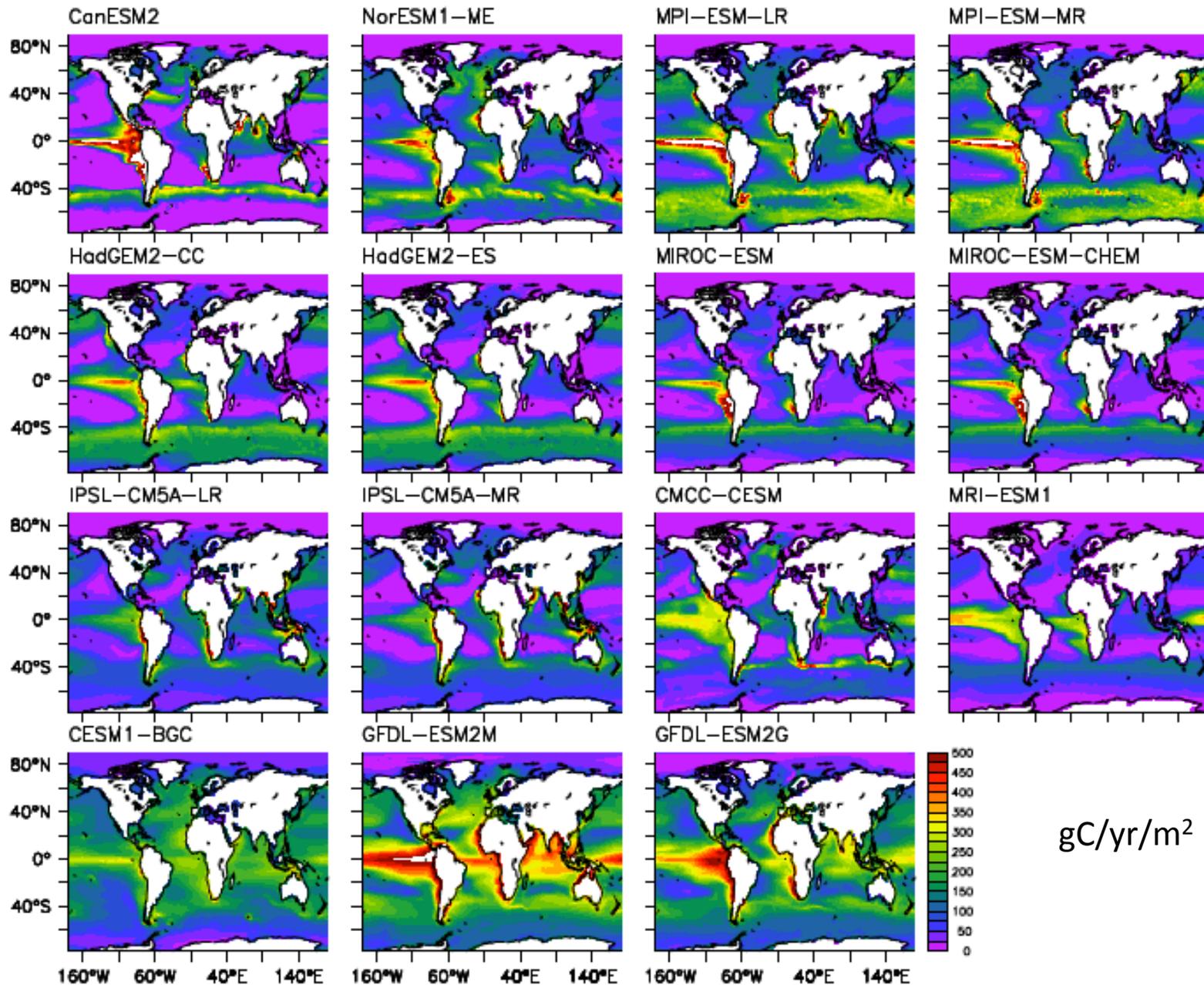
**CESM1-BGC:** NCAR carbon cycle, POP ecosystem model

**MRI-ESM1:** (Meteorological Research Institute)

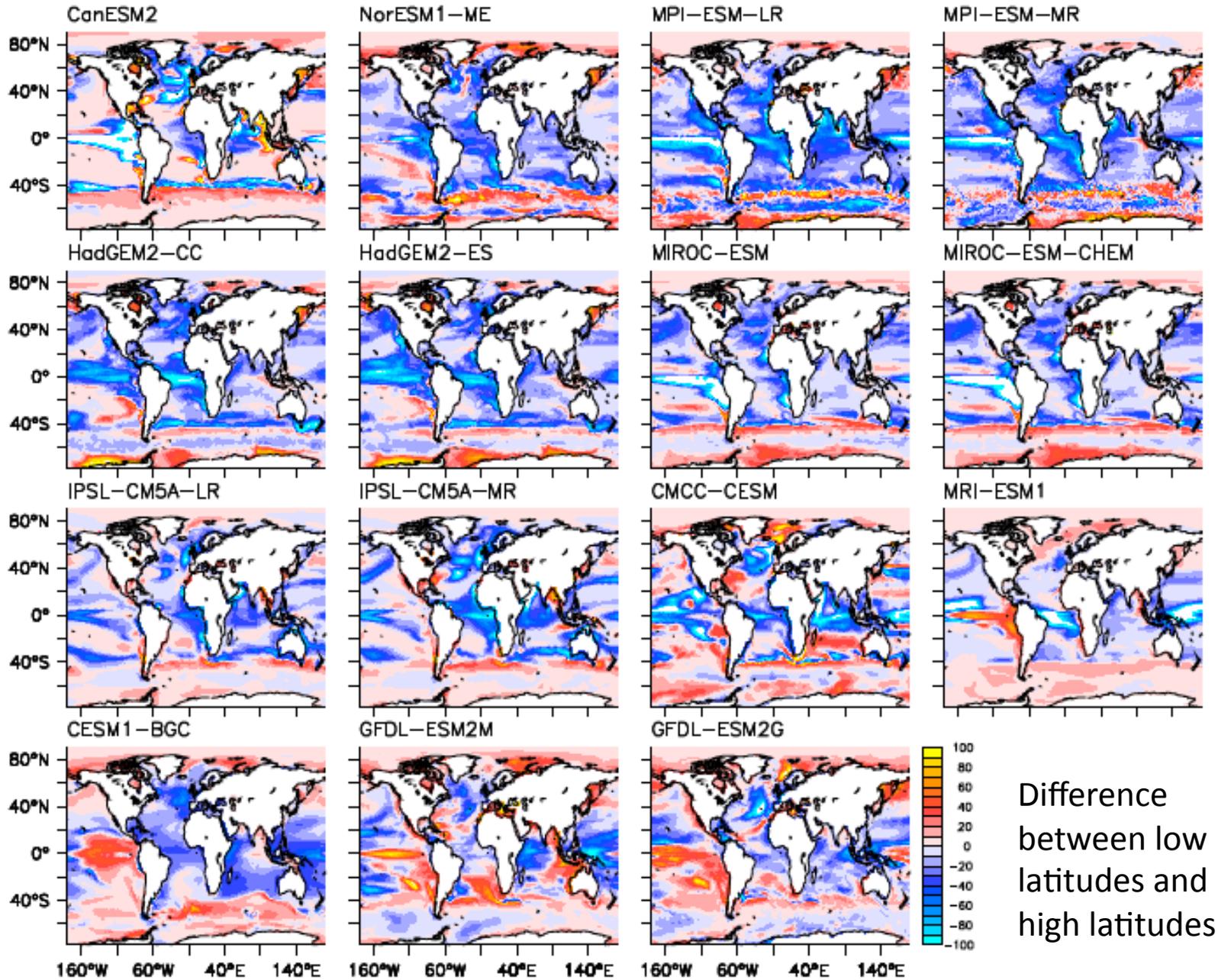
**NorESM1-ME:** (Norwegian Climate Centre)

**CMCC-CESM :** Pelagos Marine biogeochemistry model (Centro Europeo per I Cambiamenti Climatici)

# CMIP5 simulated Primary production (integrated to 100m) in the present (1980-1999)



# Change over 100 years in Primary production (2080-2099) - (1980-1999)



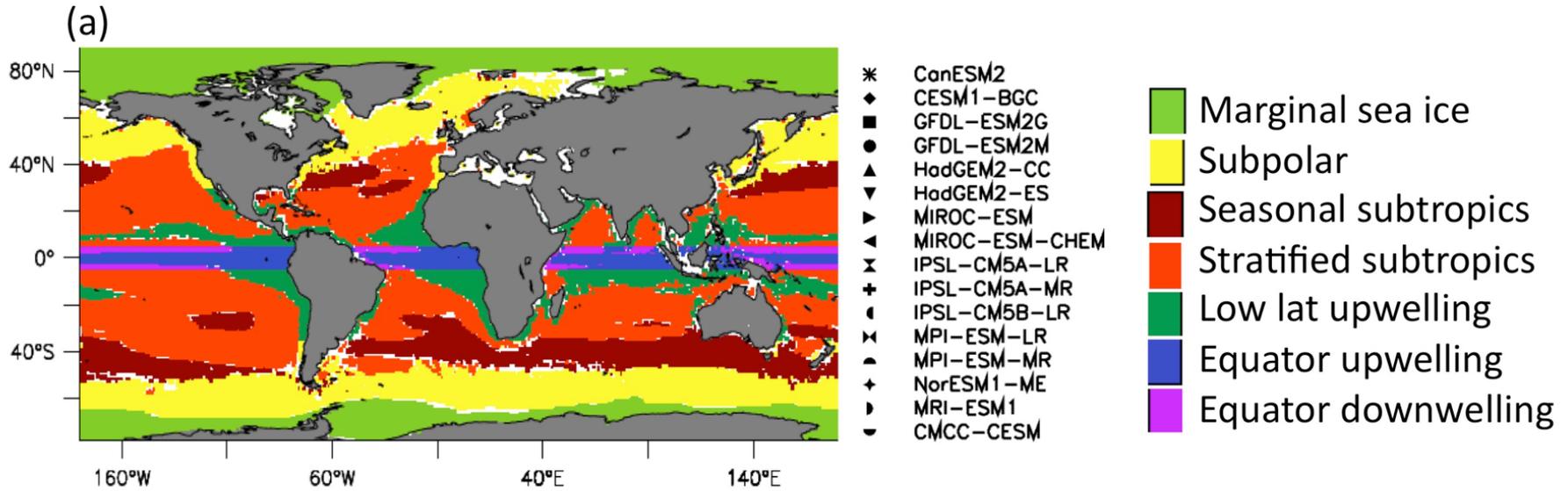
## GLOBAL CHANGE

<i>Model</i>	$\Delta SST(^{\circ}C)$	<i>PP(PgC/yr)</i>	$\Delta PP(PgC/yr)$	<i>Exp(PgC/yr)</i>	$\Delta Exp(PgC/yr)$	$\Delta(Dia$
<i>CanESM2</i>	3.174	33.007	-4.697	0.904	0.009	
<i>CESM1-BGC</i>	2.495	57.98	-2.028	1.518	-0.246	-0
<i>GFDL-ESM2G</i>	2.007	65.353	-0.616	1.742	-0.12	-0
<i>GFDL-ESM2M</i>	1.927	82.149	-0.535	2.007	-0.13	-0
<i>HadGEM2-CC</i>	3.103	36.558	-5.162	2.774	-0.367	-0
<i>HadGEM2-ES</i>	3.297	36.142	-5.213	2.743	-0.384	-0
<i>MIROC-ESM</i>	3.383	28.74	-4.432	-	-	
<i>MIROC-ESM-CHEM</i>	3.576	28.784	-4.849	-	-	
<i>IPSL-CM5A-LR</i>	3.456	37.141	-3.461	1.288	-0.203	-0
<i>IPSL-CM5A-MR</i>	3.408	35.823	-4.377	1.323	-0.204	-0
<i>MPI-ESM-LR</i>	2.51	60.278	-8.807	4.133	-0.473	
<i>MPI-ESM-MR</i>	2.463	54.461	-7.109	3.962	-0.408	
<i>NorESM1-ME</i>	2.24	41.97	-3.412	2.516	-0.122	
<i>MRI-ESM1</i>	2.033	29.377	-2.749	1.177	-0.084	
<i>CMCC-CESM</i>	2.545	37.257	-3.998	-	-	0
Observations		52				

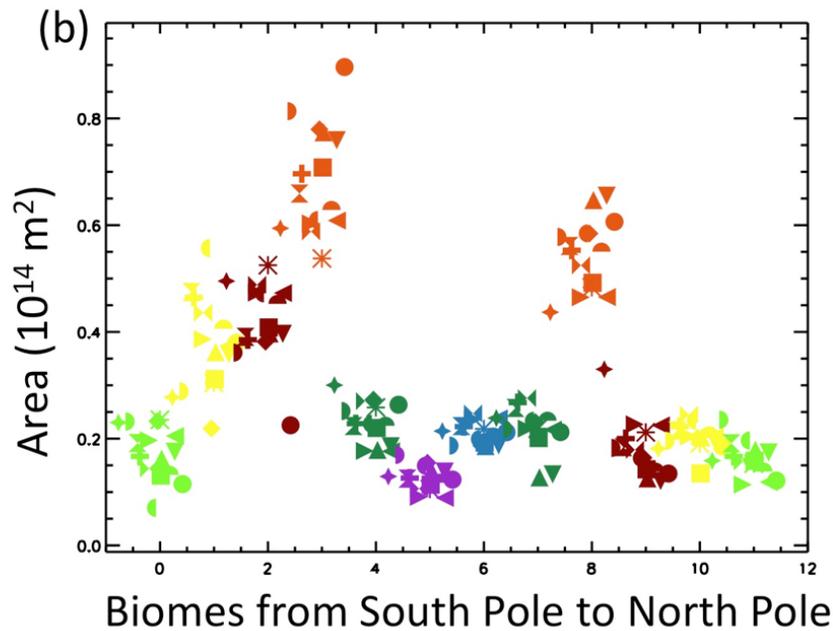
## % of global production in each zone

<i>Models / Zones</i>	<i>10S-10N (19%)</i>			<i>15N to 40N (17%)</i>			<i>15S to 40S (22%)</i>			<i>45N to 90N (9%)</i>			<i>45S to 90S (17%)</i>		
	<i>Present</i>	<i>Future</i>	<i>Δ</i>	<i>Present</i>	<i>Future</i>	<i>Δ</i>	<i>Present</i>	<i>Future</i>	<i>Δ</i>	<i>Present</i>	<i>Future</i>	<i>Δ</i>	<i>Present</i>	<i>Future</i>	<i>Δ</i>
	<i>(% of global)</i>			<i>(% of global)</i>			<i>(% of global)</i>			<i>(% of global)</i>			<i>(% of global)</i>		
<i>CanESM2</i>	32.1	25.8	69.8	13.3	15.6	-0.3	13.6	12.5	20.0	8.4	9.1	4.7	9.2	12.5	-10.9
<i>CESM1-BGC</i>	25.8	25.6	31.2	17.5	16.6	41.5	21.6	20.9	39.4	7.5	7.7	0.5	9.7	11.0	-26.5
<i>GFDL-ESM2G</i>	30.0	29.9	37.0	15.0	14.2	105.3	20.3	21.1	-67.2	5.0	5.5	-49.4	11.2	11.1	19.3
<i>GFDL-ESM2M</i>	31.0	30.5	116.6	15.1	14.8	55.0	20.5	21.0	-55.1	5.1	5.3	-19.5	10.1	10.1	15.2
<i>HadGEM2-CC</i>	24.7	21.6	43.1	6.8	5.4	15.5	15.9	15.2	19.9	7.8	8.3	4.4	26.9	32.3	-5.7
<i>HadGEM2-ES</i>	25.5	21.8	47.5	6.8	5.2	16.3	16.0	15.5	18.8	7.8	8.4	4.7	26.1	32.1	-9.7
<i>MIROC-ESM</i>	18.9	14.4	43.9	12.0	10.5	20.5	26.0	25.9	26.6	6.1	5.9	7.2	17.8	22.7	-9.2
<i>MIROC-ESM-CHEM</i>	19.4	14.4	44.4	12.0	10.4	20.0	26.0	25.2	30.0	6.0	6.1	5.4	17.3	23.2	-11.6
<i>IPSL-CM5A-LR</i>	26.1	24.4	42.5	13.8	13.4	17.1	22.9	22.7	25.5	6.7	6.5	8.9	12.7	14.5	-5.2
<i>IPSL-CM5A-MR</i>	26.7	24.6	41.7	13.2	12.2	20.5	21.0	20.9	21.4	8.1	7.5	11.7	13.3	15.9	-5.6
<i>MPI-ESM-LR</i>	26.6	23.0	47.8	11.1	10.1	16.7	17.6	17.3	19.2	5.9	7.0	-0.7	21.6	25.3	-0.4
<i>MPI-ESM-MR</i>	25.5	22.1	47.8	10.3	9.2	17.6	16.6	16.3	18.8	6.4	7.1	1.6	24.0	28.1	-3.2
<i>NorESM1-ME</i>	21.5	19.8	40.5	12.0	11.5	18.5	19.3	18.0	33.1	7.9	8.7	-0.9	19.3	22.8	-19.8
<i>MRI-ESM1</i>	41.3	37.3	80.6	7.9	7.2	14.7	18.0	18.9	8.8	3.9	4.7	-3.5	11.6	14.5	-16.4
<i>CMCC-CESM</i>	33.6	28.0	79.5	11.9	11.7	13.2	20.5	23.4	-2.9	5.2	5.4	3.7	10.9	13.3	-8.6

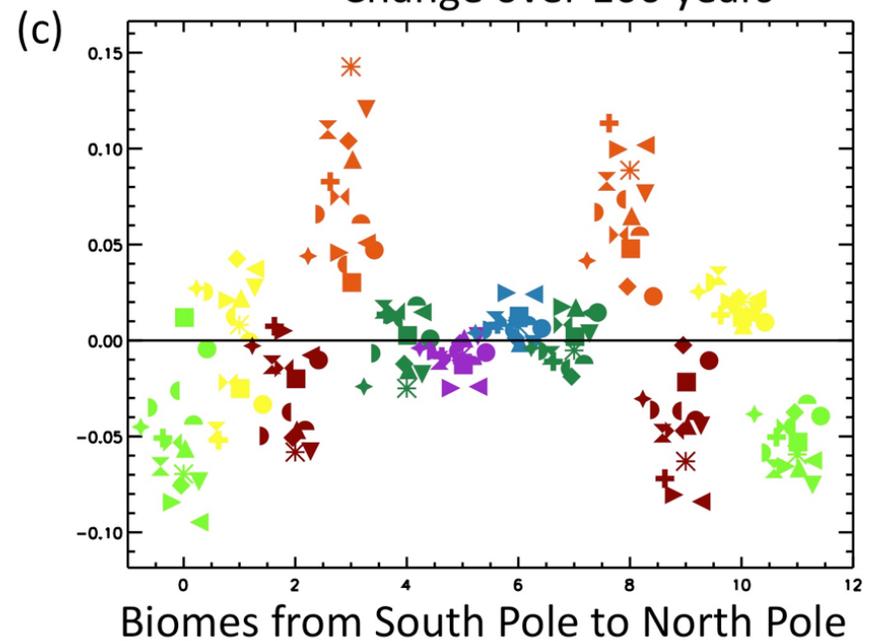
# Biomes



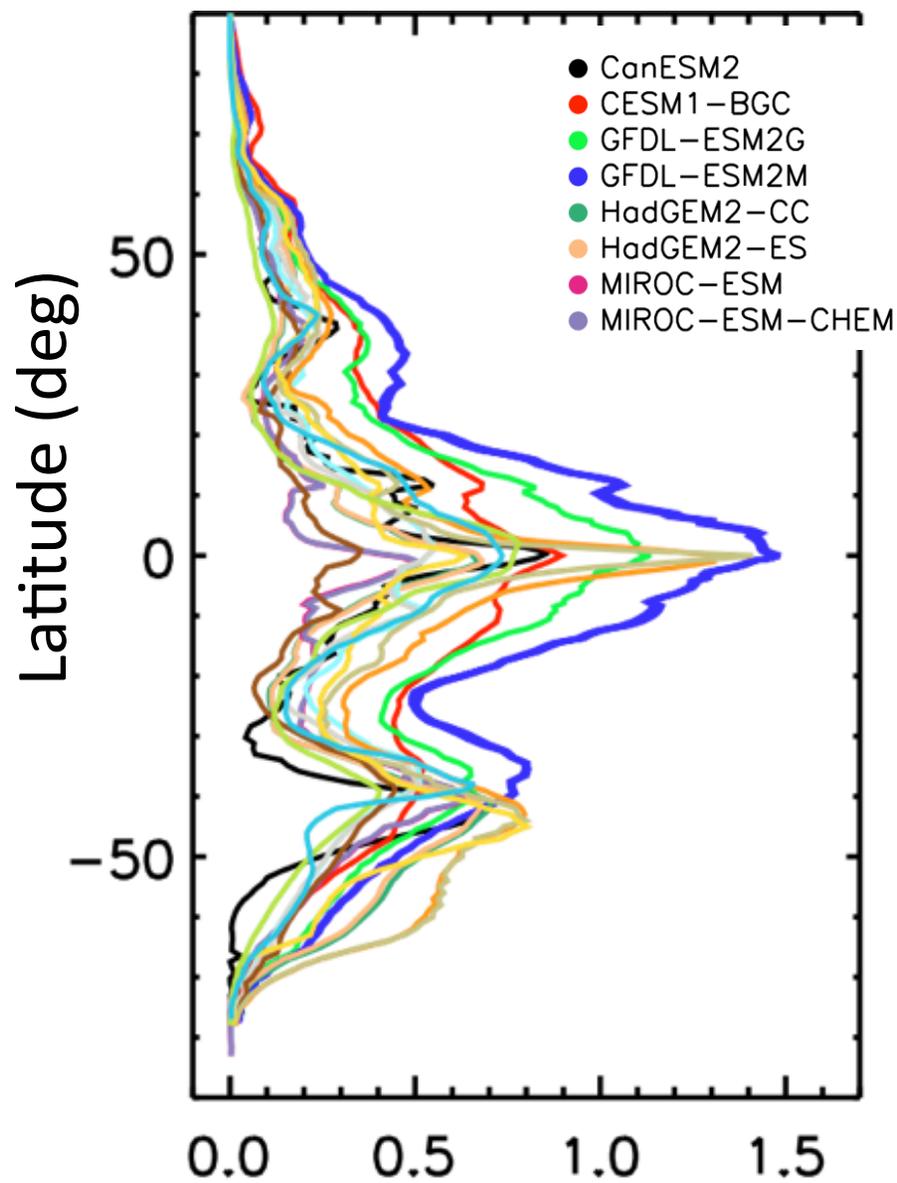
Historical area of biomes



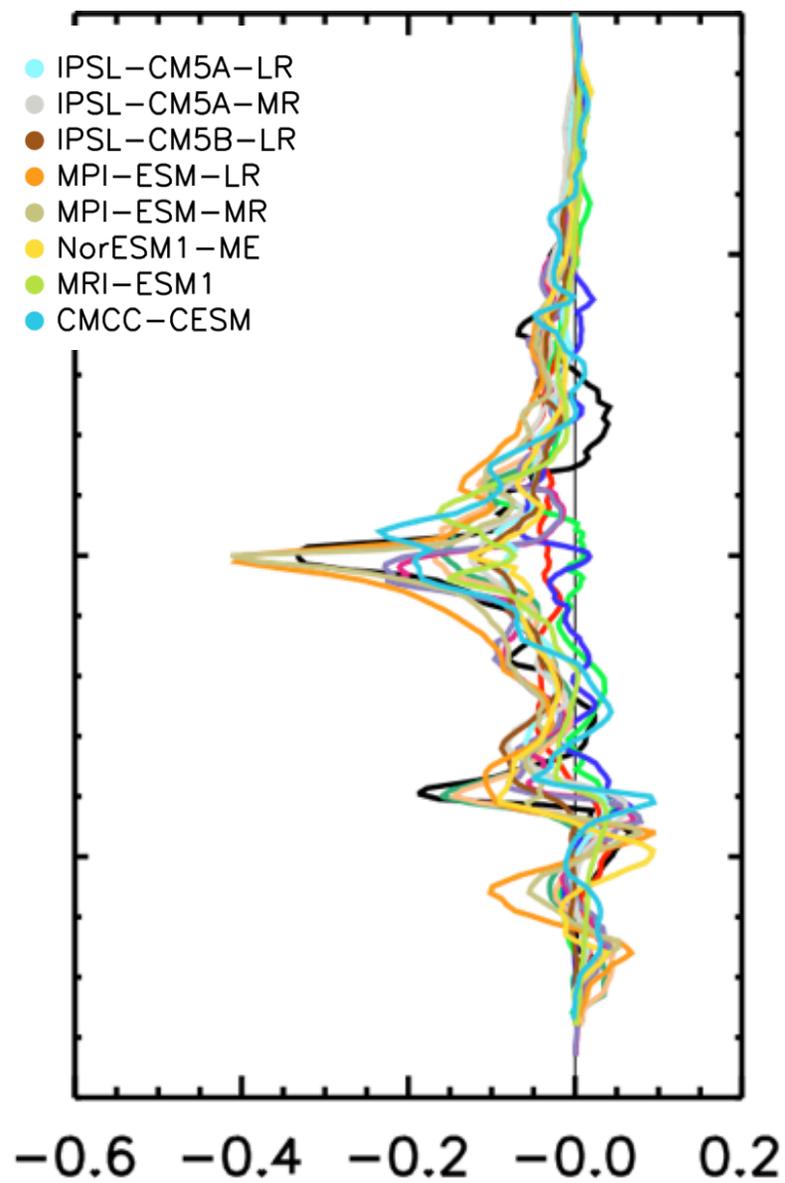
Change over 100 years



PP (PgC/deg/yr)



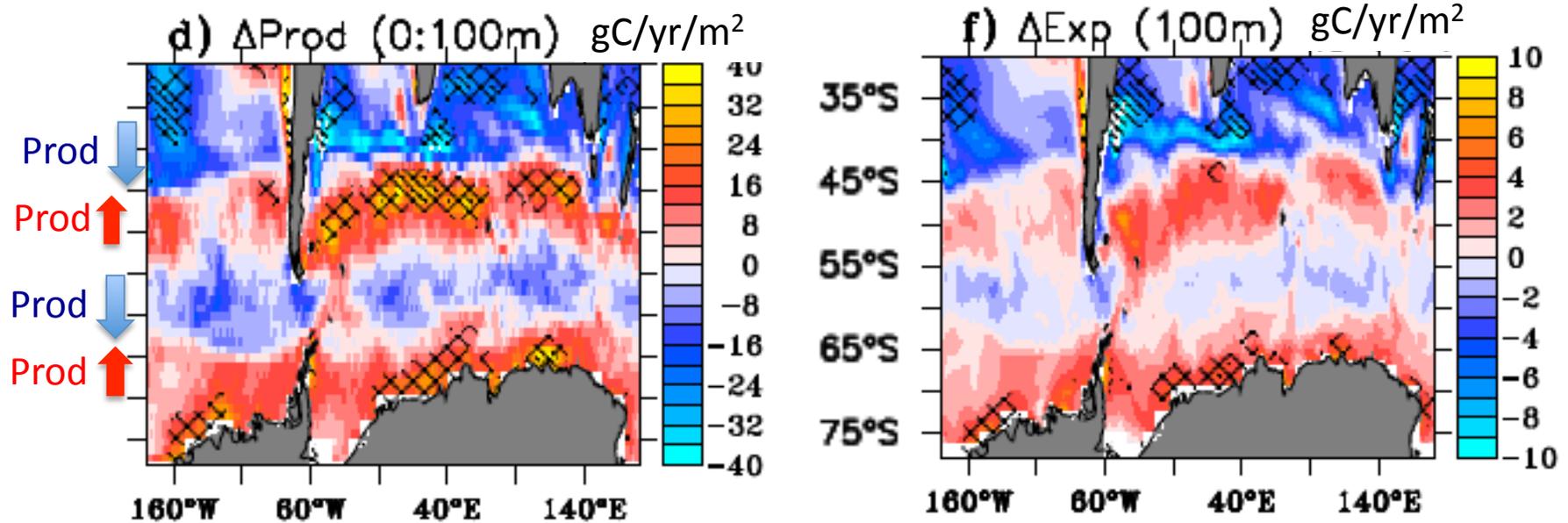
$\Delta$ PP (PgC/deg/yr)



Change from (1980-1999) to (2080-2099).

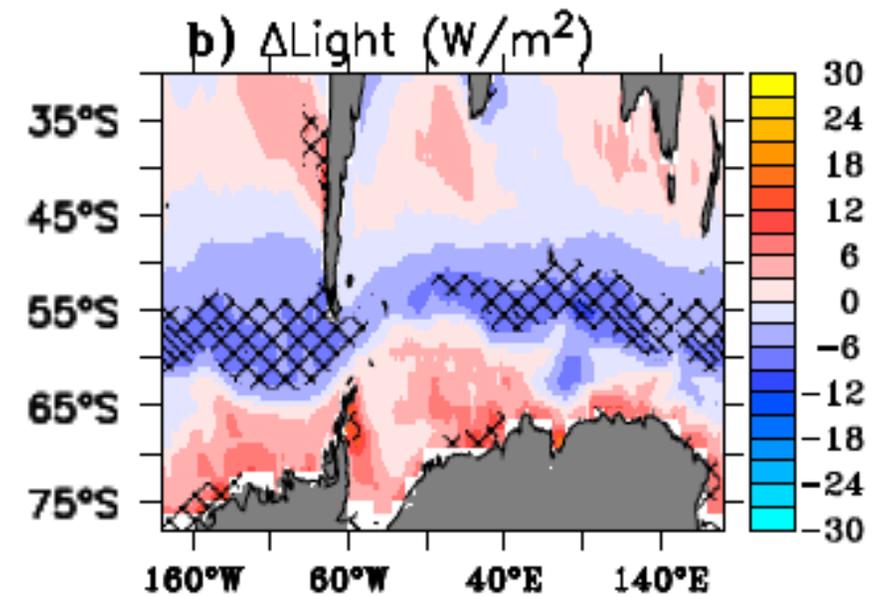
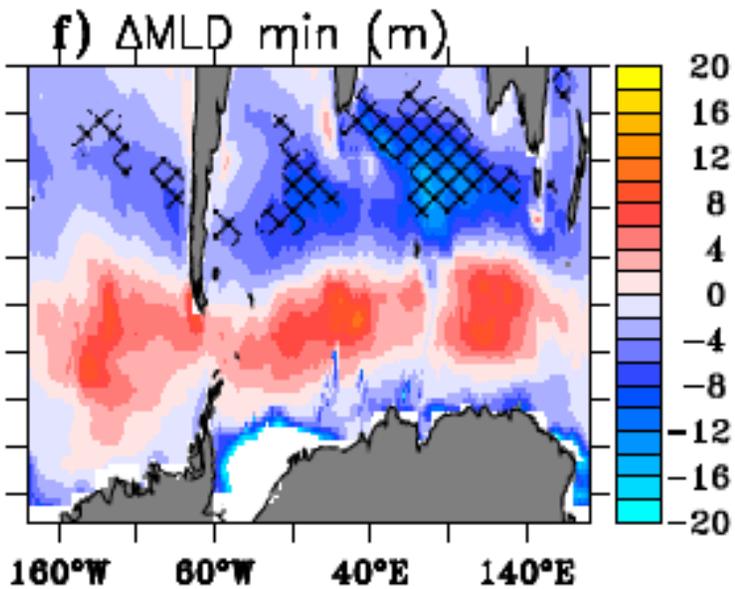
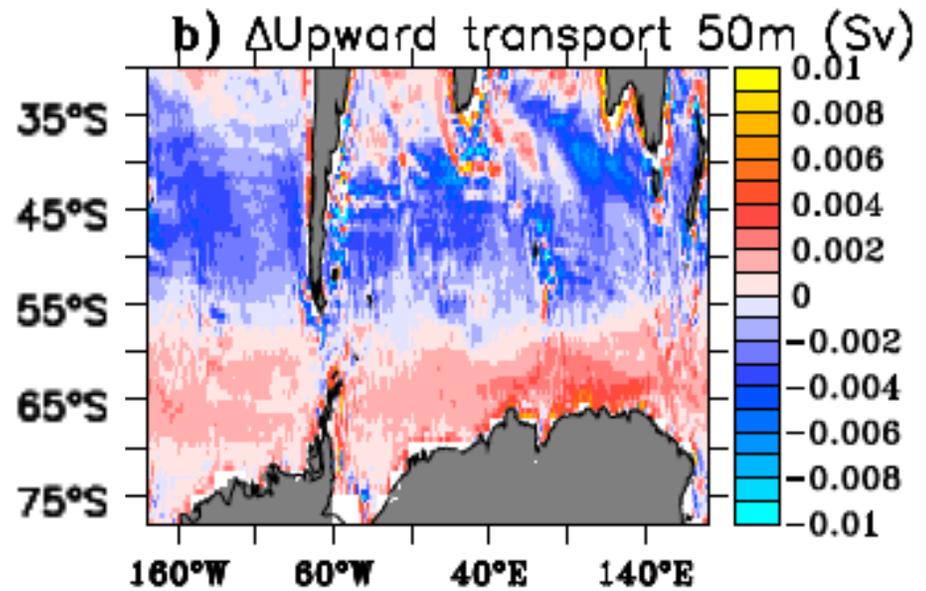
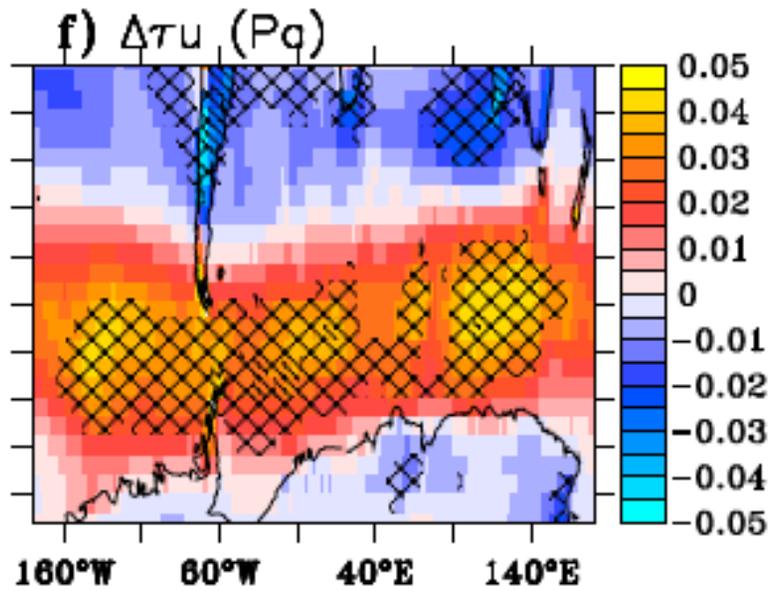
Mean over all the models.

Masked areas show high consistency among models.

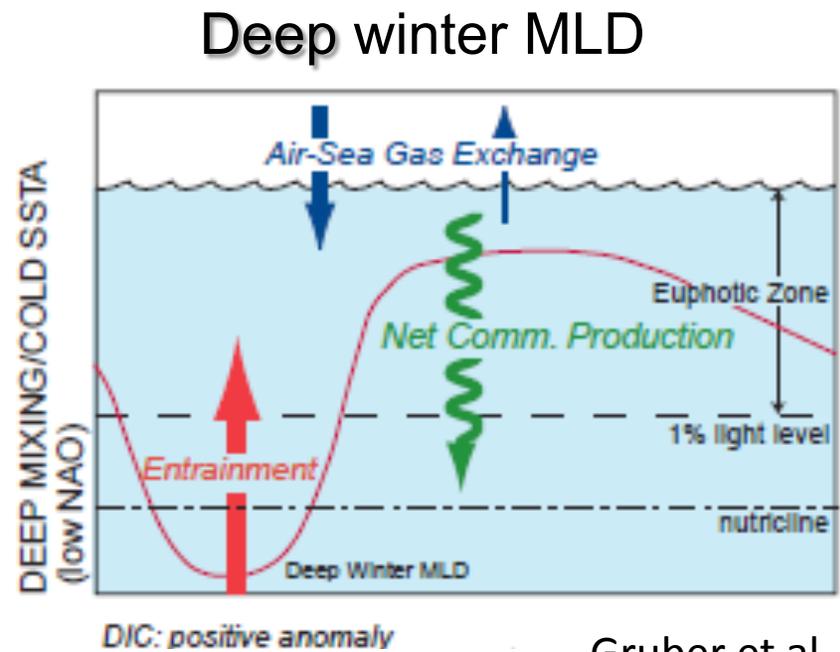
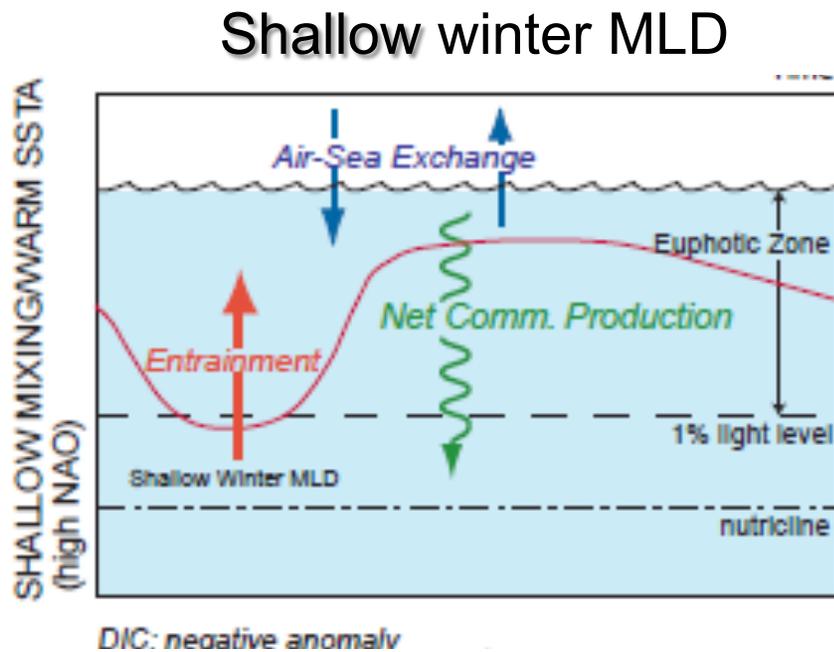


What's happening with the physics?

$\Delta \rightarrow$  (1980-1999) to (2080-2099).



## Physical Mechanisms :



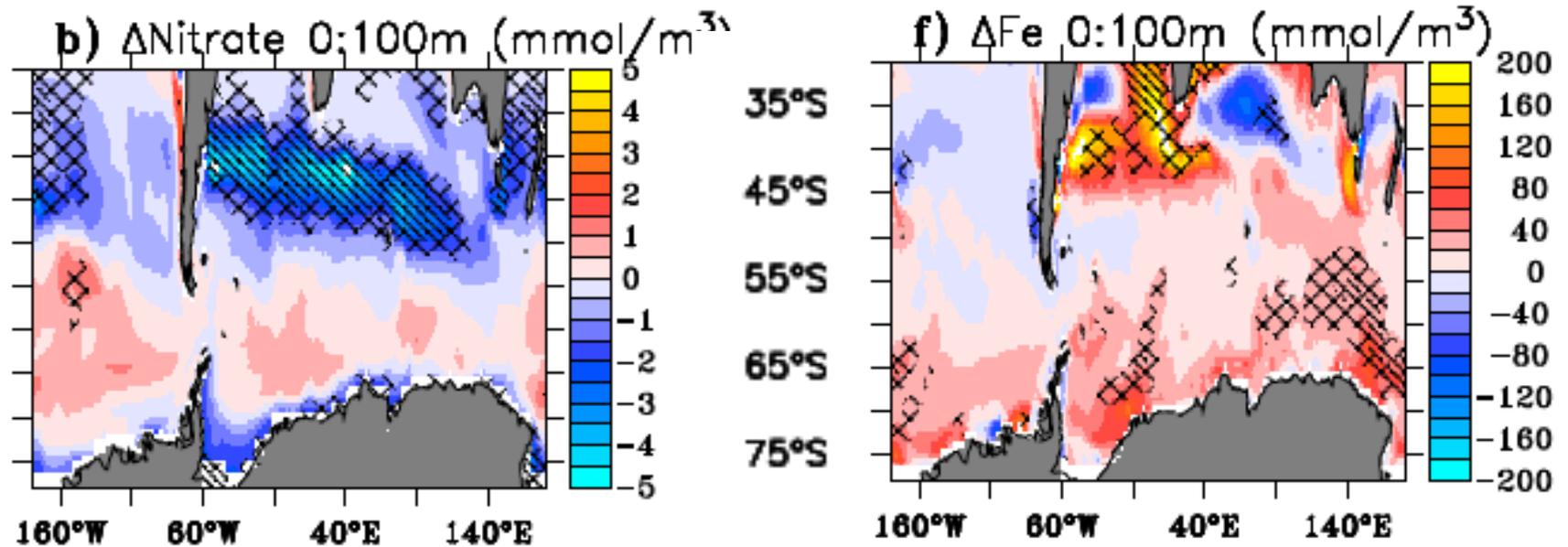
Gruber et al. 2002

**M1: Deeper max MLD → higher nutrient pool → more production in the spring/summer (e.g., Gruber et al. 2002)**

**M2: Deeper min MLD → more light limitation → less production in the spring/summer**

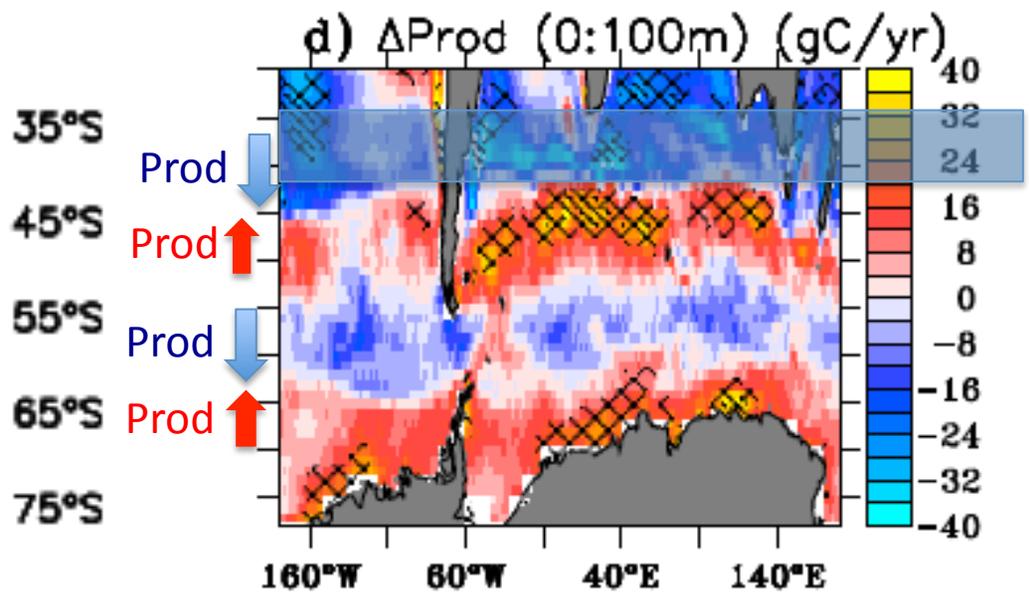
$\Delta \rightarrow$  (1980-1999) to (2080-2099).

And the nutrients?

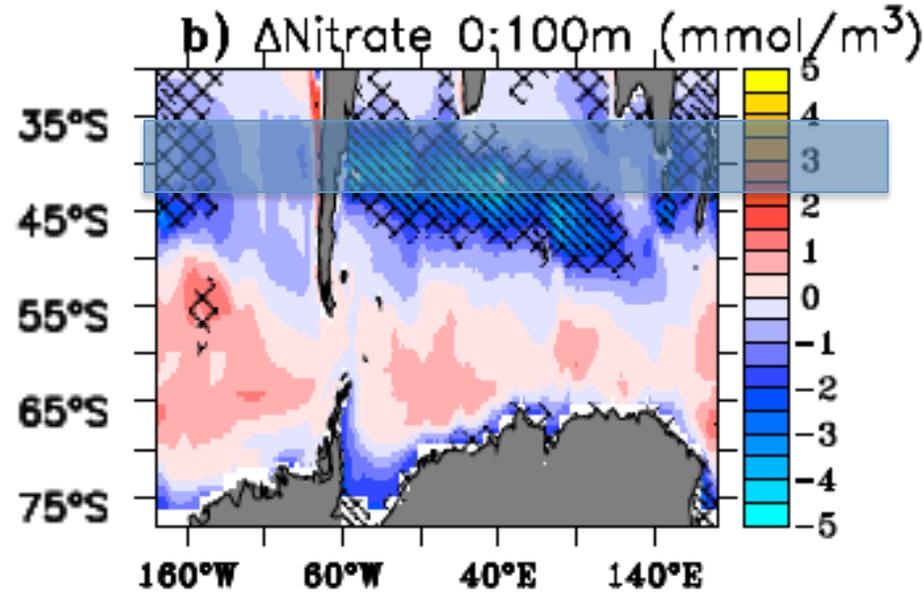


Iron increase? Sediments,  
circulation?  
Misumi et al, 2013, studies iron  
budget in NCAR model

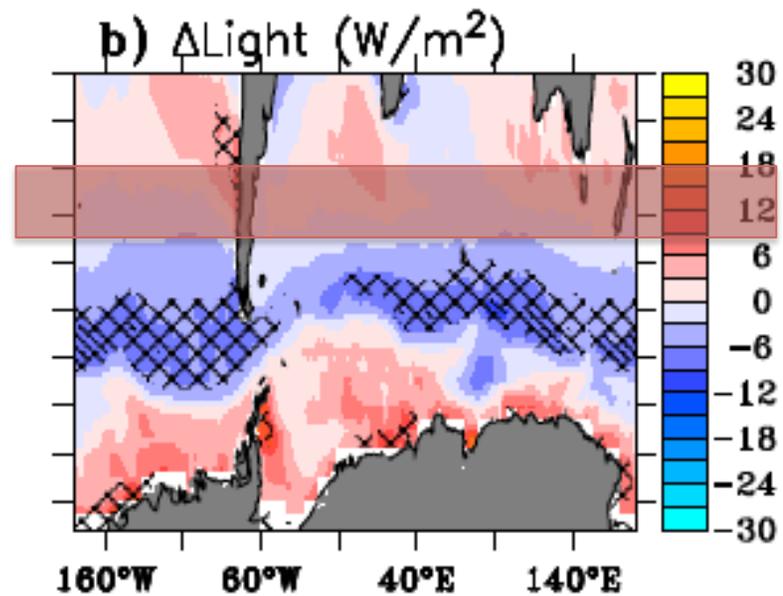
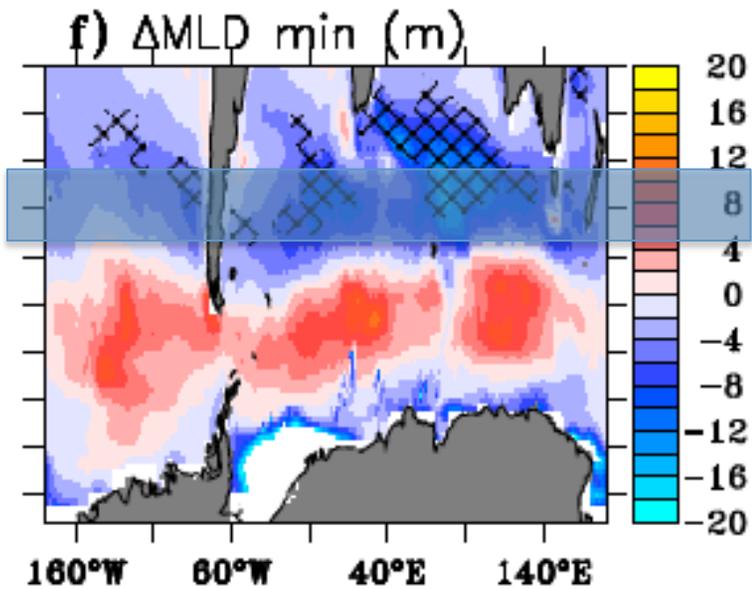
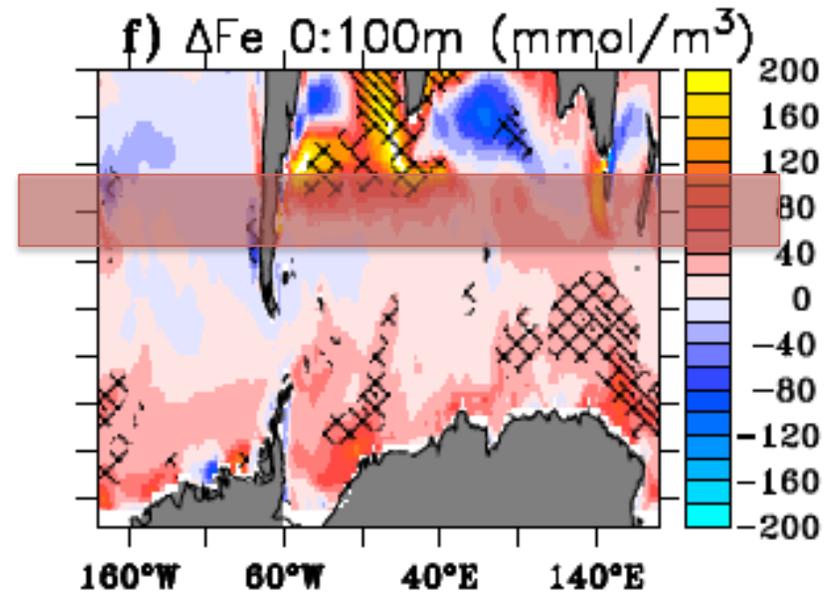
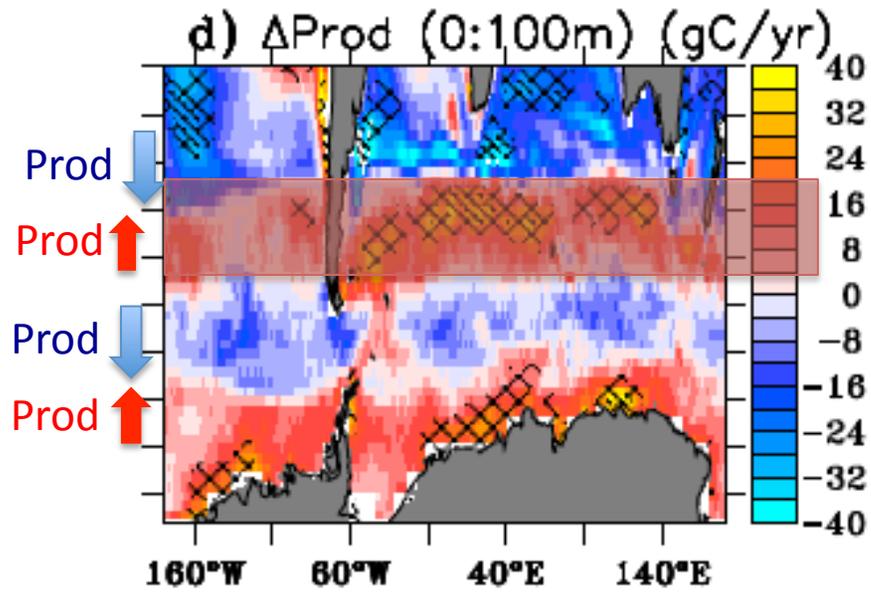
$\Delta \rightarrow$  (1980-1999) to (2080-2099).



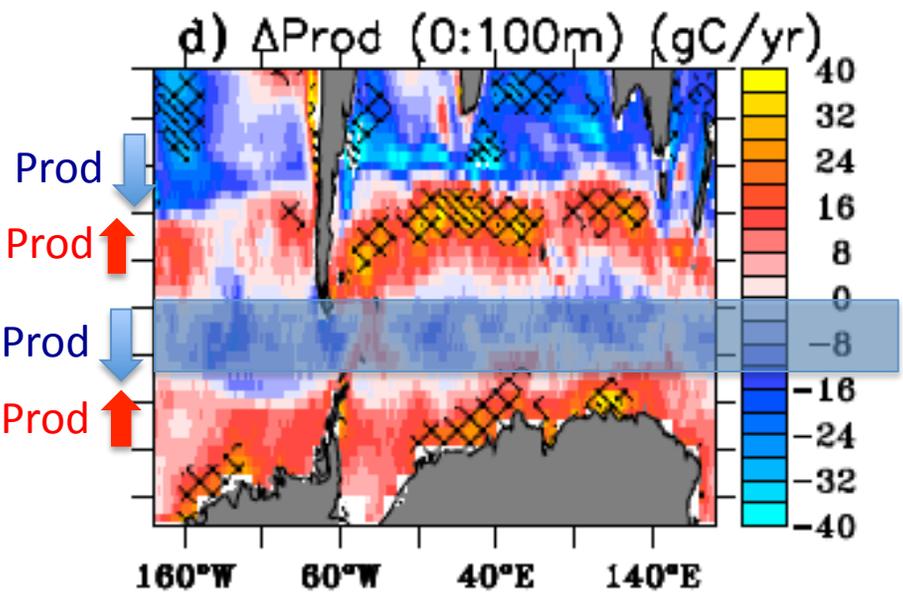
1<sup>st</sup> band: nitrate limited



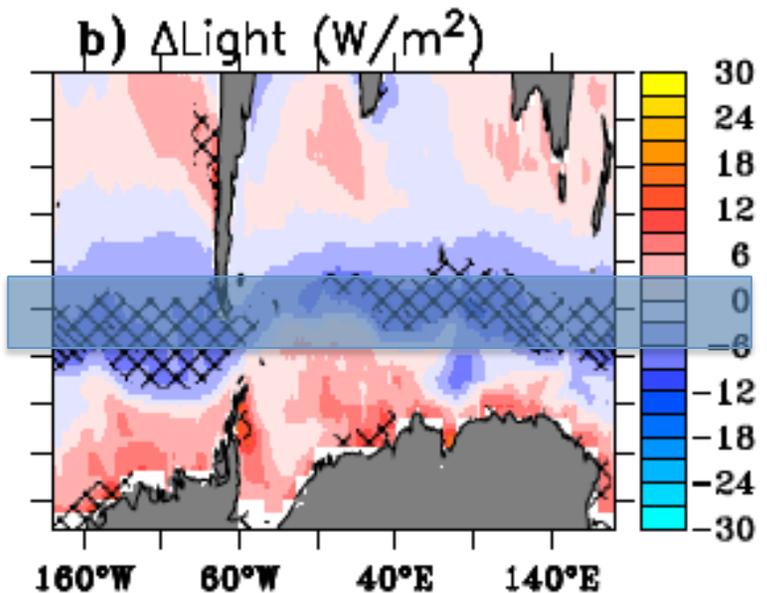
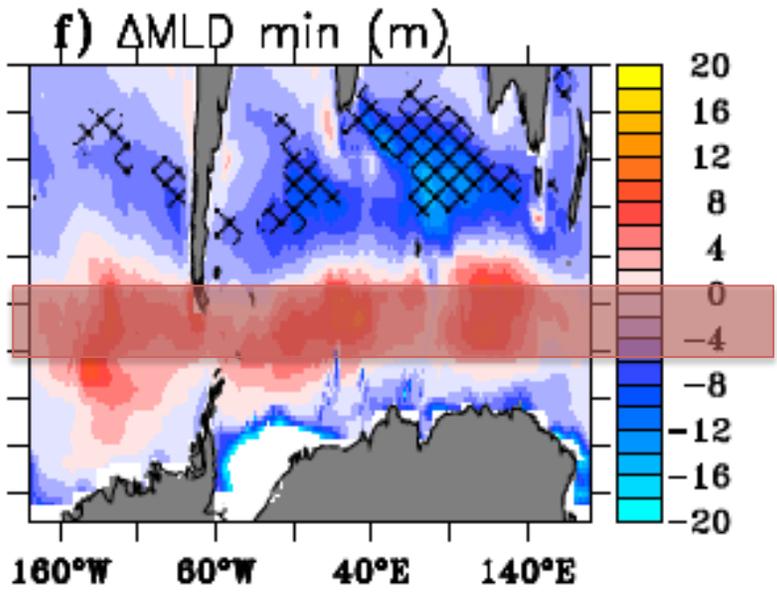
2nd band: light and iron limited



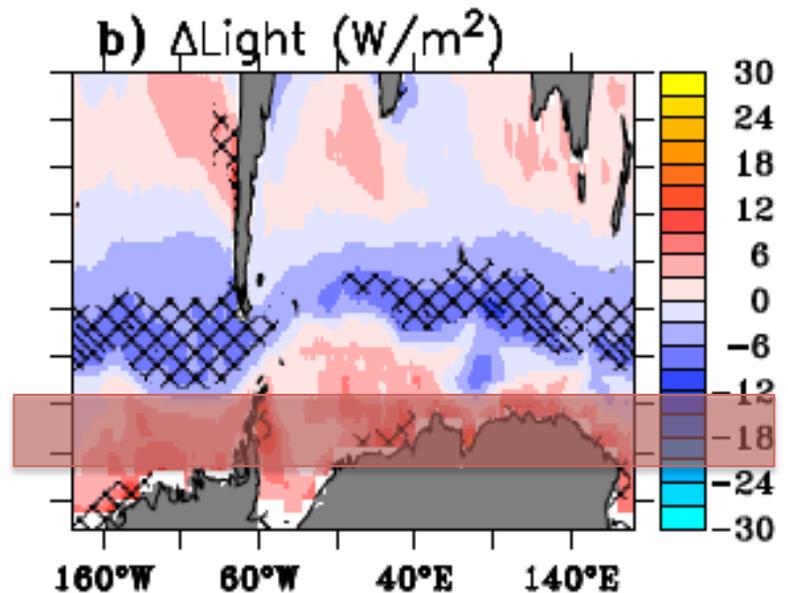
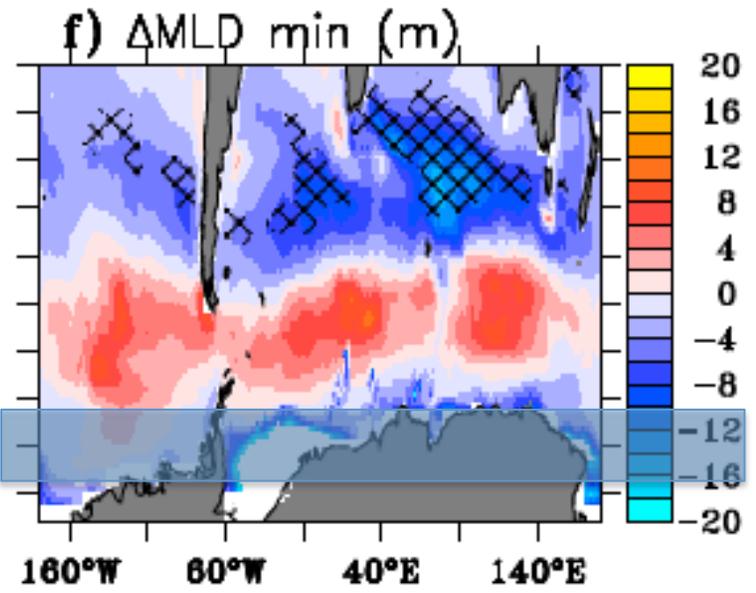
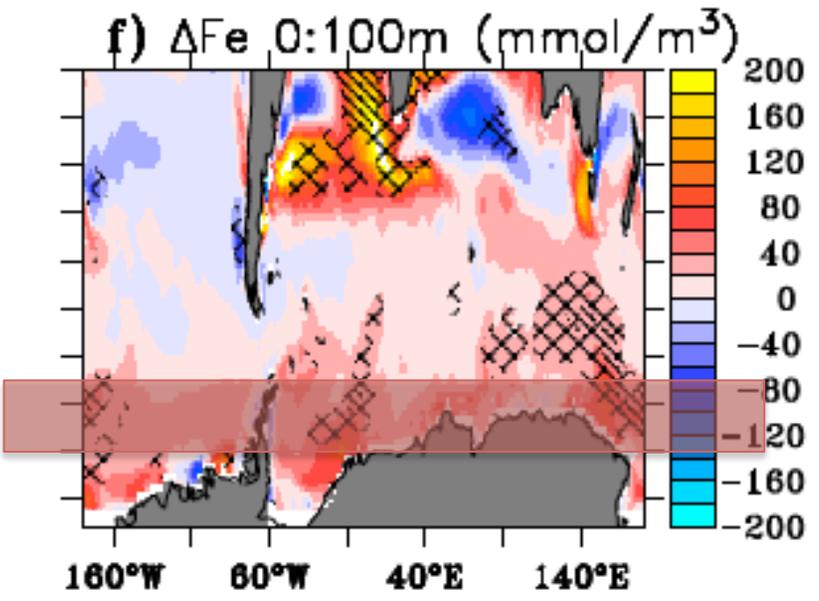
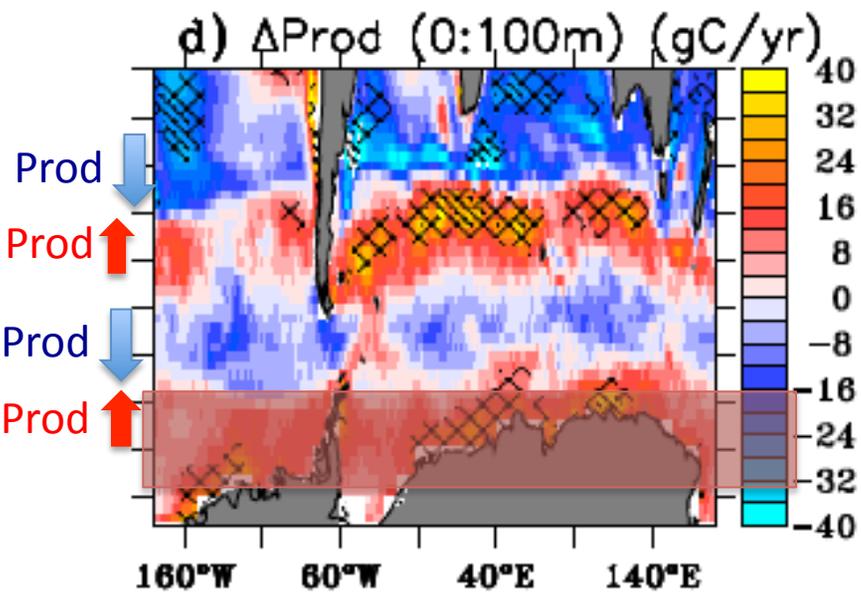
$\Delta \rightarrow$  (1980-1999) to (2080-2099).



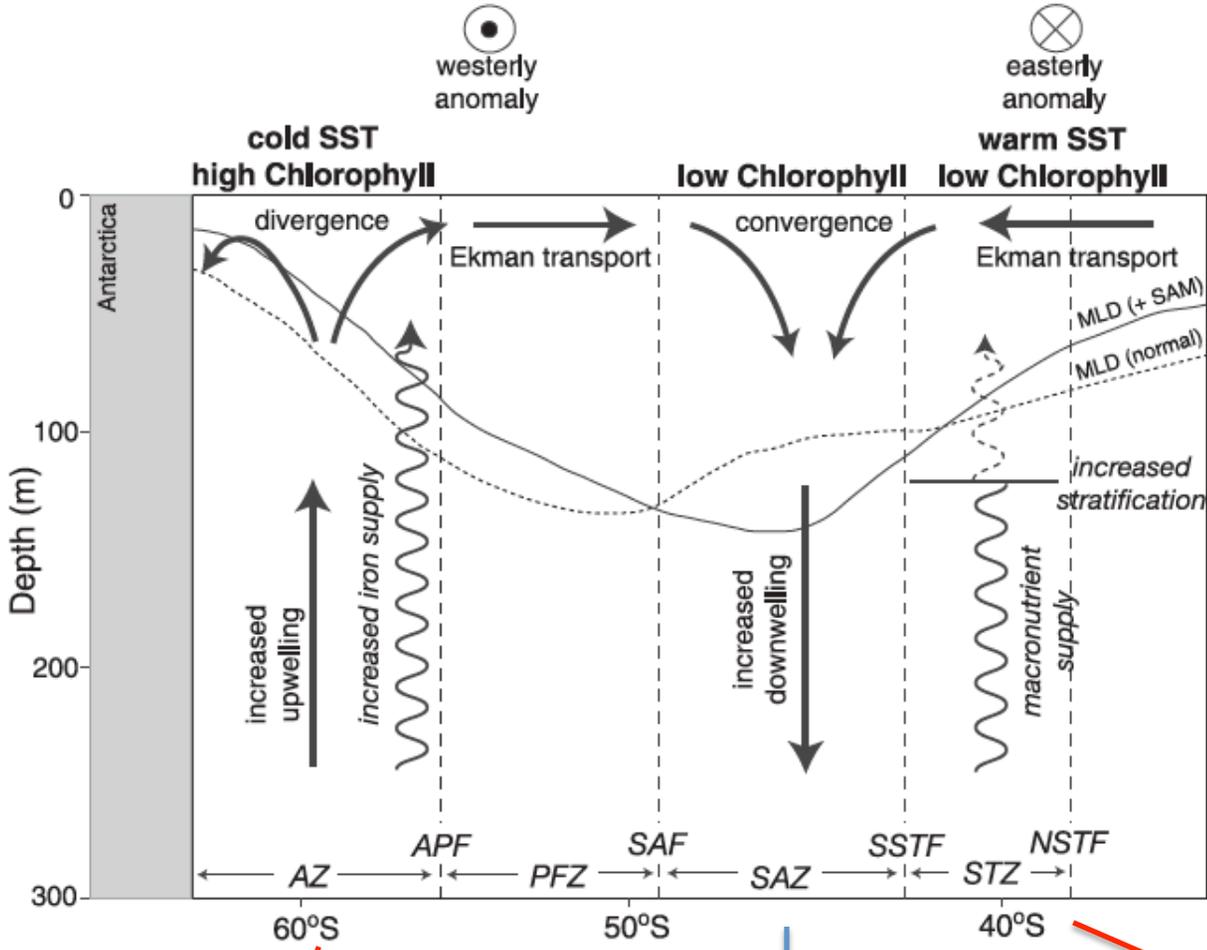
3<sup>rd</sup> band: light limited



4th band: light and iron limited



# Proposed Southern Ocean response in the 21<sup>st</sup> century



Modify the picture proposed by Lovenduski and Gruber (2005) based on the response to a positive phase of SAM.

Future → more SAM-like.

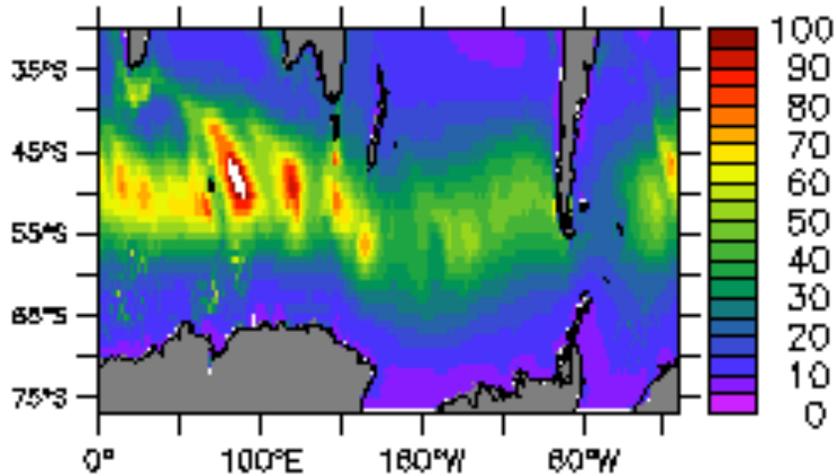
**Increased production**  
 + iron supply  
 + light supply

**Decreased production**  
 deeper MLD  
 - light supply

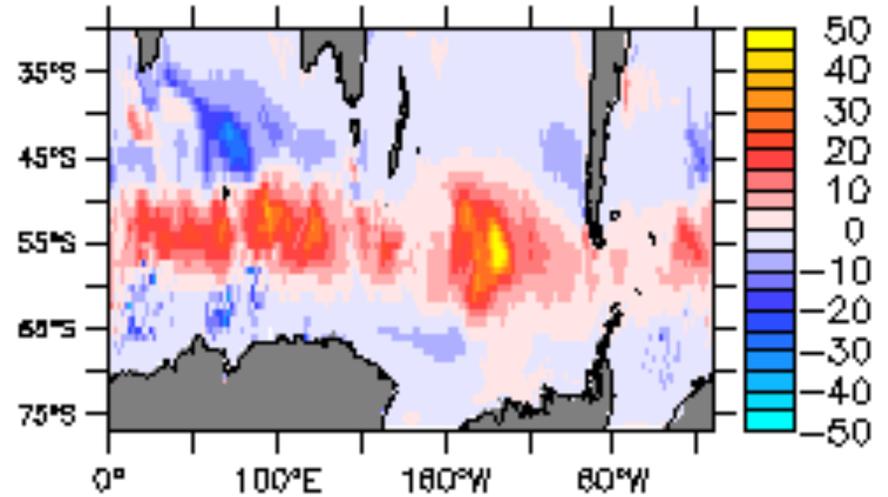
**Increased production**  
 + temperature (+ heat convergence due to subtropical expansion)  
 Despite nutrient & light decrease

# SAM and MLD correlation

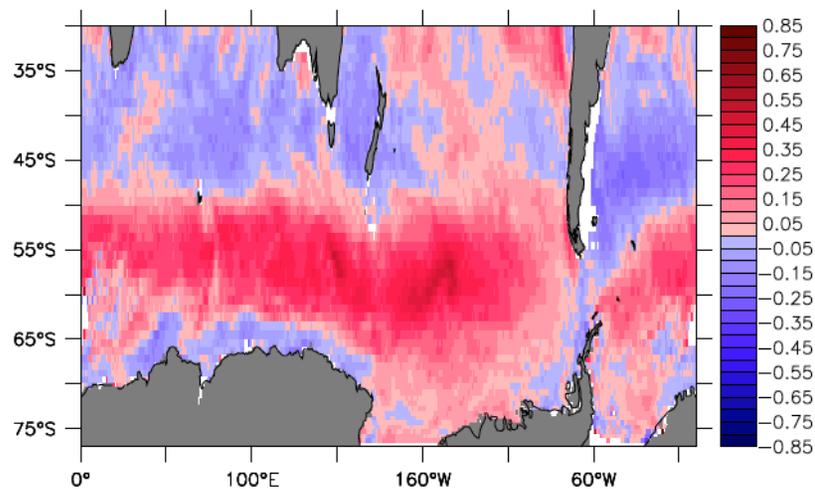
MLD\_min present (1950-1999)



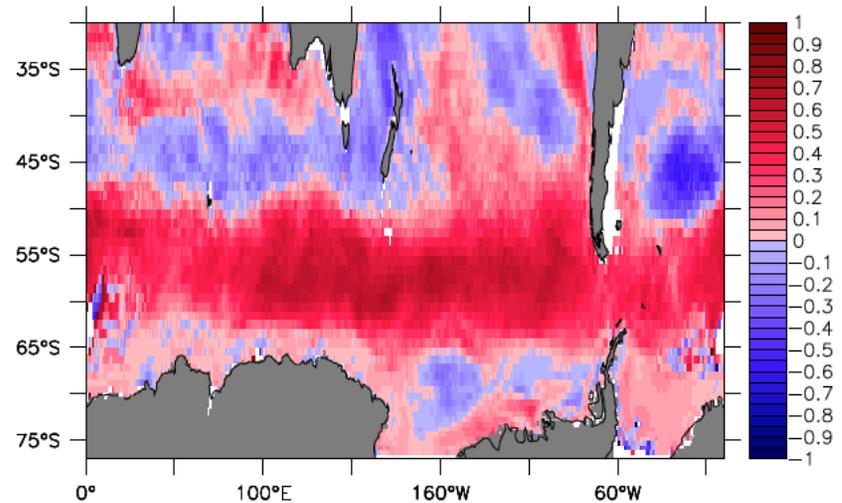
MLD min change (2050-2099) – (1950-1999)



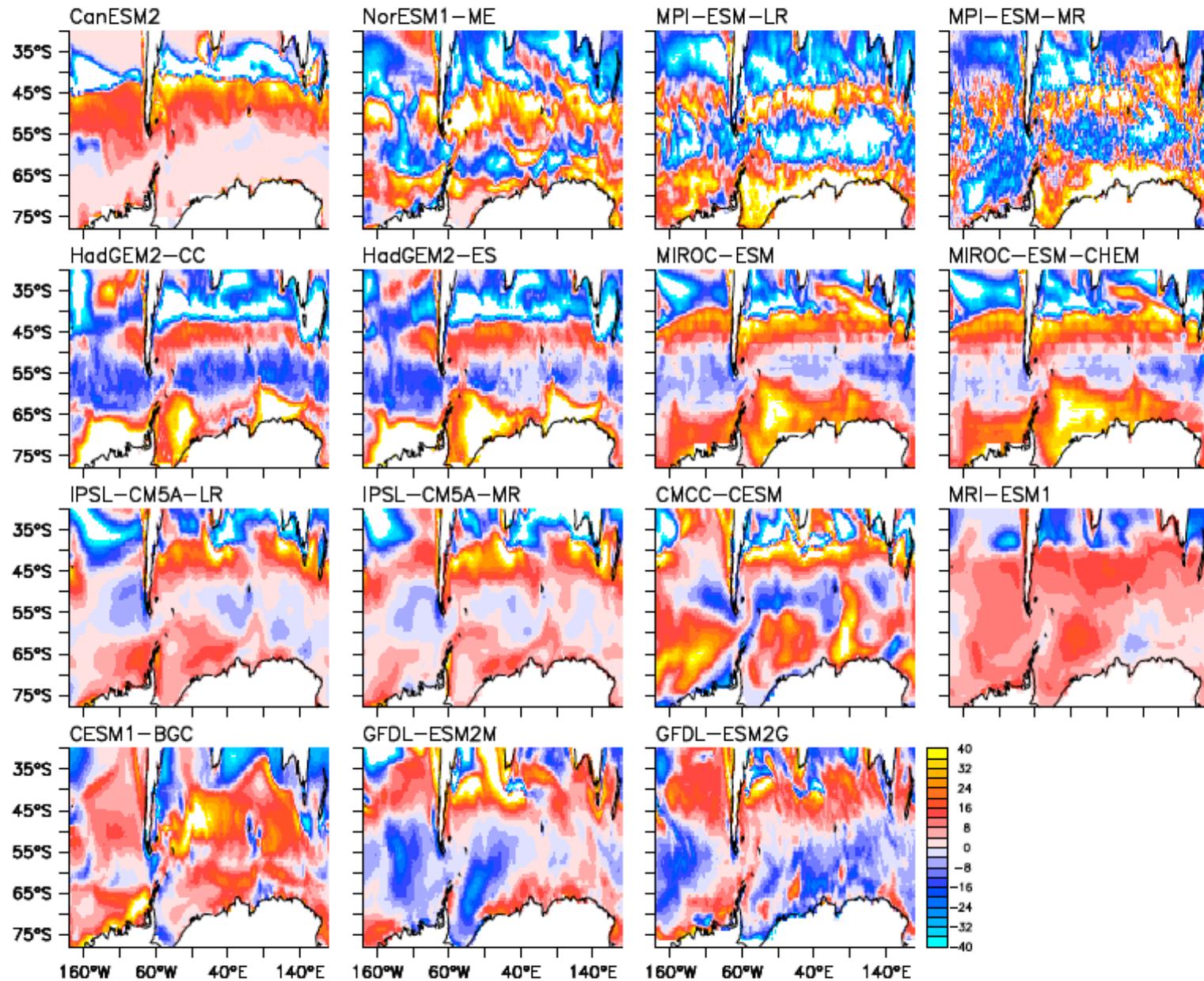
SAM and MLD anomaly monthly correlation



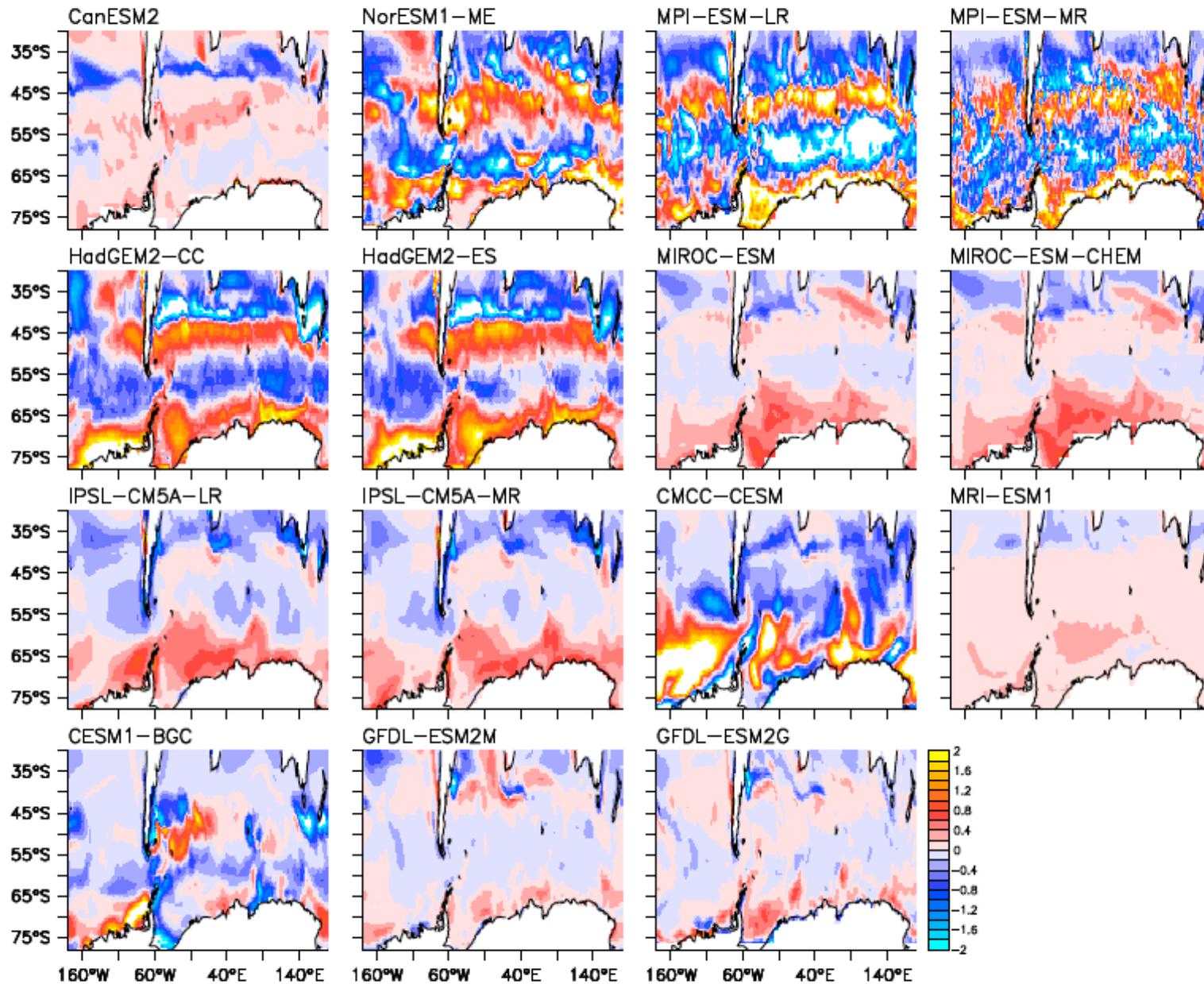
SAM (summer) and MLD\_min yearly correlation



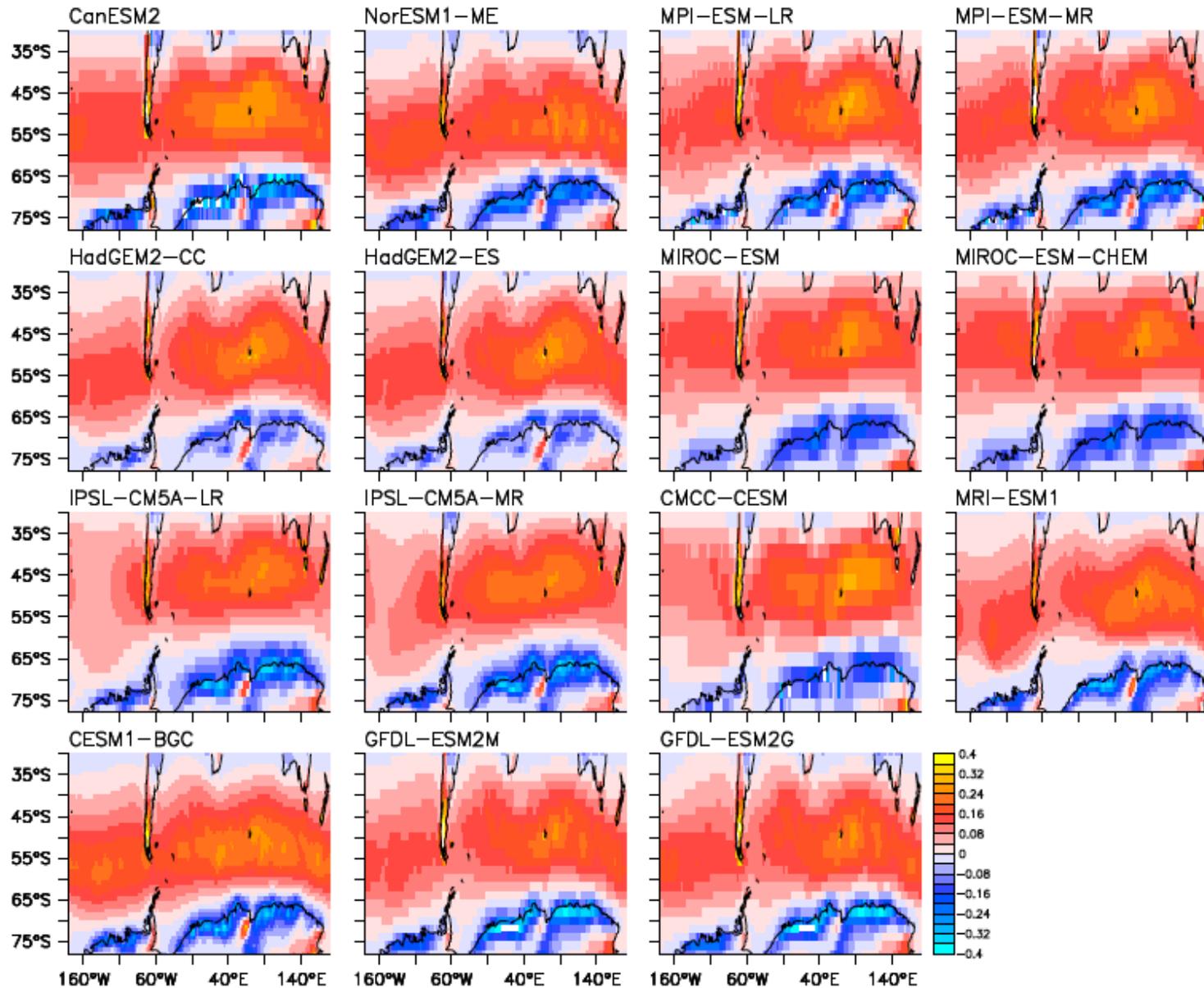
# Change in production $\text{gC/yr/m}^2$ (1980-1999) to (2080-2099)



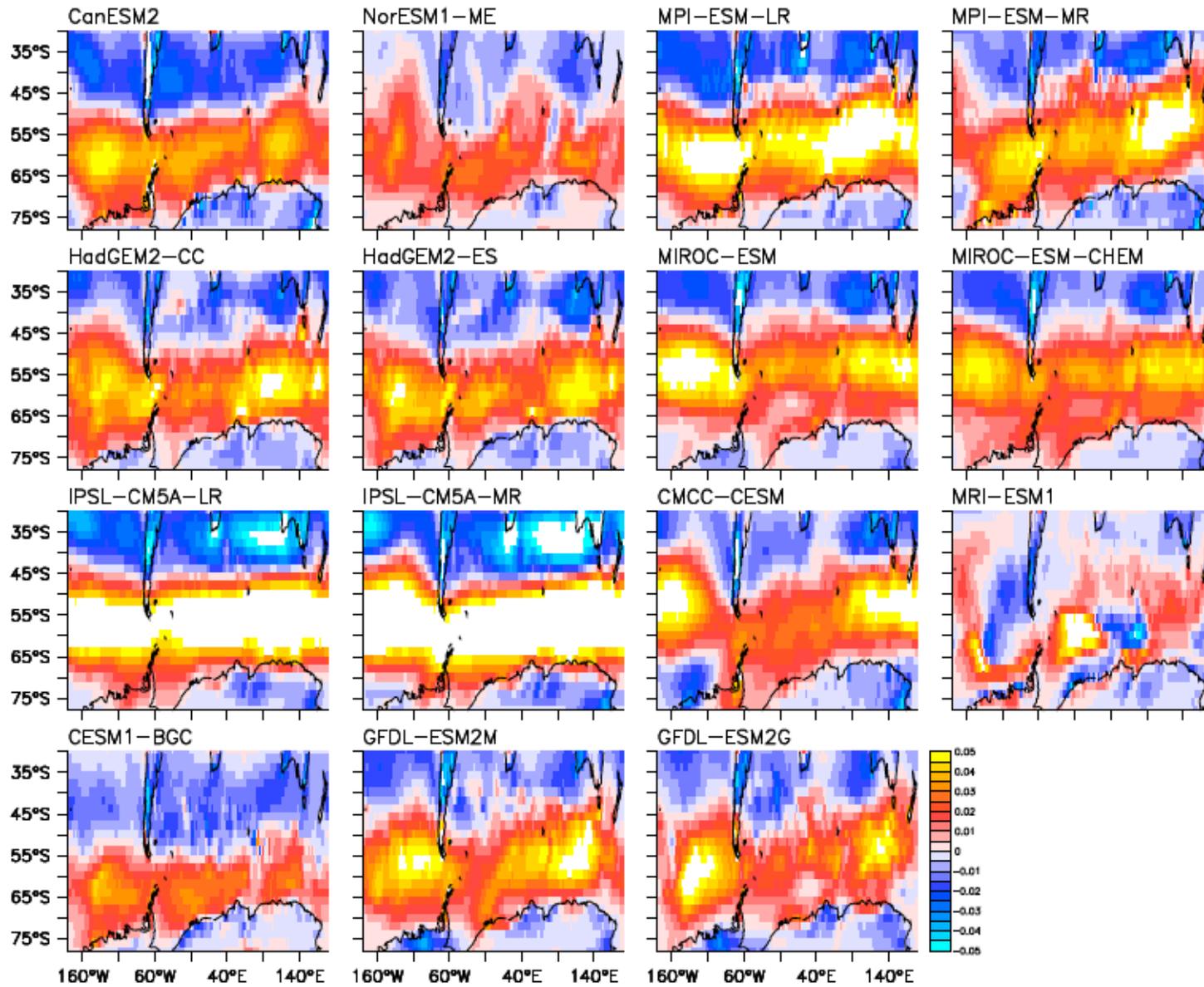
# Change in surface phytoplankton mmol/m<sup>3</sup> (1980-1999) to (2080-2099)



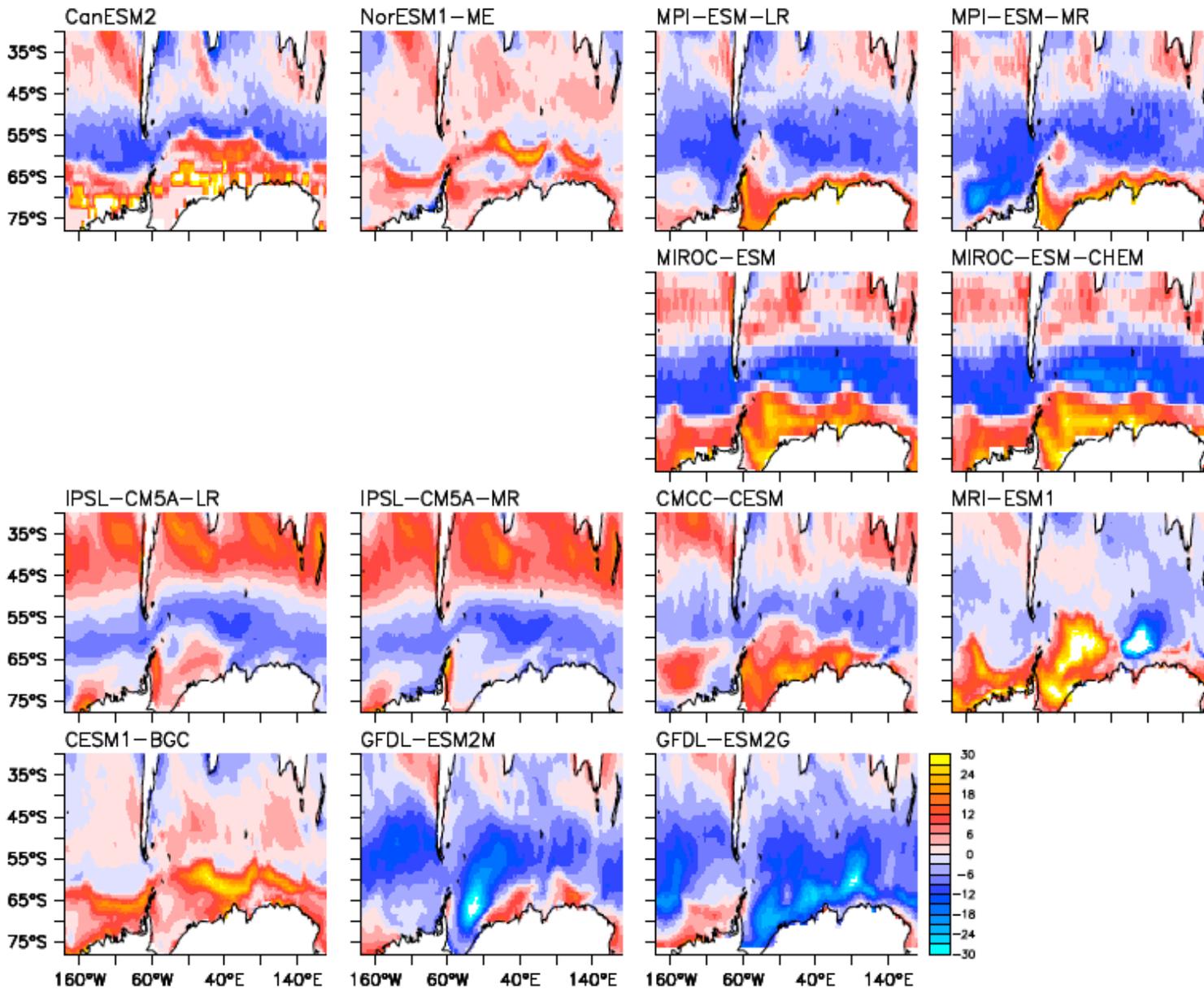
# Wind stress u-direction Pa in the present (1980-1999)



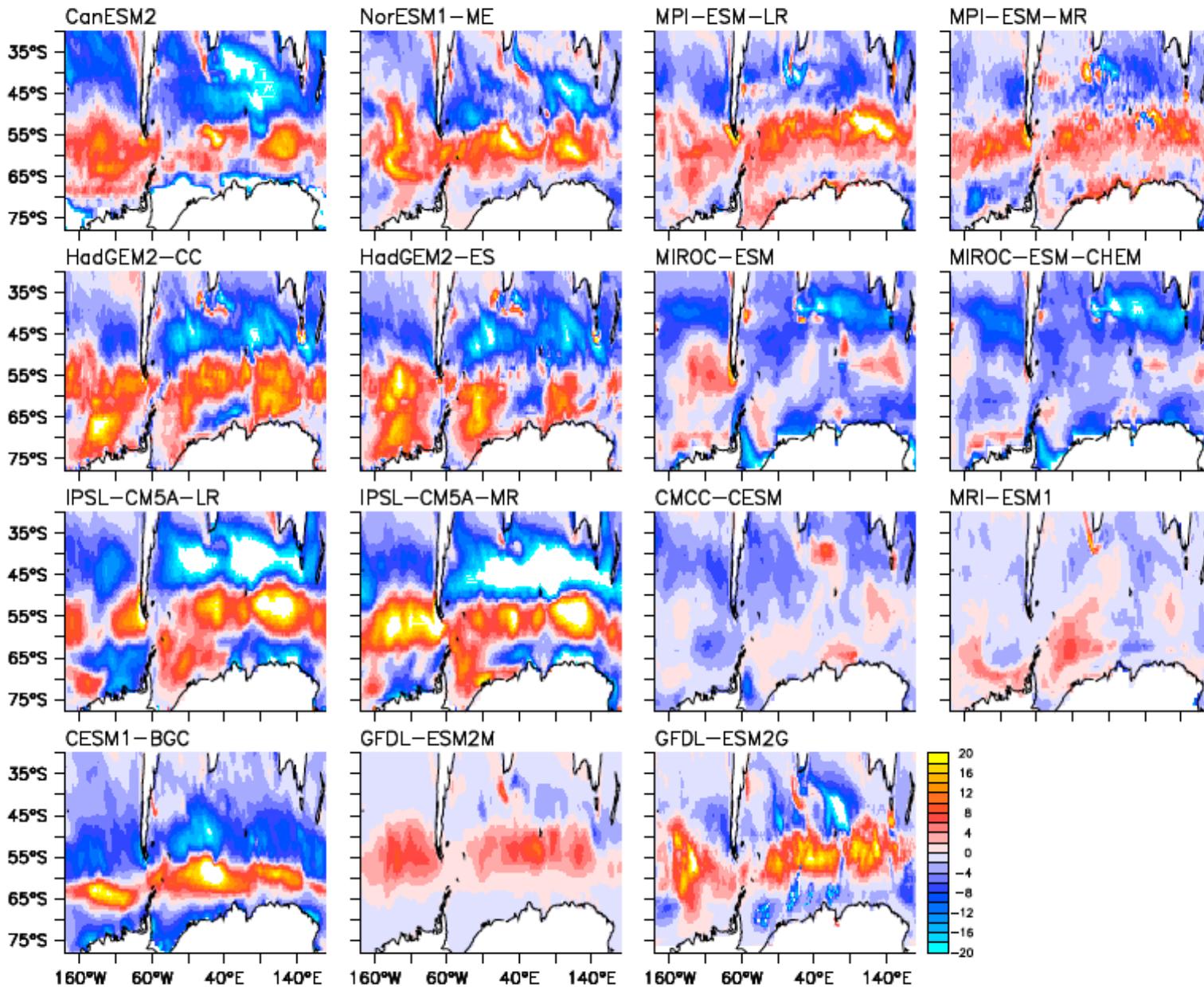
# Change in wind stress u-direction Pa (1980-1999) to (2080-2099)



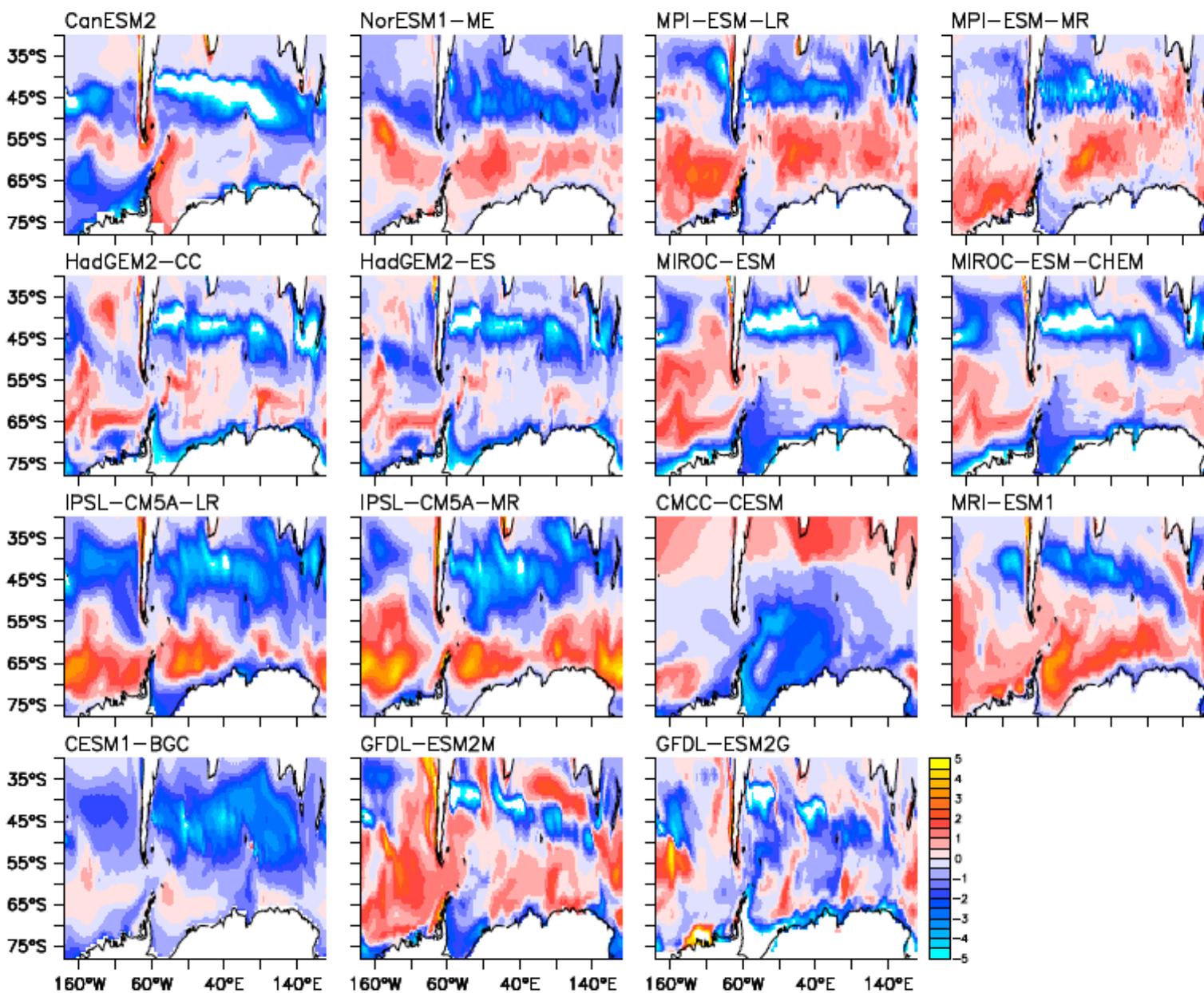
# Change in light at surface $W/m^2$ (1980-1999) to (2080-2099)



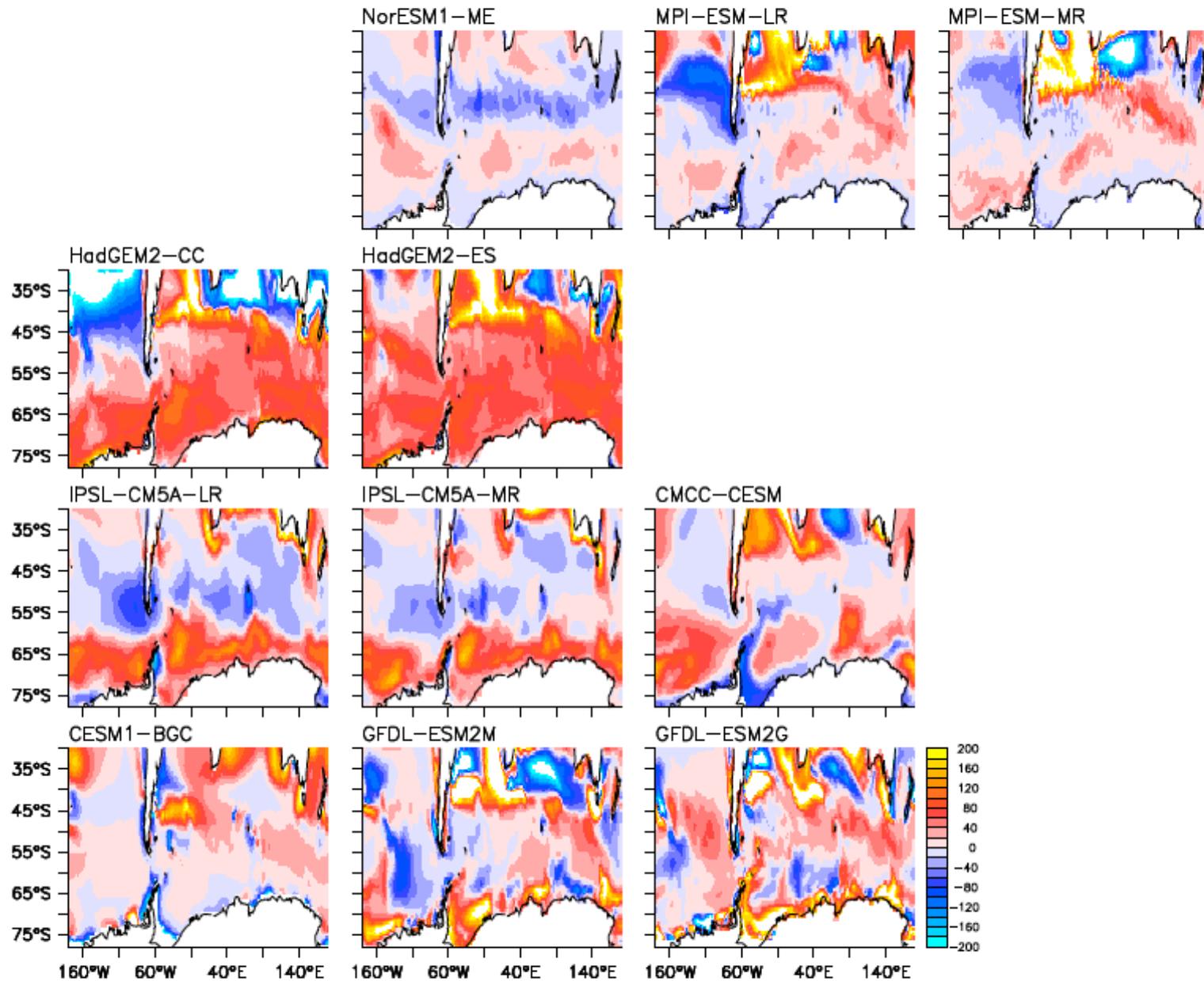
# Change in MLD min in meters (1980-1999) to (2080-2099)



# Change in nitrate $\text{mmol/m}^3$ (1980-1999) to (2080-2099)



# Change in iron nmol/m<sup>3</sup> (1980-1999) to (2080-2099)

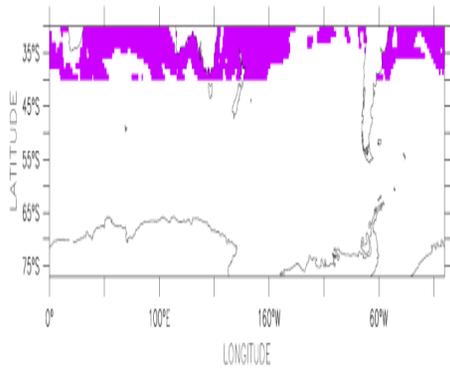


In detail...

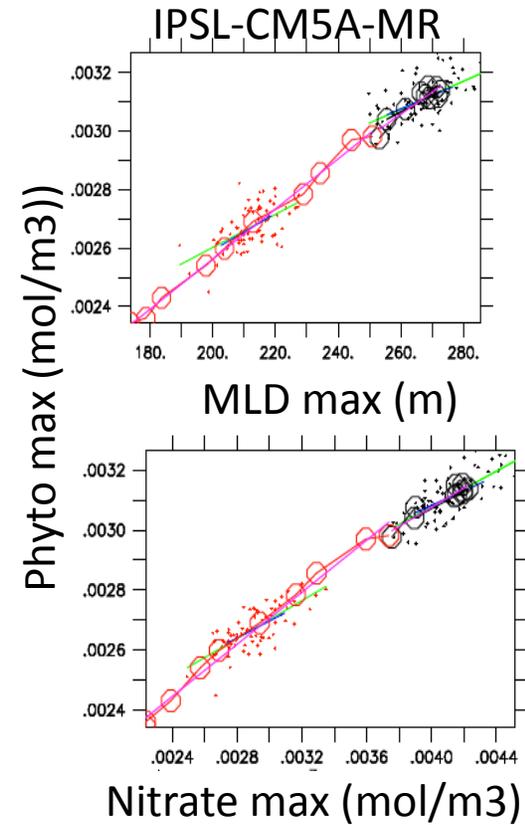
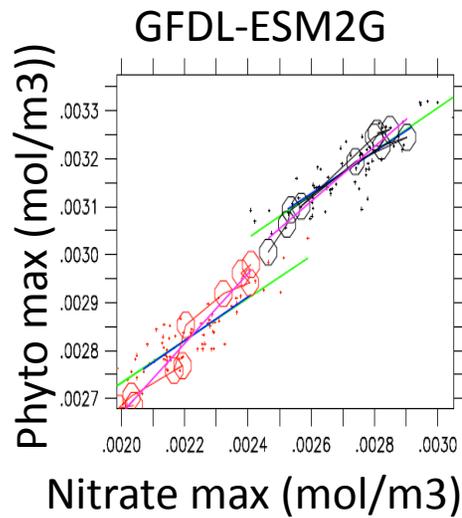
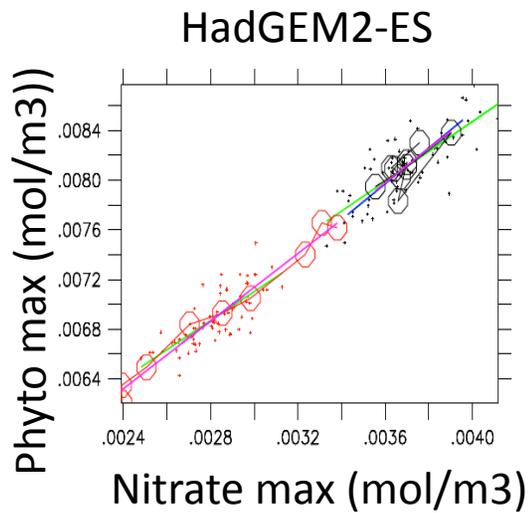
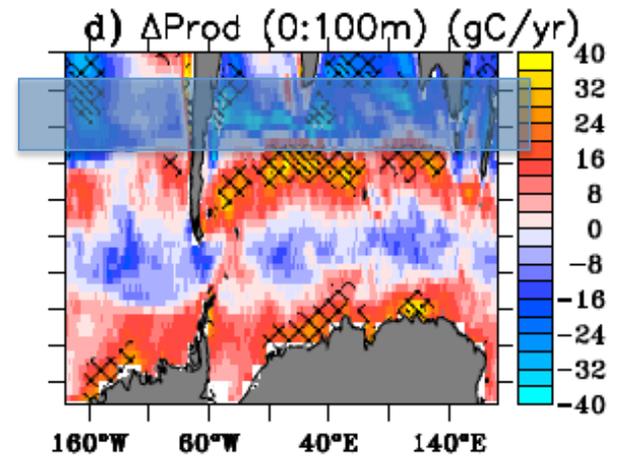
We studied three models (so far):

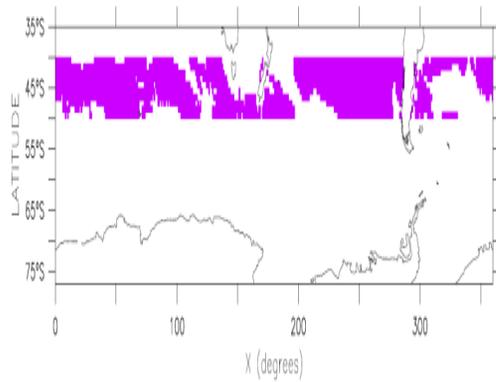
GFDL-ESM2G, HadGEM2-ES, IPSL-CM5A-MR.

Which mechanisms remain important through different time scales?

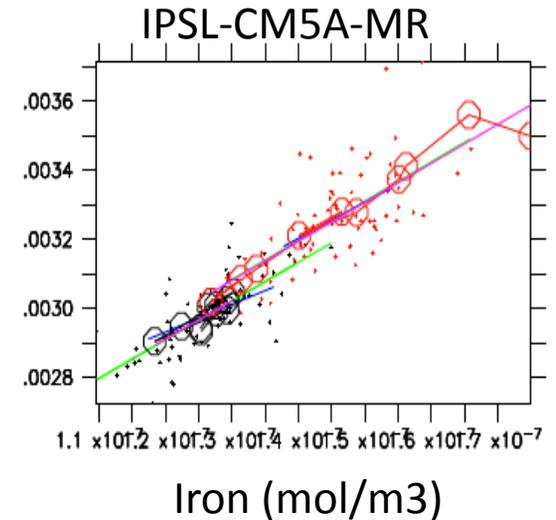
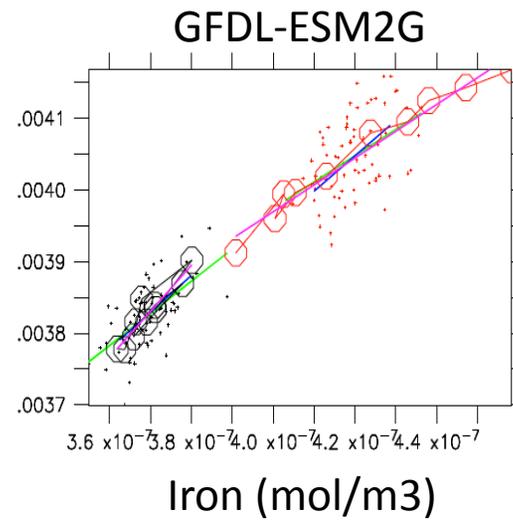
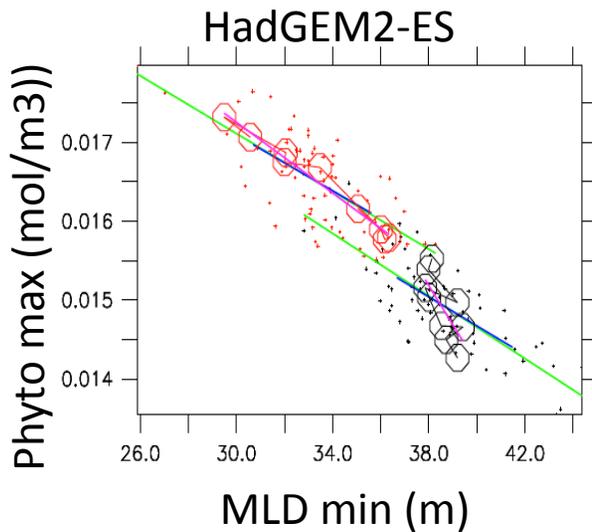
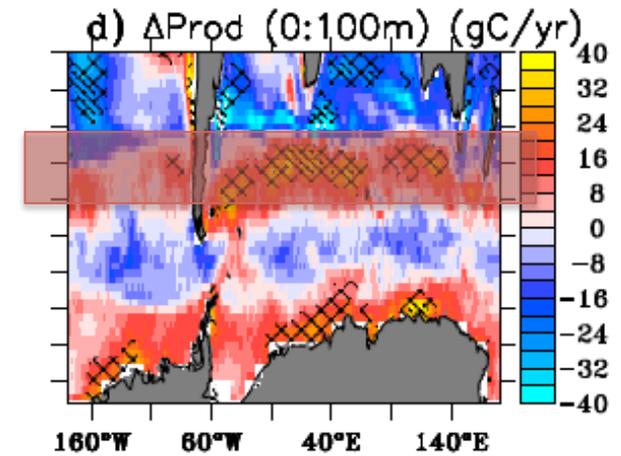


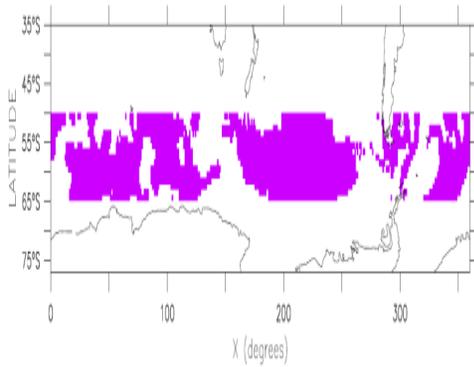
a) Model GFDL-ESM2G: masked region between 30S and 40S where surface yearly max phytoplankton concentrations **decrease** between rcp8.5 (2050-99) and historical (1950-99)



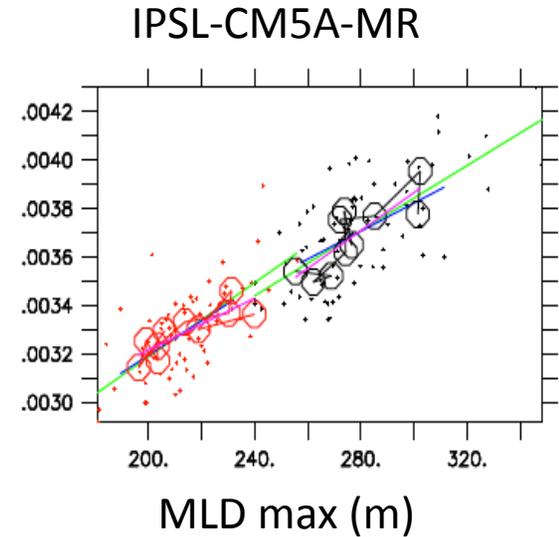
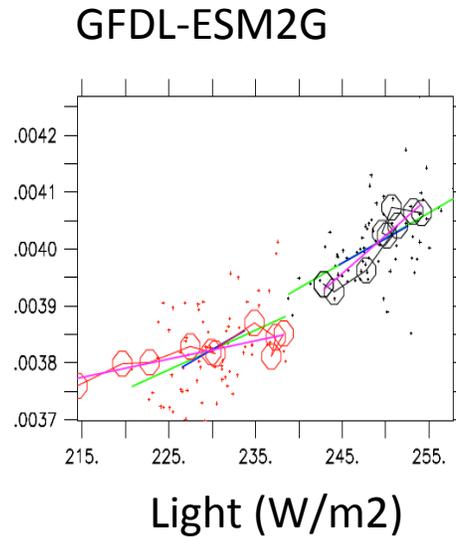
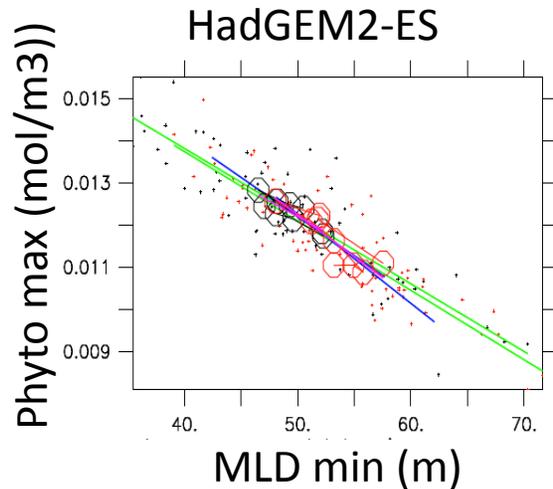
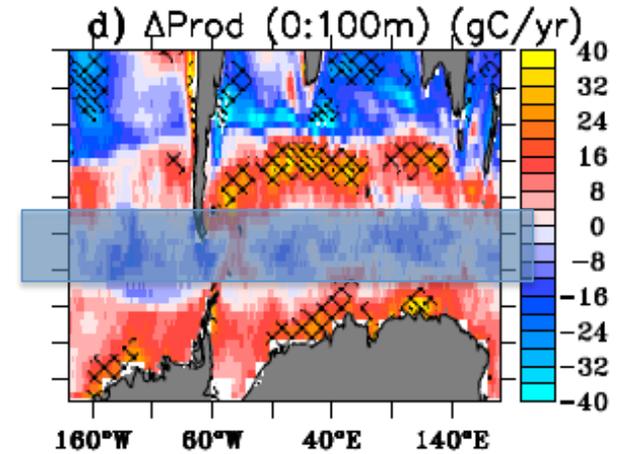


**b) Model GFDL-ESM2G: masked region between 40S and 50S where surface yearly max phytoplankton concentrations **increase** between rcp8.5 (2050-99) and historical (1950-99)**

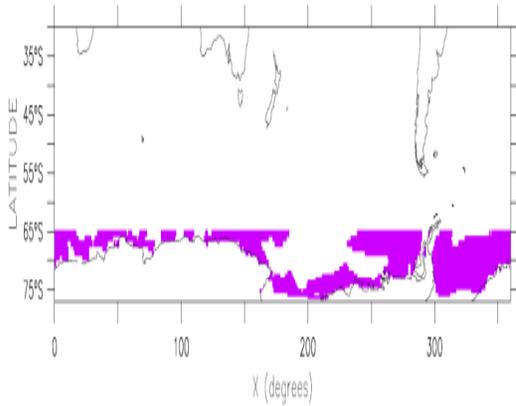




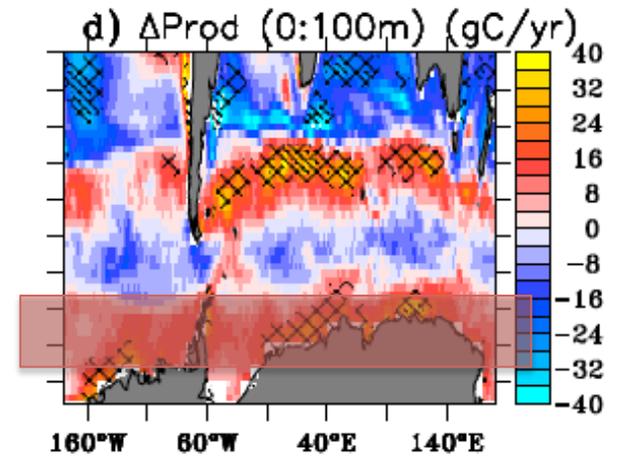
**Model GFDL-ESM2G:**  
 masked region between  
**50S and 65S** where  
 surface yearly max  
 phytoplankton  
 concentrations **decrease**  
 between rcp8.5  
 (2050-99) and historical  
 (1950-99)



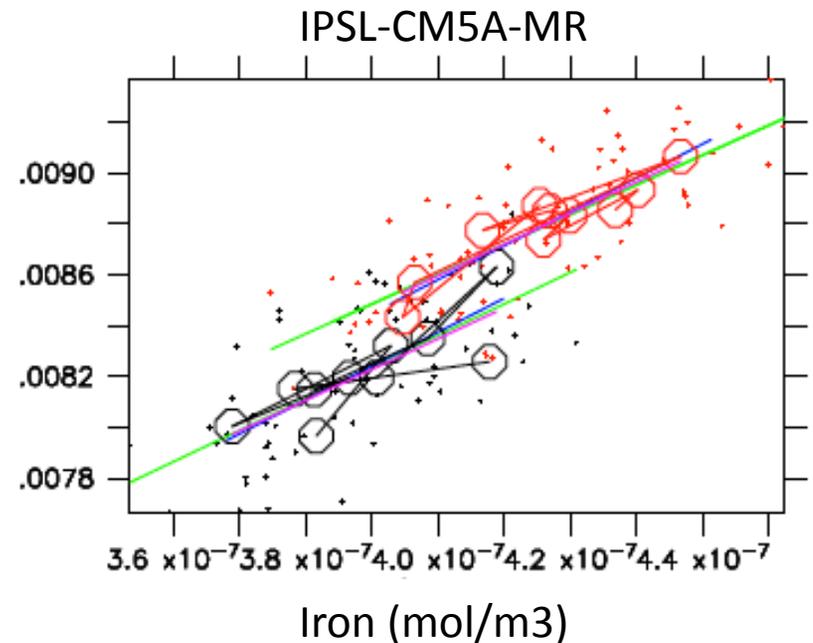
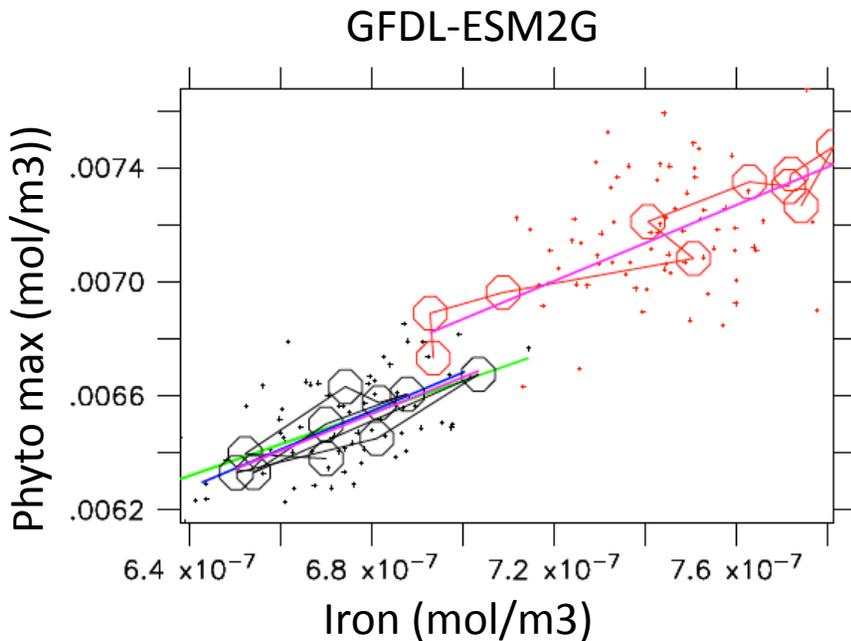
+ light, MLDmin

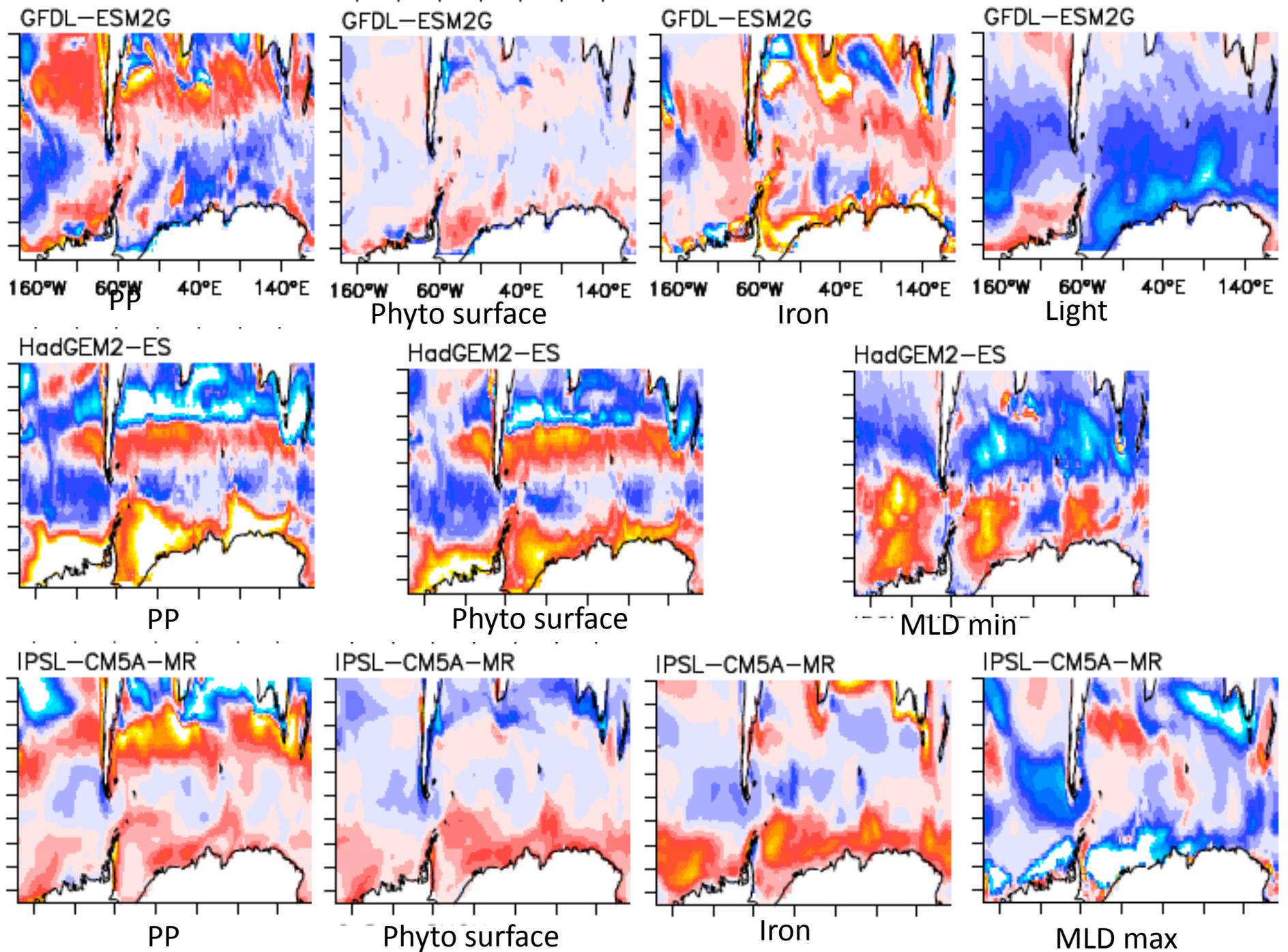


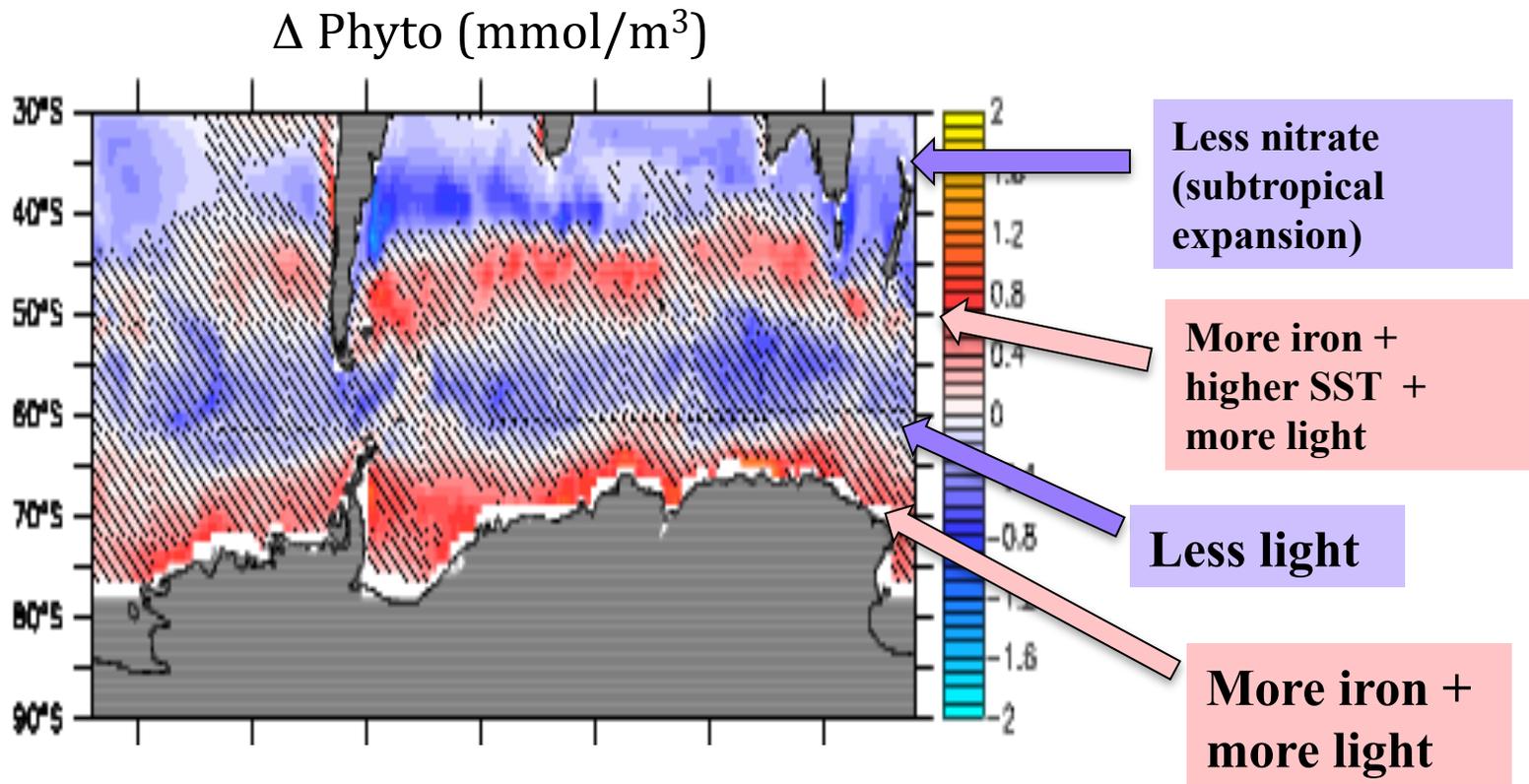
**c) Model GFDL-ESM2G: masked region south of 65S where surface yearly max phytoplankton concentrations **increase** between rcp8.5 (2050-99) and historical (1950-99)**



HadGEM2-ES → light?







### Summarizing Figure

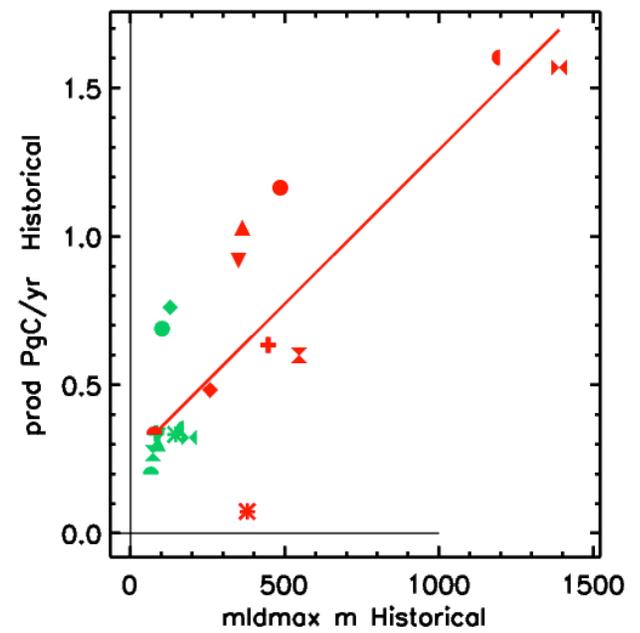
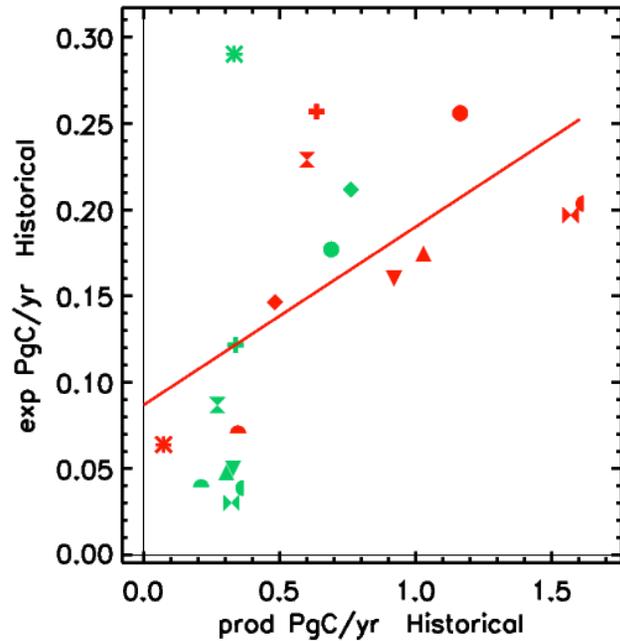
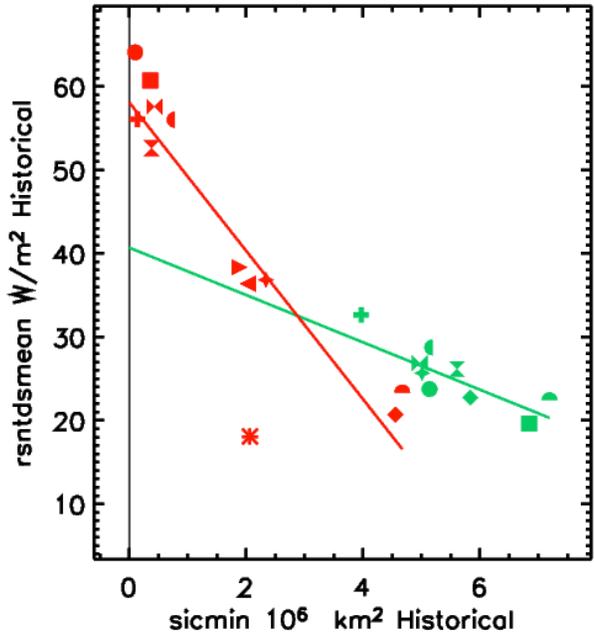
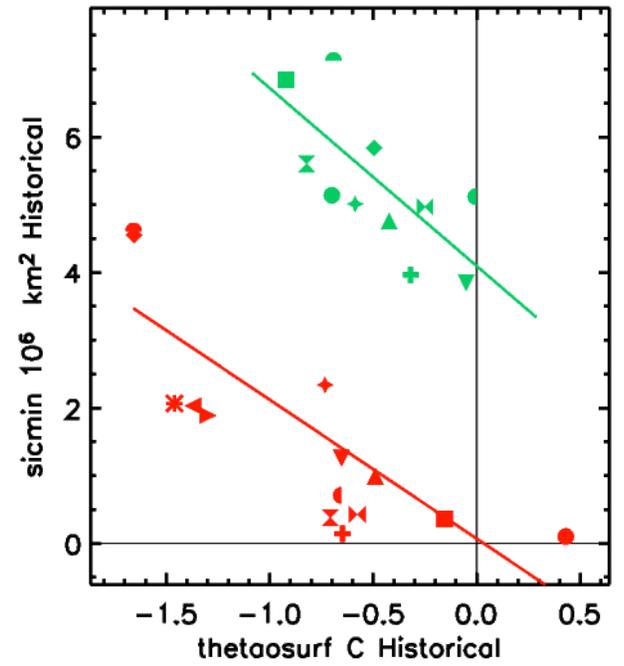
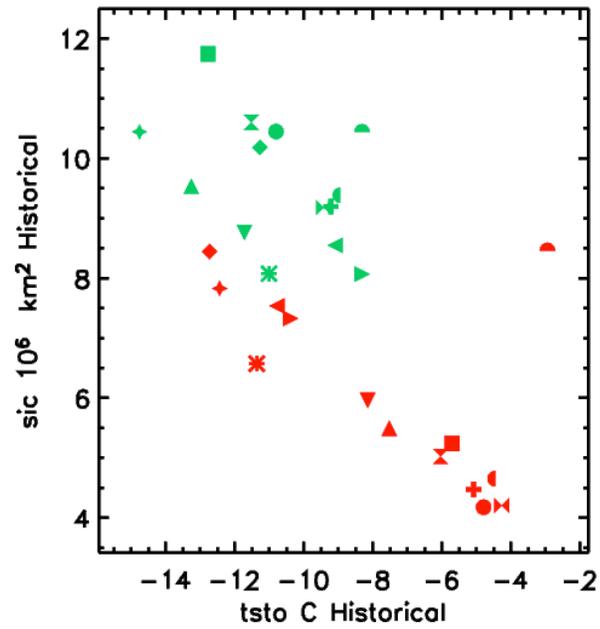
- Band north of 40S:** *Production decrease* – Nitrate is most important
- Band at 40S-50S:** *Production increase* – Sea surface temperature, iron, and light are most important
- Band at 50S-65S:** *Production decrease* – Photosynthetically available light supply is most important
- Band south of 65S:** *Production increase* – Iron and photosynthetically available light supply are most important

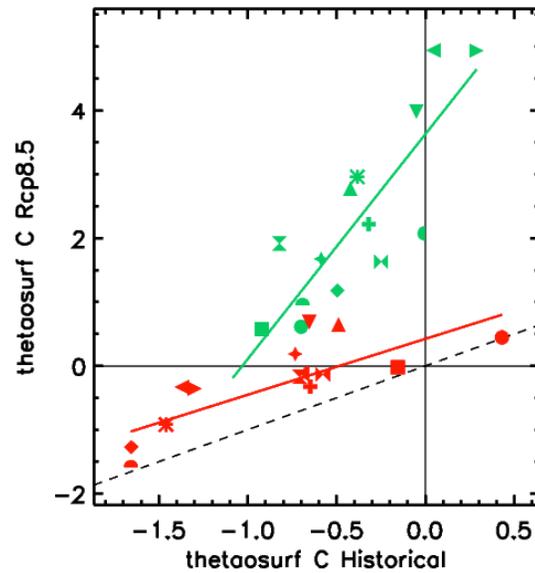
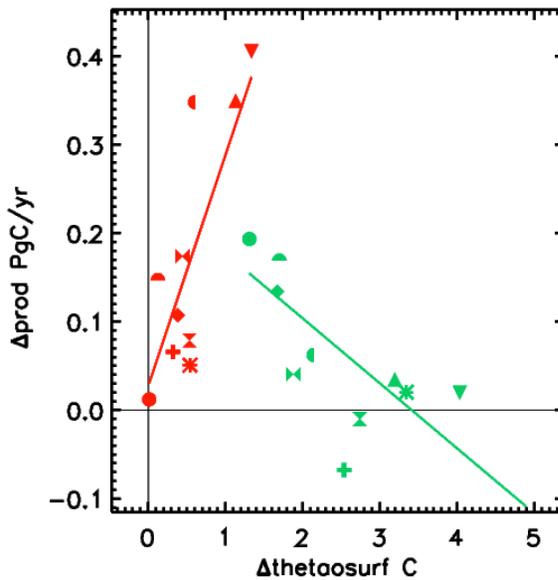
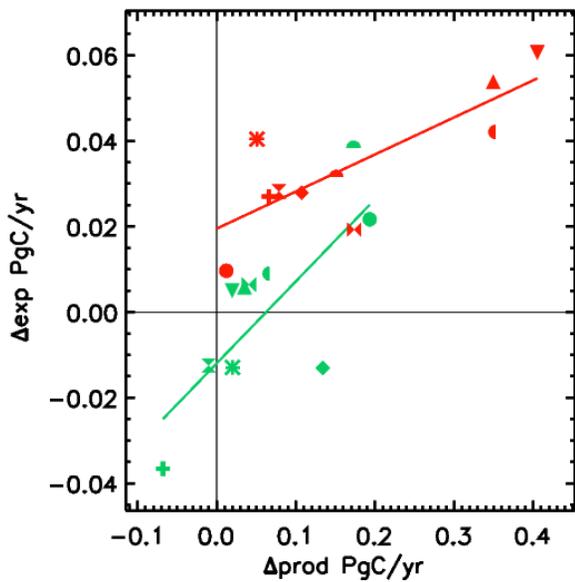
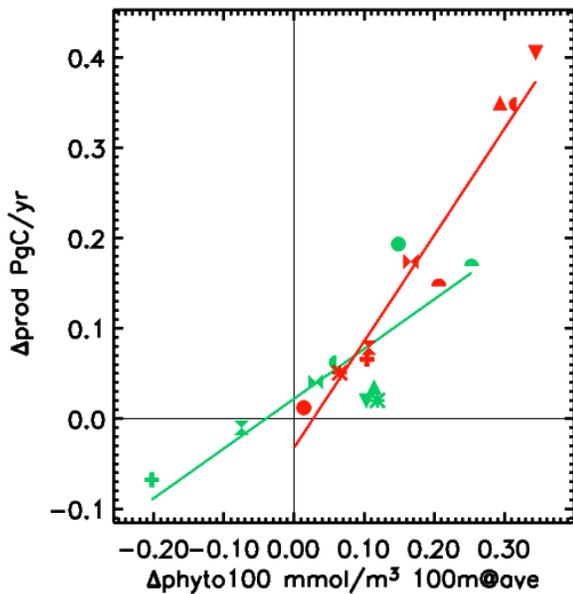
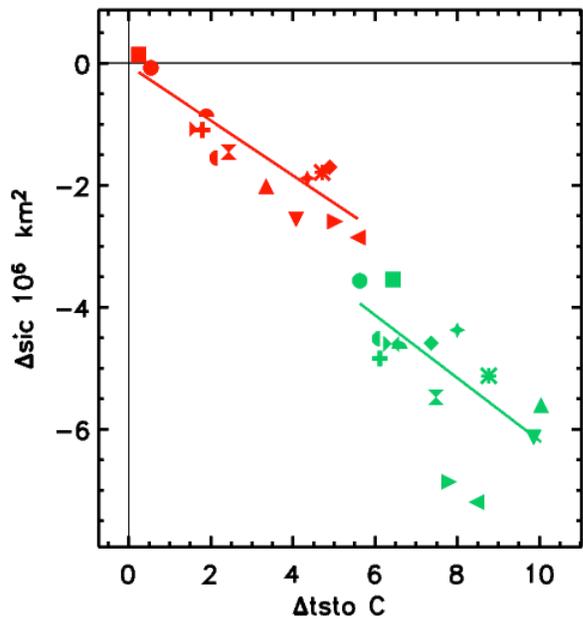
# Conclusions: Southern Ocean phyto and climate change

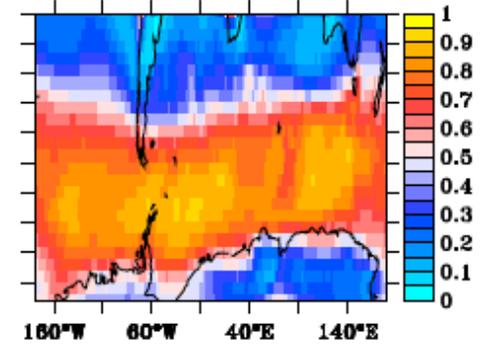
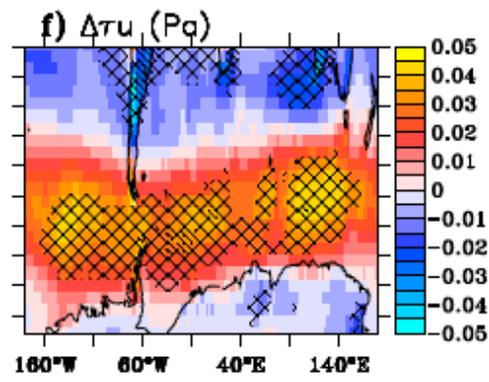
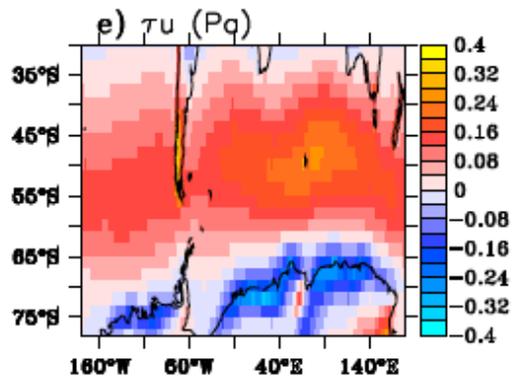
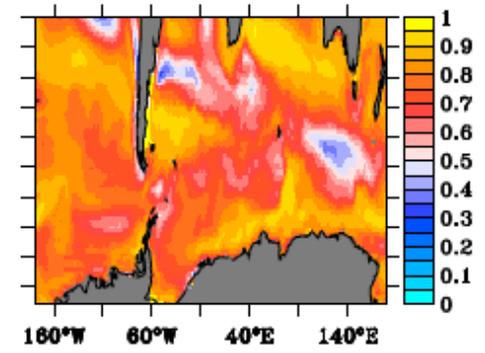
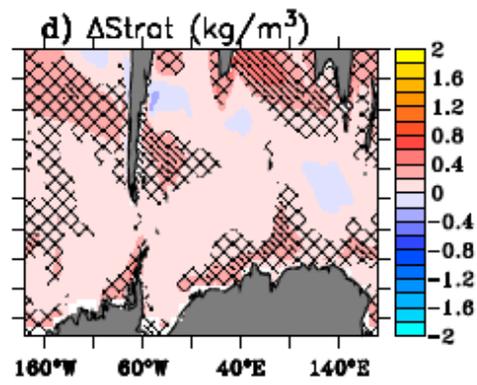
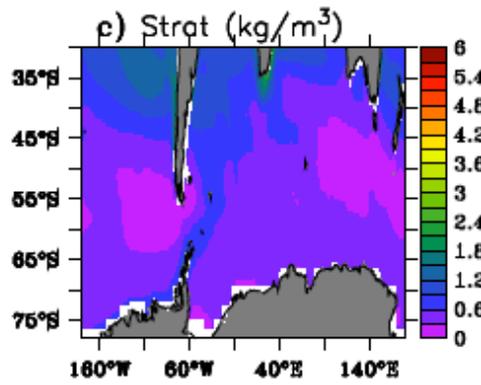
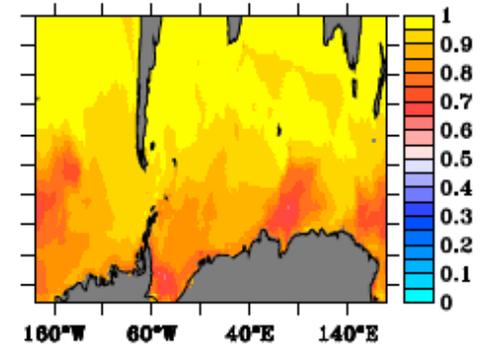
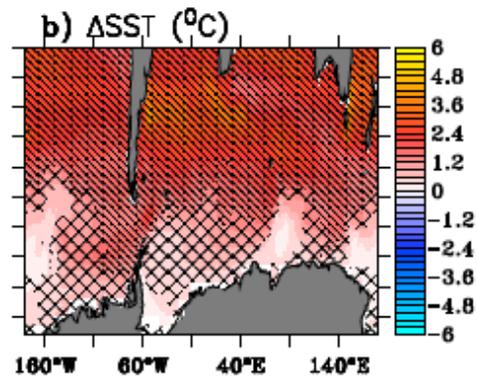
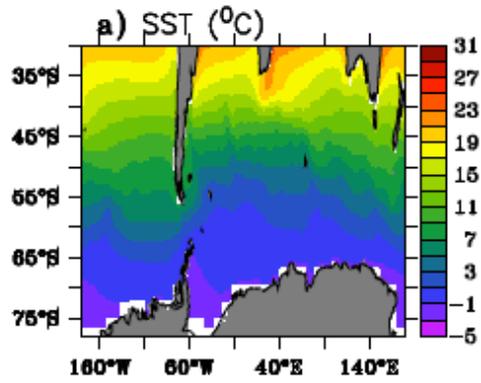
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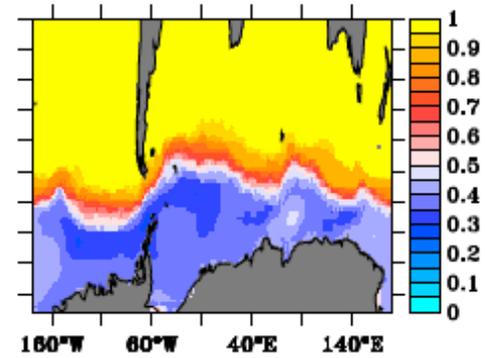
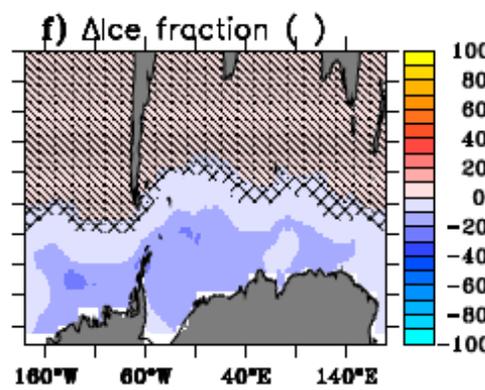
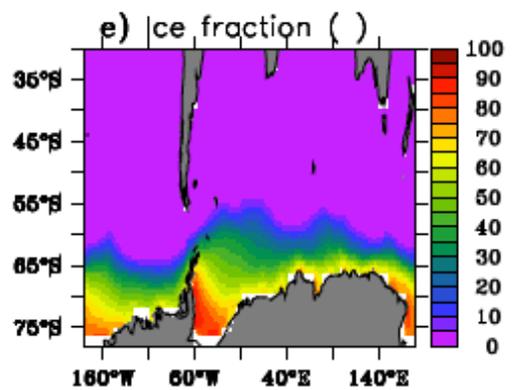
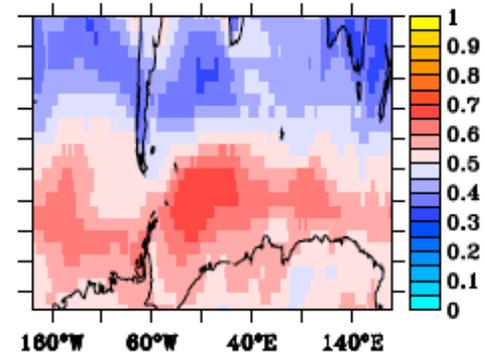
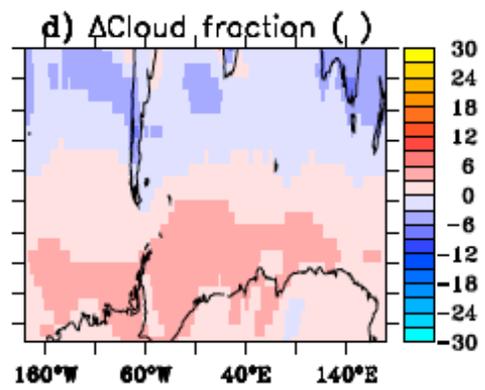
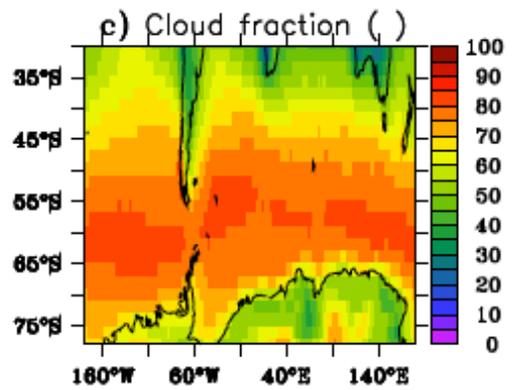
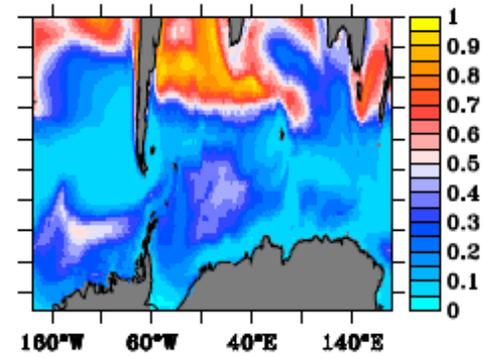
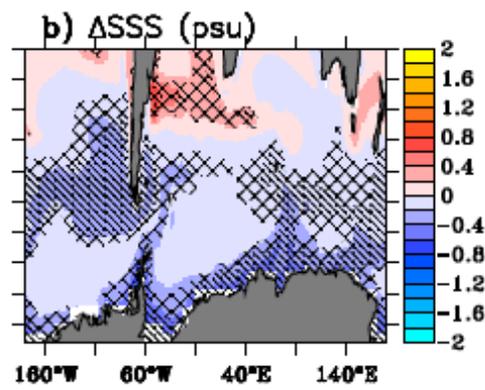
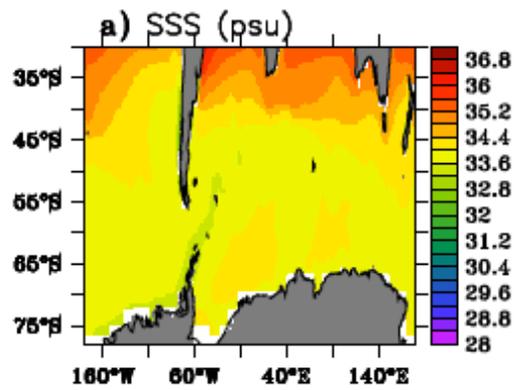
- ***Proposed “Banded” response of the S. Ocean to future climate change (model average over 100 yrs) :***
  - 40S-50S: Production increase:** Temp + IPAR + shallower spring MLD (most models), Fe in GFDL model?
  - 50S-65S: Production decrease:** IPAR decrease
  - S of 65S: Production increase:** more IPAR + more Fe (rivers, continent)
- ***Fe supply pathways + Cloud details + Ice details : important for the productivity response.***
- ***100 yr Productivity response partially explained by increasing SAM ?*** Interannual correlations with SAM show 3 bands (similar to Lovenduski & Gruber 2005), more pronounced in the future. How to extend this analysis across all models ?

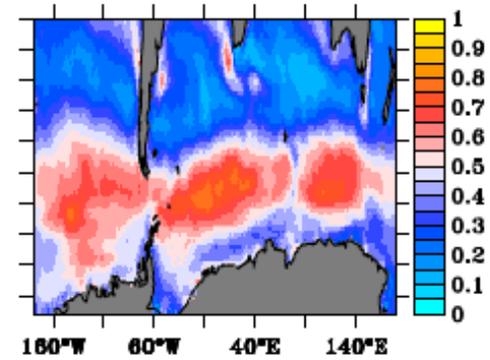
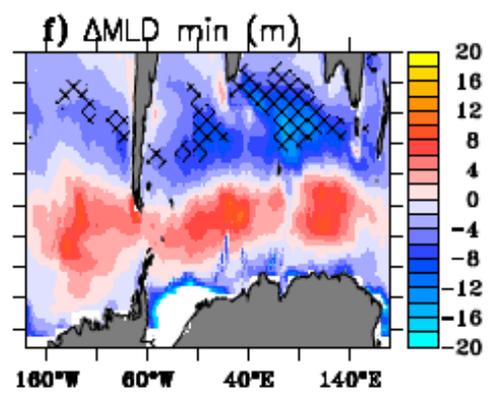
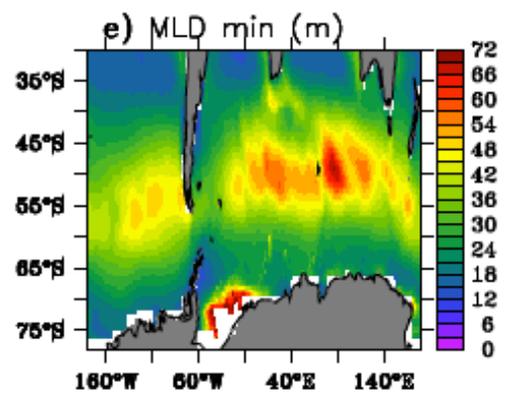
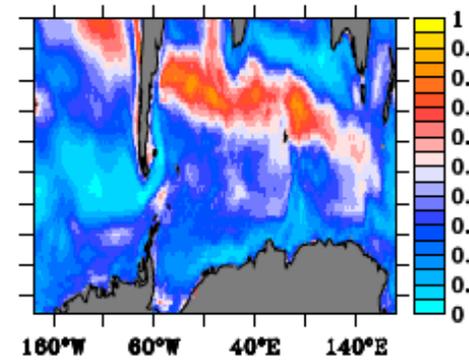
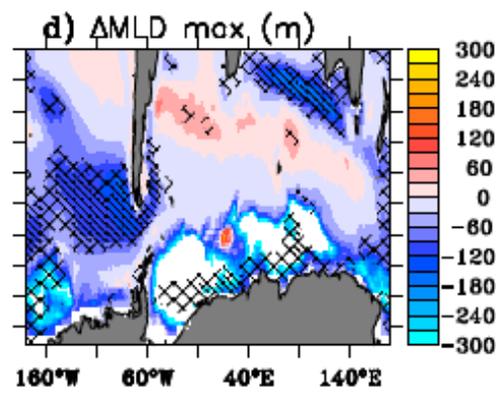
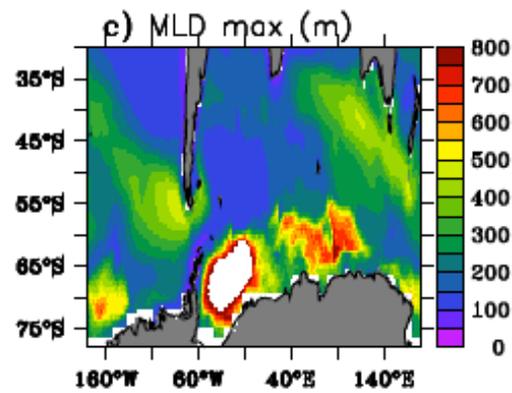
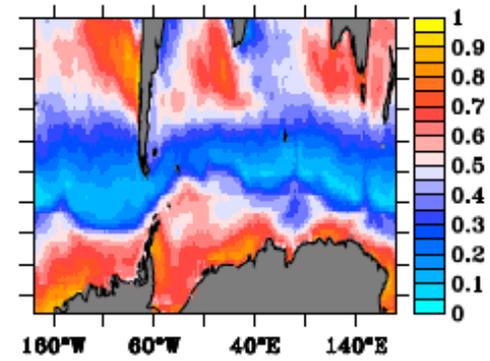
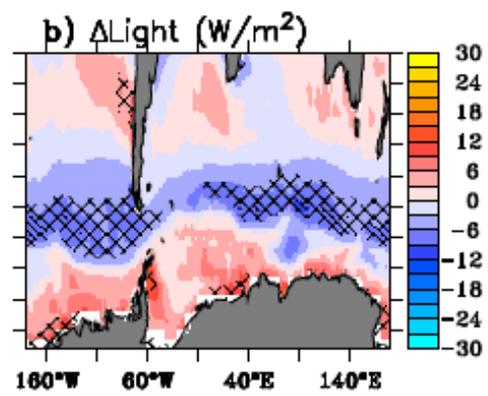
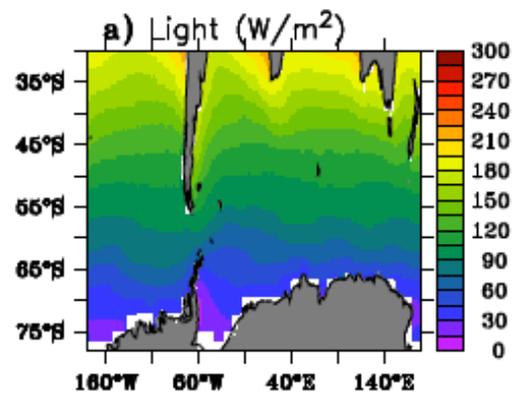
- ✱ CanESM2
- ◆ CESM1-BGC
- GFDL-ESM2G
- GFDL-ESM2M
- ▲ HadGEM2-CC
- ▼ HadGEM2-ES
- ▶ MIROC-ESM
- ▲ MIROC-ESM-CHEM
- ✕ IPSL-CM5A-LR
- ✚ IPSL-CM5A-MR
- ◐ MPI-ESM-LR
- ✕ MPI-ESM-MR
- ◑ NorESM1-ME
- ✚ MRI-ESM1
- ◑ CMCC-CESM

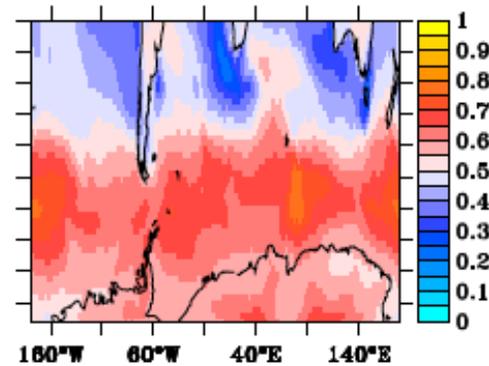
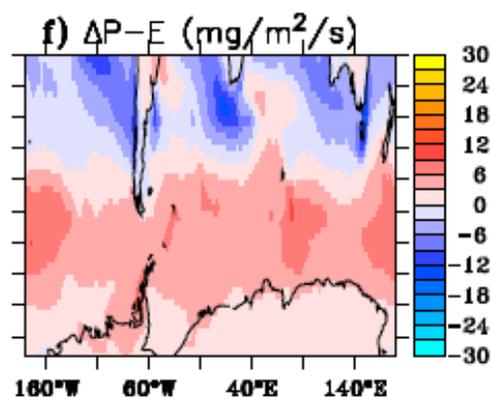
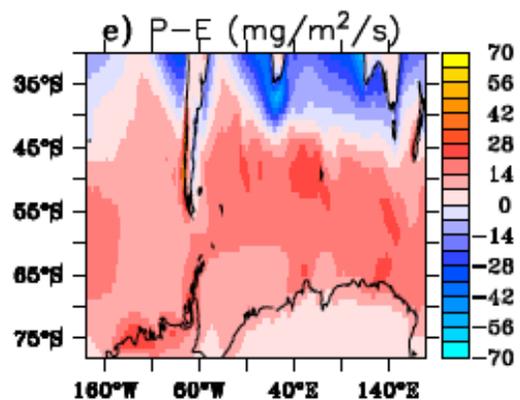
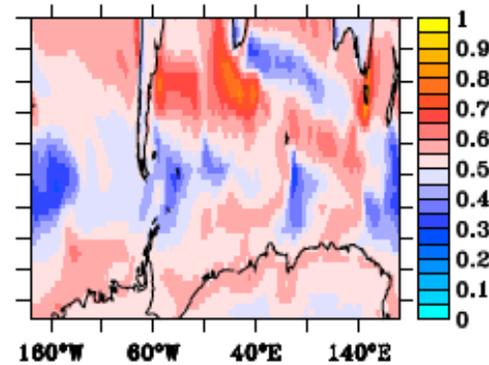
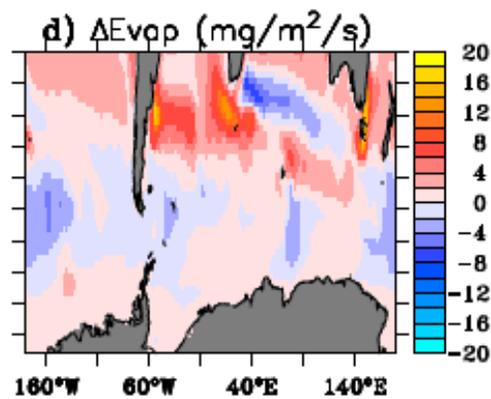
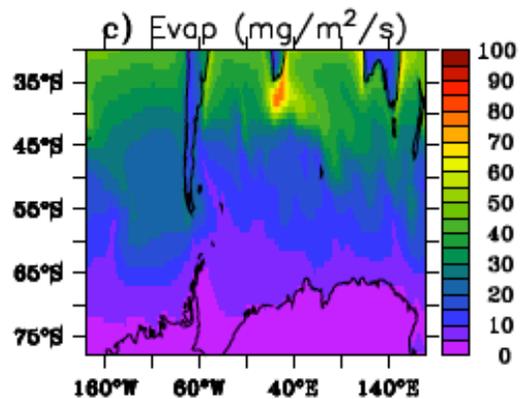
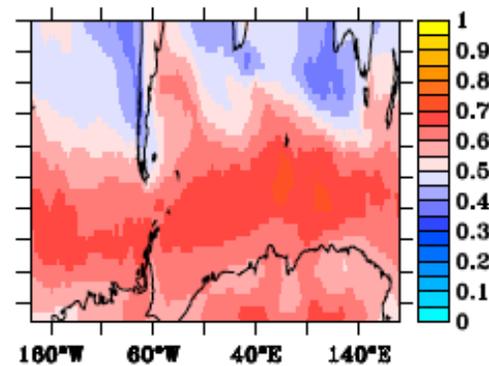
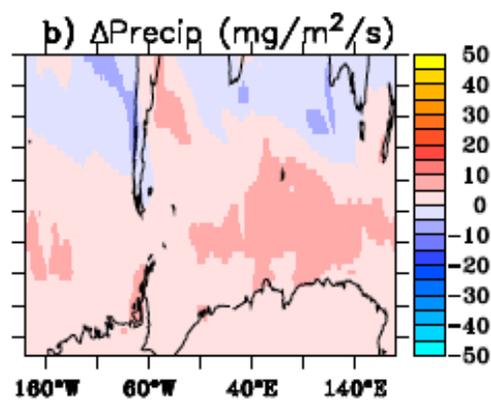
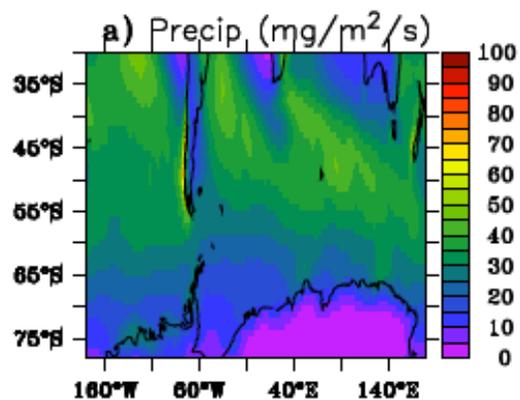


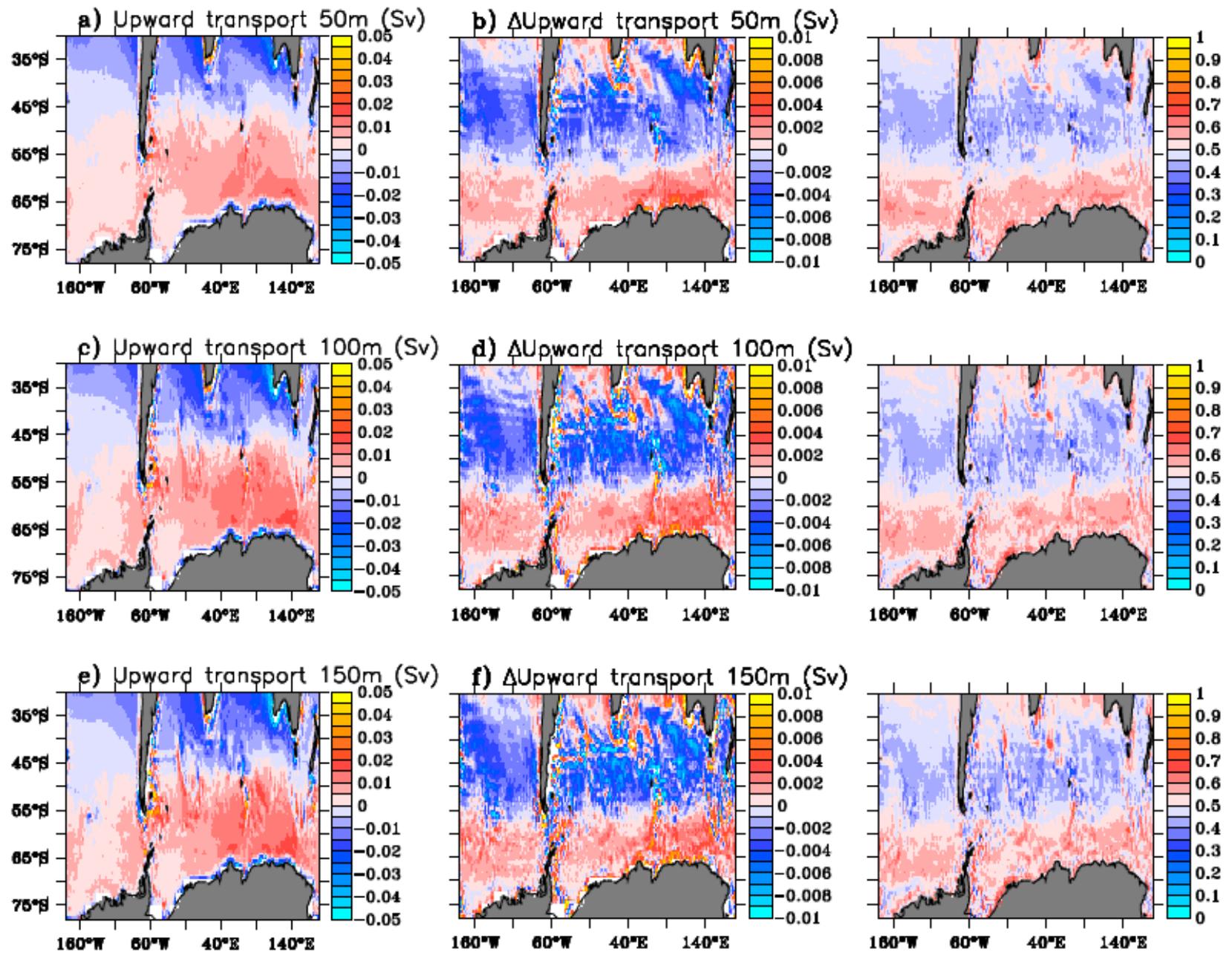




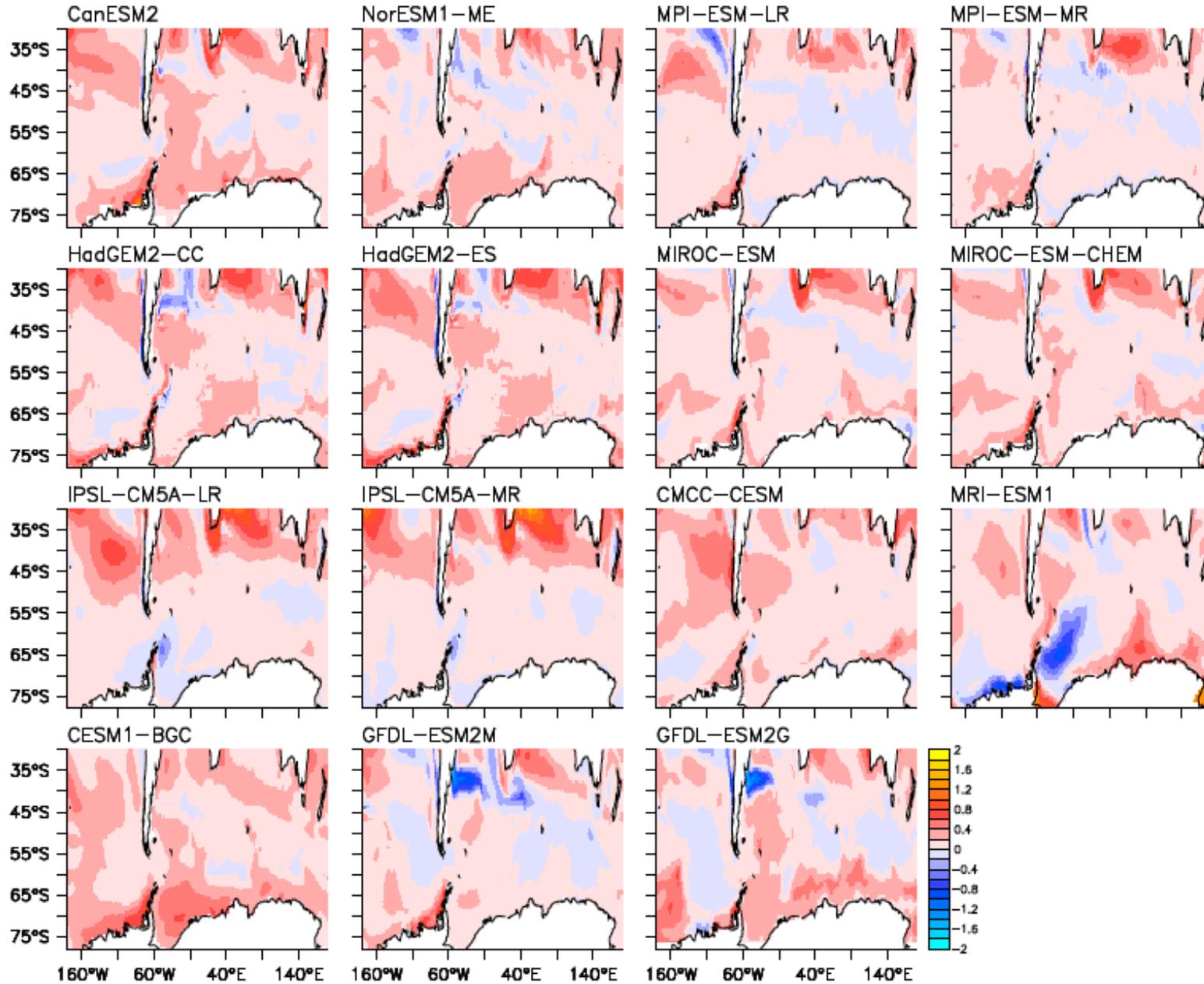




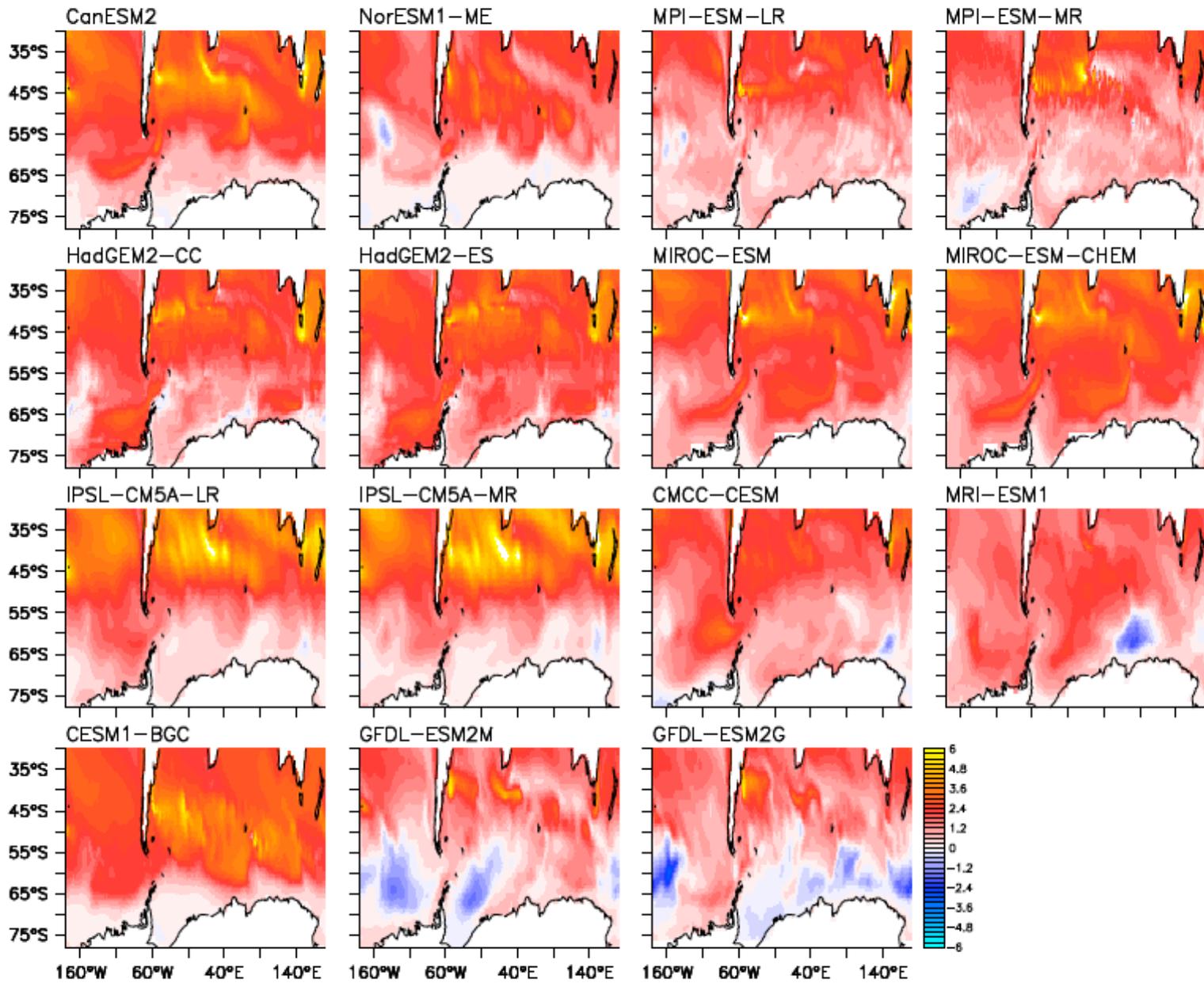




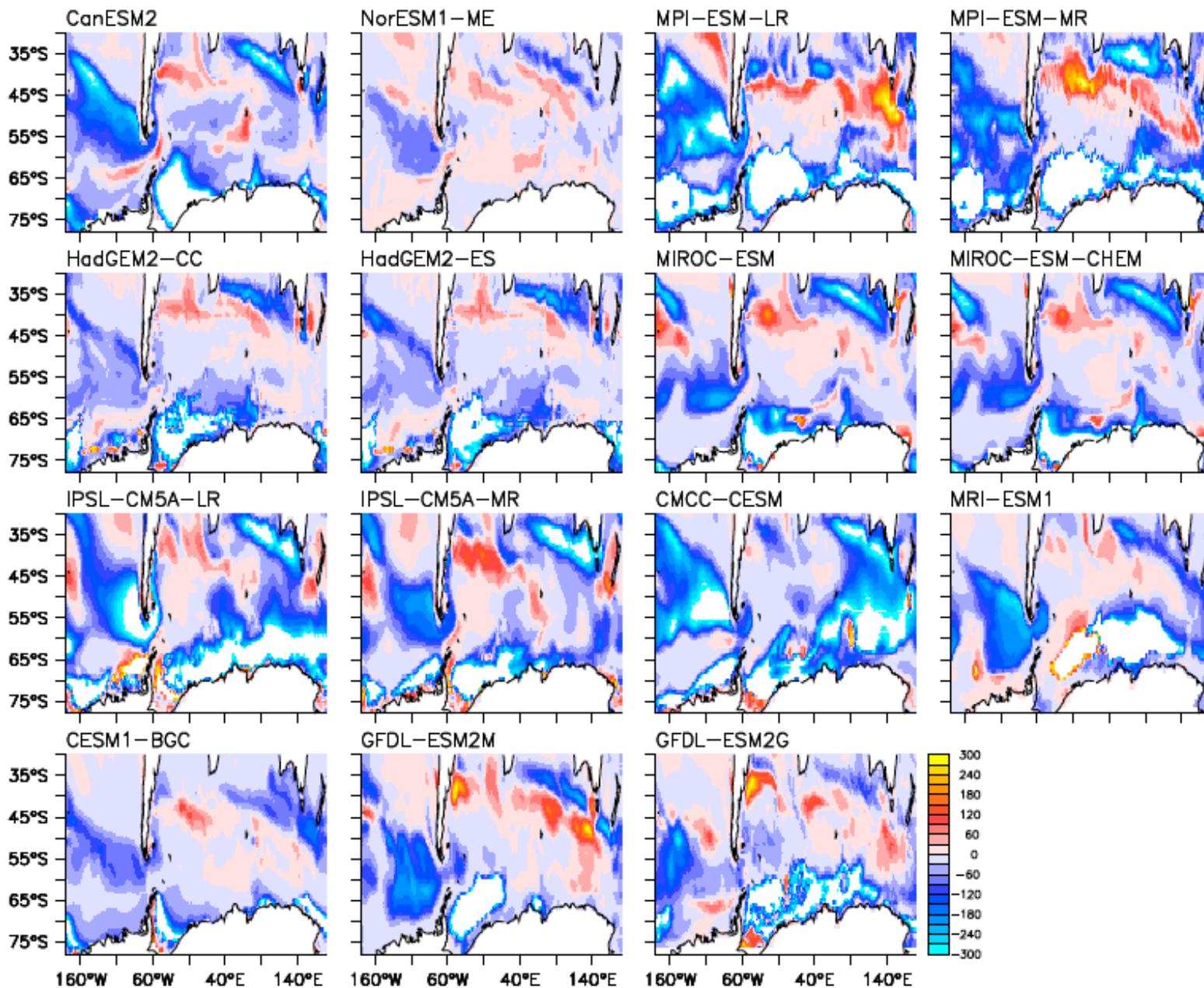
# $\Delta$ Stratification



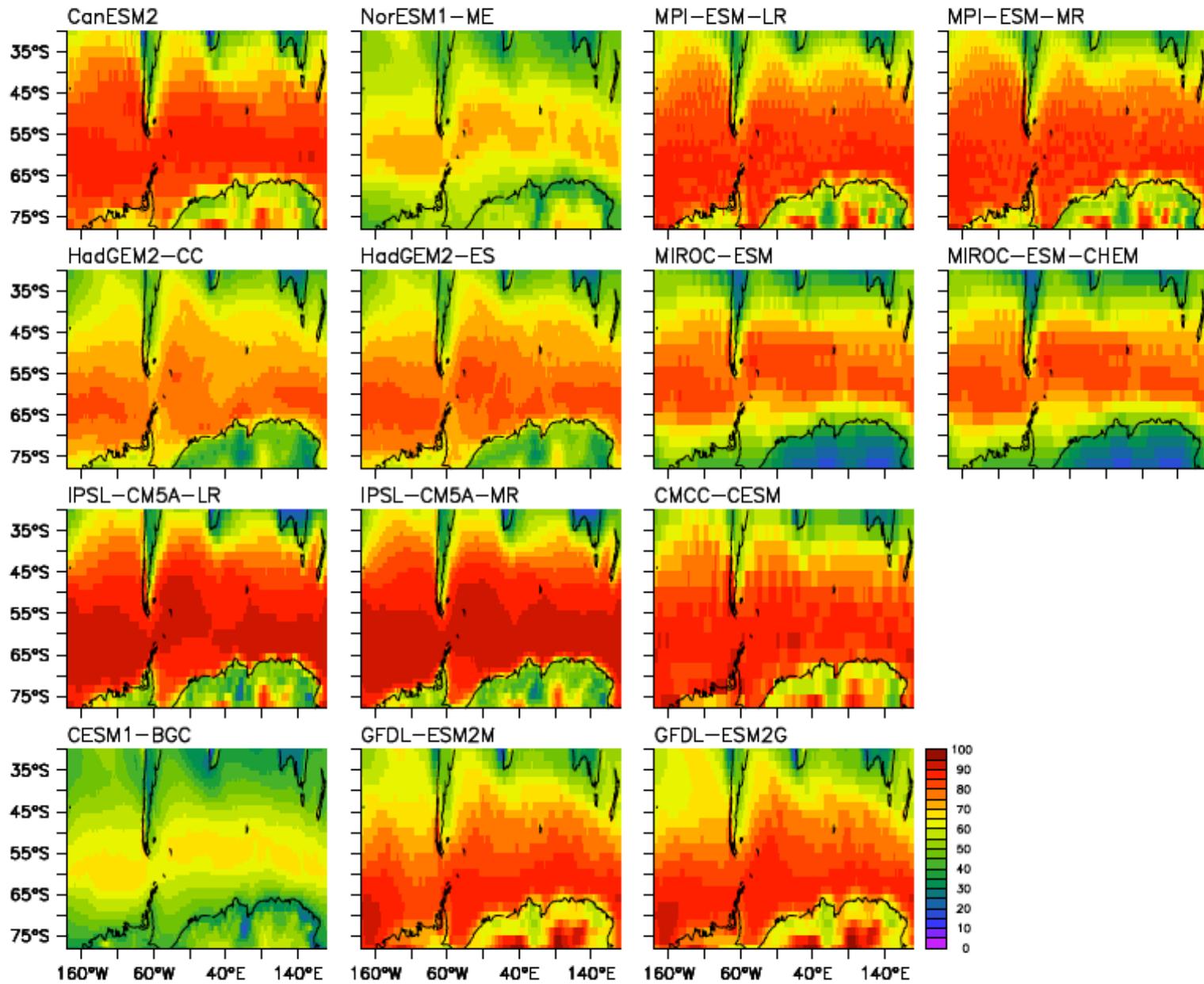
# $\Delta$ SST



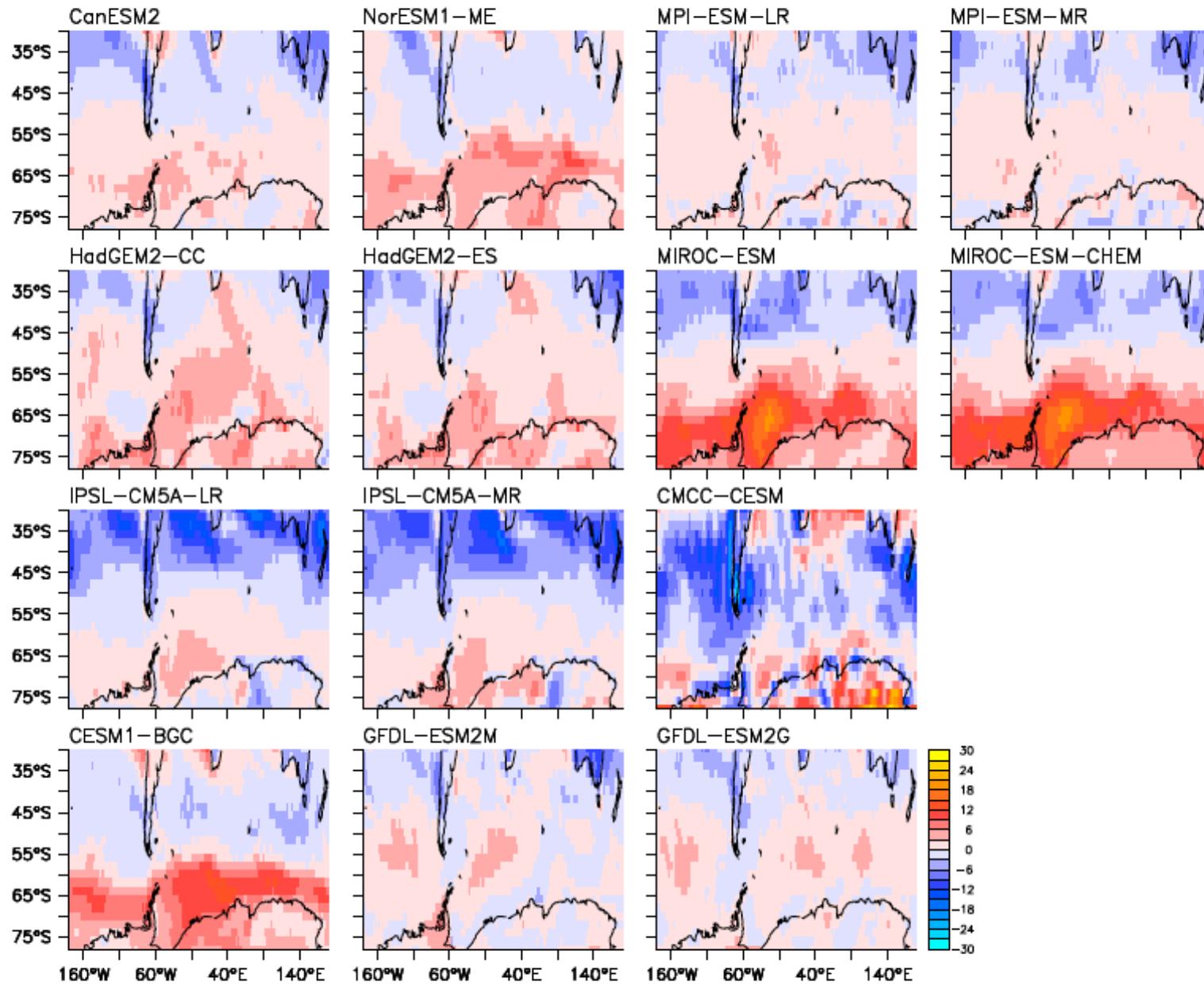
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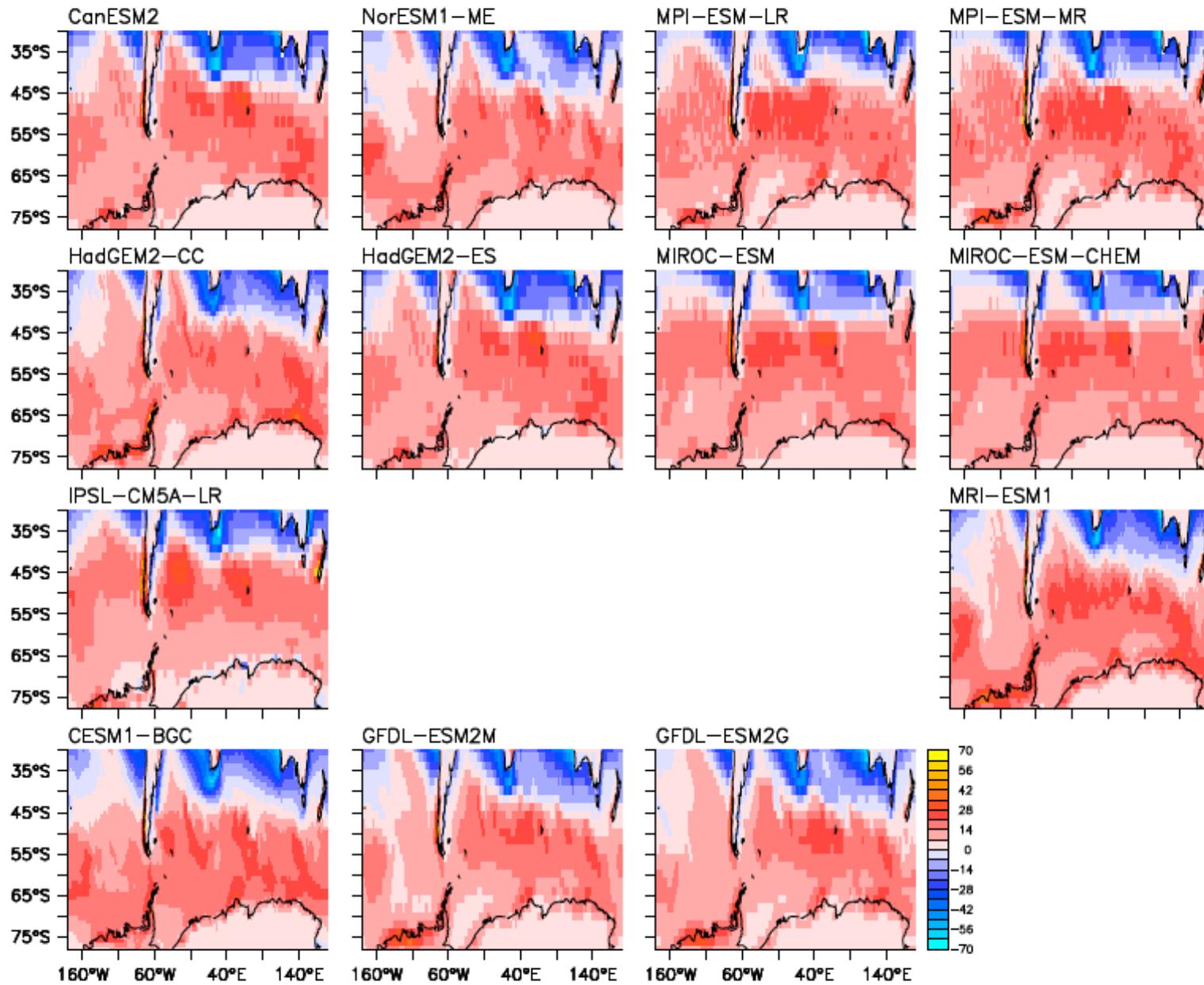
# Clouds present



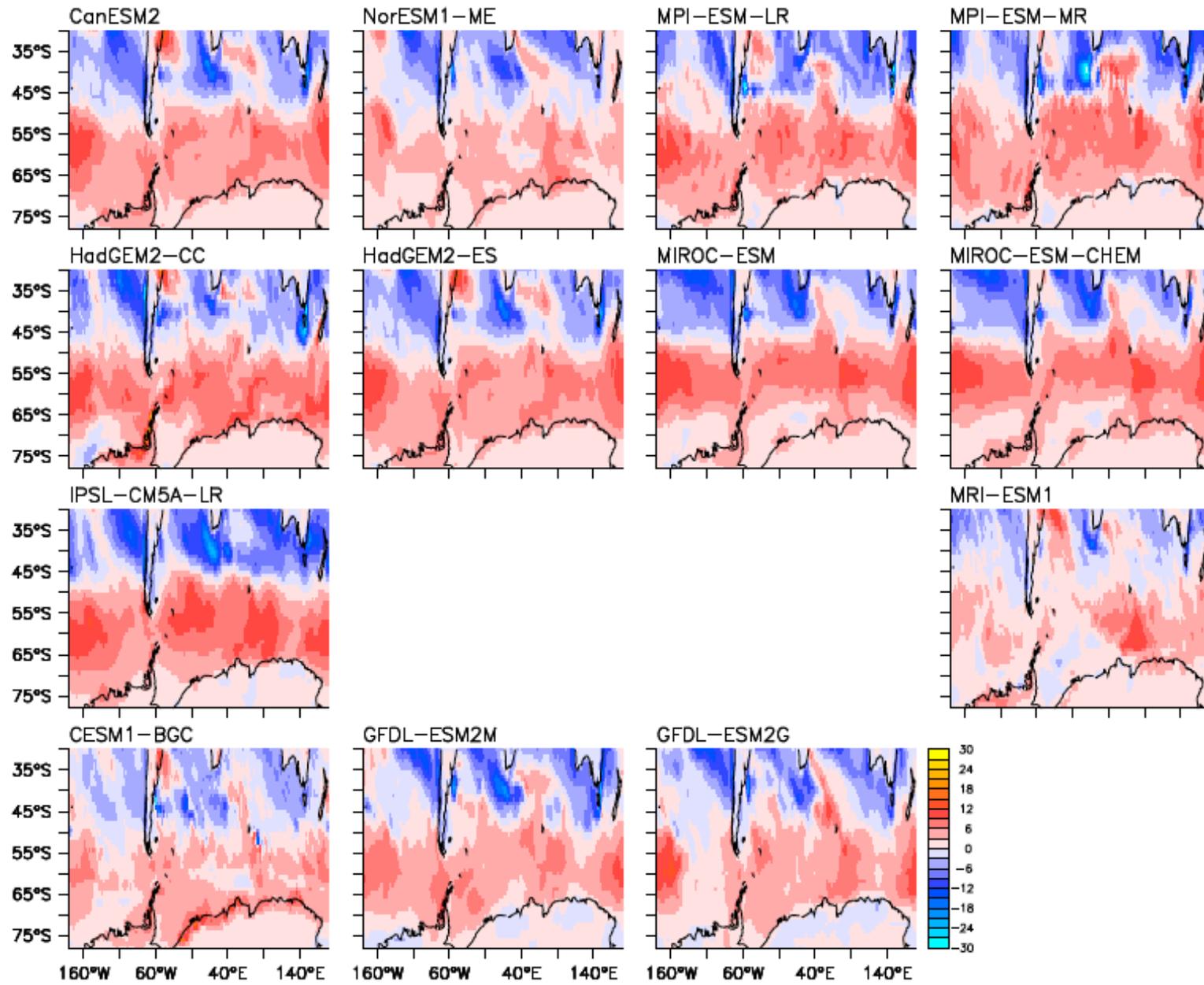
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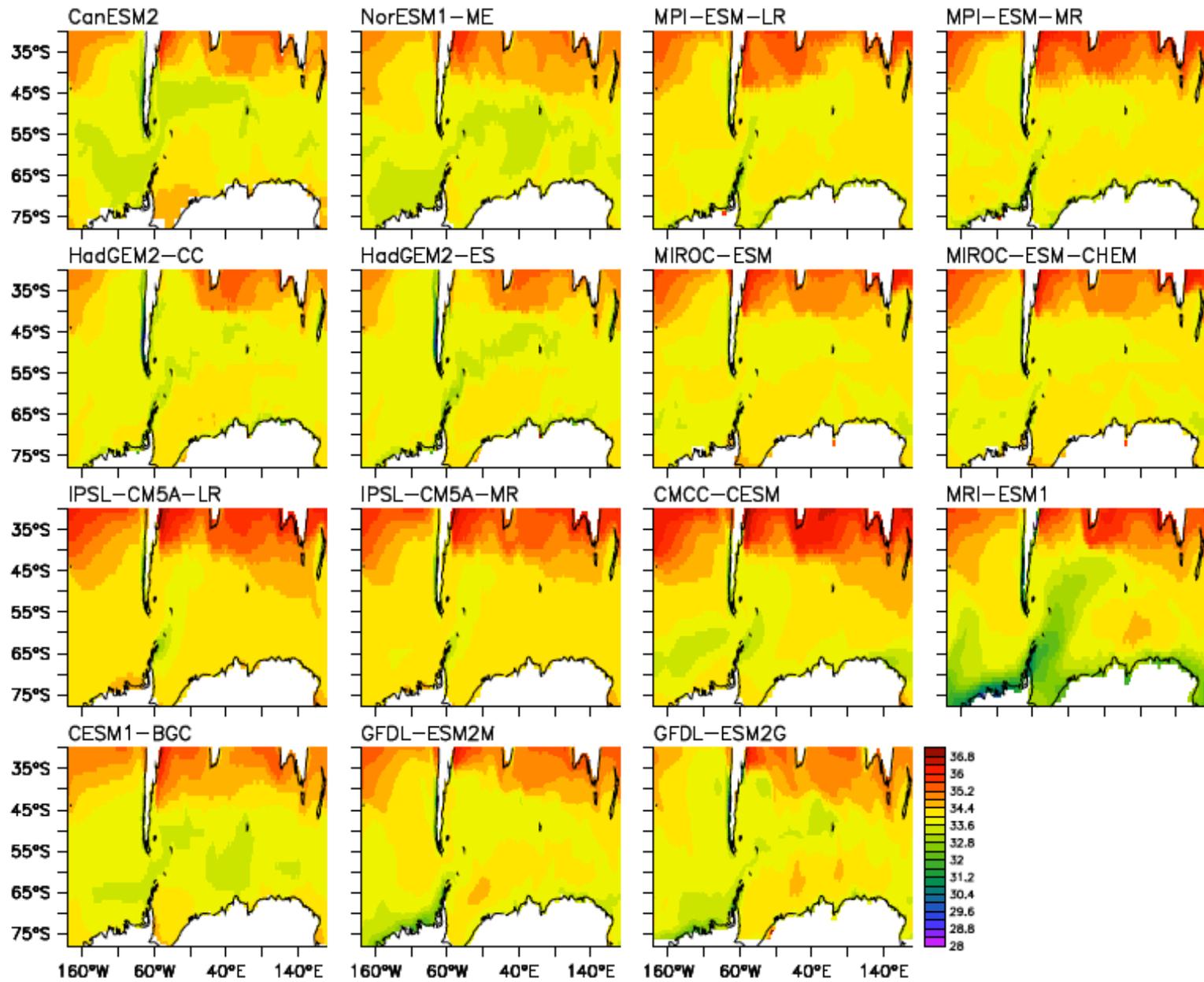
# P-E present



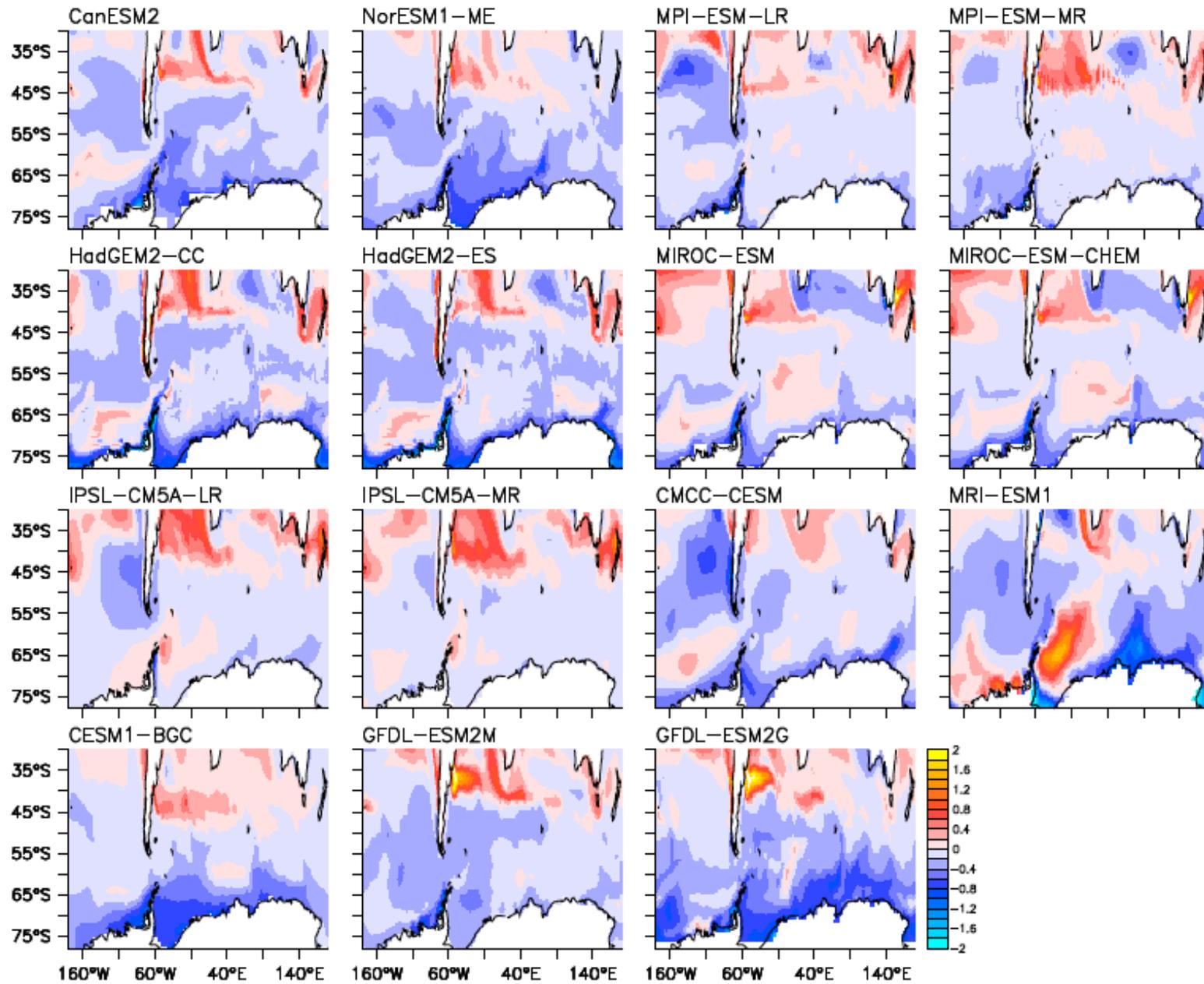
# $\Delta P-E$



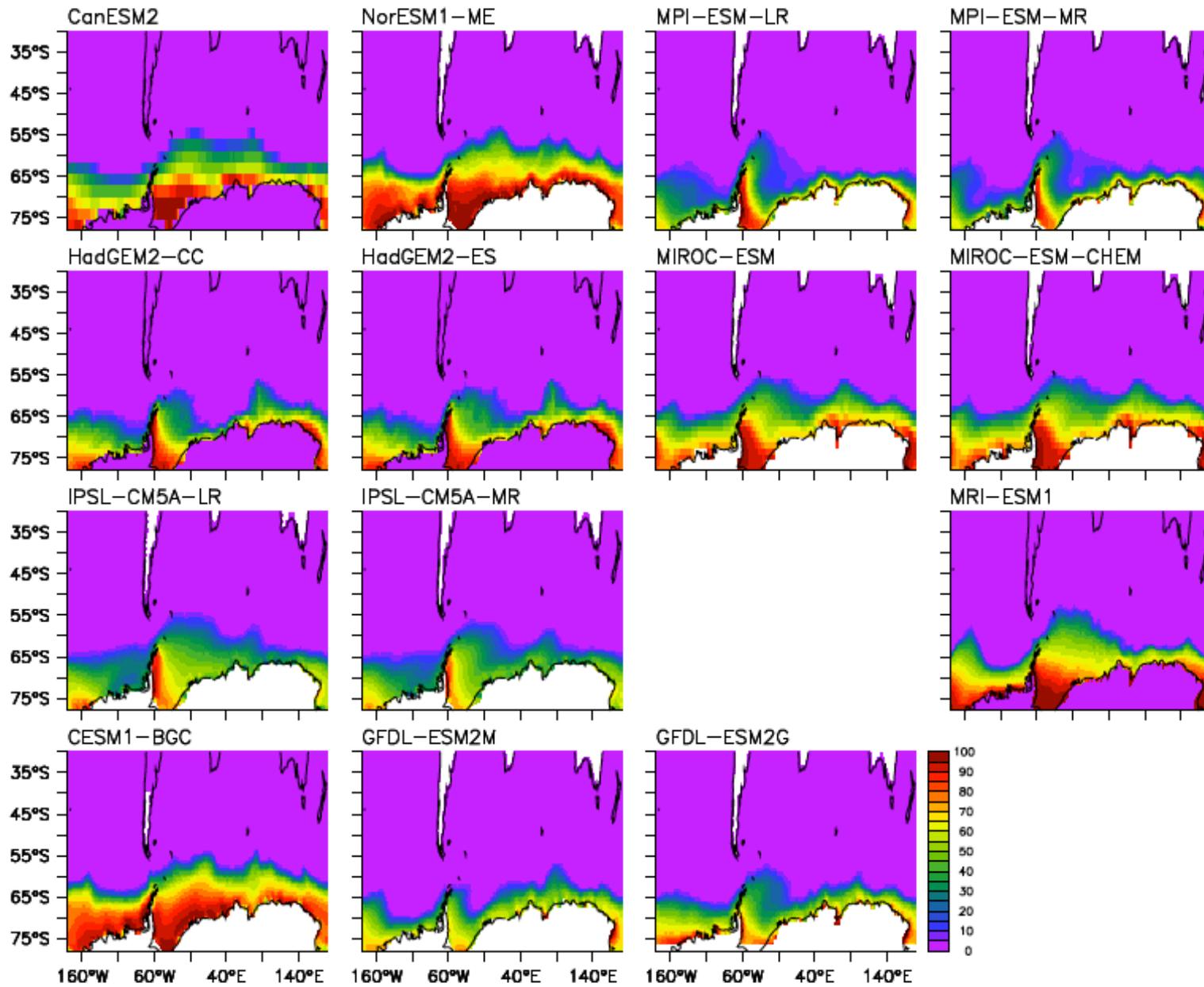
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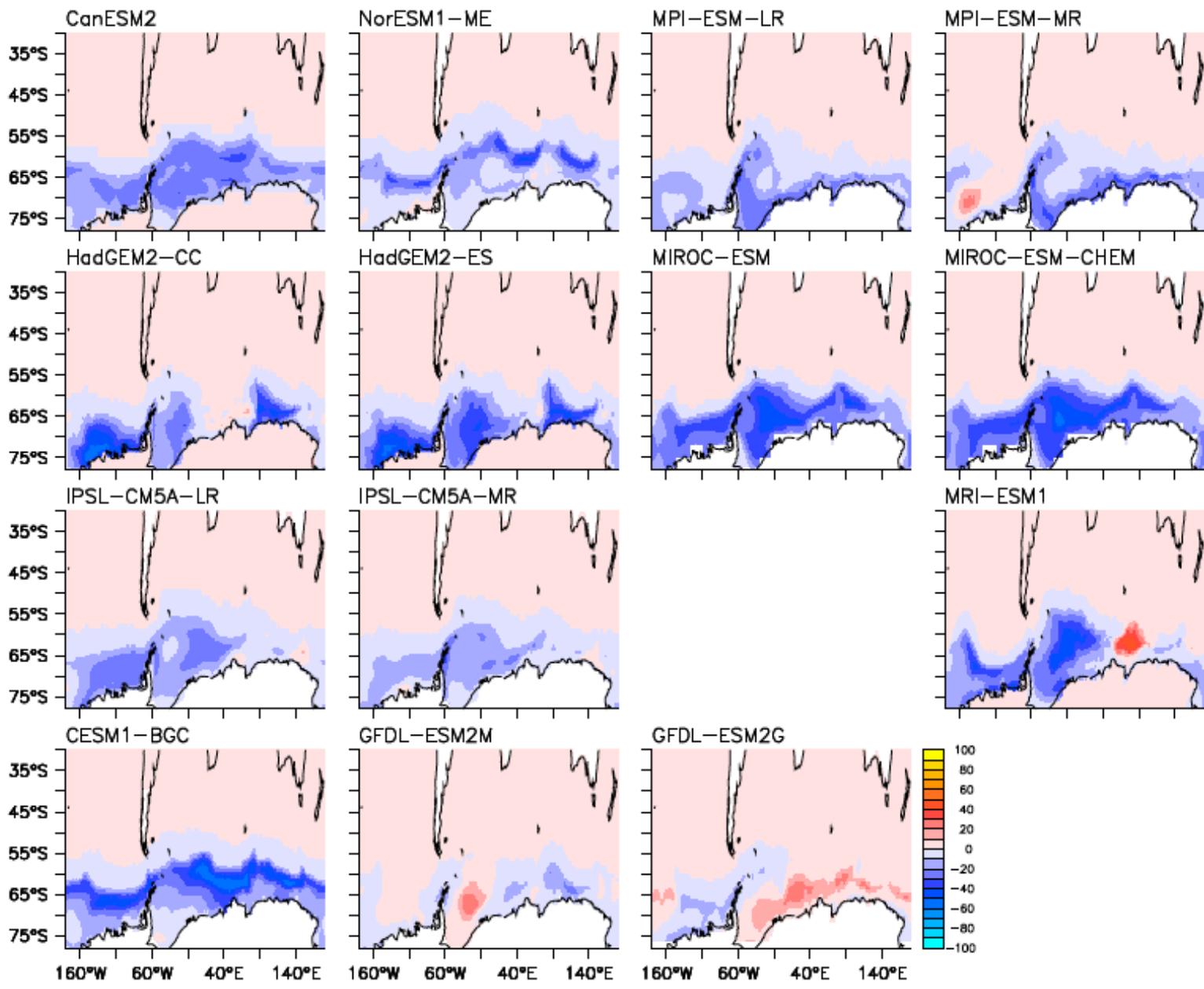
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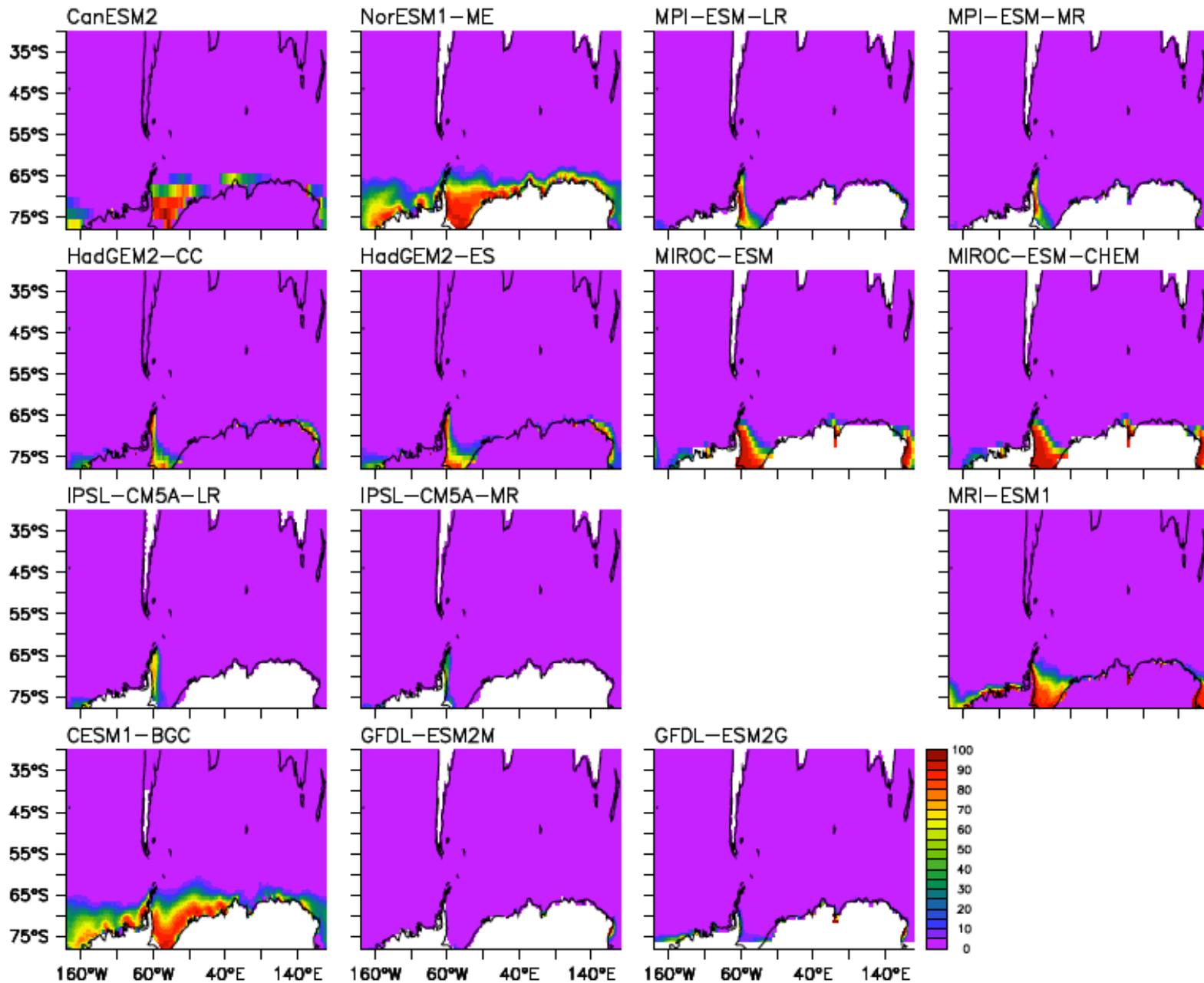
# Ice present



# $\Delta$ ice



# Summer ice present



# $\Delta$ summer ice

