Southern Ocean response to climate change in the CMIP5 models:

Linking biology to physics

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7th 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

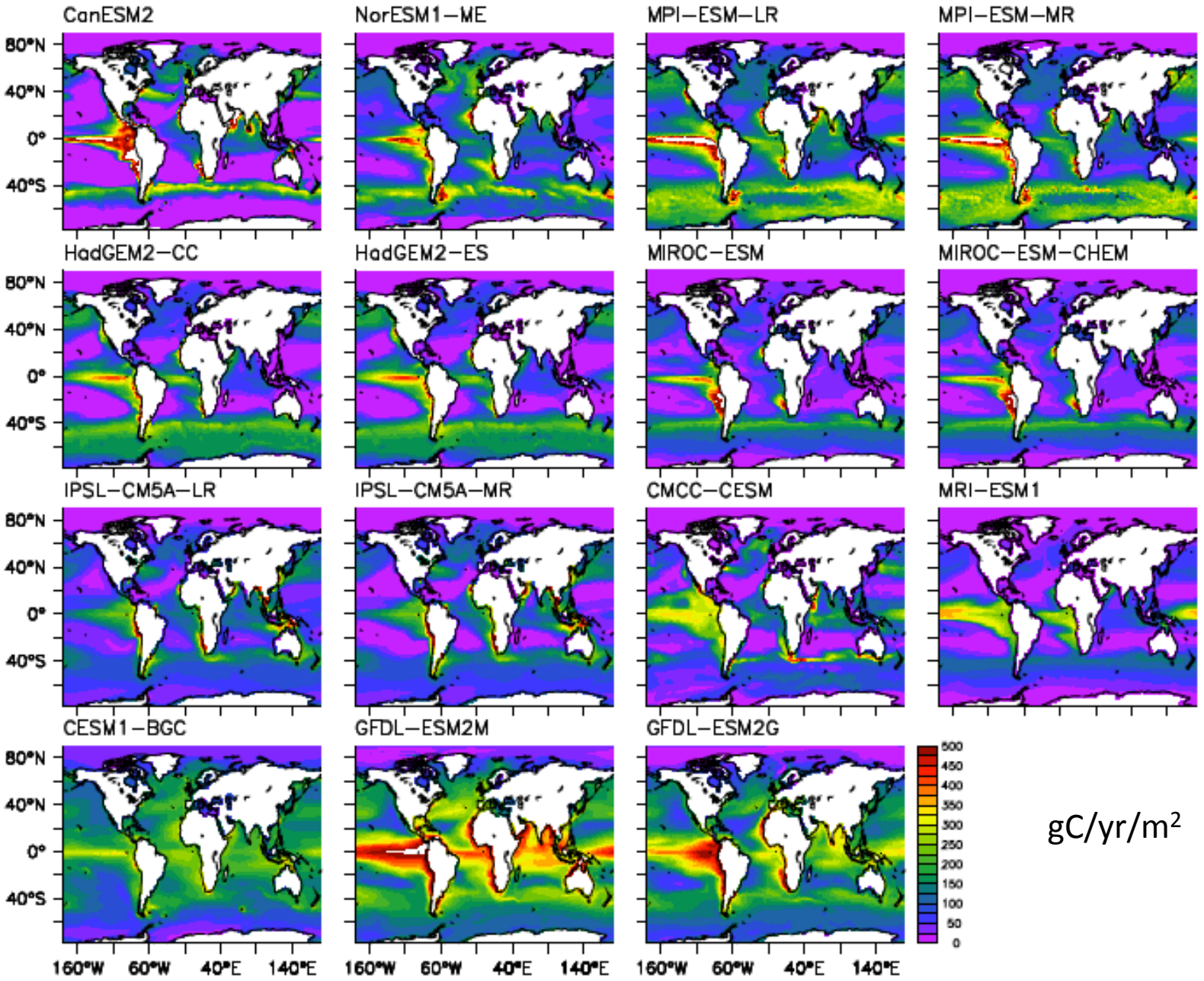
CESM1-BGC: NCAR carbon cycle, POP ecosystem model

MRI-ESM1: (Meteorological Research Institute)

NorESM1-ME: (Norwegian Climate Centre)

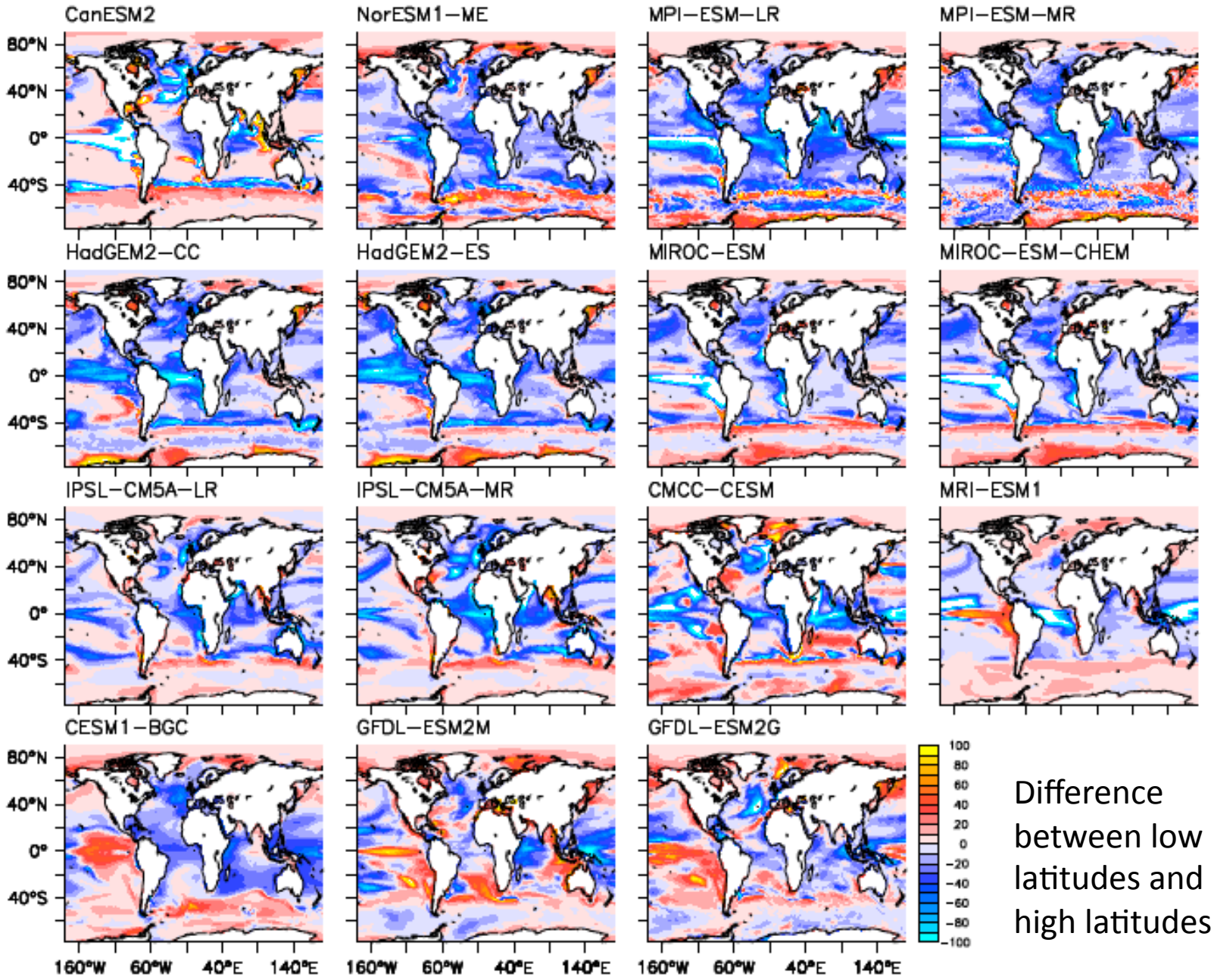
CMCC-CESM : Pelagos Marine biogeochemistry model (Centro Europeo per l Cambiamenti Climatici)

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



gC/yr/m^2

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



Difference between low latitudes and high latitudes

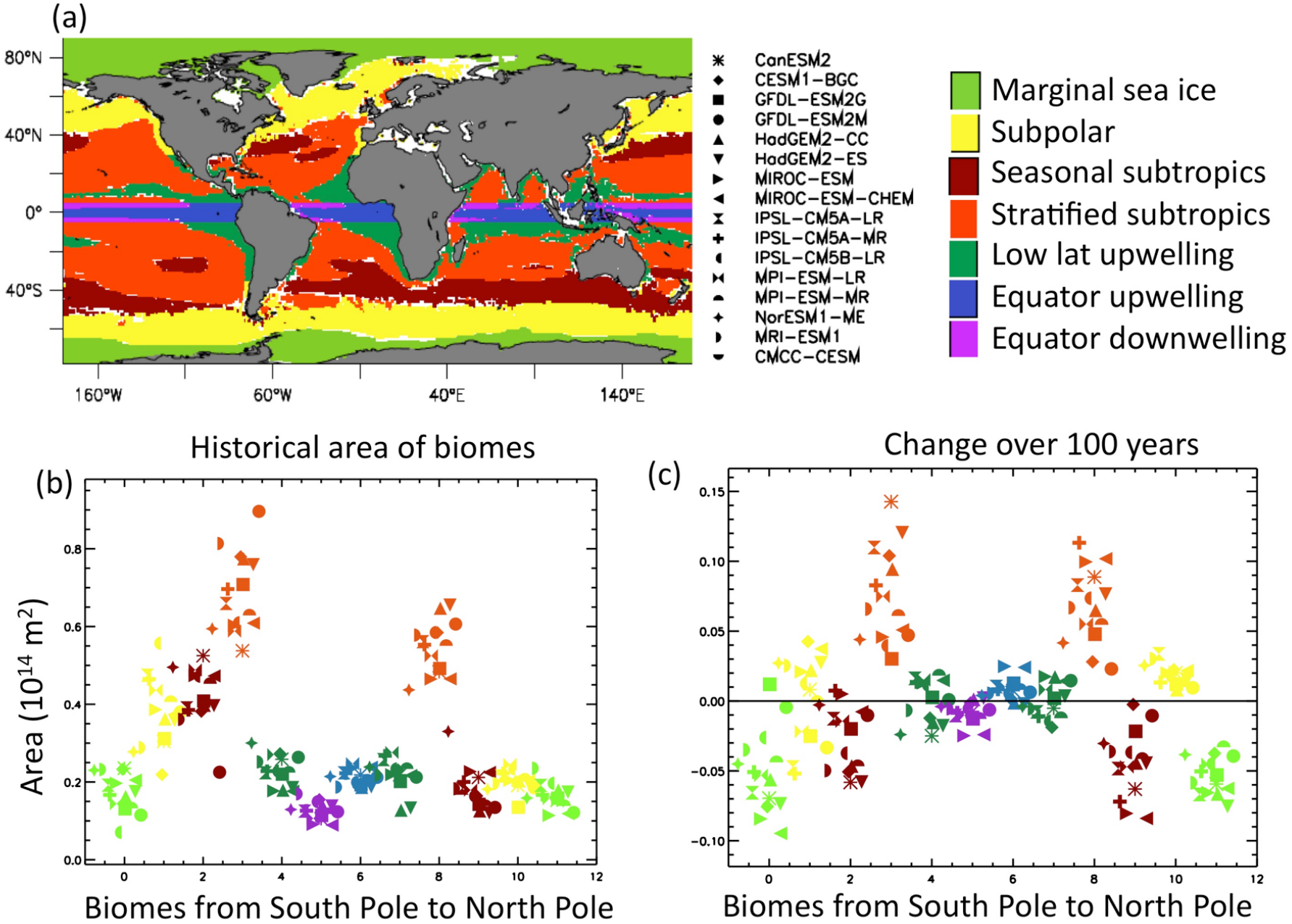
GLOBAL CHANGE

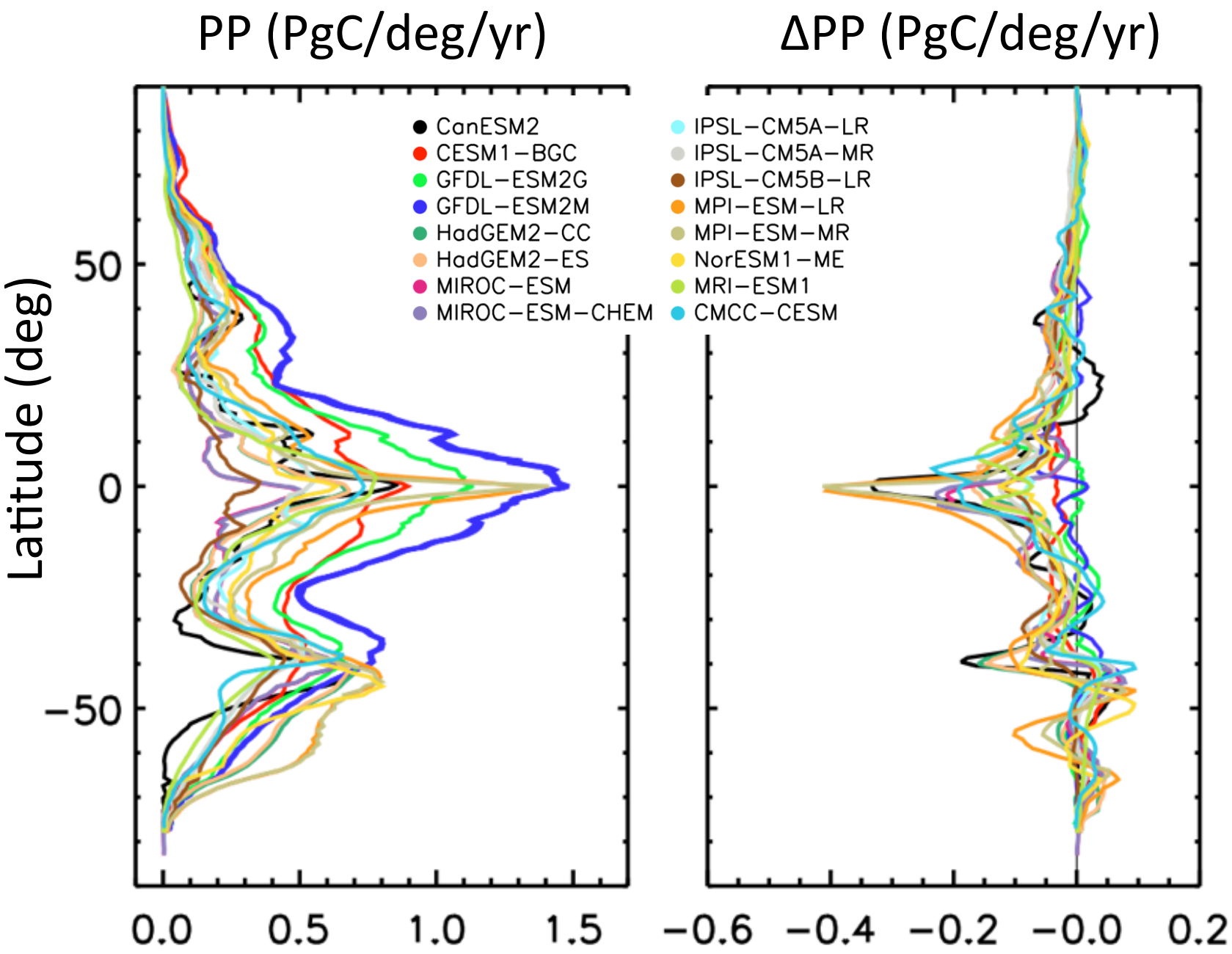
Model	ΔSST(ºC)	PP(PgC/yr)	ΔPP(PgC/yr)	Exp(PgC/yr)	ΔExp(PgC/yr)	Δ(Dia
CanESM2	3.174	33.007	-4.697	0.904	0.009	
CESM1-BGC	2.495	57.98	-2.028	1.518	-0.246	-0
GFDL-ESM2G	2.007	65.353	-0.616	1.742	-0.12	-0
GFDL-ESM2M	1.927	82.149	-0.535	2.007	-0.13	-0
HadGEM2-CC	3.103	36.558	-5.162	2.774	-0.367	-0
HadGEM2-ES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

% of global production in each zone

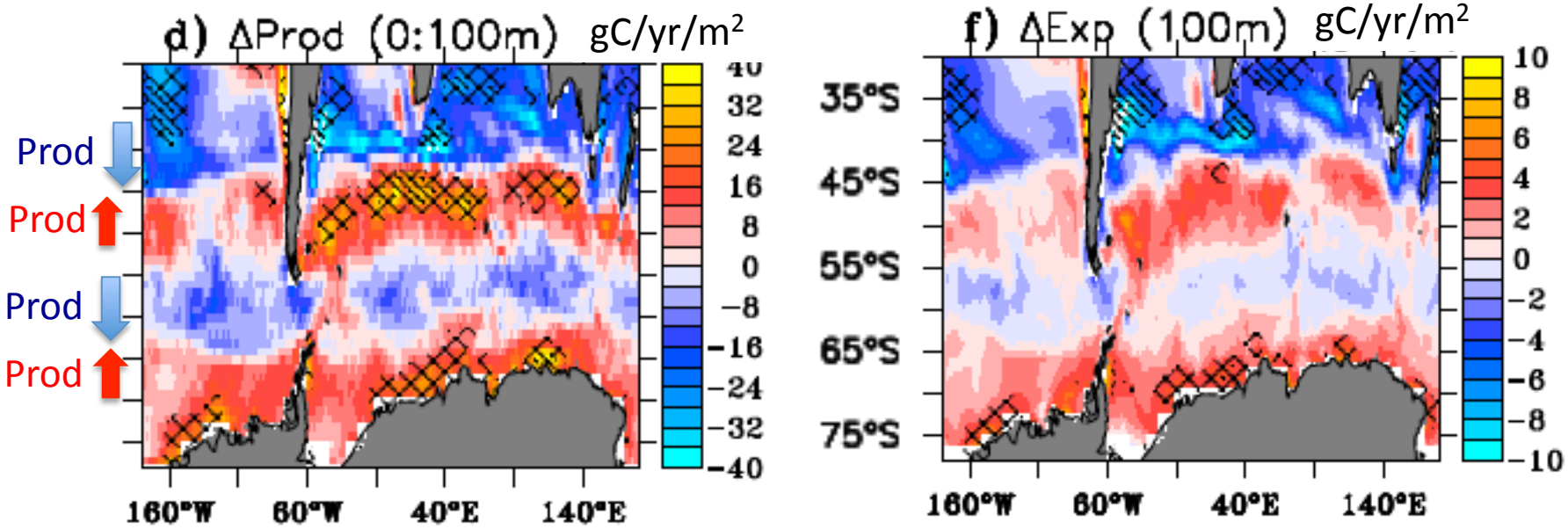
Models / Zones	10S-10N (19%) Present (% of global)	10S-10N (19%) Future (% of global)	10S-10N (19%) Δ (% of global)	15N to 40N (17%) Present (% of global)	15N to 40N (17%) Future (% of global)	15N to 40N (17%) Δ (% of global)	15S to 40S (22%) Present (% of global)	15S to 40S (22%) Future (% of global)	15S to 40S (22%) Δ (% of global)	45N to 90N (9%) Present (% of global)	45N to 90N (9%) Future (% of global)	45N to 90N (9%) Δ (% of global)	45S to 90S (17%) Present (% of global)	45S to 90S (17%) Future (% of global)	45S to 90S (17%) Δ (% of global)
CanESM2	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
CESM1-BGC	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
GFDL-ESM2G	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
GFDL-ESM2M	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
HadGEM2-CC	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
HadGEM2-ES	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
MIROC-ESM	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
MIROC-ESM-CHEM	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
IPSL-CM5A-LR	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
IPSL-CM5A-MR	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
MPI-ESM-LR	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
MPI-ESM-MR	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
NorESM1-ME	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
MRI-ESM1	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
CMCC-CESM	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


(a)
80°N
40°N
0°
40°S
160°W
60°W
40°E
140°E
CanESM2
CESM1-BGC
GFDL-ESM2G
GFDL-ESM2M
HadGEM2-CC
HadGEM2-ES
MIROC-ESM
MIROC-ESM-CHEM
IPSL-CM5A-LR
IPSL-CM5A-MR
IPSL-CM5B-LR
MPI-ESM-LR
MPI-ESM-MR
NorESM1-ME
MRI-ESM1
CMCC-CESM
Marginal sea ice
Subpolar
Seasonal subtropics
Stratified subtropics
Low lat upwelling
Equator upwelling
Equator downwelling
Historical area of biomes
(b)
Area (10^{14} m^2)
0.0
0.2
0.4
0.6
0.8
0
2
4
6
8
10
12
Biomes from South Pole to North Pole
Change over 100 years
(c)
0.15
0.10
0.05
0.00
-0.05
-0.10
0
2
4
6
8
10
12
Biomes from South Pole to North Pole

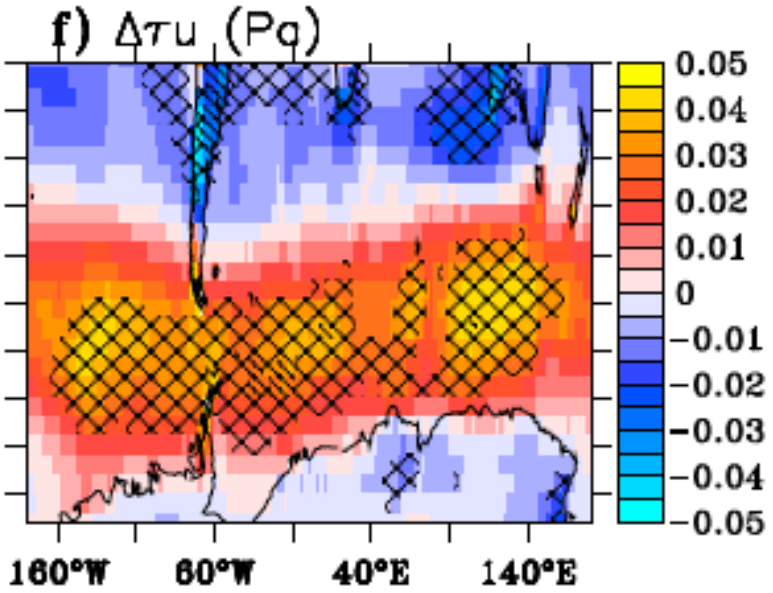

PP (PgC/deg/yr)
ΔPP (PgC/deg/yr)
Latitude (deg)
50
0
−50
0.0
0.5
1.0
1.5
−0.6
−0.4
−0.2
−0.0
0.2
CanESM2
CESM1−BGC
GFDL−ESM2G
GFDL−ESM2M
HadGEM2−CC
HadGEM2−ES
MIROC−ESM
MIROC−ESM−CHEM
IPSL−CM5A−LR
IPSL−CM5A−MR
IPSL−CM5B−LR
MPI−ESM−LR
MPI−ESM−MR
NorESM1−ME
MRI−ESM1
CMCC−CESM

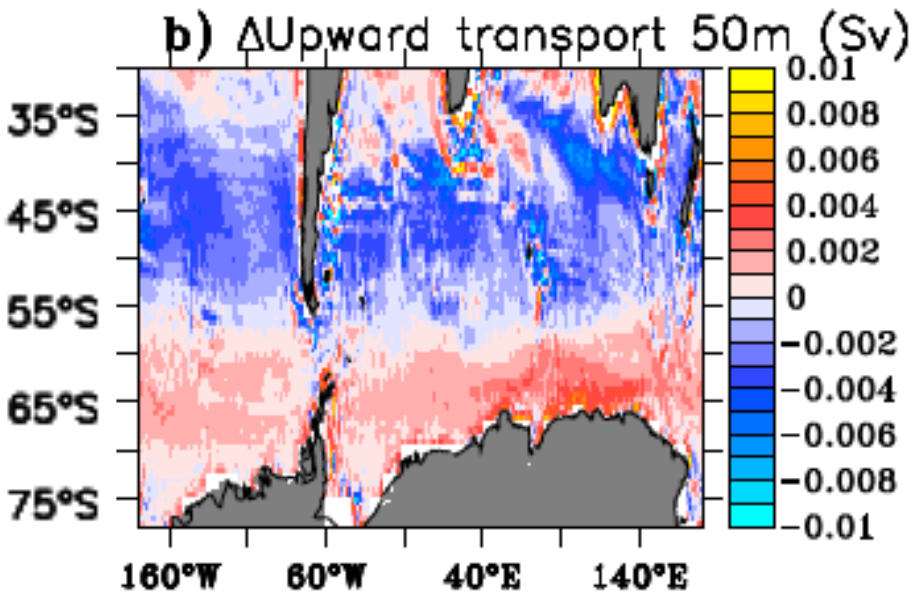
Change from (1980-1999) to (2080-2099).
Mean over all the models.
Masked areas show high consistency among models.

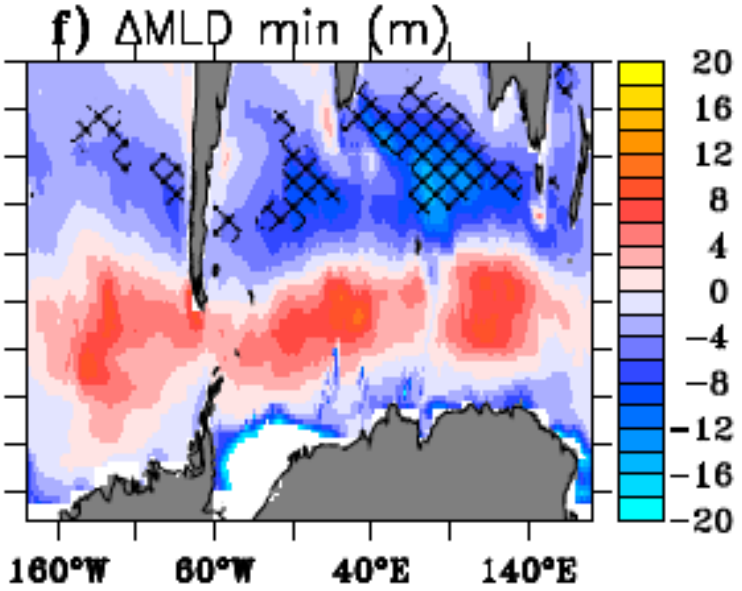


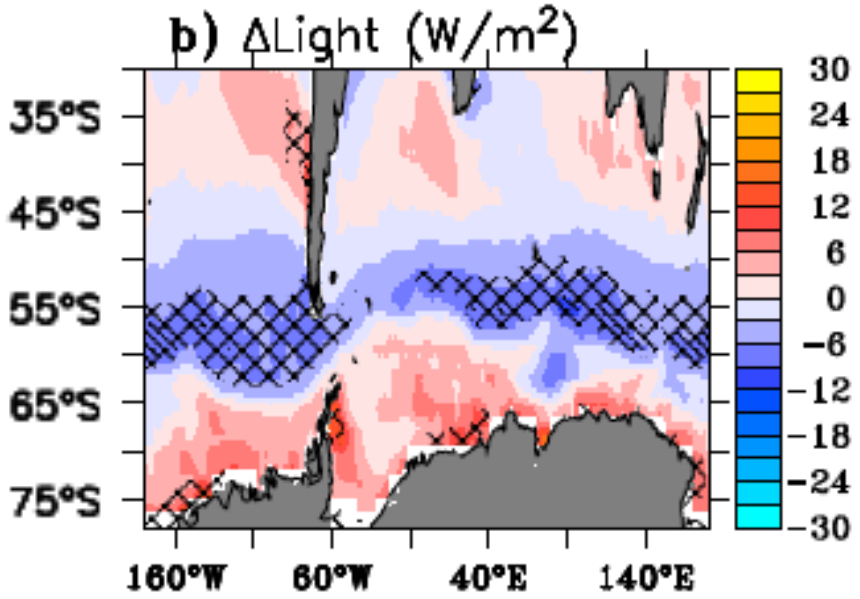
What's happening with the physics?

Δ → (1980-1999) to (2080-2099).



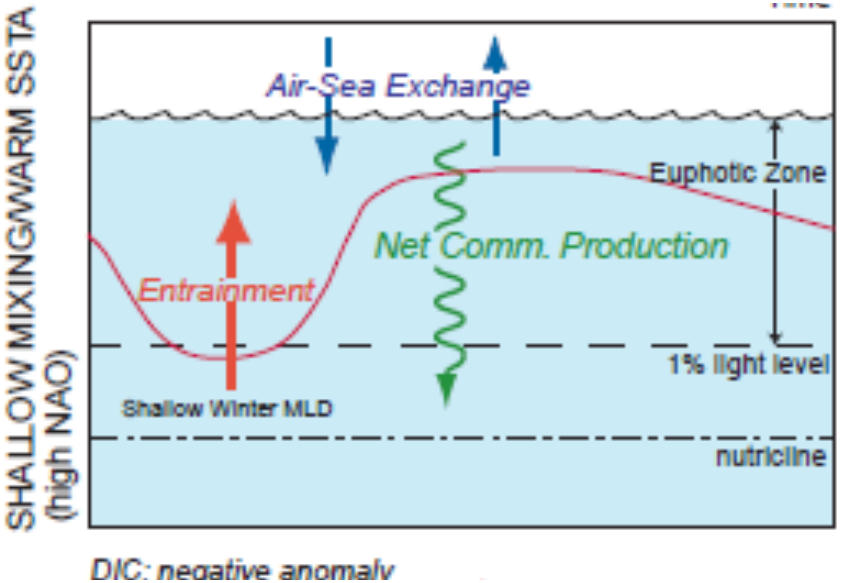




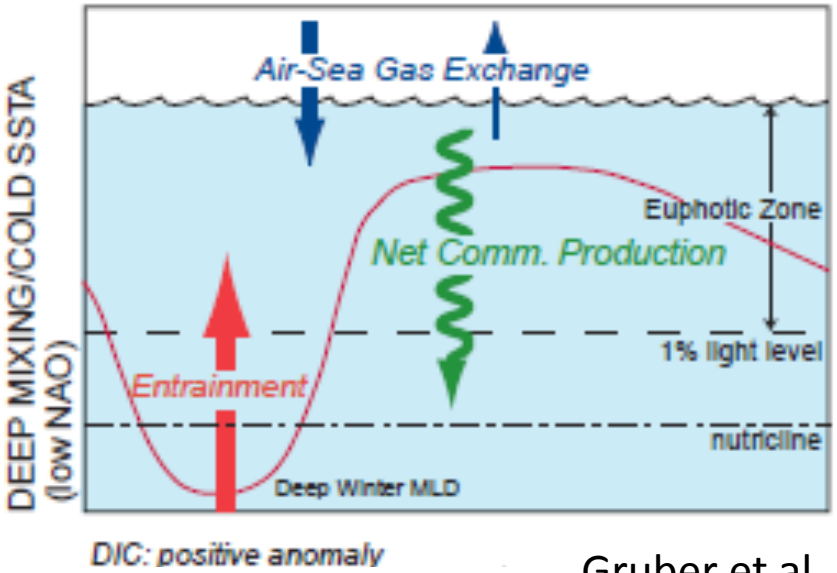


Physical Mechanisms :

Shallow winter MLD



Deep winter MLD



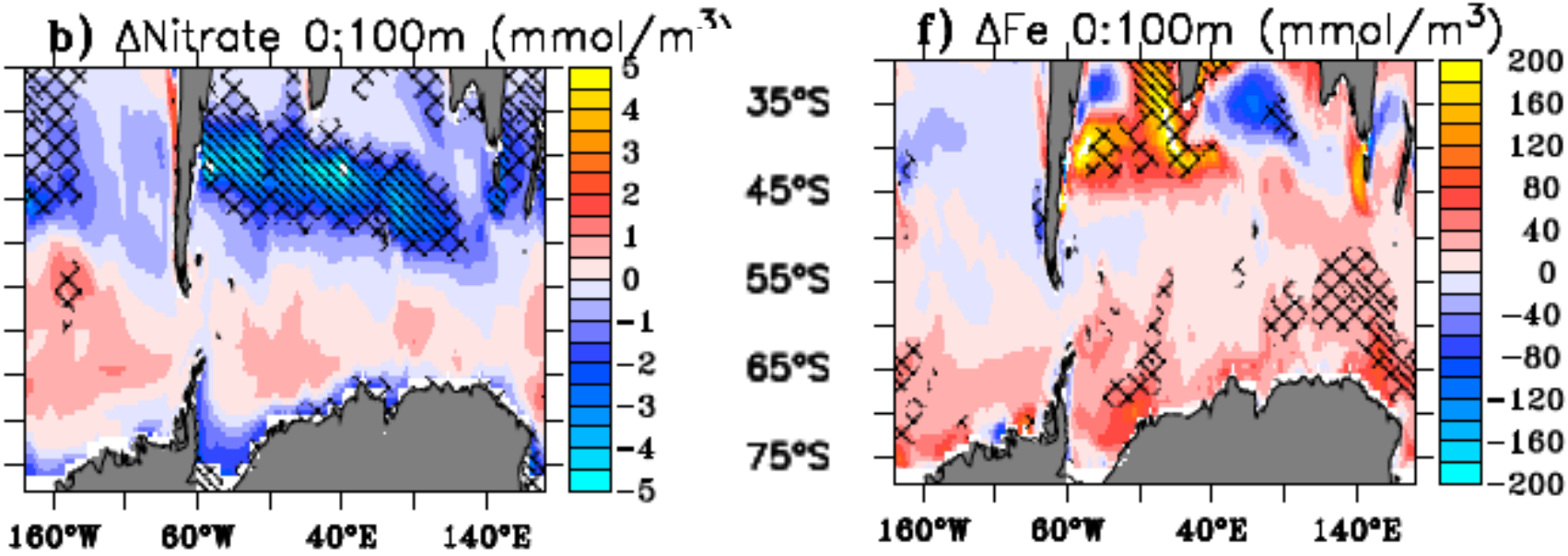
Gruber et al. 2002

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

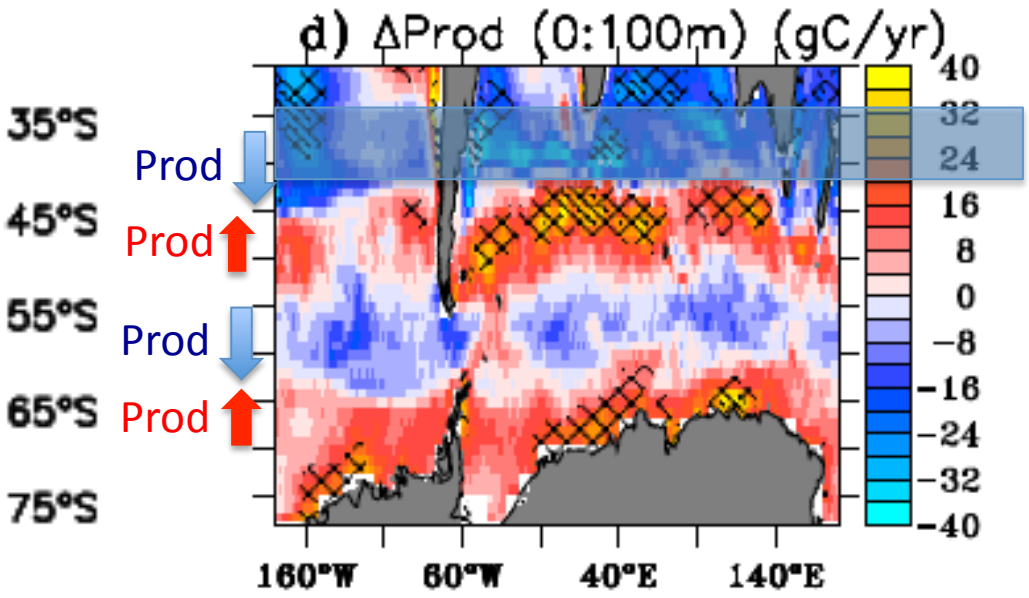
Δ → (1980-1999) to (2080-2099).

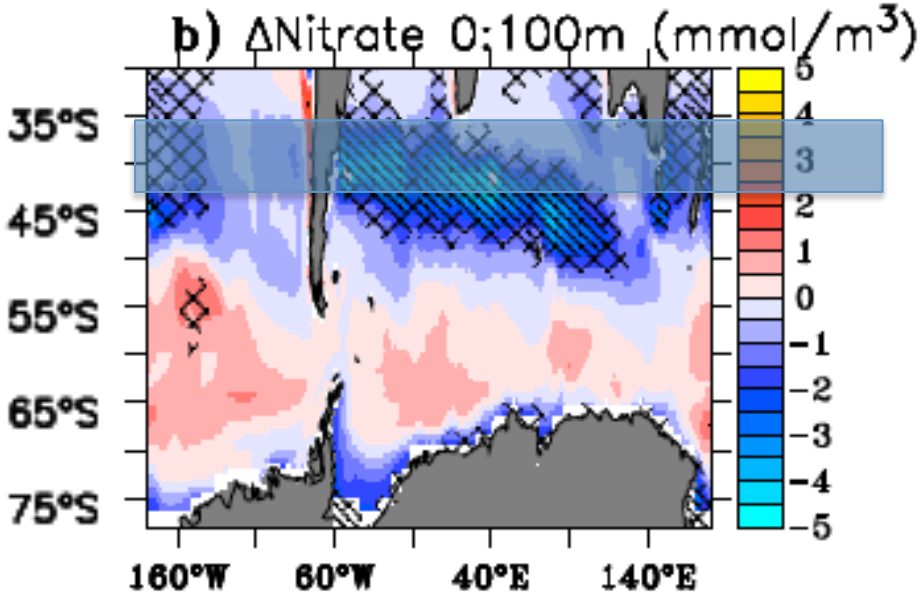
And the nutrients?



Iron increase? Sediments, circulation?

Misumi et al, 2013, studies iron budget in NCAR model

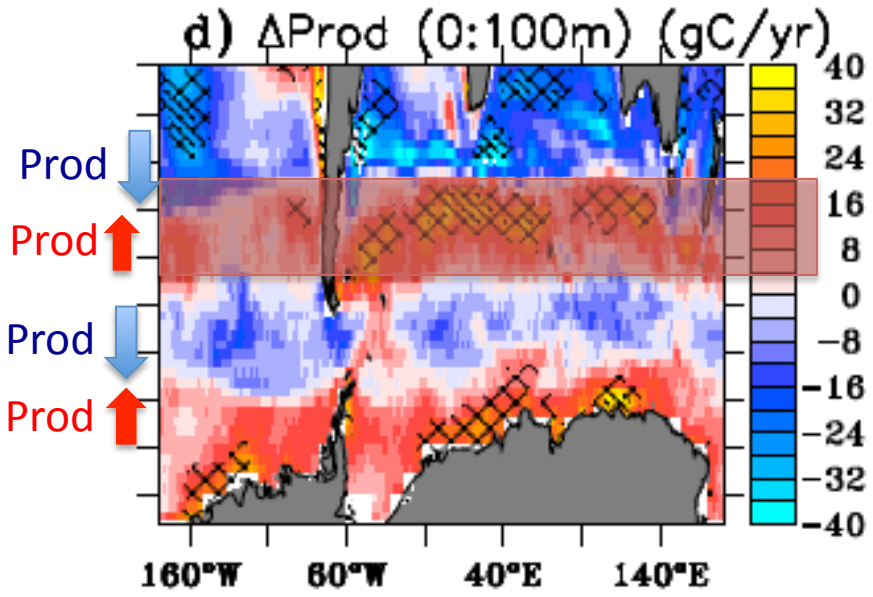


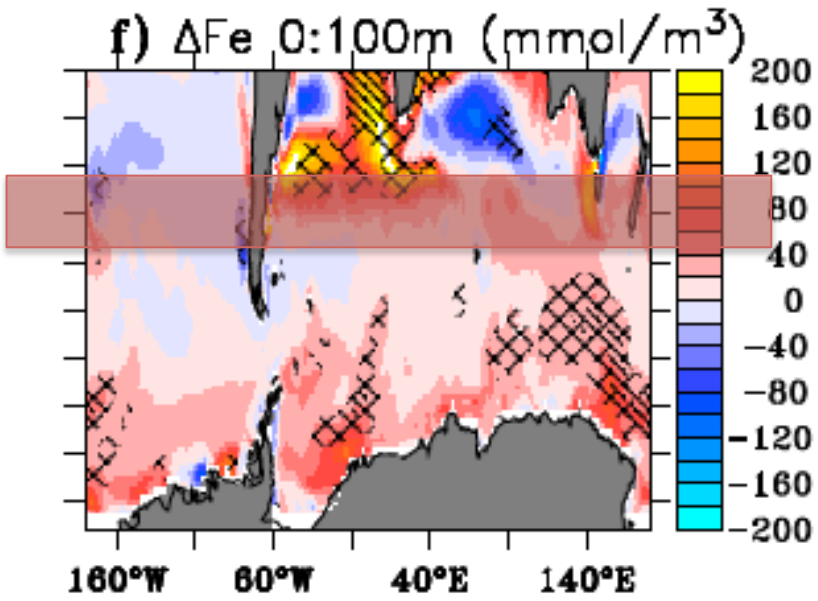


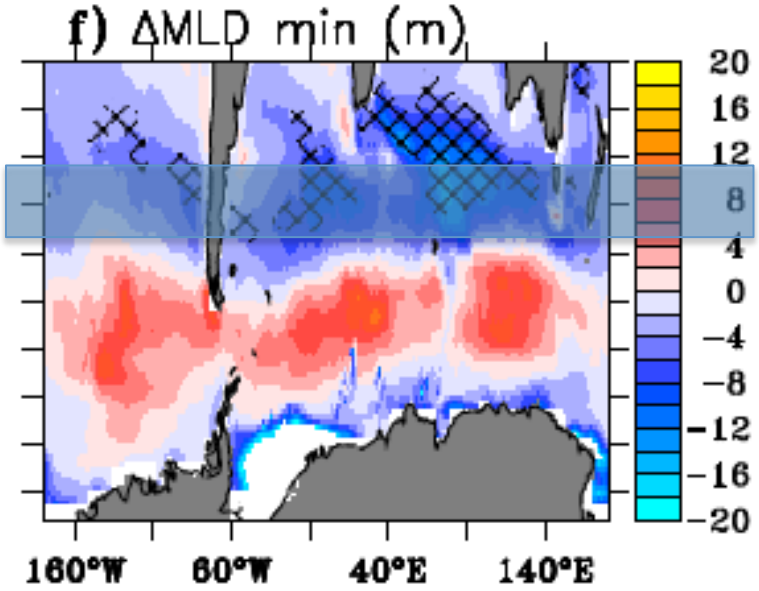
Δ → (1980-1999) to (2080-2099).

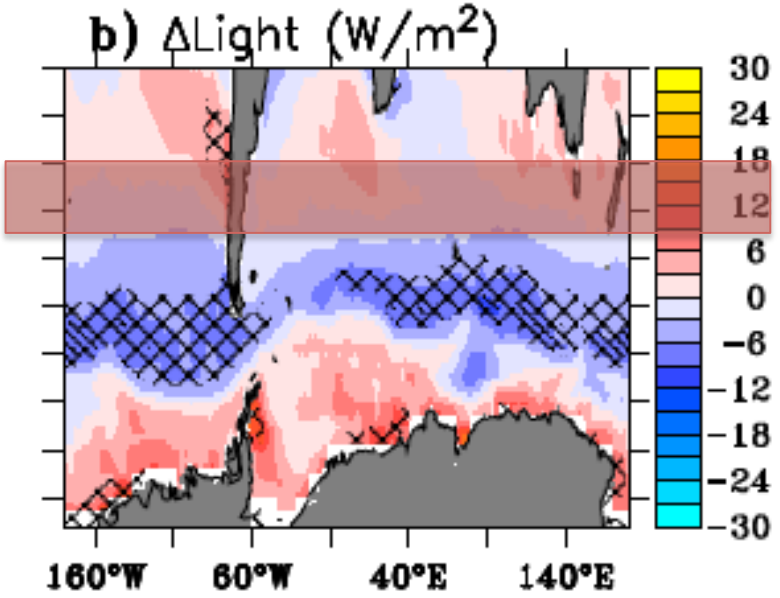
1st band: nitrate limited

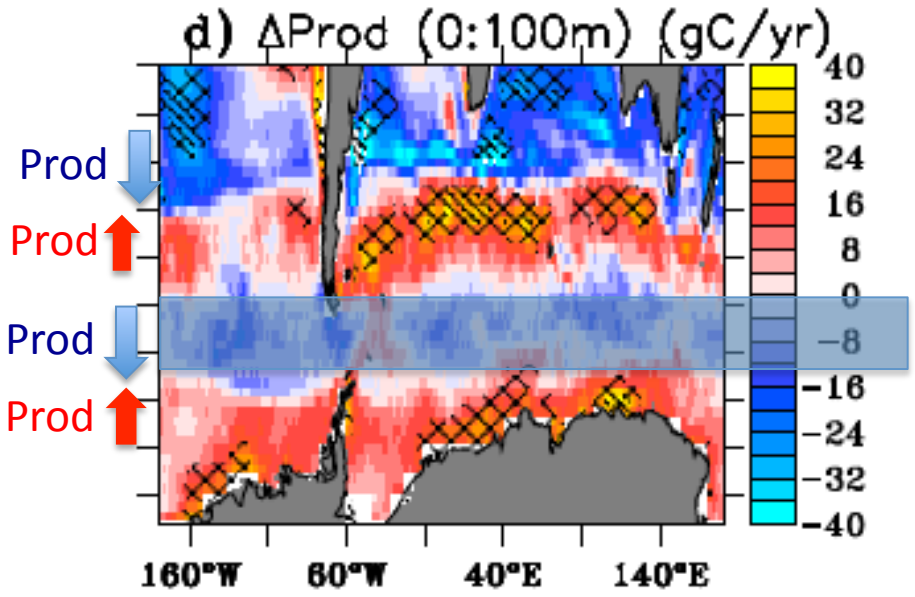
2nd band: light and iron limited





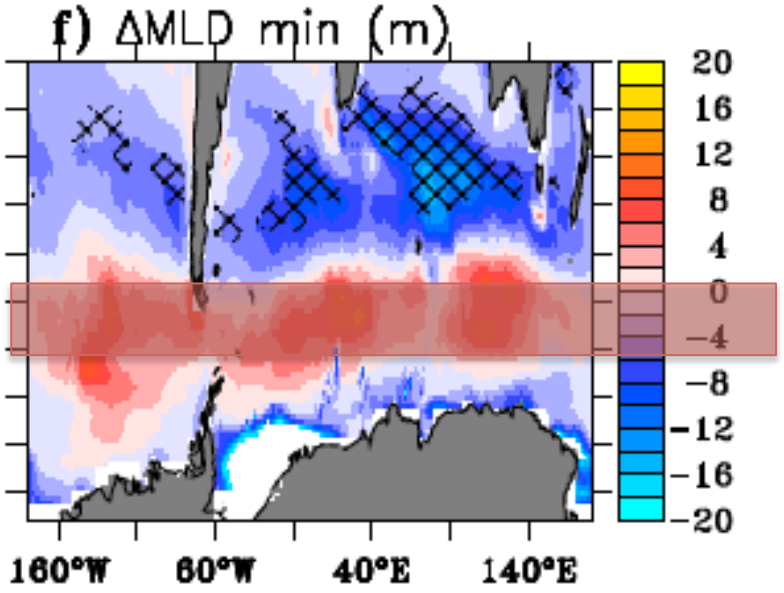


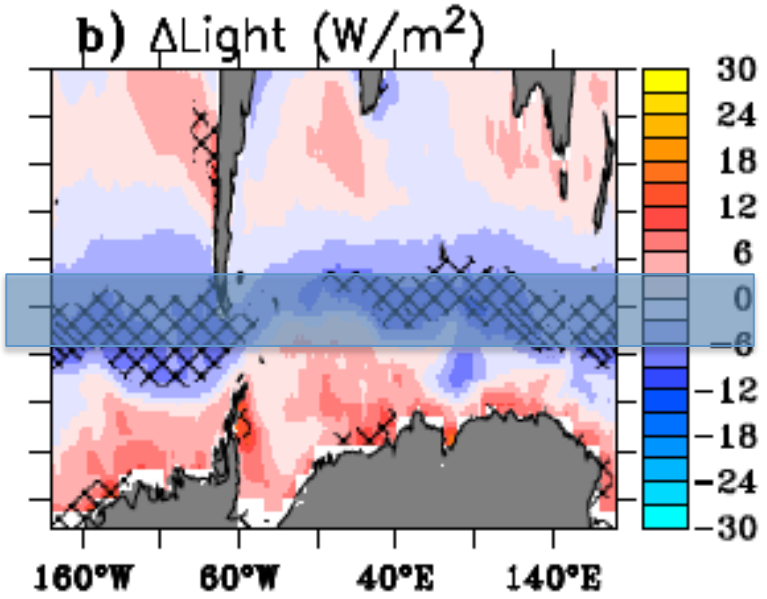




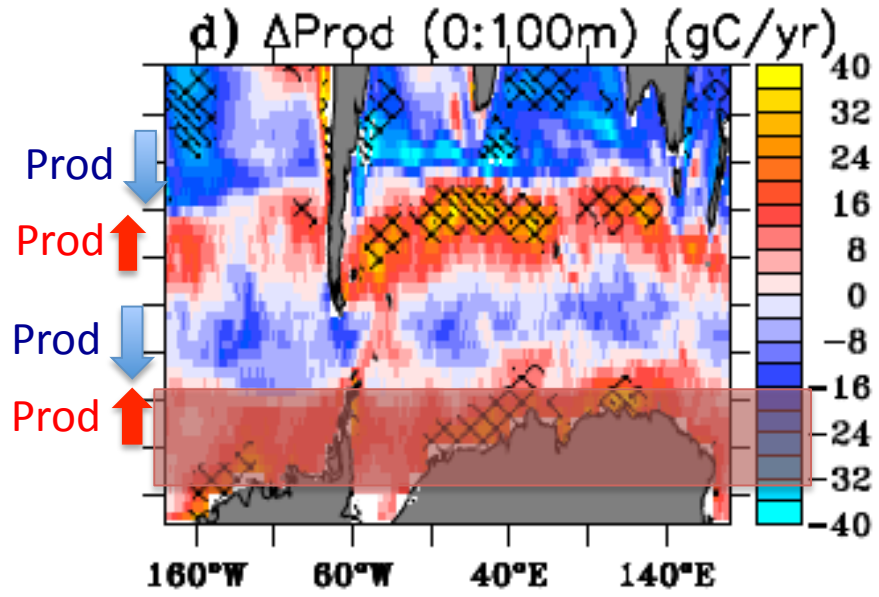
Δ → (1980-1999) to (2080-2099).

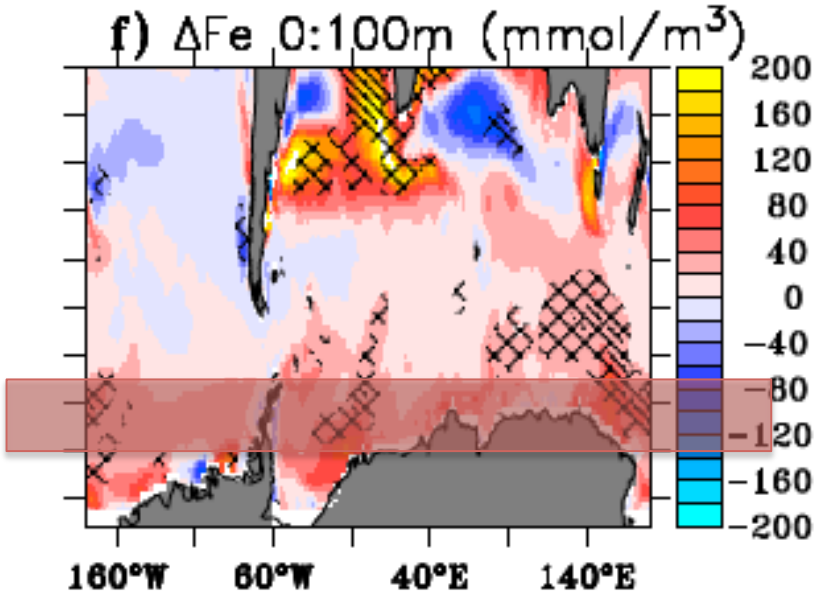
3rd band: light limited

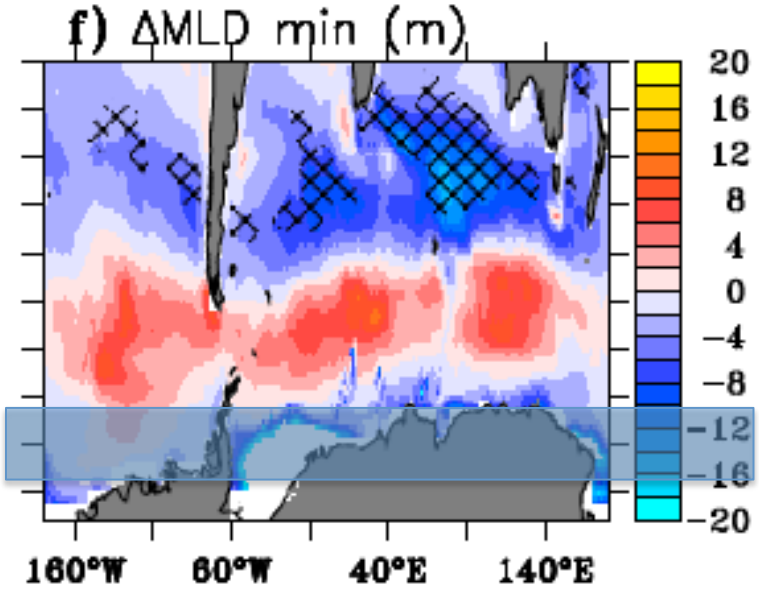


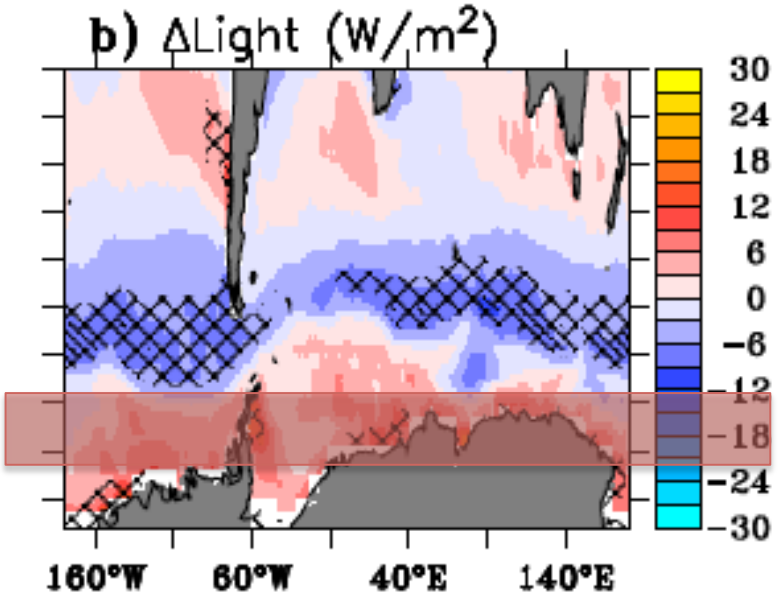


4th band: light and iron limited

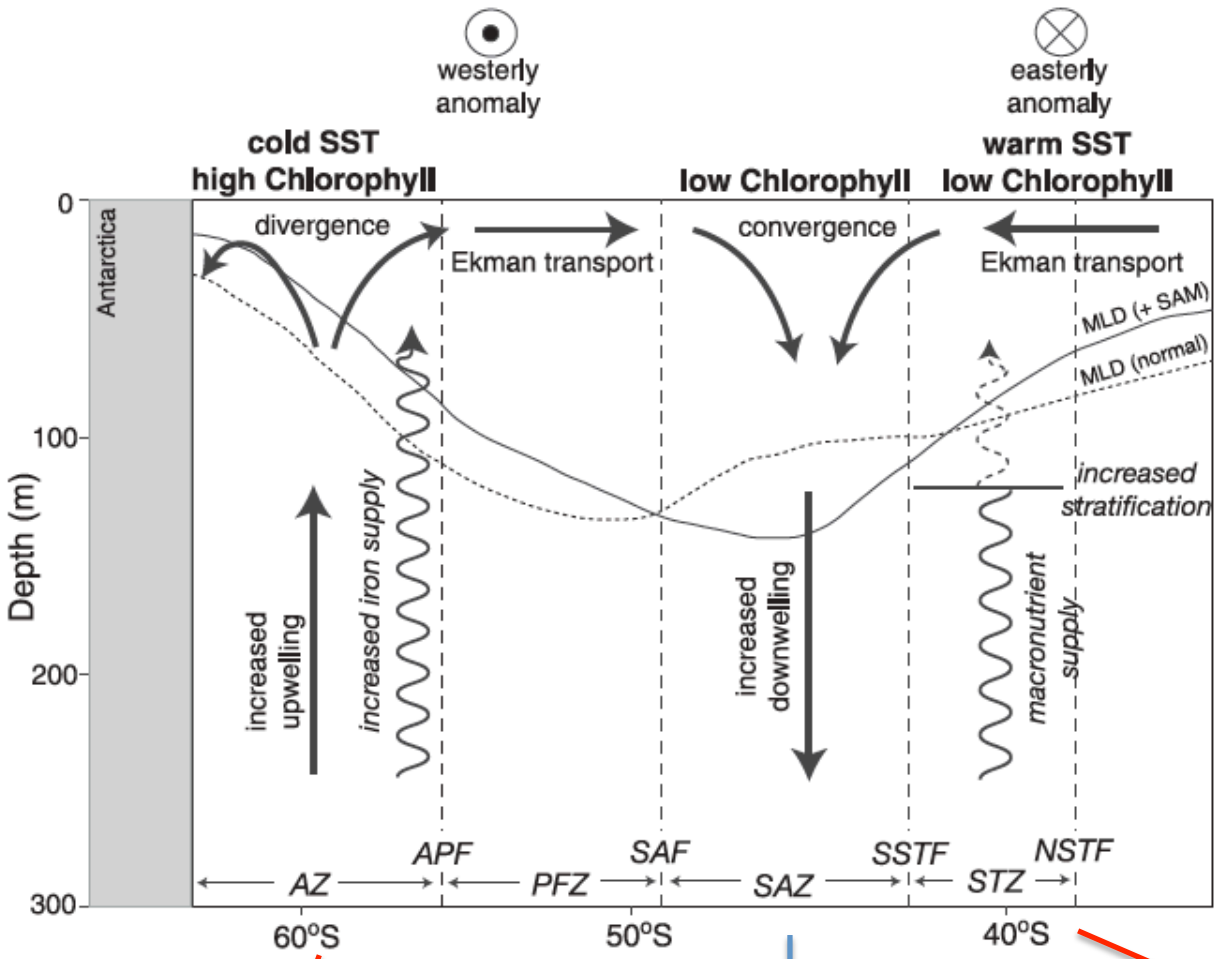








Proposed Southern Ocean response in the 21st century



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

Future → more SAM-like.

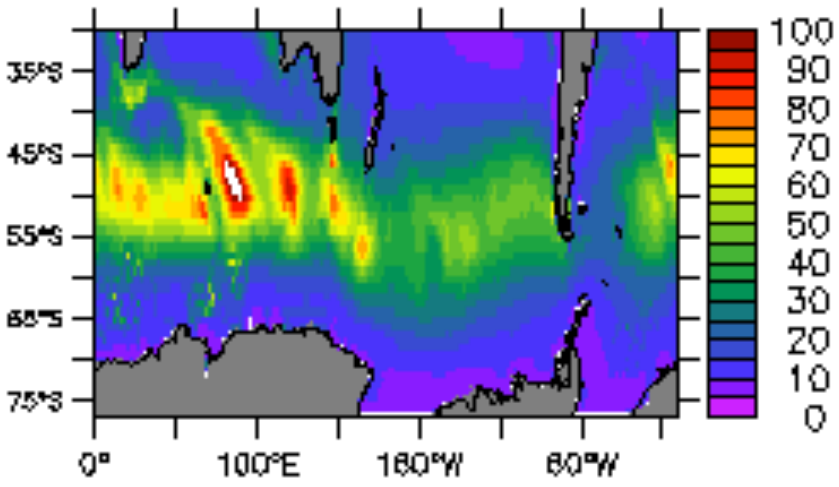
Increased production
+ iron supply
+ light supply

Decreased production
deeper MLD
– light supply

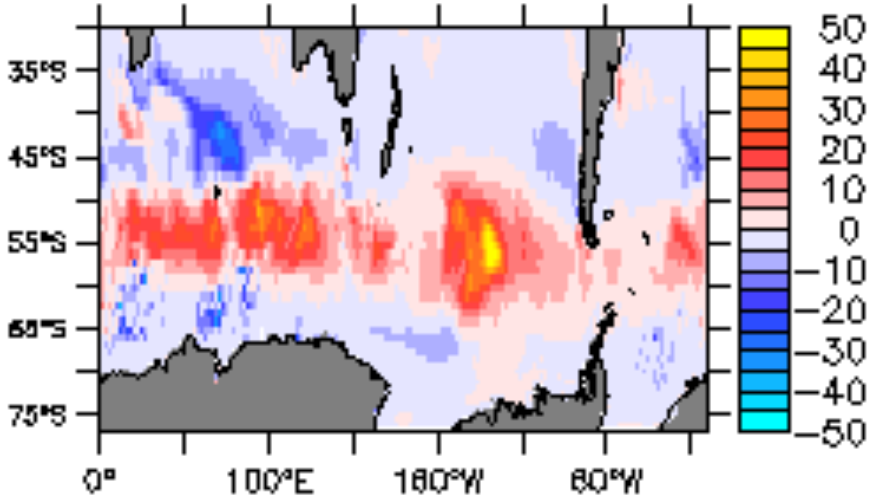
Increased production
+ temperature (+ heat convergence due to subtropical expansion)
Despite nutrient & light decrease

SAM and MLD correlation

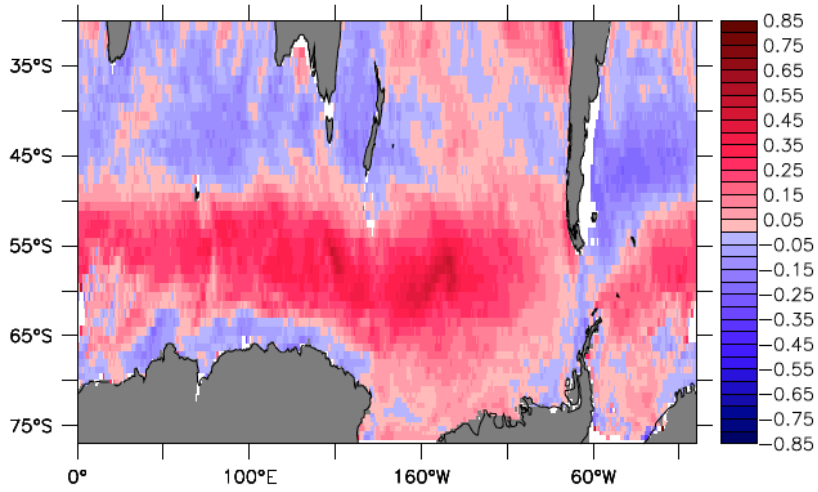
MLD_min present (1950-1999)



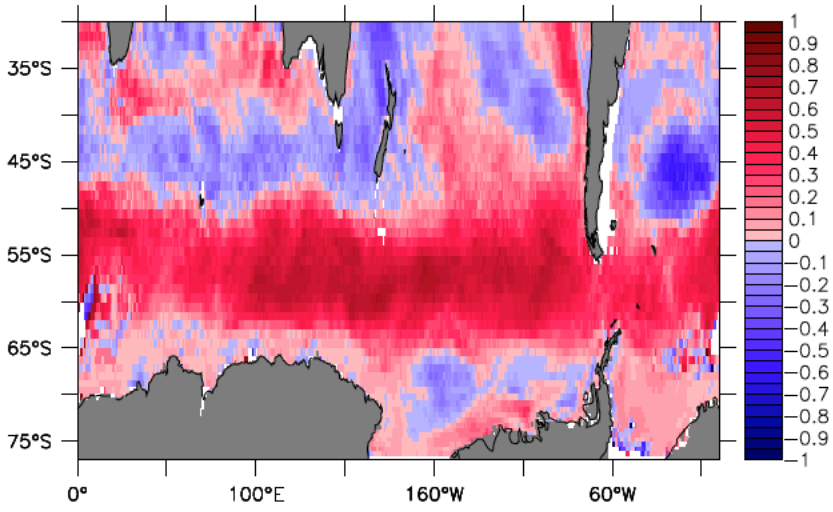
MLD min change (2050-2099) – (1950-1999)



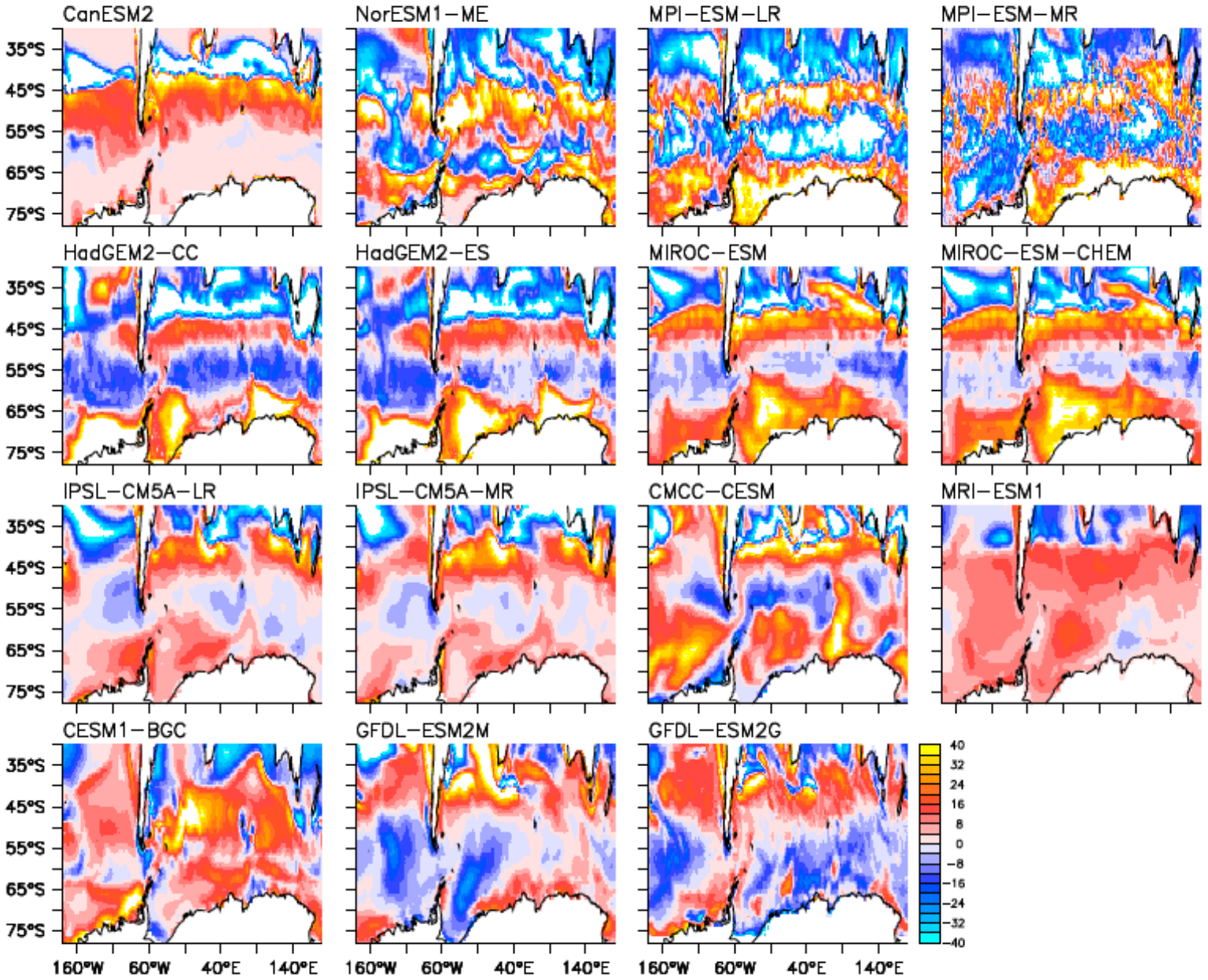
SAM and MLD anomaly monthly correlation



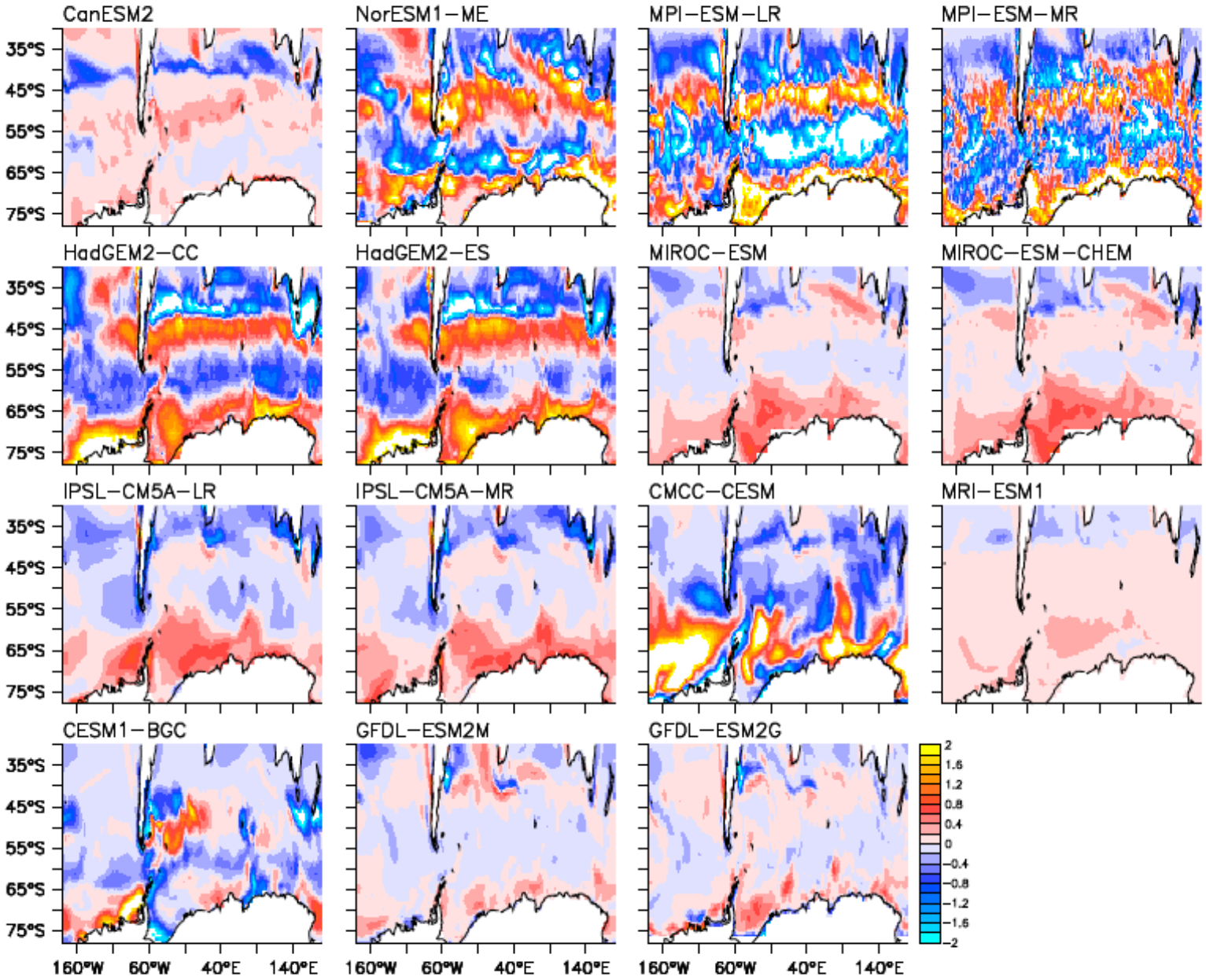
SAM (summer) and MLD_min yearly correlation



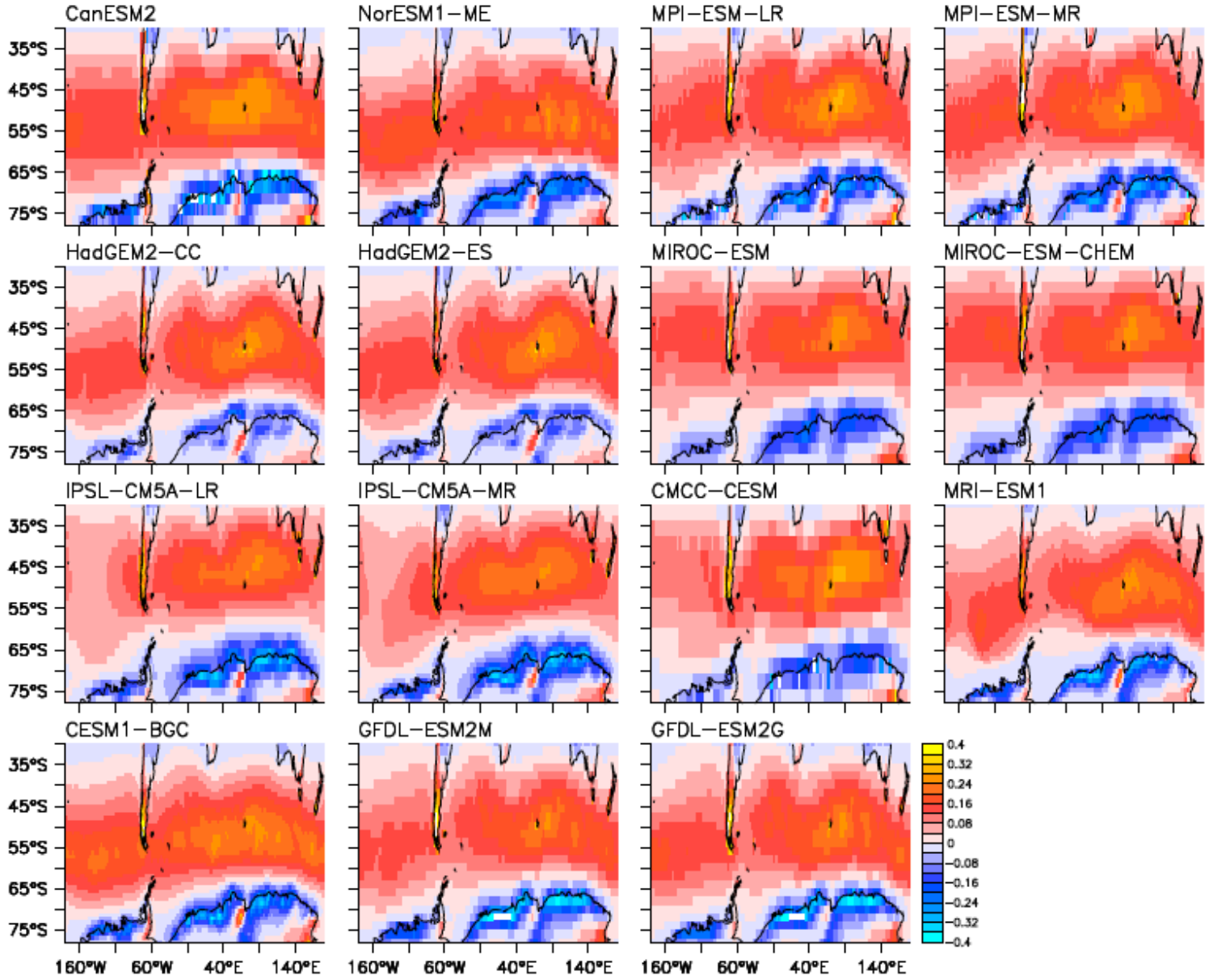
Change in production gC/yr/m^2 (1980-1999) to (2080-2099)



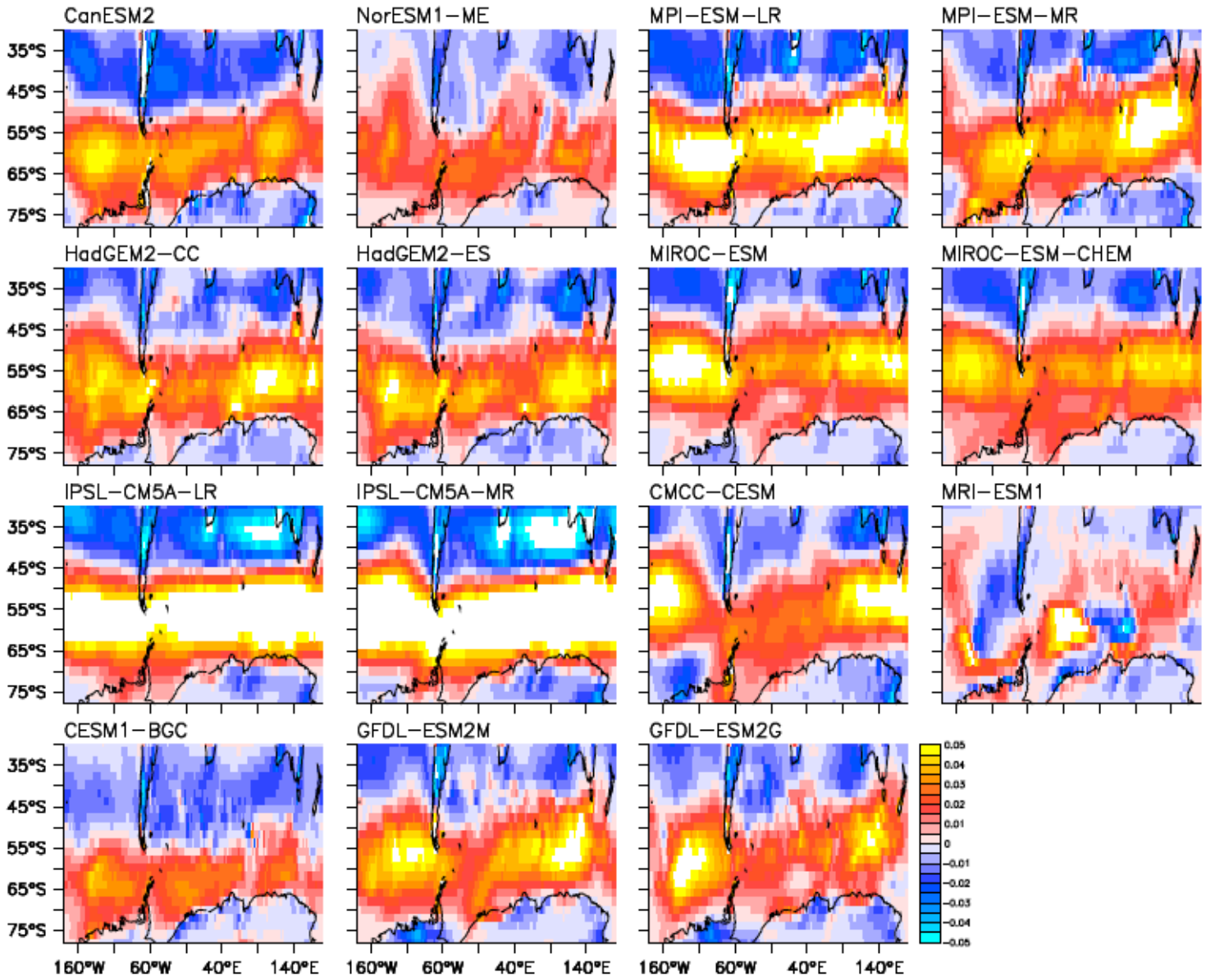
Change in surface phytoplannkton mmol/m^3 (1980-1999) to (2080-2099)



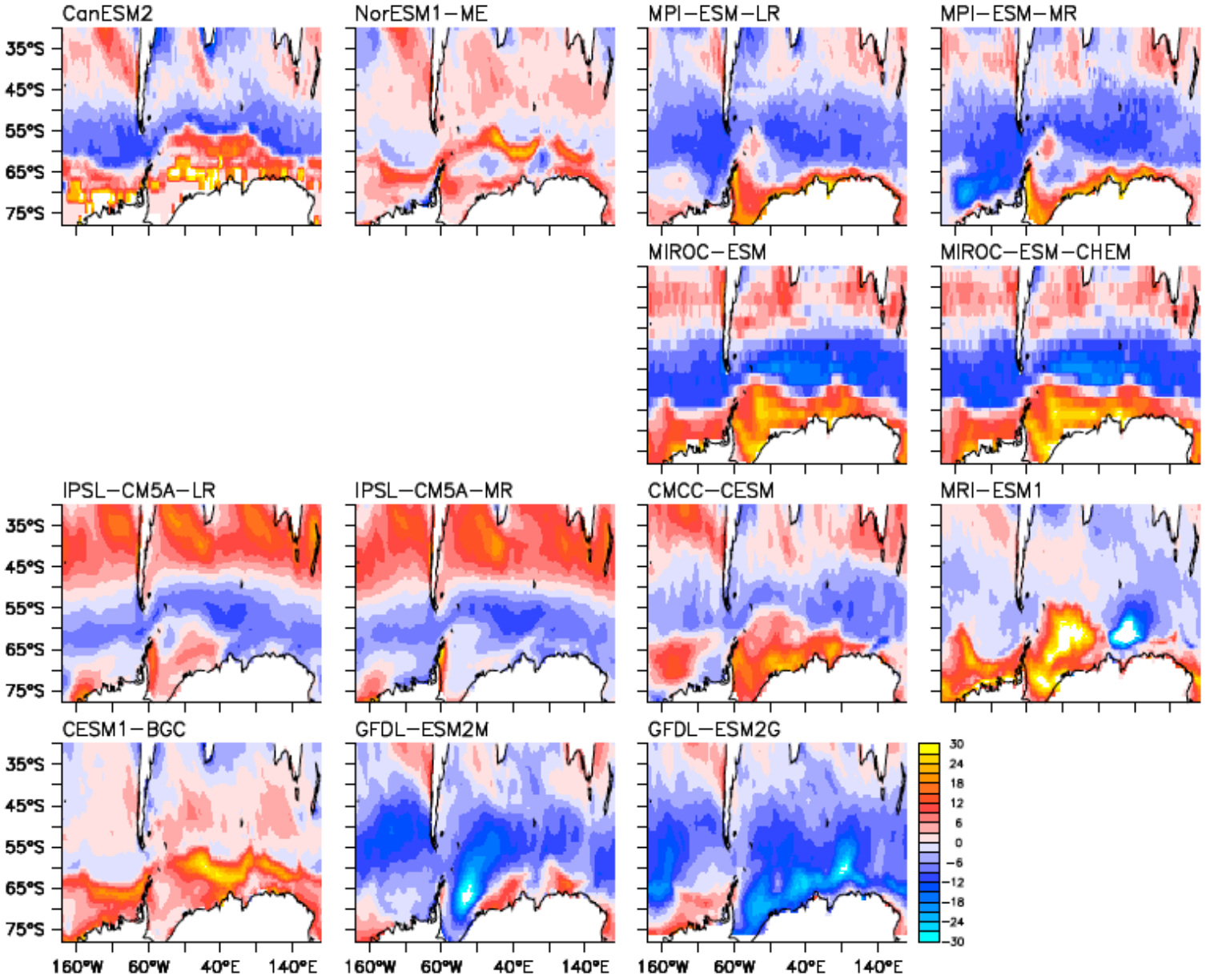
Wind stress u-direction Pa in the present (1980-1999)



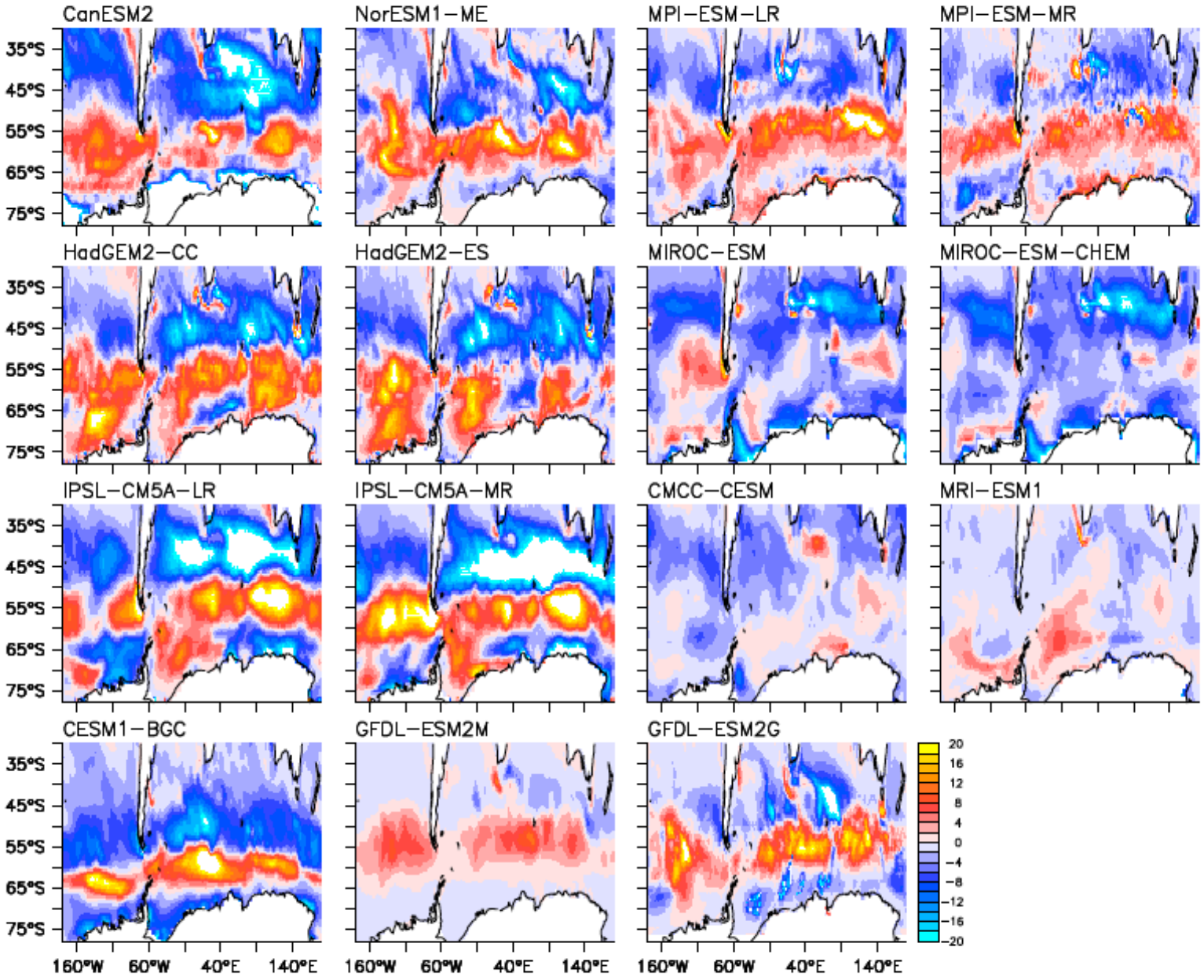
Change in wind stress u-direction Pa (1980-1999) to (2080-2099)



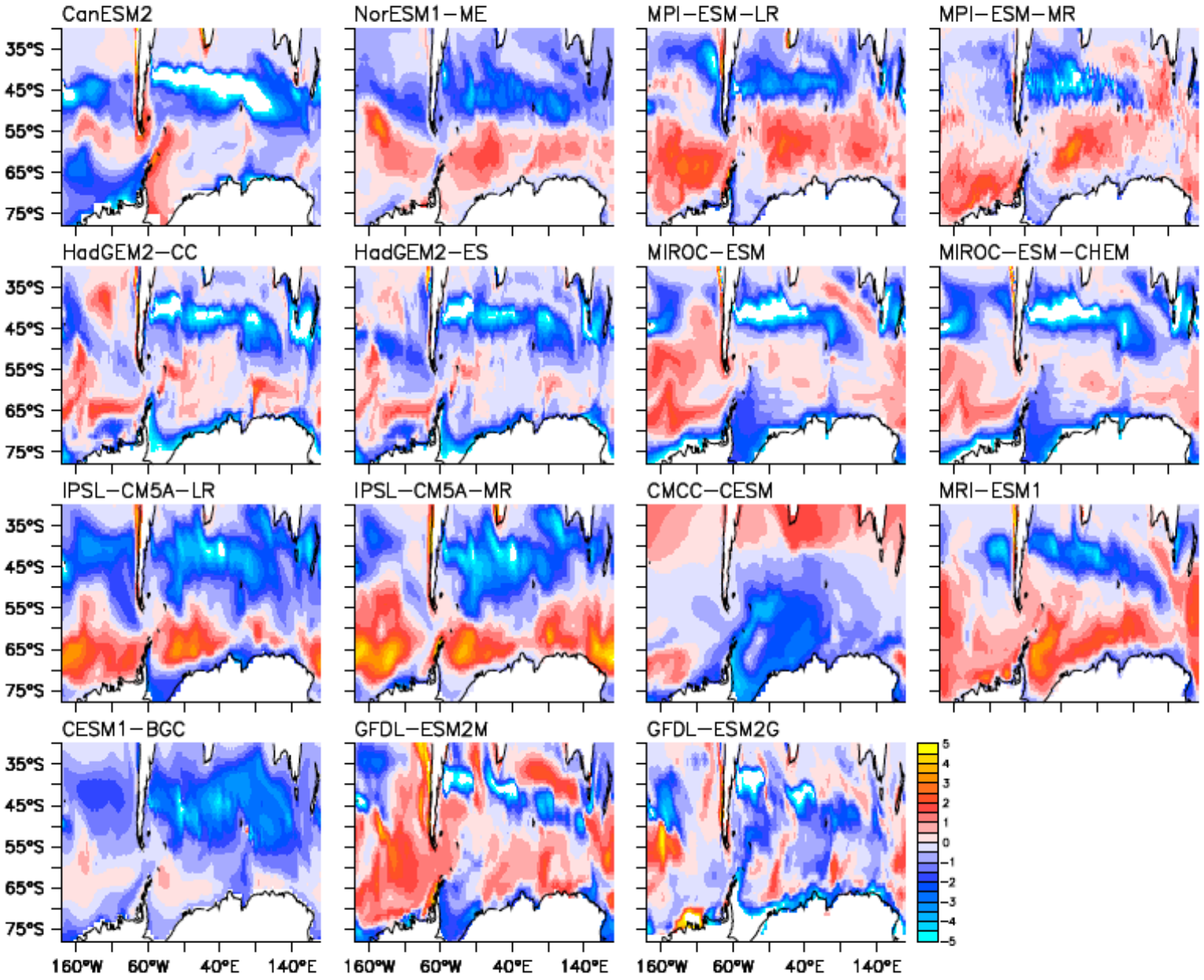
Change in light at surface W/m^2 (1980-1999) to (2080-2099)



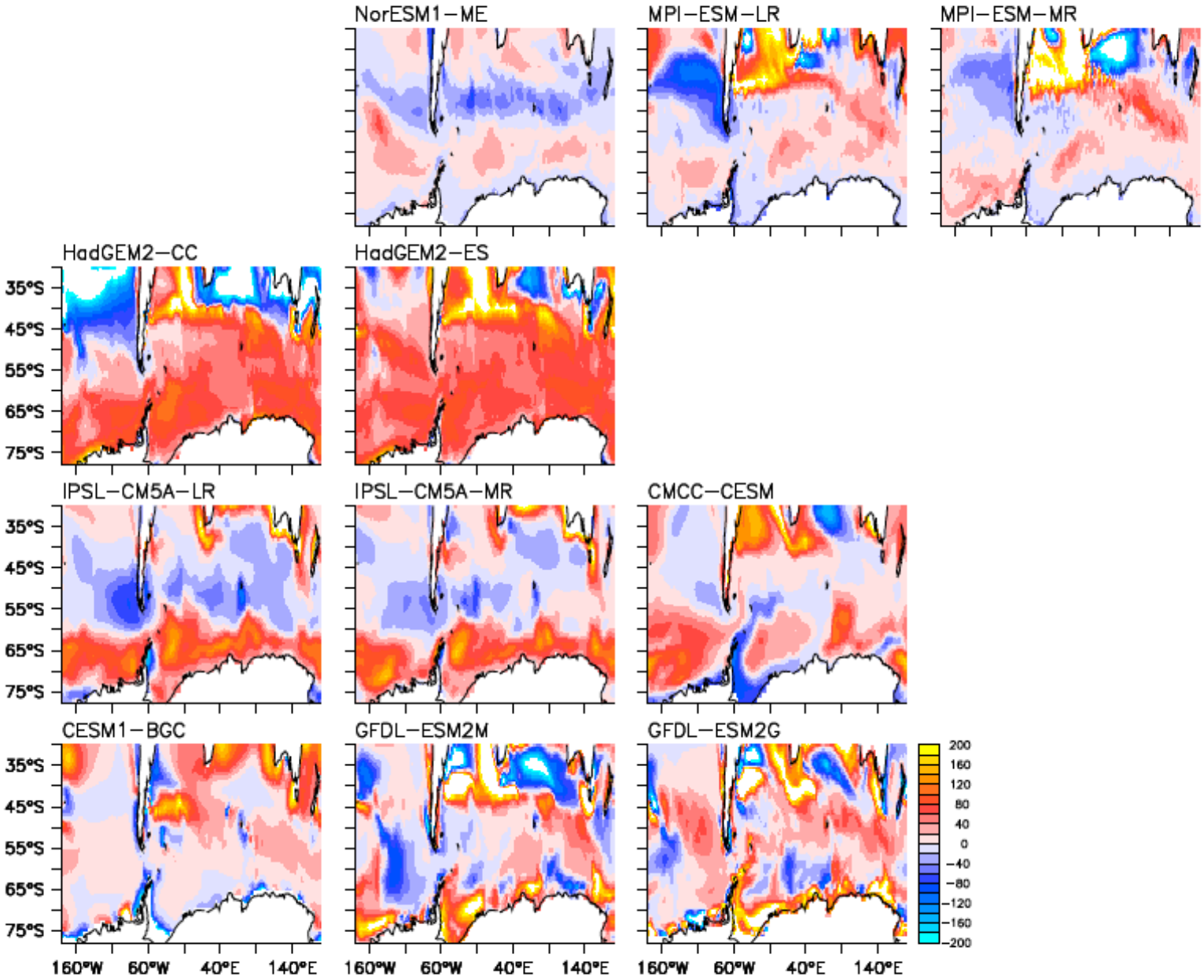
Change in MLD min in meters (1980-1999) to (2080-2099)



Change in nitrate mmol/m^3 (1980-1999) to (2080-2099)



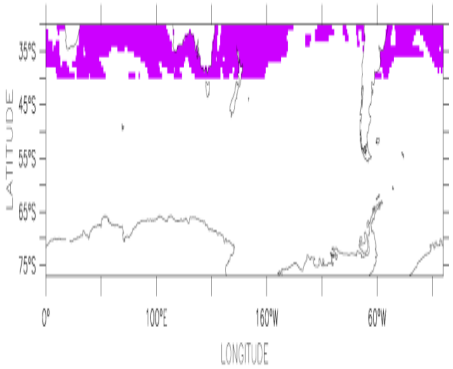
Change in iron nmol/m^3 (1980-1999) to (2080-2099)



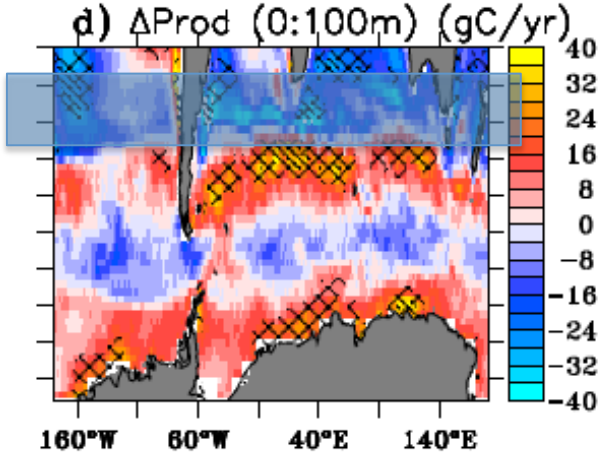
In detail…

We studied three models (so far):
GFDL-ESM2G, HadGEM2-ES, IPSL-CM5A-MR.

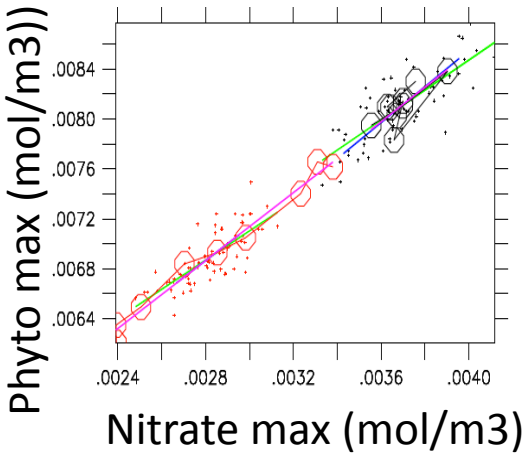
Which mechanisms remain important through different time scales?



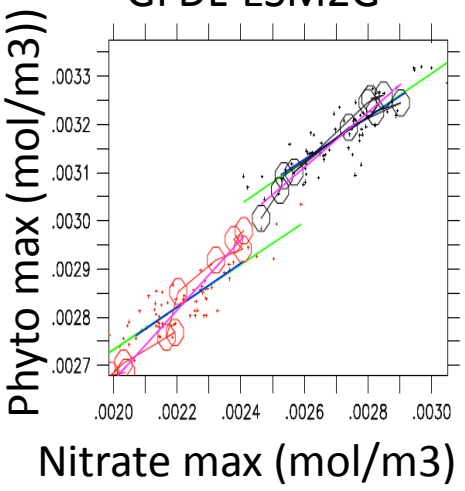
a) Model GFDL-ESM2G: masked region between **30S and 40S** where surface yearly max phytoplankton concentrations **decrease** between rcp8.5 (2050-99) and historical (1950-99)



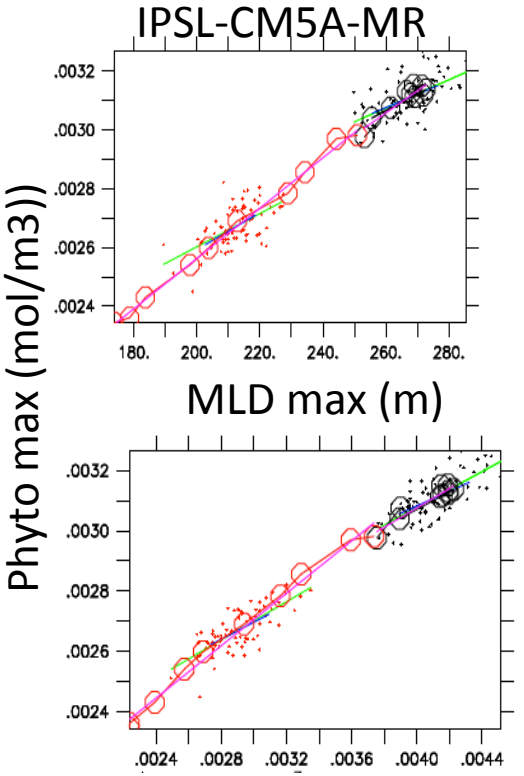
HadGEM2-ES

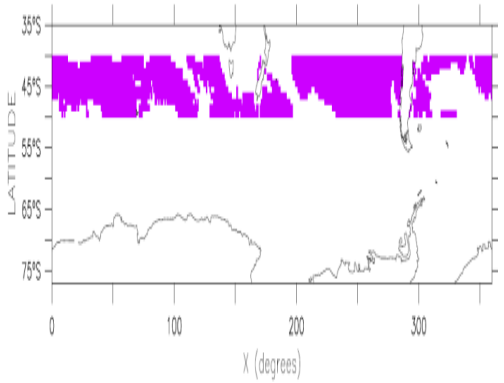


GFDL-ESM2G

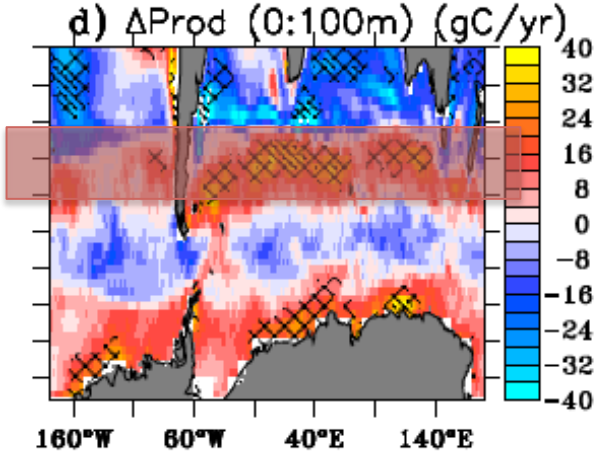


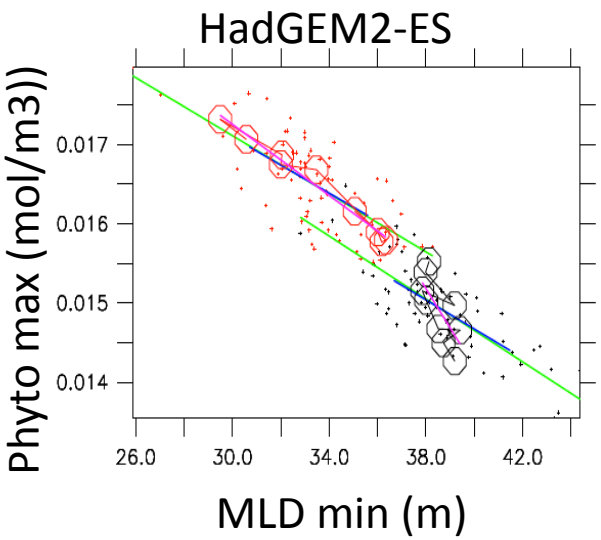
IPSL-CM5A-MR

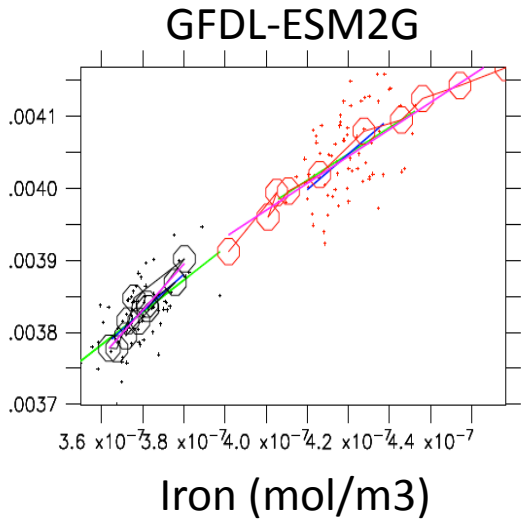


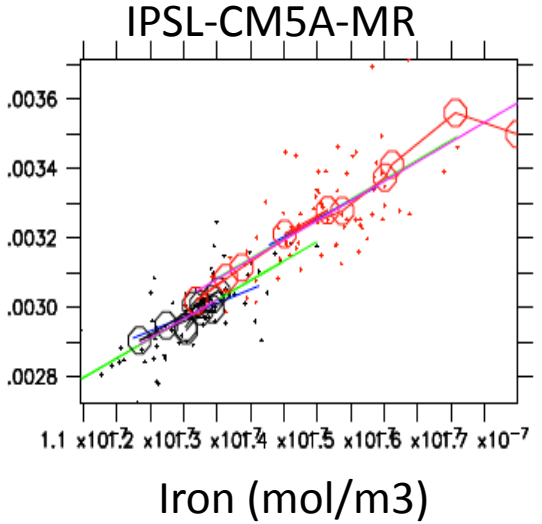


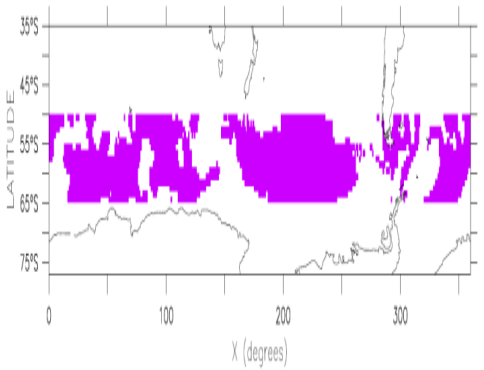
b) Model GFDL-ESM2G: masked region between **40S and 50S** where surface yearly max phytoplankton concentrations **increase** between rcp8.5 (2050-99) and historical (1950-99)



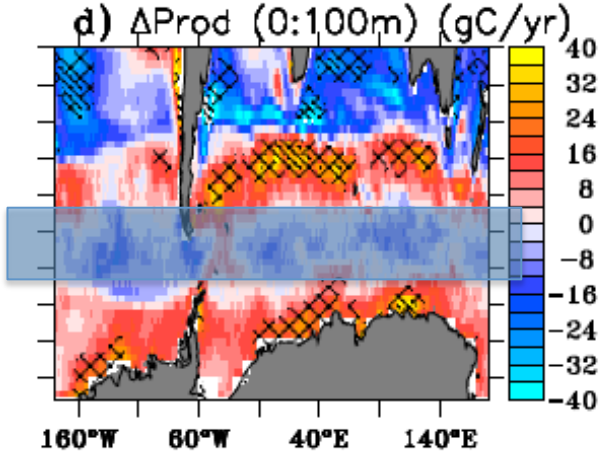




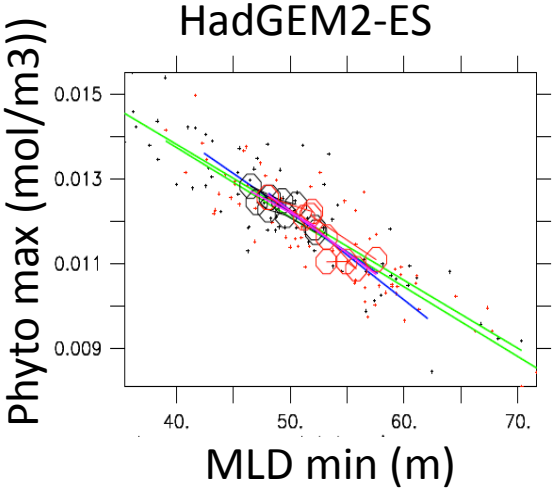




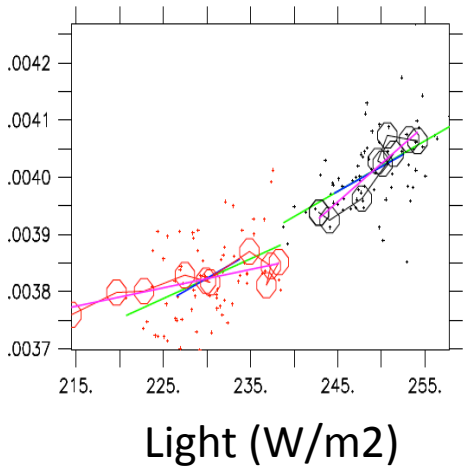
Model GFDL-ESM2G: masked region between **50S and 65S** where surface yearly max phytoplankton concentrations **decrease** between rcp8.5 (2050-99) and historical (1950-99)



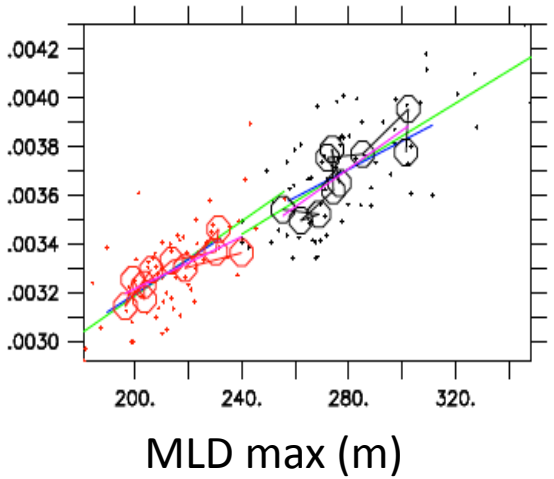
HadGEM2-ES



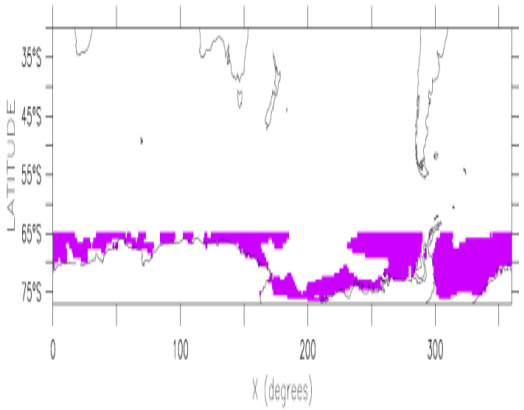
GFDL-ESM2G



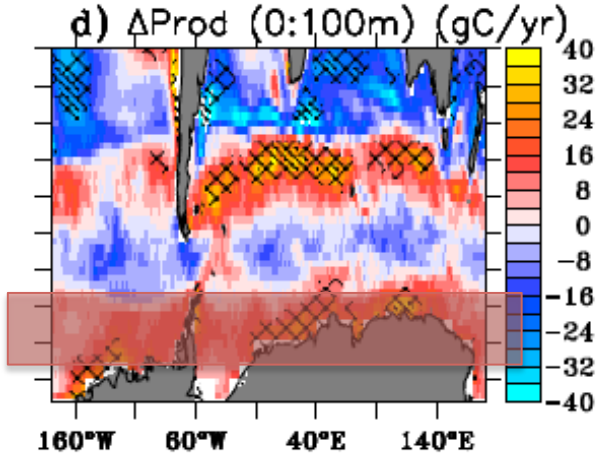
IPSL-CM5A-MR



+ light, MLDmin

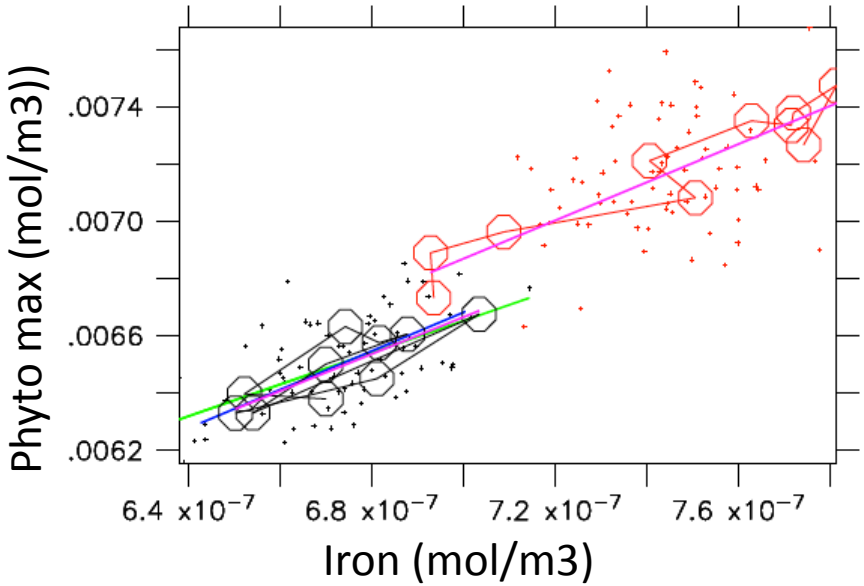


c) Model GFDL-ESM2G: masked region **south of 65S** where surface yearly max phytoplankton concentrations **increase** between rcp8.5 (2050-99) and historical (1950-99)

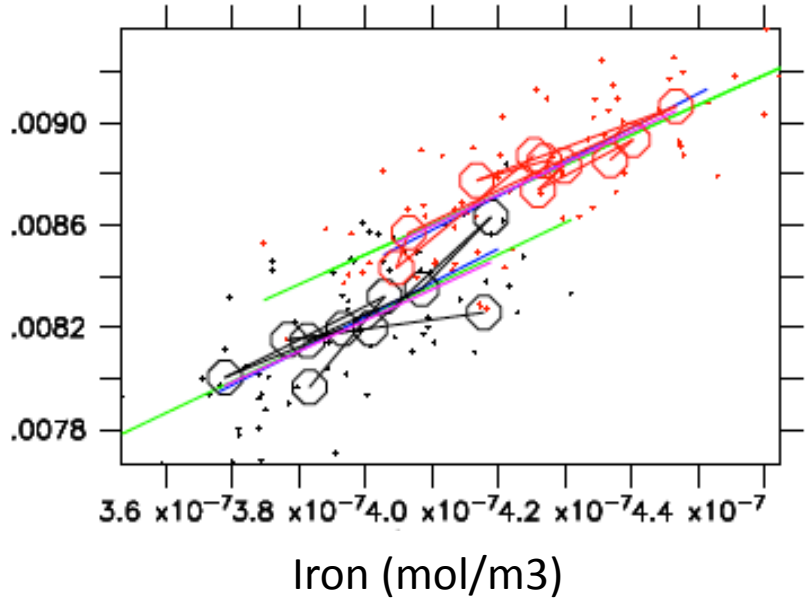


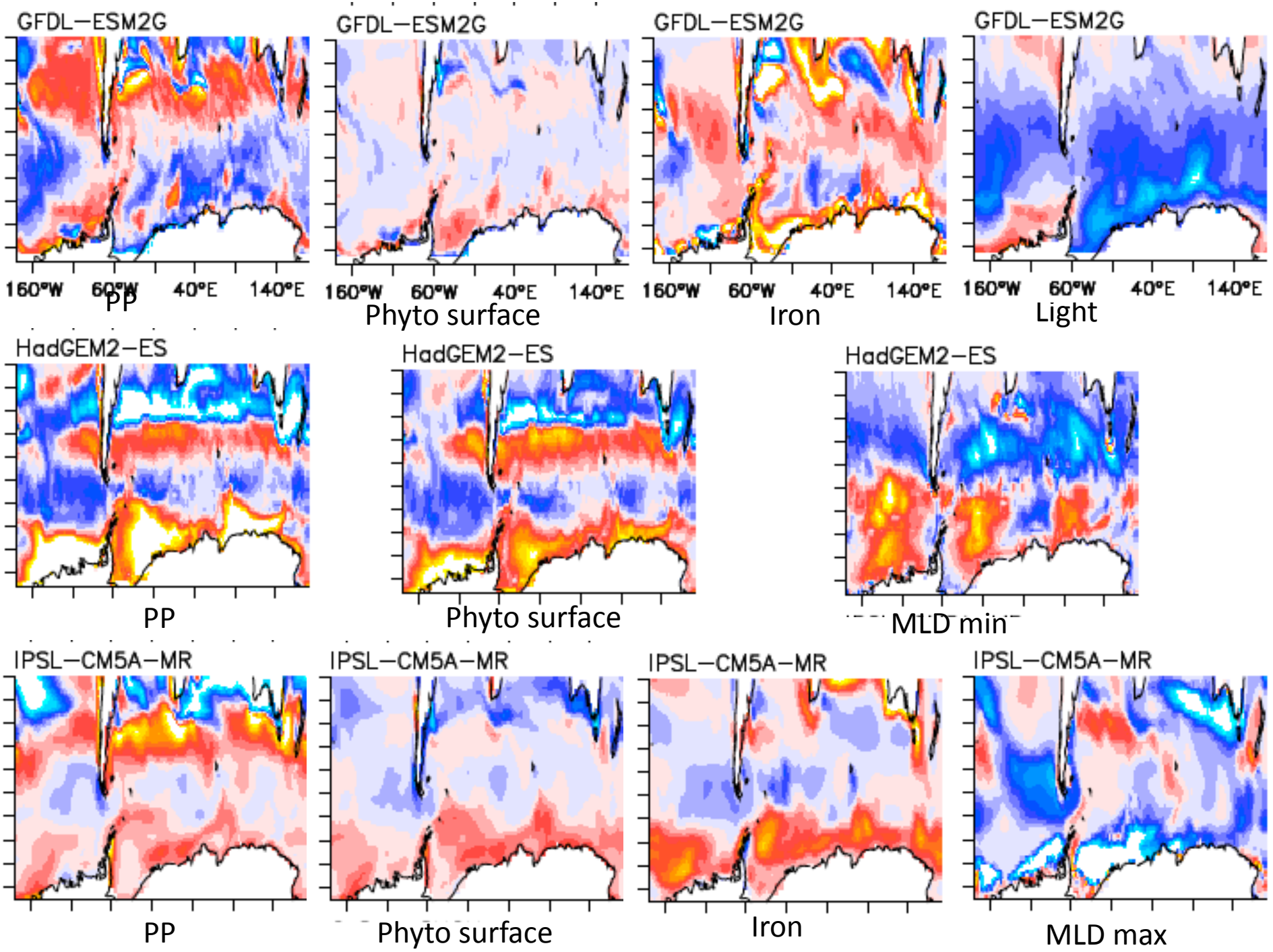
HadGEM2-ES → light?

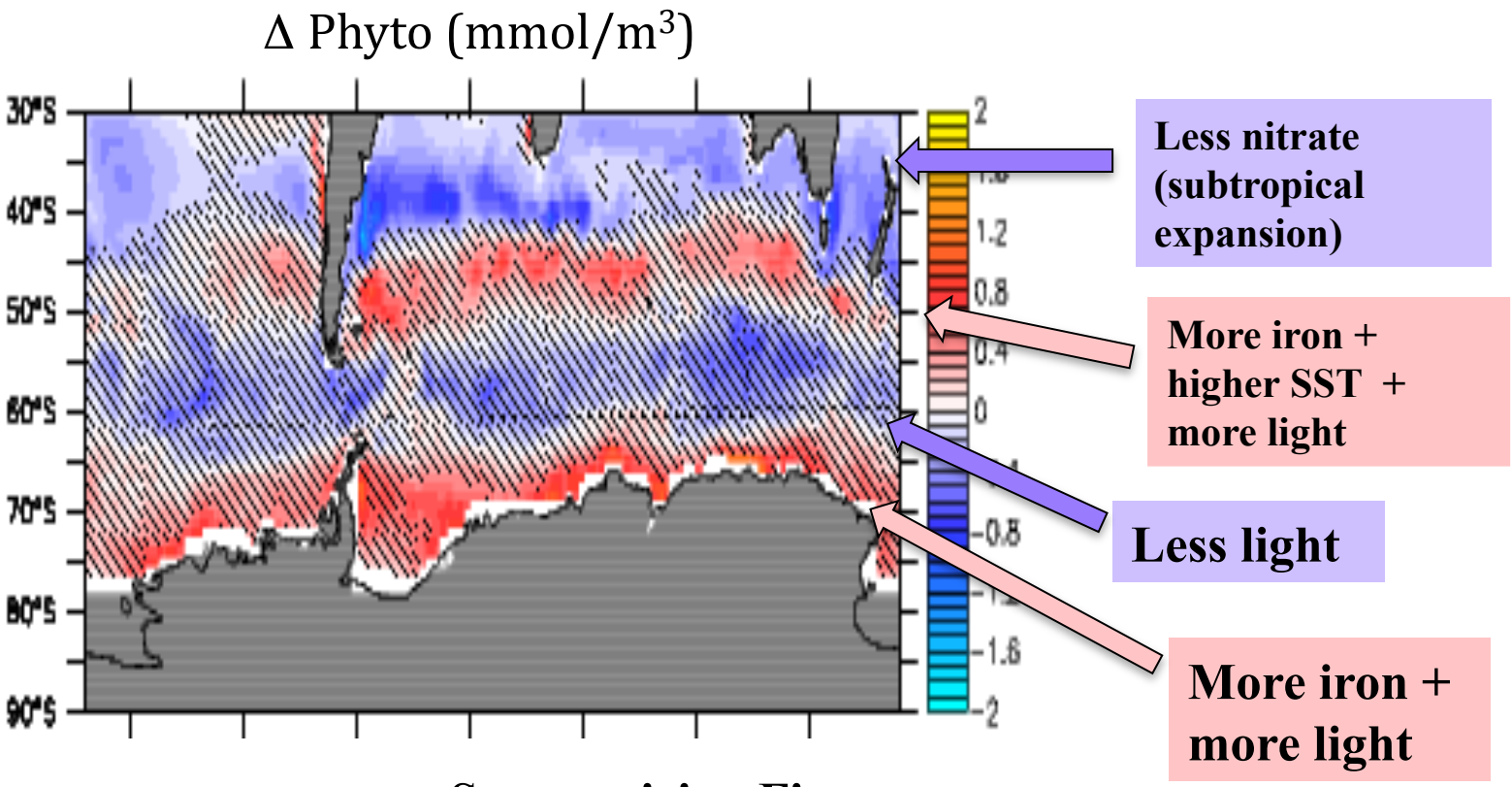
GFDL-ESM2G



IPSL-CM5A-MR




GFDL–ESM2G
160°W
60°W
40°E
140°E
PP
GFDL–ESM2G
160°W
60°W
40°E
140°E
Phyto surface
GFDL–ESM2G
160°W
60°W
40°E
140°E
Iron
GFDL–ESM2G
160°W
60°W
40°E
140°E
Light
HadGEM2–ES
PP
HadGEM2–ES
Phyto surface
HadGEM2–ES
MLD min
IPSL–CM5A–MR
PP
IPSL–CM5A–MR
Phyto surface
IPSL–CM5A–MR
Iron
IPSL–CM5A–MR
MLD max



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

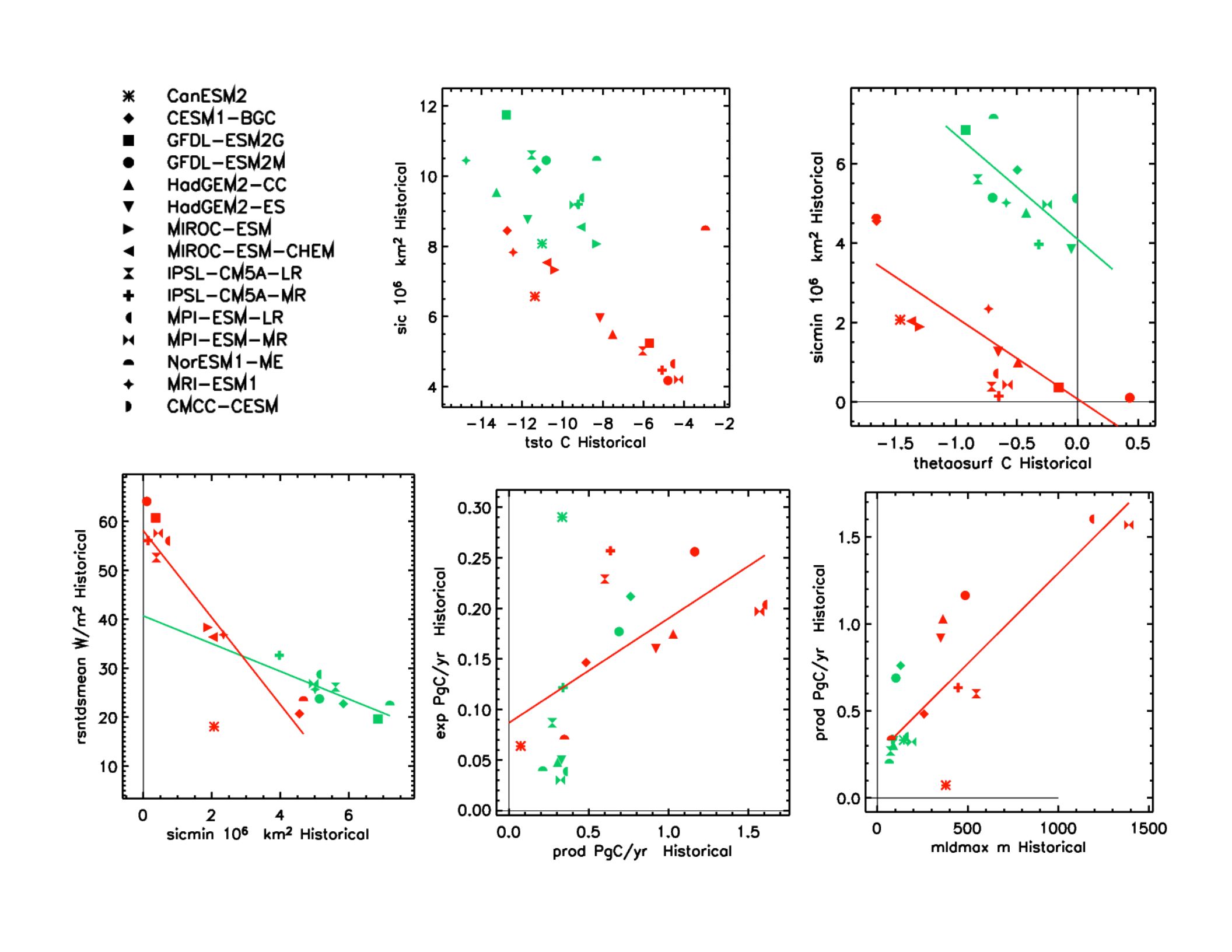
Conclusions: Southern Ocean phyto and climate change

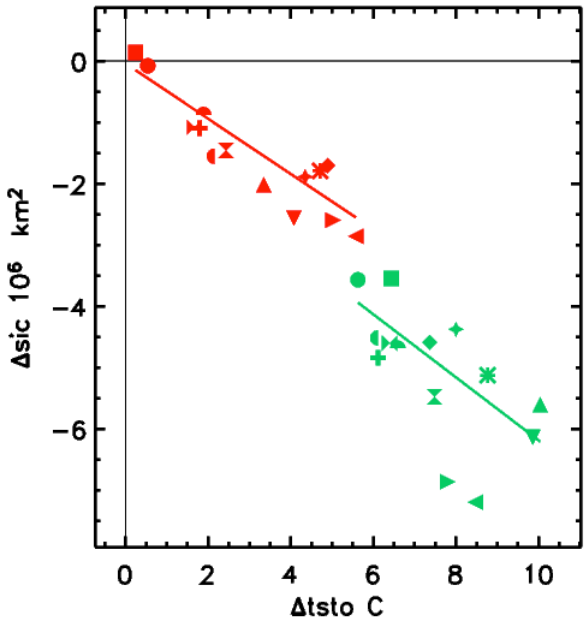
- ***Proposed "Banded" response of the S. Ocean to future climate change (model average over 100 yrs) :***

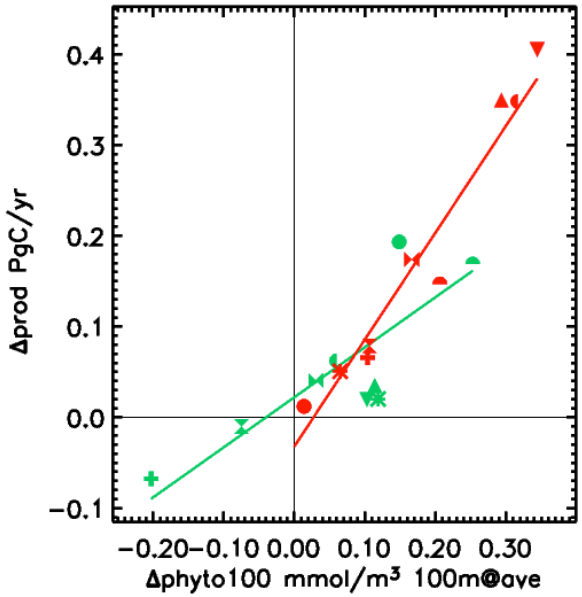
  a) **40S-50S: Production increase:** Temp + IPAR + shallower spring MLD (most models), Fe in GFDL model?
  b) **50S-65S**: **Production decrease:** IPAR decrease
  c) **S of 65S: Production increase:** more IPAR + more Fe (rivers, continent)

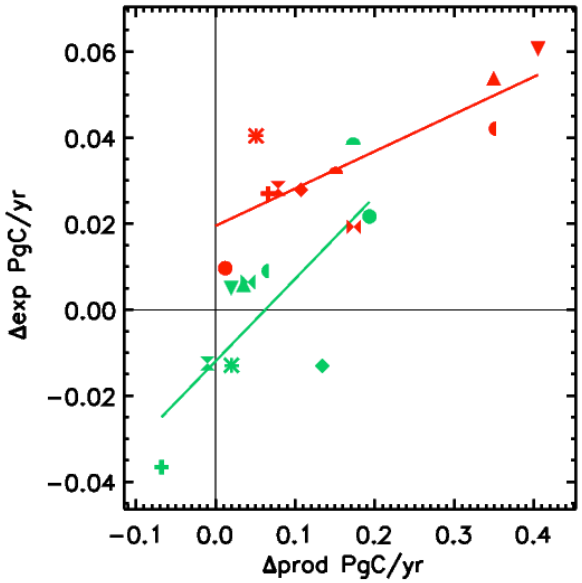
- ***Fe supply pathways + Cloud details + Ice details : important for the productivity response.***

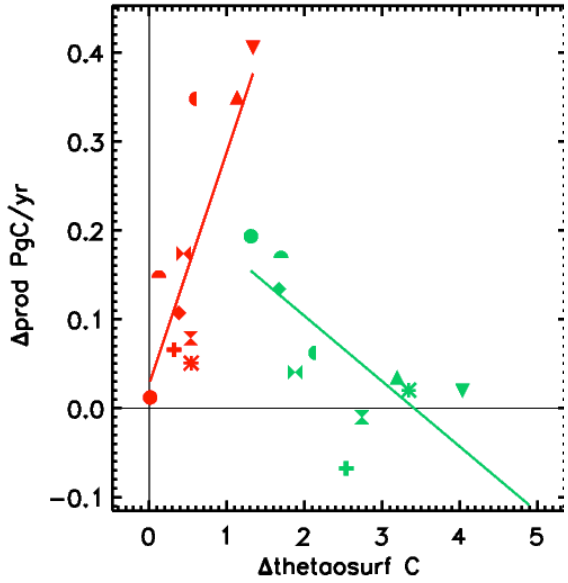
- ***100 yr Productivity response partially explained by increasing SAM ?*** Interannual correlations with SAM show 3 bands (similar to Lovenduski & Gruber 2005), more pronounced in the future. How to extend this analysis across all models ?

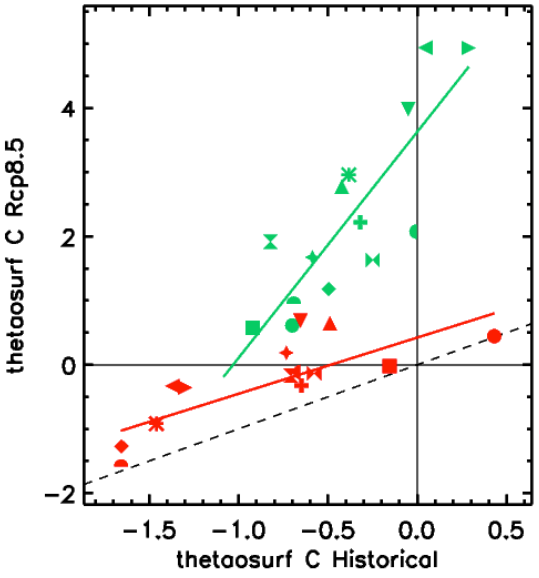

CanESM2
CESM1-BGC
GFDL-ESM2G
GFDL-ESM2M
HadGEM2-CC
HadGEM2-ES
MIROC-ESM
MIROC-ESM-CHEM
IPSL-CM5A-LR
IPSL-CM5A-MR
MPI-ESM-LR
MPI-ESM-MR
NorESM1-ME
MRI-ESM1
CMCC-CESM
sic 10⁶ km² Historical
tsto C Historical
sicmin 10⁶ km² Historical
thetaosurf C Historical
rsntdsmean W/m² Historical
sicmin 10⁶ km² Historical
exp PgC/yr Historical
prod PgC/yr Historical
prod PgC/yr Historical
mldmax m Historical

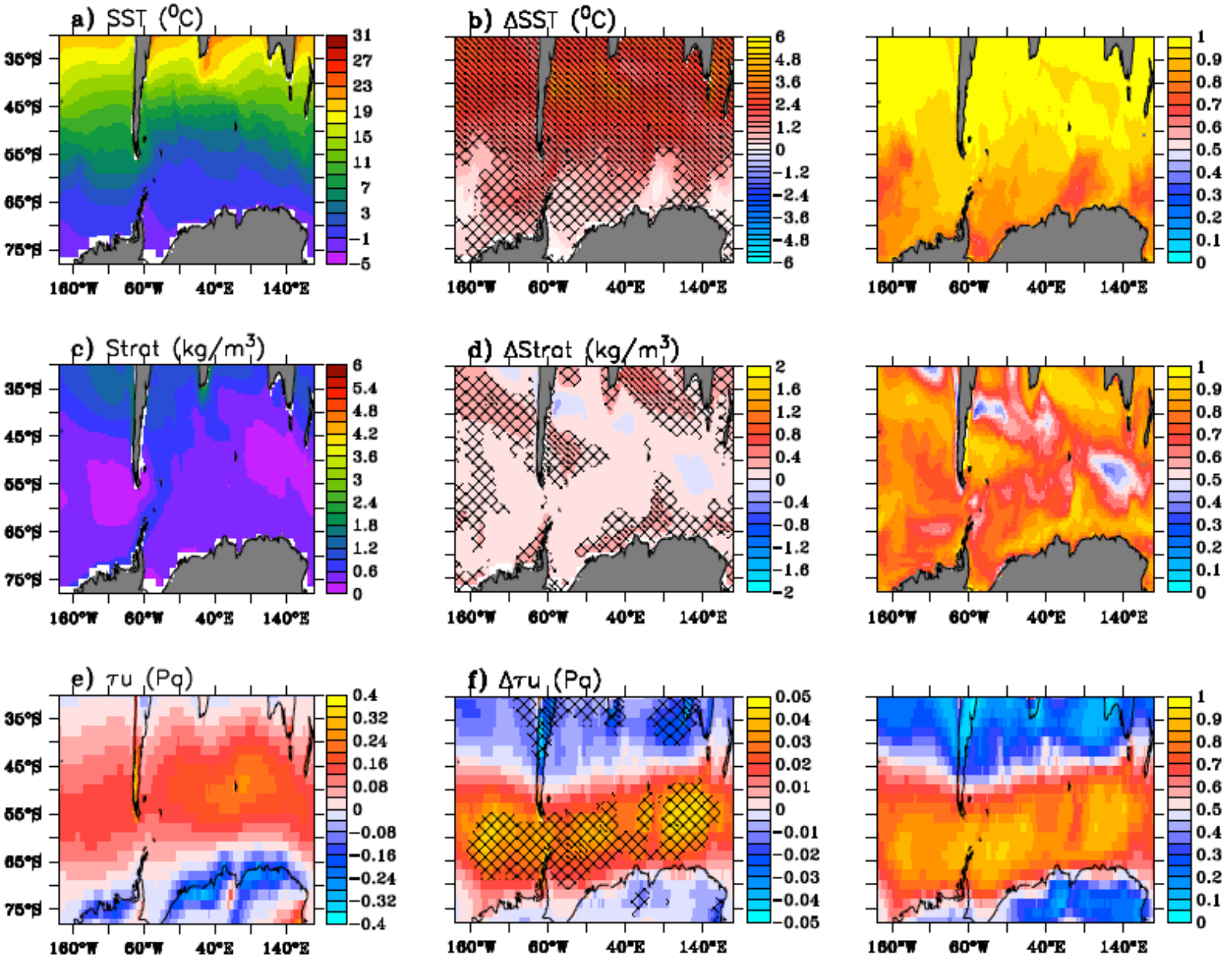

Δsic 10⁶ km²
Δtsto C

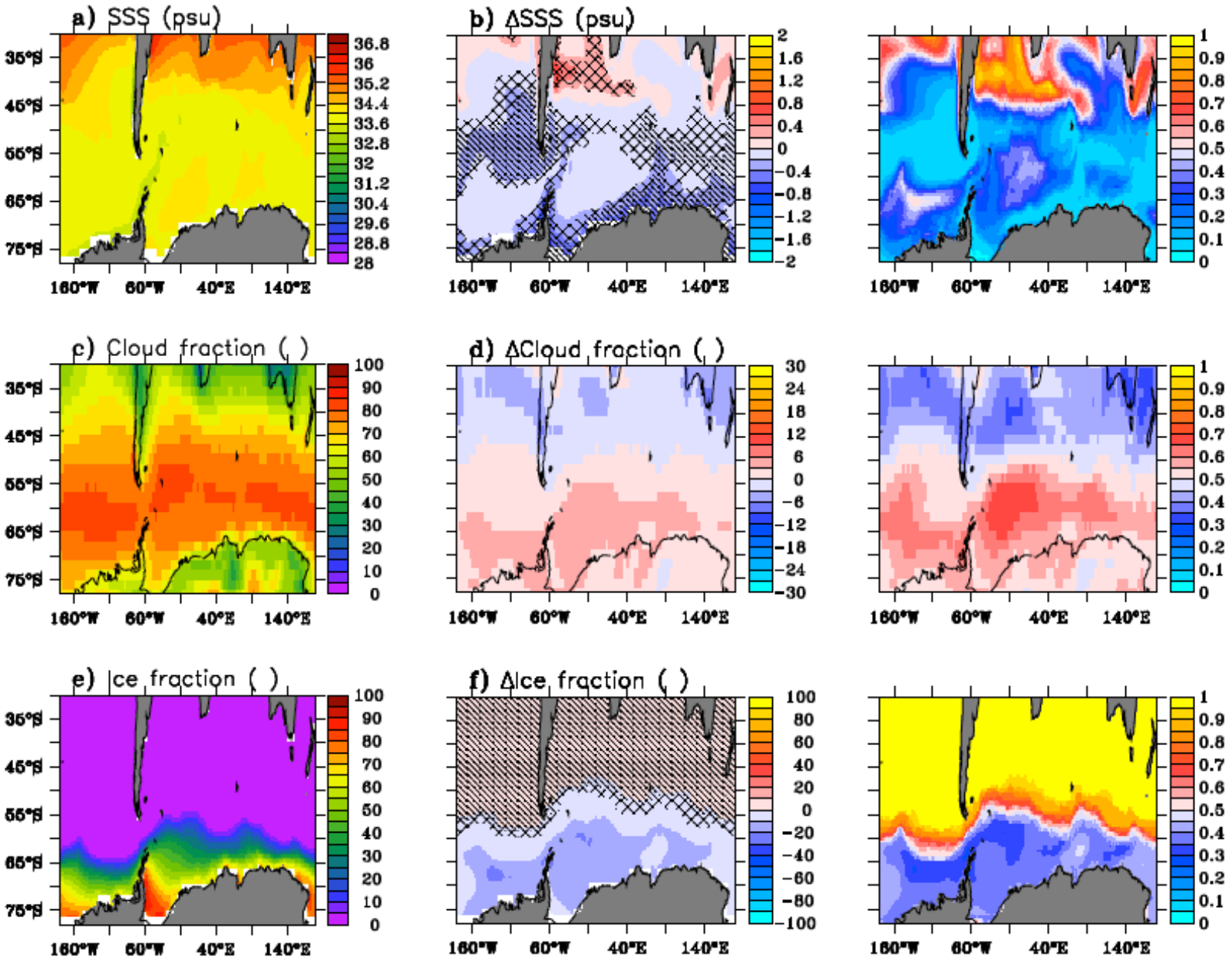

Δprod PgC/yr
Δphyto100 mmol/m³ 100m@ave

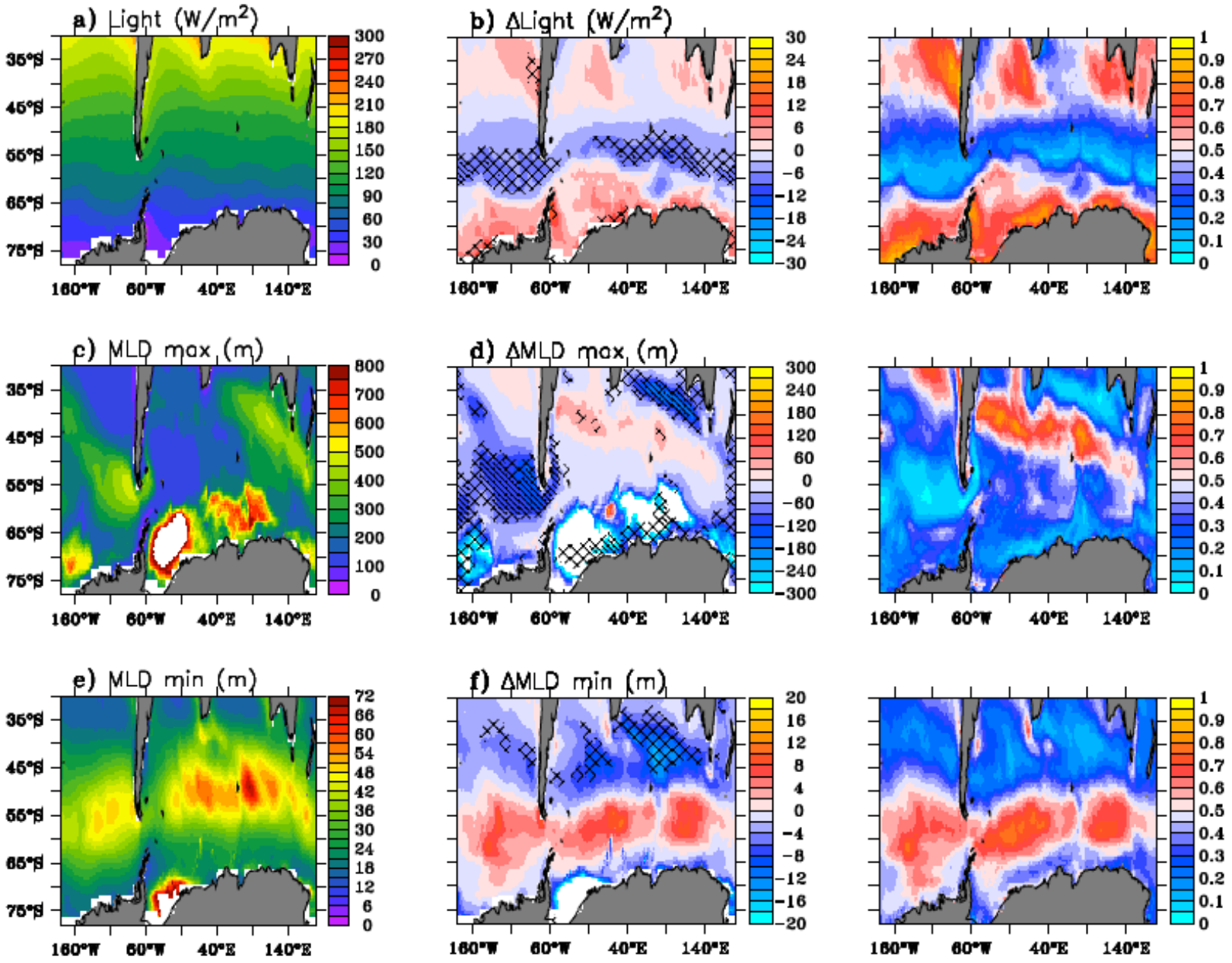

Δexp PgC/yr
Δprod PgC/yr

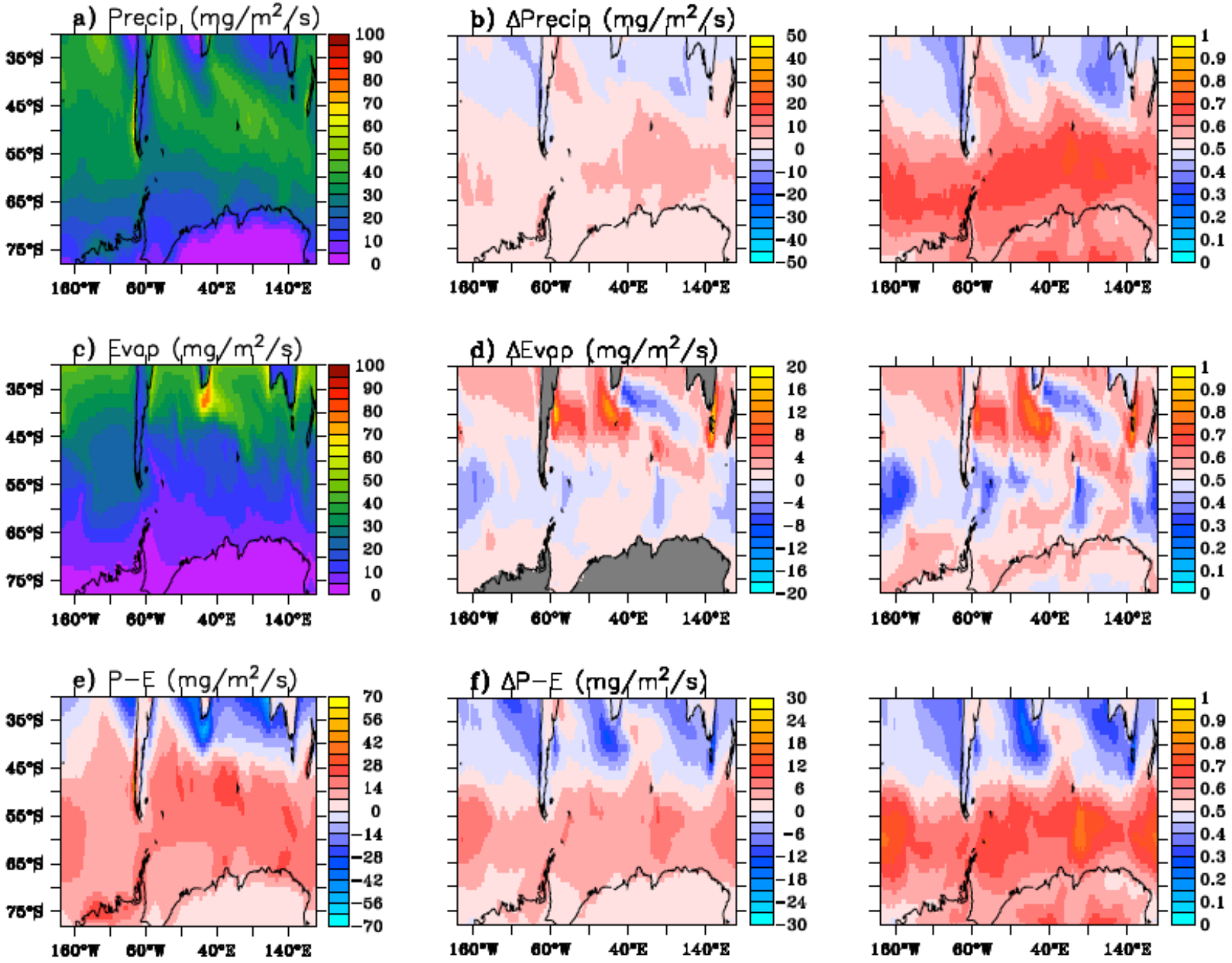

Δprod PgC/yr
Δthetaosurf C

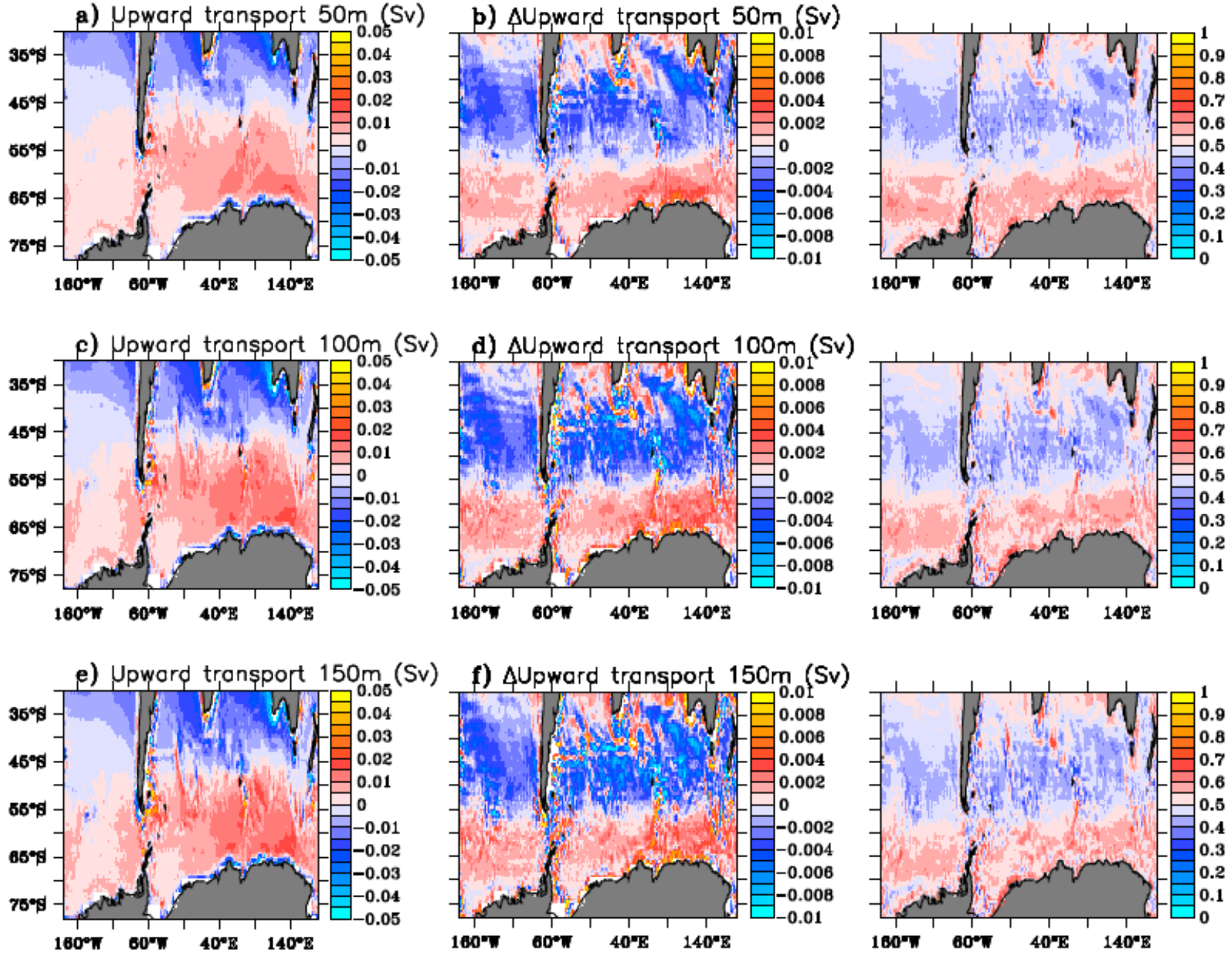

thetaosurf C Rcp8.5
thetaosurf C Historical


a) SST (°C)
31
27
23
19
15
11
7
3
−1
−5
b) ΔSST (°C)
6
4.8
3.6
2.4
1.2
0
−1.2
−2.4
−3.6
−4.8
−6
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
c) Strat (kg/m3)
6
5.4
4.8
4.2
3.6
3
2.4
1.8
1.2
0.6
0
d) ΔStrat (kg/m3)
2
1.6
1.2
0.8
0.4
0
−0.4
−0.8
−1.2
−1.6
−2
e) τu (Pa)
0.4
0.32
0.24
0.16
0.08
0
−0.08
−0.16
−0.24
−0.32
−0.4
f) Δτu (Pa)
0.05
0.04
0.03
0.02
0.01
0
−0.01
−0.02
−0.03
−0.04
−0.05
35°S
45°S
55°S
65°S
75°S
160°W
60°W
40°E
140°E

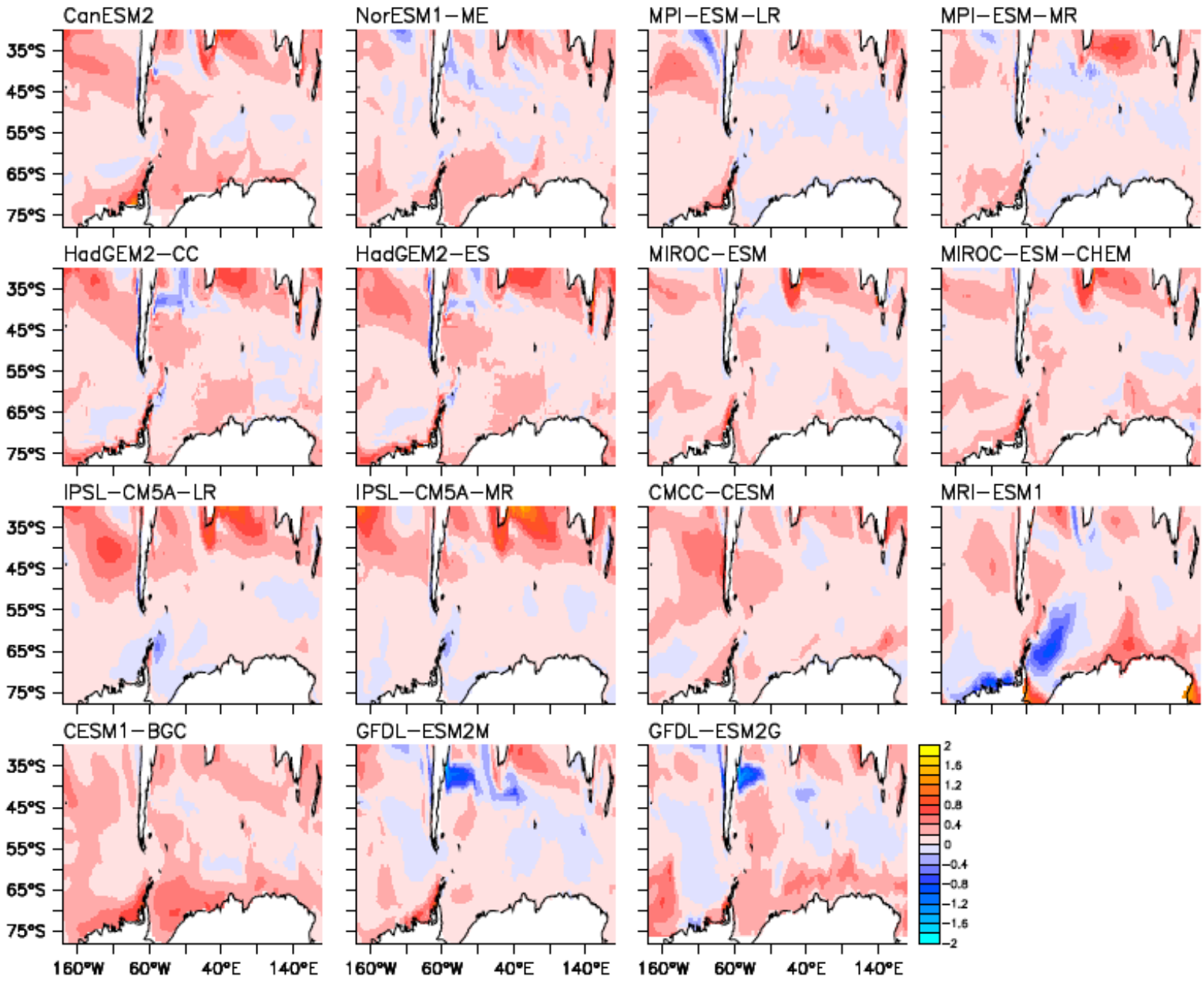

a) SSS (psu)
36.8
36
35.2
34.4
33.6
32.8
32
31.2
30.4
29.6
28.8
28
b) ΔSSS (psu)
2
1.6
1.2
0.8
0.4
0
−0.4
−0.8
−1.2
−1.6
−2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
c) Cloud fraction ( )
100
90
80
70
60
50
40
30
20
10
0
d) ΔCloud fraction ( )
30
24
18
12
6
0
−6
−12
−18
−24
−30
e) Ice fraction ( )
f) ΔIce fraction ( )
100
80
60
40
20
0
−20
−40
−60
−80
−100
35°S
45°S
55°S
65°S
75°S
160°W
60°W
40°E
140°E


a) Light (W/m²)
300
270
240
210
180
150
120
90
60
30
0
b) ΔLight (W/m²)
30
24
18
12
6
0
−6
−12
−18
−24
−30
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
c) MLD max (m)
800
700
600
500
400
300
200
100
0
d) ΔMLD max (m)
300
240
180
120
60
0
−60
−120
−180
−240
−300
e) MLD min (m)
72
66
60
54
48
42
36
30
24
18
12
6
0
f) ΔMLD min (m)
20
16
12
8
4
0
−4
−8
−12
−16
−20
35°S
45°S
55°S
65°S
75°S
160°W
60°W
40°E
140°E

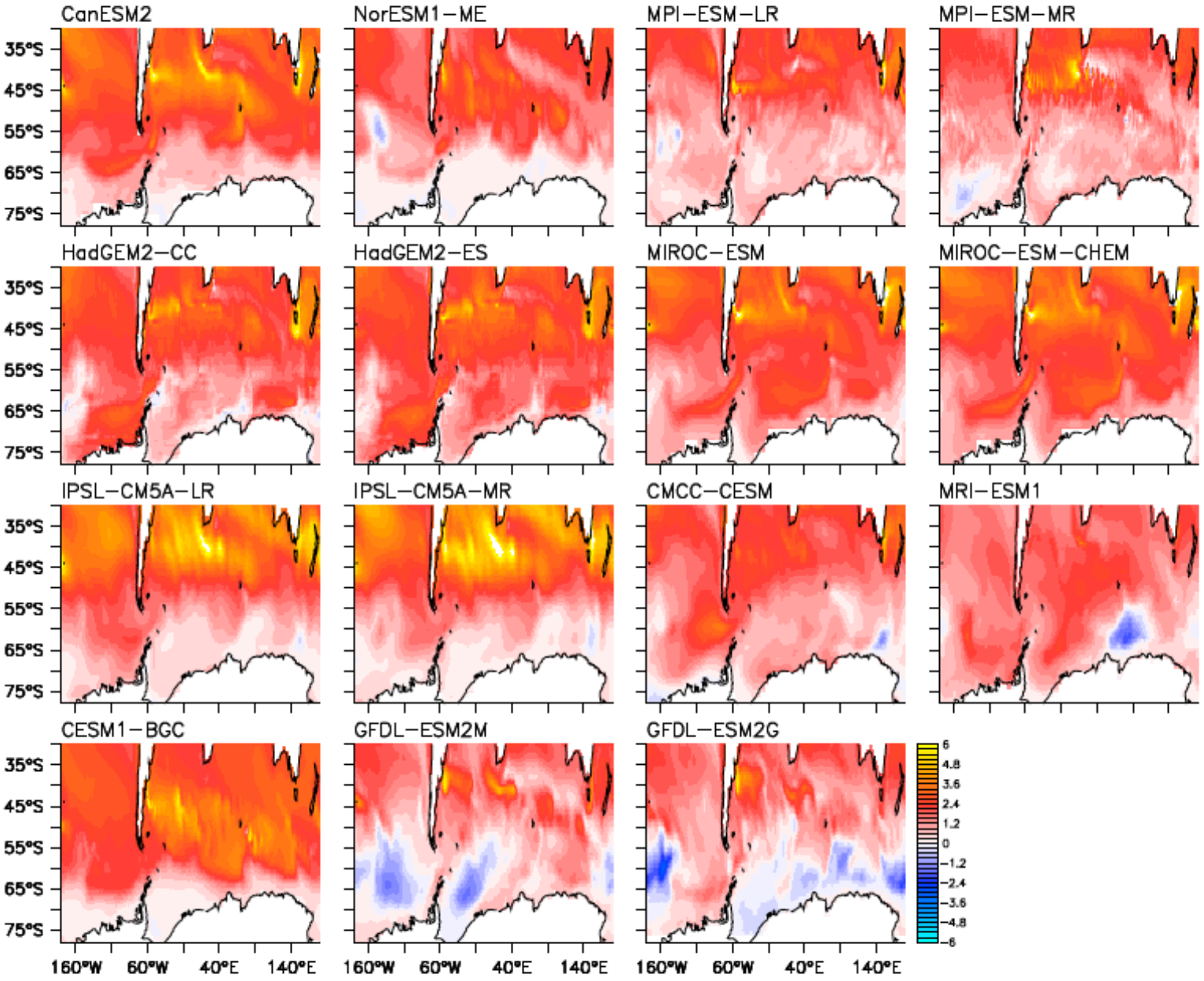

a) Precip (mg/m²/s)
b) ΔPrecip (mg/m²/s)
c) Evap (mg/m²/s)
d) ΔEvap (mg/m²/s)
e) P−E (mg/m²/s)
f) ΔP−E (mg/m²/s)
35°S
45°S
55°S
65°S
75°S
160°W
60°W
40°E
140°E
100 90 80 70 60 50 40 30 20 10 0
50 40 30 20 10 0 −10 −20 −30 −40 −50
20 16 12 8 4 0 −4 −8 −12 −16 −20
70 56 42 28 14 0 −14 −28 −42 −56 −70
30 24 18 12 6 0 −6 −12 −18 −24 −30
1 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0


a) Upward transport 50m (Sv)
b) ΔUpward transport 50m (Sv)
c) Upward transport 100m (Sv)
d) ΔUpward transport 100m (Sv)
e) Upward transport 150m (Sv)
f) ΔUpward transport 150m (Sv)
35°S
45°S
55°S
65°S
75°S
160°W
60°W
40°E
140°E
0.05
0.04
0.03
0.02
0.01
0
−0.01
−0.02
−0.03
−0.04
−0.05
0.01
0.008
0.006
0.004
0.002
0
−0.002
−0.004
−0.006
−0.008
−0.01
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

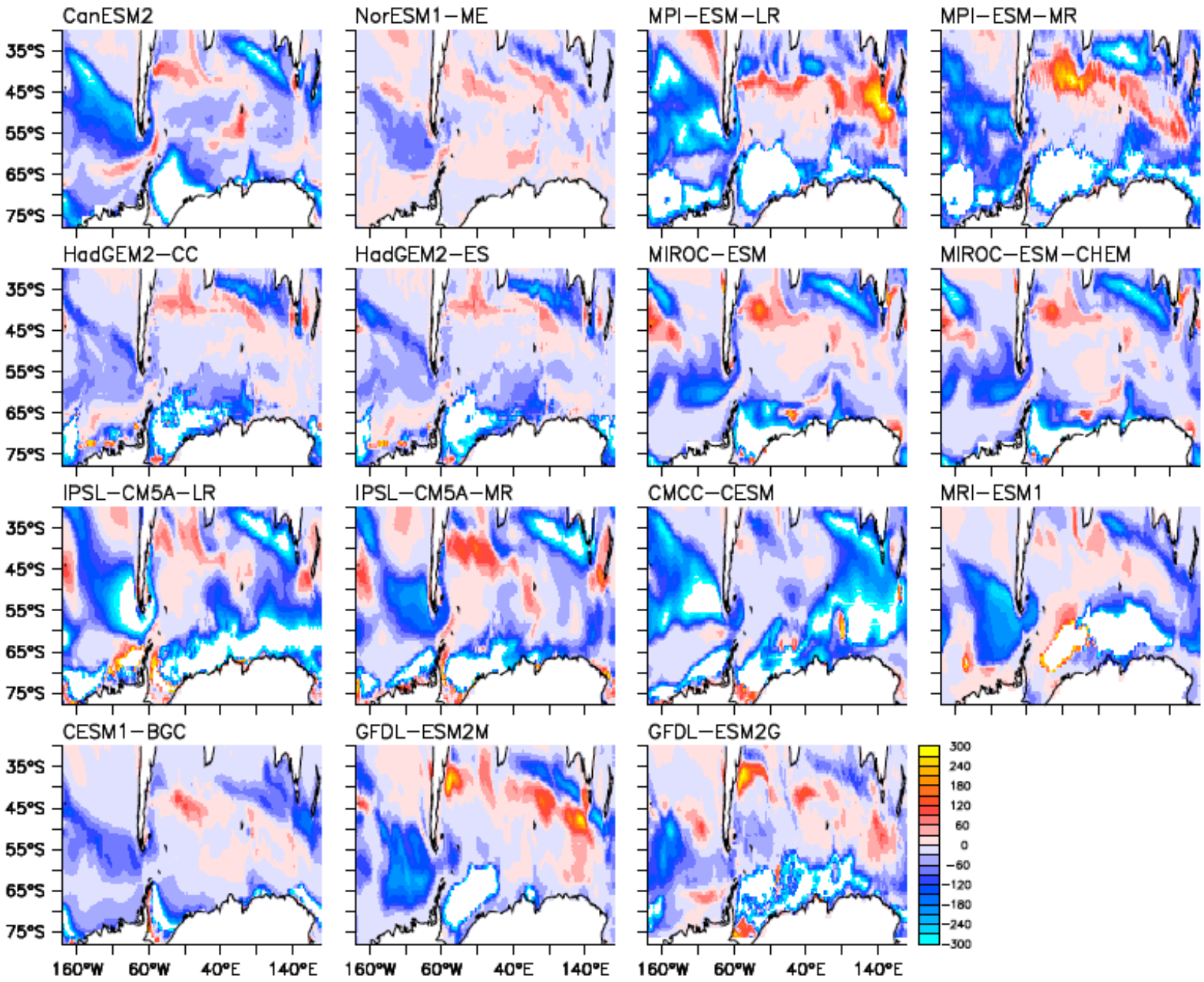
Δ Stratification



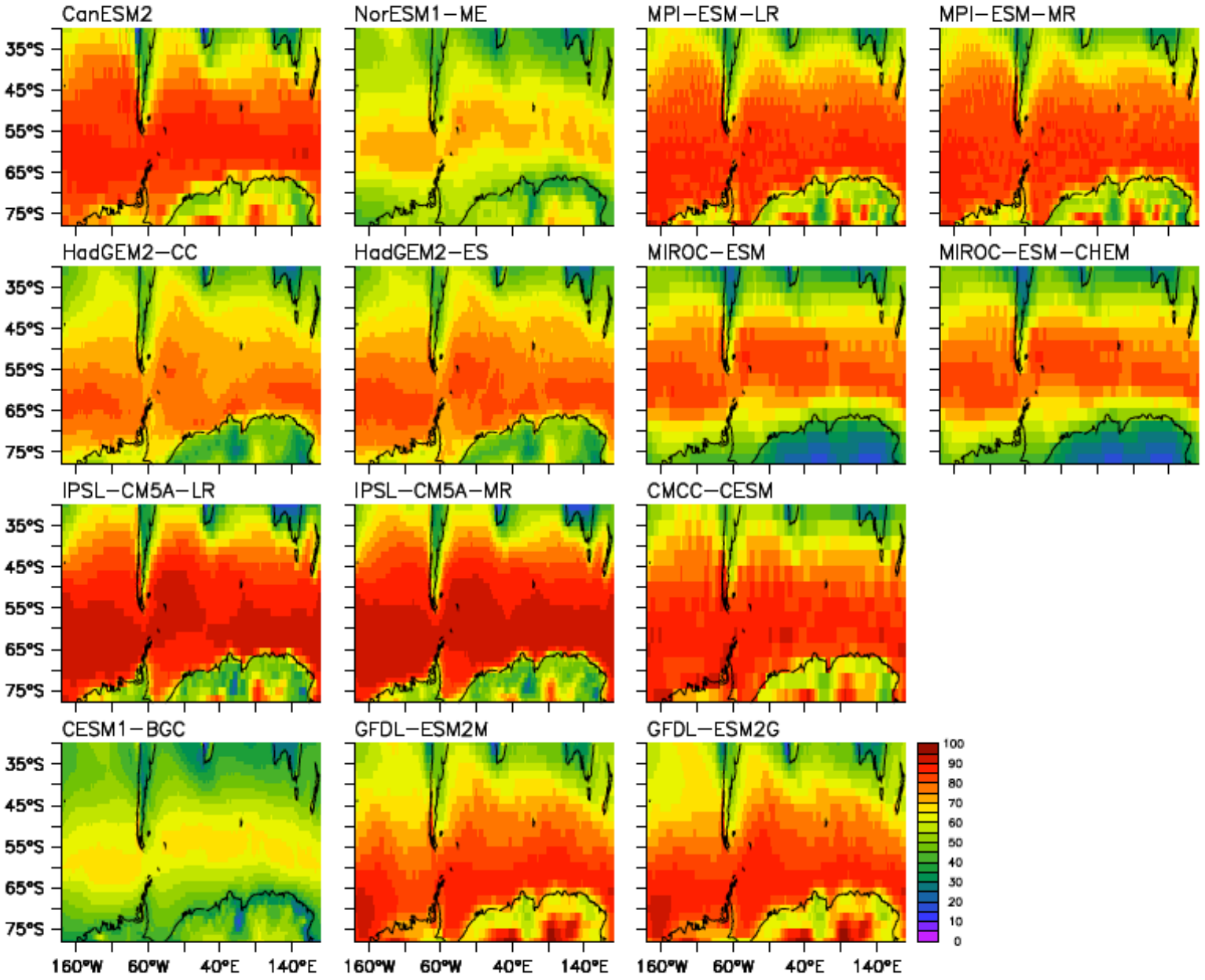
Δ SST


CanESM2
NorESM1−ME
MPI−ESM−LR
MPI−ESM−MR
HadGEM2−CC
HadGEM2−ES
MIROC−ESM
MIROC−ESM−CHEM
IPSL−CM5A−LR
IPSL−CM5A−MR
CMCC−CESM
MRI−ESM1
CESM1−BGC
GFDL−ESM2M
GFDL−ESM2G
35°S
45°S
55°S
65°S
75°S
160°W
60°W
40°E
140°E
6
4.8
3.6
2.4
1.2
0
−1.2
−2.4
−3.6
−4.8
−6

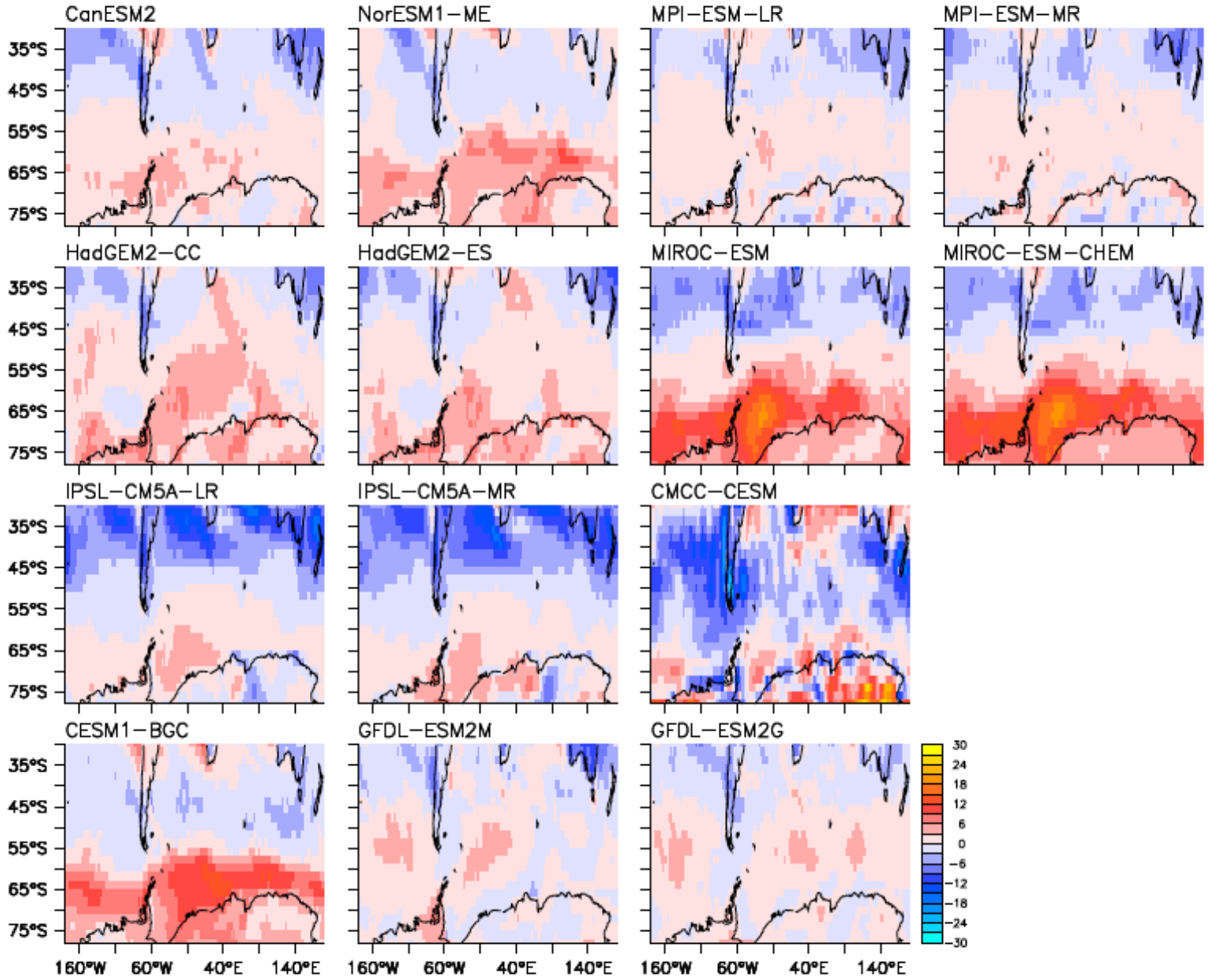
Δ MLDmax


CanESM2
NorESM1−ME
MPI−ESM−LR
MPI−ESM−MR
HadGEM2−CC
HadGEM2−ES
MIROC−ESM
MIROC−ESM−CHEM
IPSL−CM5A−LR
IPSL−CM5A−MR
CMCC−CESM
MRI−ESM1
CESM1−BGC
GFDL−ESM2M
GFDL−ESM2G
35°S
45°S
55°S
65°S
75°S
160°W
60°W
40°E
140°E
300
240
180
120
60
0
−60
−120
−180
−240
−300

Clouds present



Δ clouds


CanESM2
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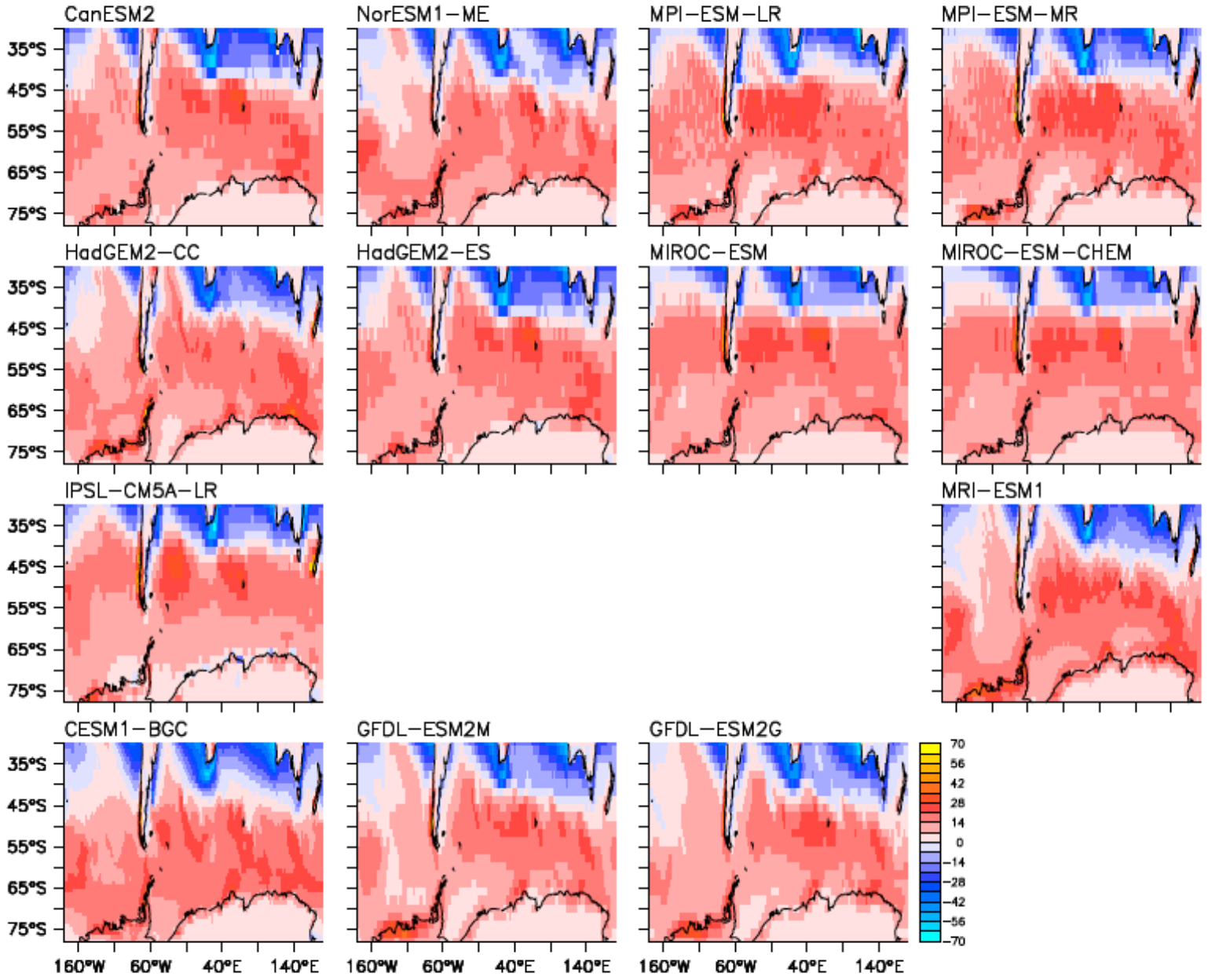
MPI−ESM−LR
MPI−ESM−MR
HadGEM2−CC
HadGEM2−ES
MIROC−ESM
MIROC−ESM−CHEM
IPSL−CM5A−LR
IPSL−CM5A−MR
CMCC−CESM
CESM1−BGC
GFDL−ESM2M
GFDL−ESM2G
35°S
45°S
55°S
65°S
75°S
160°W
60°W
40°E
140°E
30
24
18
12
6
0
−6
−12
−18
−24
−30

P-E present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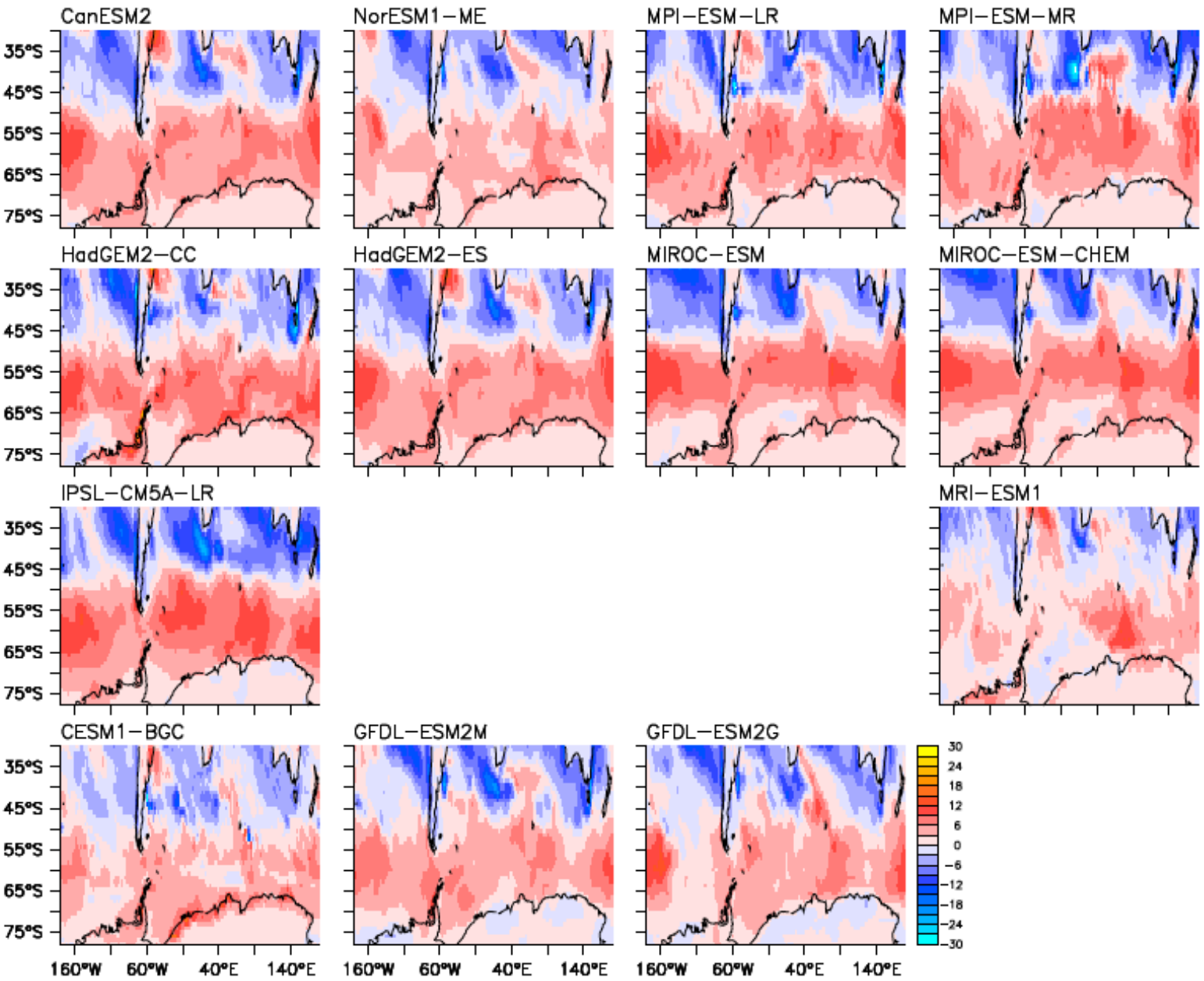
MPI−ESM−MR
HadGEM2−CC
HadGEM2−ES
MIROC−ESM
MIROC−ESM−CHEM
IPSL−CM5A−LR
MRI−ESM1
CESM1−BGC
GFDL−ESM2M
GFDL−ESM2G
35°S
45°S
55°S
65°S
75°S
160°W
60°W
40°E
140°E
70
56
42
28
14
0
−14
−28
−42
−56
−70

Δ P-E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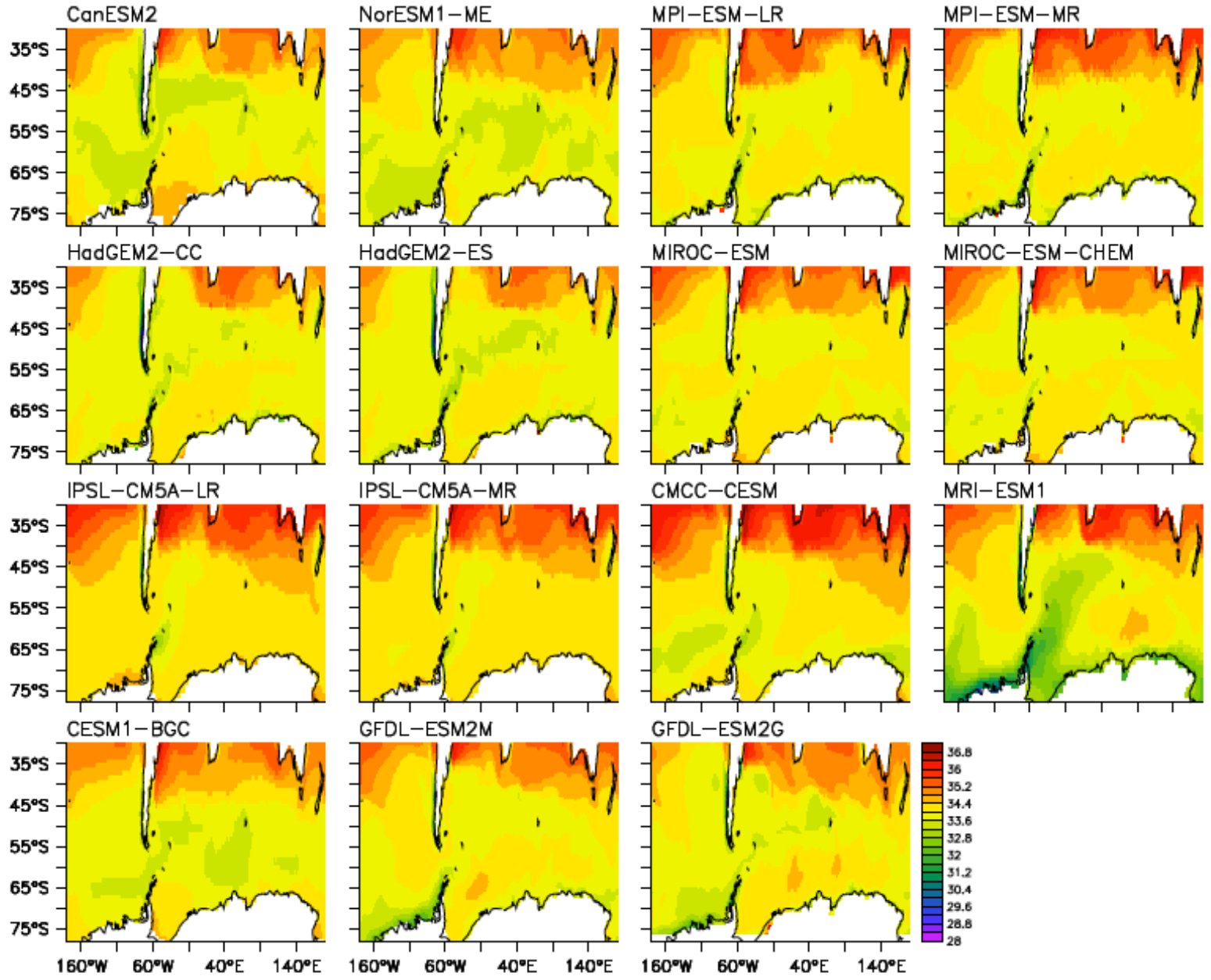
MPI−ESM−MR
HadGEM2−CC
HadGEM2−ES
MIROC−ESM
MIROC−ESM−CHEM
IPSL−CM5A−LR
MRI−ESM1
CESM1−BGC
GFDL−ESM2M
GFDL−ESM2G
35°S
45°S
55°S
65°S
75°S
160°W
60°W
40°E
140°E
30
24
18
12
6
0
−6
−12
−18
−24
−30

SSS present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HadGEM2−ES
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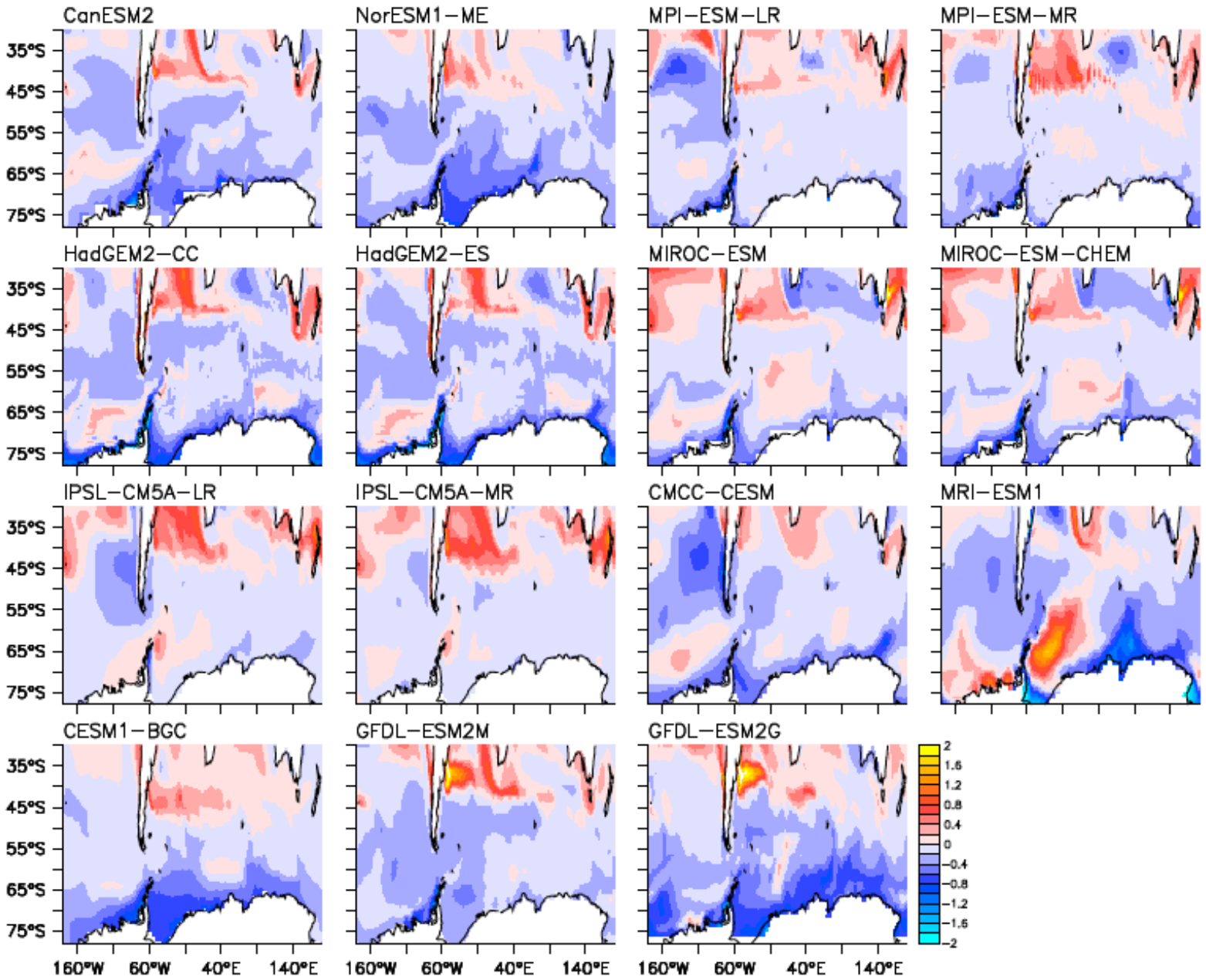
IPSL−CM5A−LR
IPSL−CM5A−MR
CMCC−CESM
MRI−ESM1
CESM1−BGC
GFDL−ESM2M
GFDL−ESM2G
35°S
45°S
55°S
65°S
75°S
160°W
60°W
40°E
140°E
36.8
36
35.2
34.4
33.6
32.8
32
31.2
30.4
29.6
28.8
28

Δ SSS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MPI−ESM−MR
HadGEM2−CC
HadGEM2−ES
MIROC−ESM
MIROC−ESM−CHEM
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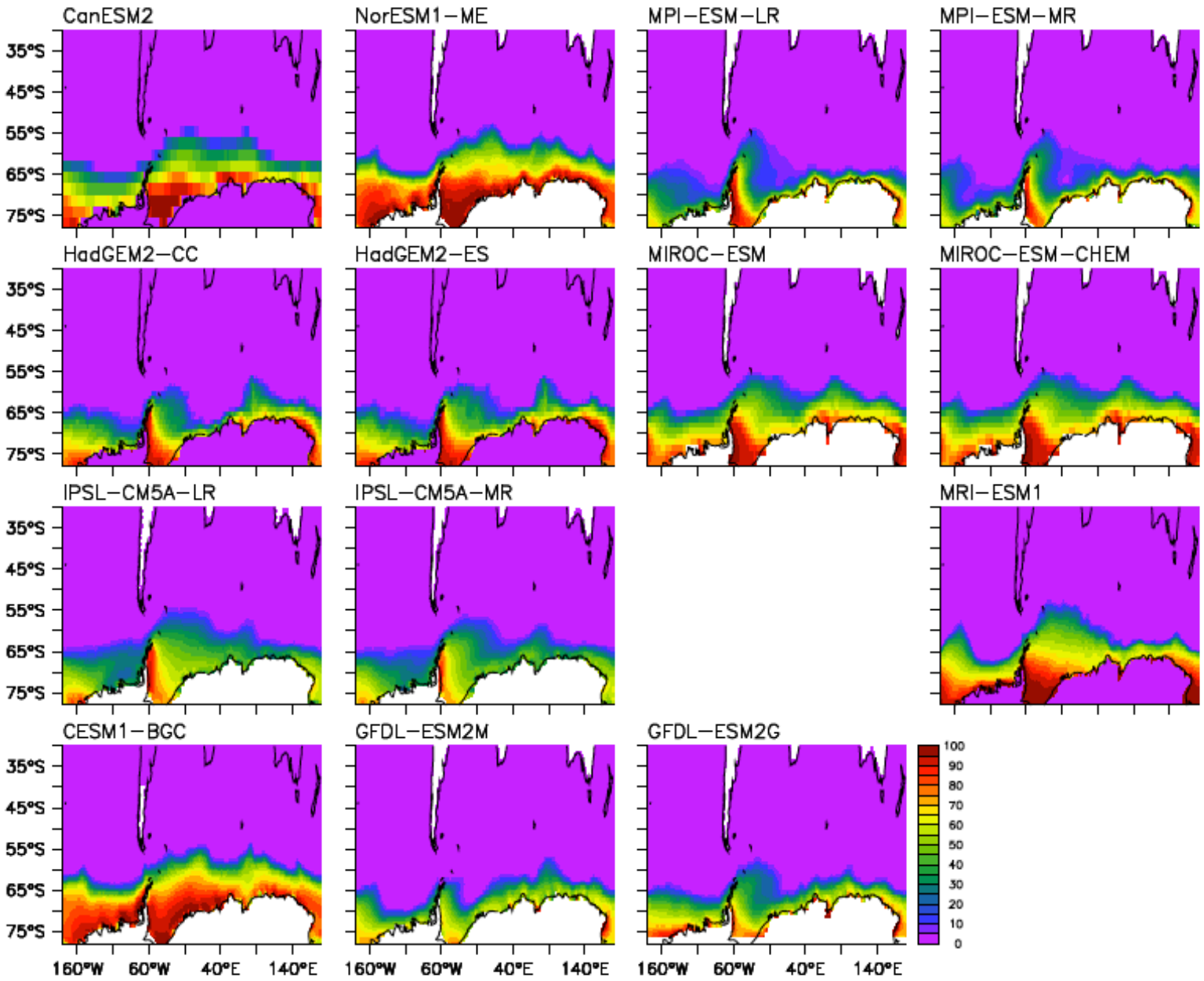
IPSL−CM5A−MR
CMCC−CESM
MRI−ESM1
CESM1−BGC
GFDL−ESM2M
GFDL−ESM2G
35°S
45°S
55°S
65°S
75°S
160°W
60°W
40°E
140°E
2
1.6
1.2
0.8
0.4
0
−0.4
−0.8
−1.2
−1.6
−2

Ice present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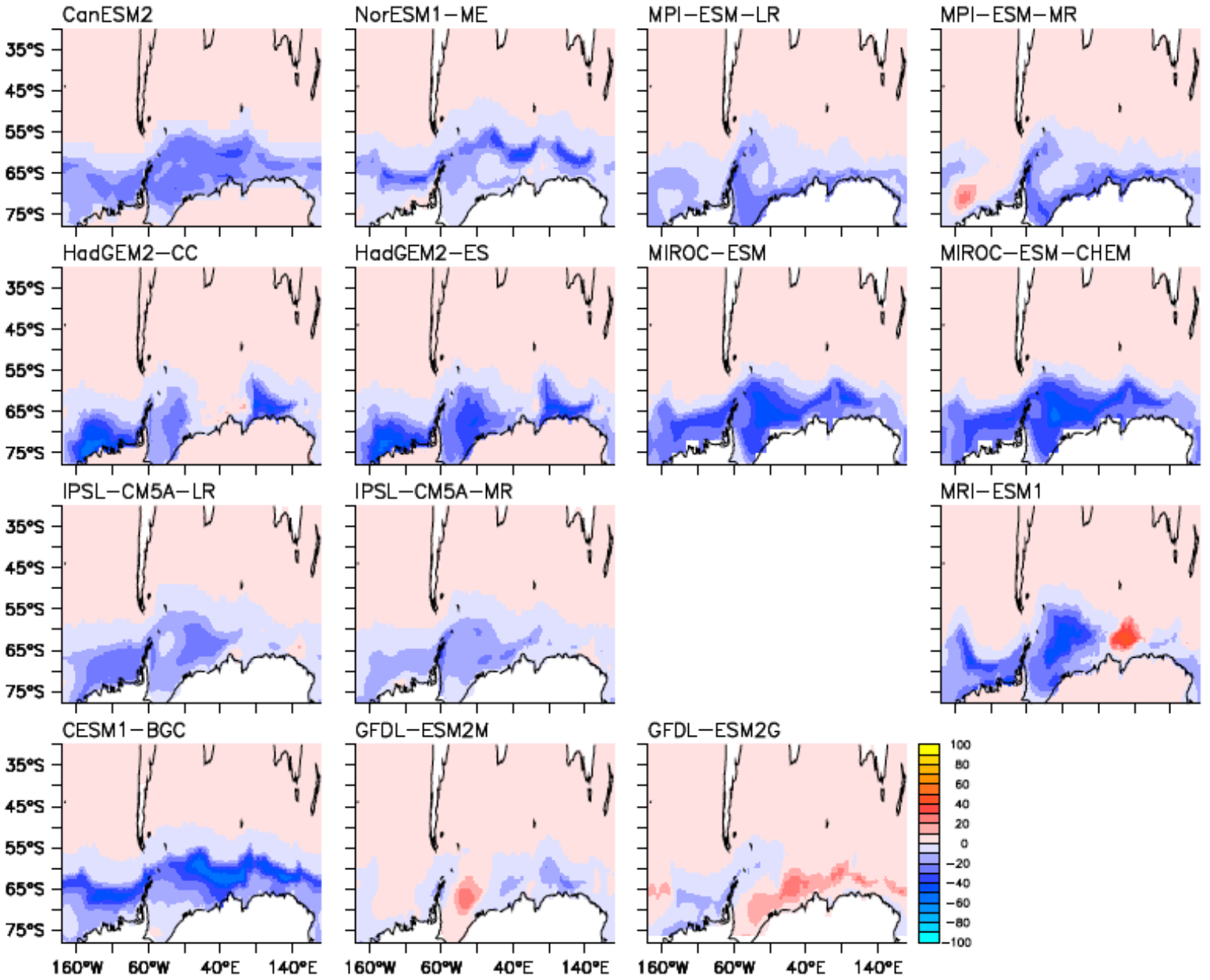
MPI−ESM−MR
HadGEM2−CC
HadGEM2−ES
MIROC−ESM
MIROC−ESM−CHEM
IPSL−CM5A−LR
IPSL−CM5A−MR
MRI−ESM1
CESM1−BGC
GFDL−ESM2M
GFDL−ESM2G
35°S
45°S
55°S
65°S
75°S
160°W
60°W
40°E
140°E
100
90
80
70
60
50
40
30
20
10
0

Δ ice


CanESM2
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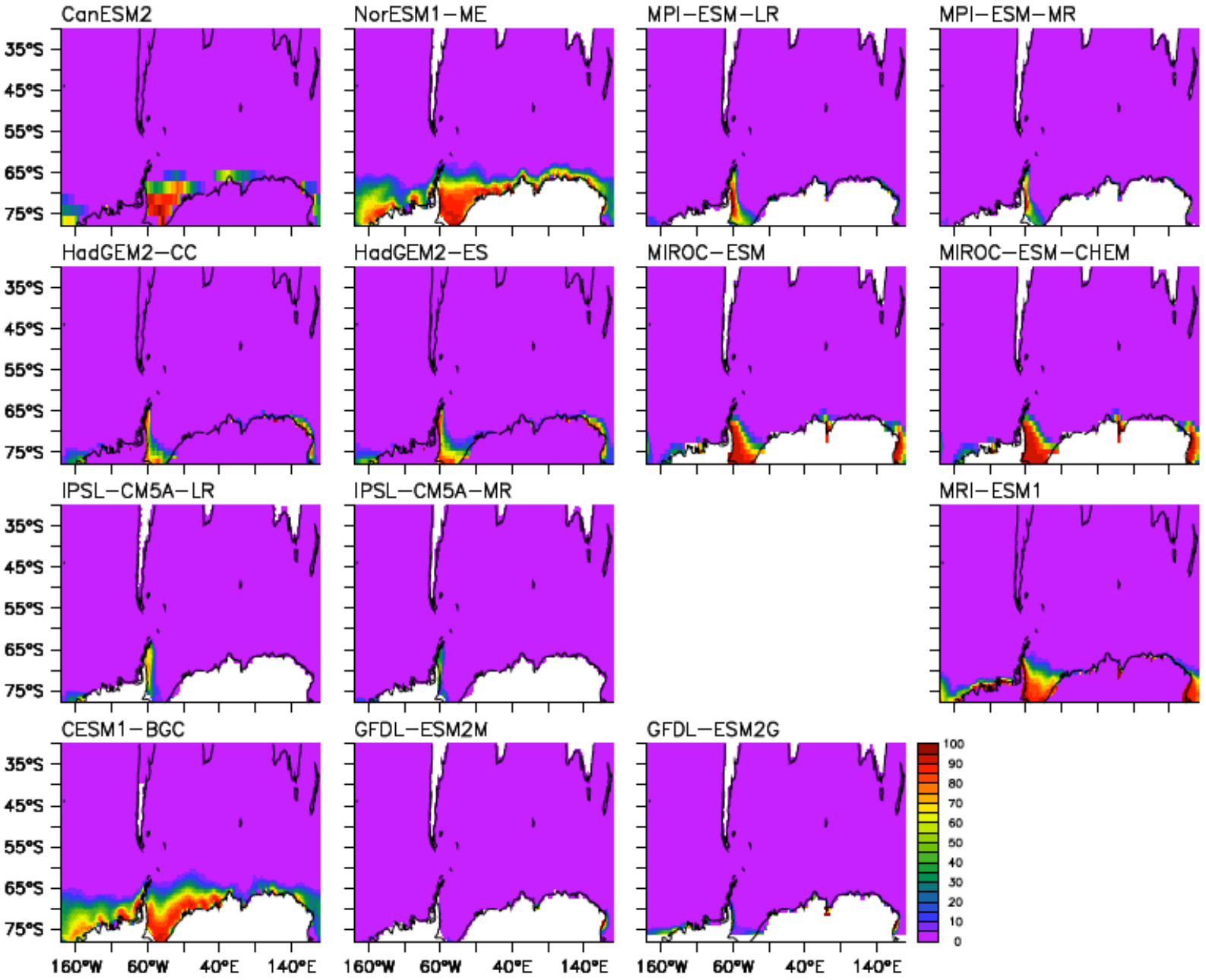
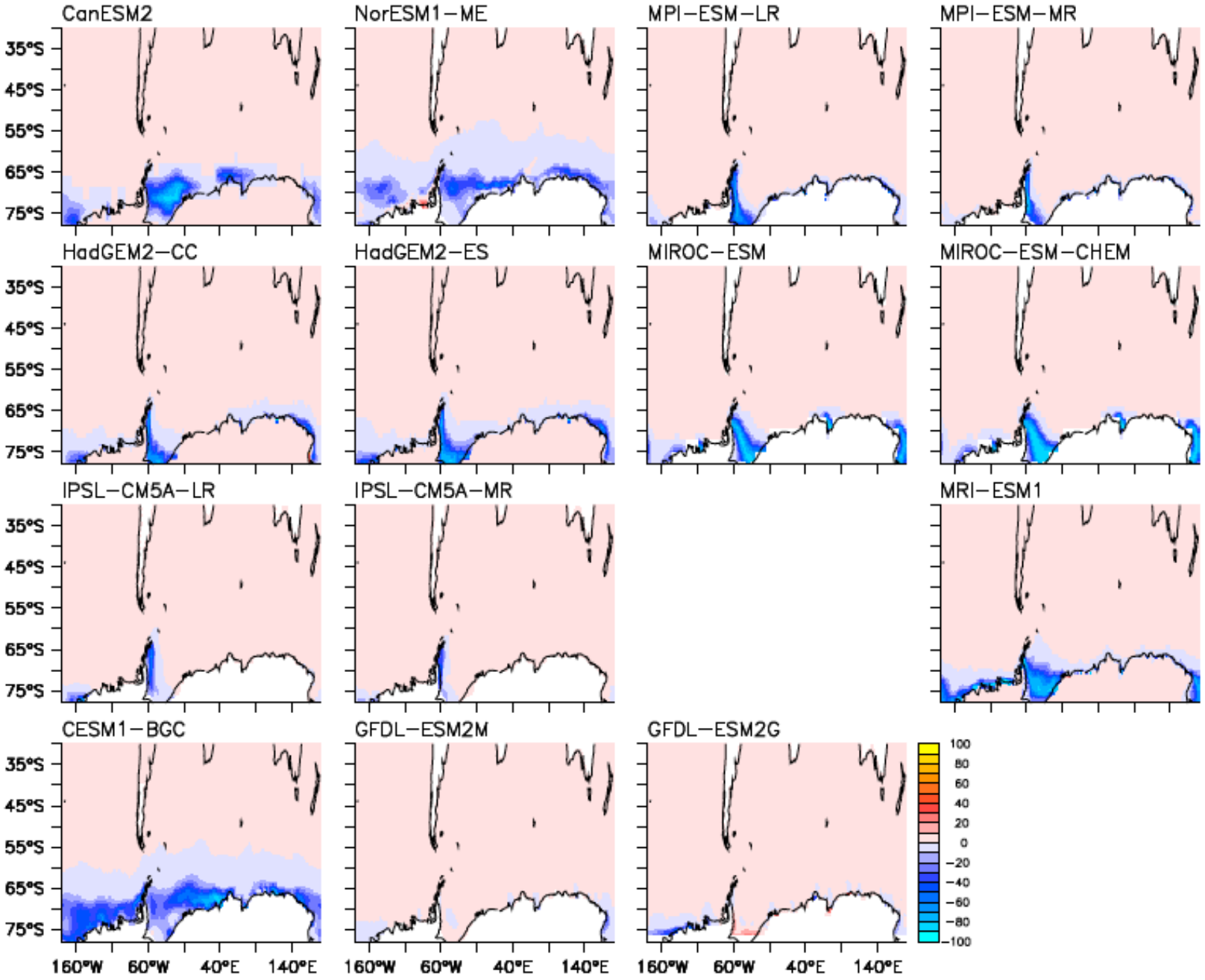
MPI−ESM−LR
MPI−ESM−MR
HadGEM2−CC
HadGEM2−ES
MIROC−ESM
MIROC−ESM−CHEM
IPSL−CM5A−LR
IPSL−CM5A−MR
MRI−ESM1
CESM1−BGC
GFDL−ESM2M
GFDL−ESM2G
35°S
45°S
55°S
65°S
75°S
160°W
60°W
40°E
140°E
100
80
60
40
20
0
−20
−40
−60
−80
−100

Summer ice present



Δ summer ice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MPI−ESM−MR
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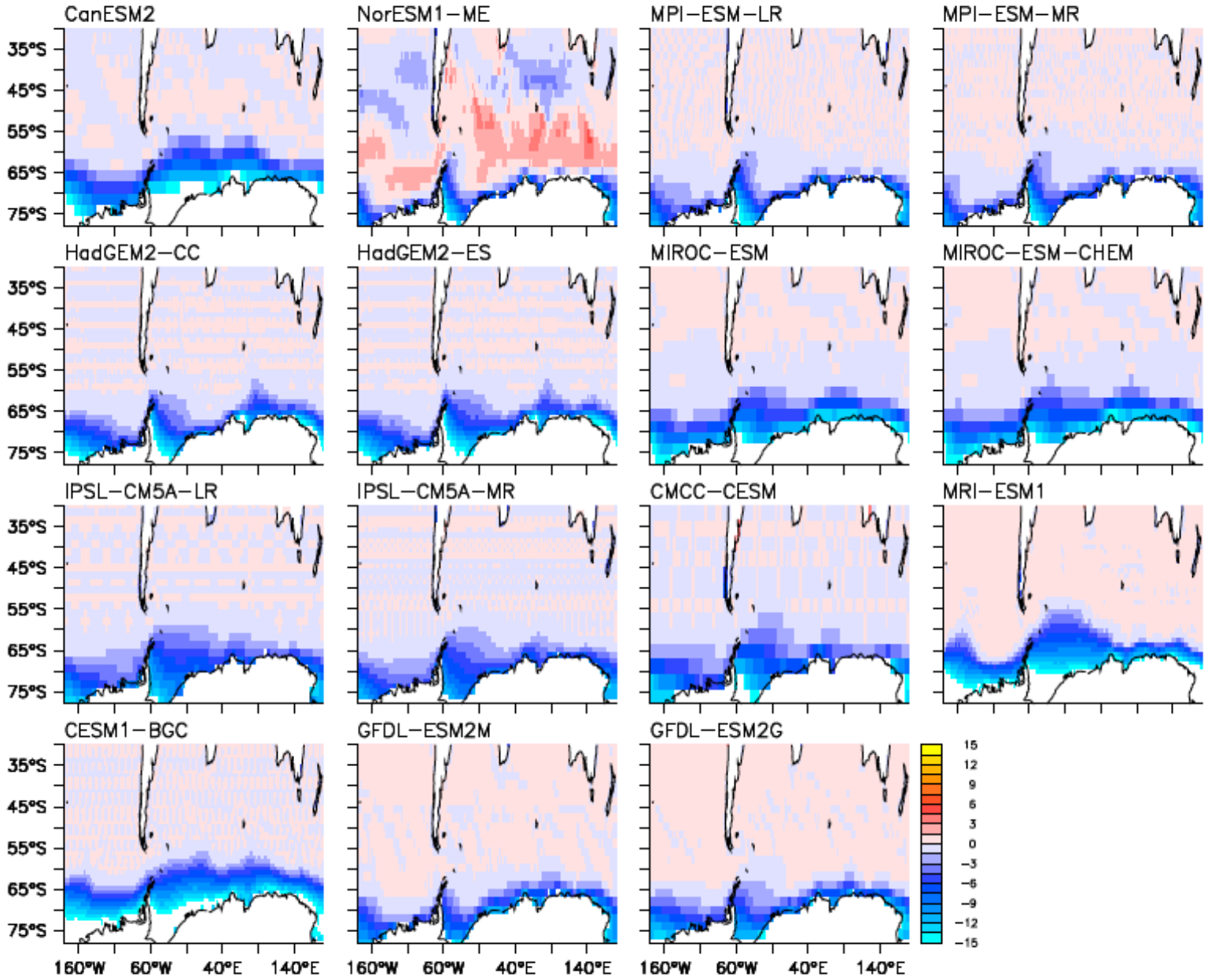
HadGEM2−ES
MIROC−ESM
MIROC−ESM−CHEM
IPSL−CM5A−LR
IPSL−CM5A−MR
MRI−ESM1
CESM1−BGC
GFDL−ESM2M
GFDL−ESM2G
35°S
45°S
55°S
65°S
75°S
160°W
60°W
40°E
140°E
100
80
60
40
20
0
−20
−40
−60
−80
−100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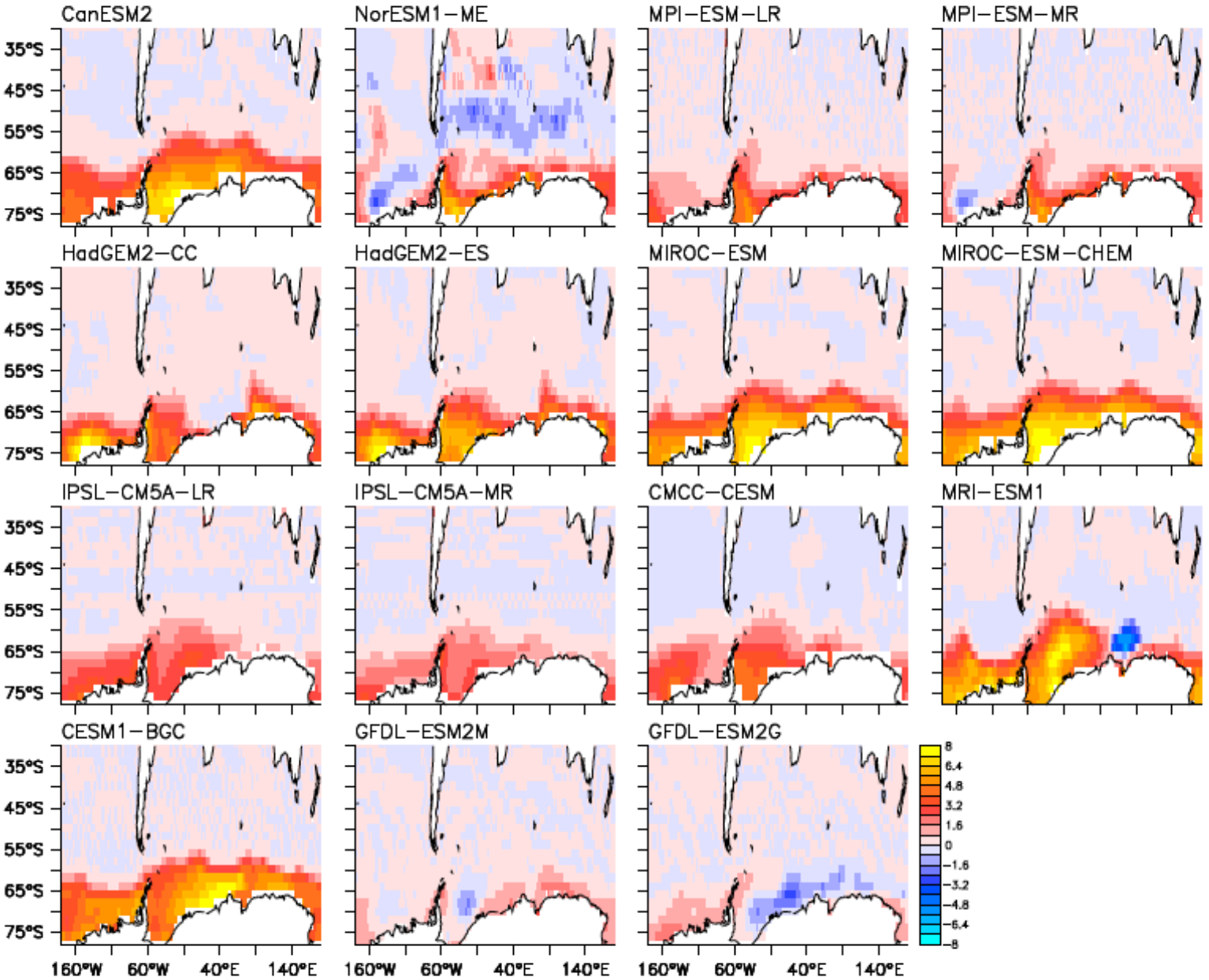
MPI−ESM−LR
MPI−ESM−MR
HadGEM2−CC
HadGEM2−ES
MIROC−ESM
MIROC−ESM−CHEM
IPSL−CM5A−LR
IPSL−CM5A−MR
CMCC−CESM
MRI−ESM1
CESM1−BGC
GFDL−ESM2M
GFDL−ESM2G
35°S
45°S
55°S
65°S
75°S
160°W
60°W
40°E
140°E
15
12
9
6
3
0
−3
−6
−9
−12
−15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HadGEM2−CC
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MIROC−ESM−CHEM
IPSL−CM5A−LR
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CMCC−CESM
MRI−ESM1
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GFDL−ESM2M
GFDL−ESM2G
35°S
45°S
55°S
65°S
75°S
160°W
60°W
40°E
140°E
8
6.4
4.8
3.2
1.6
0
−1.6
−3.2
−4.8
−6.4
−8