National Oceanography Centre

Marine Systems Modelling

CRESCENDO

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Patterns of ocean interior remineralisation and their change under climate change in CMIP6 models

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with thanks to …

NCAR

Institut Pierre Simon Laplace

EC-EARTH

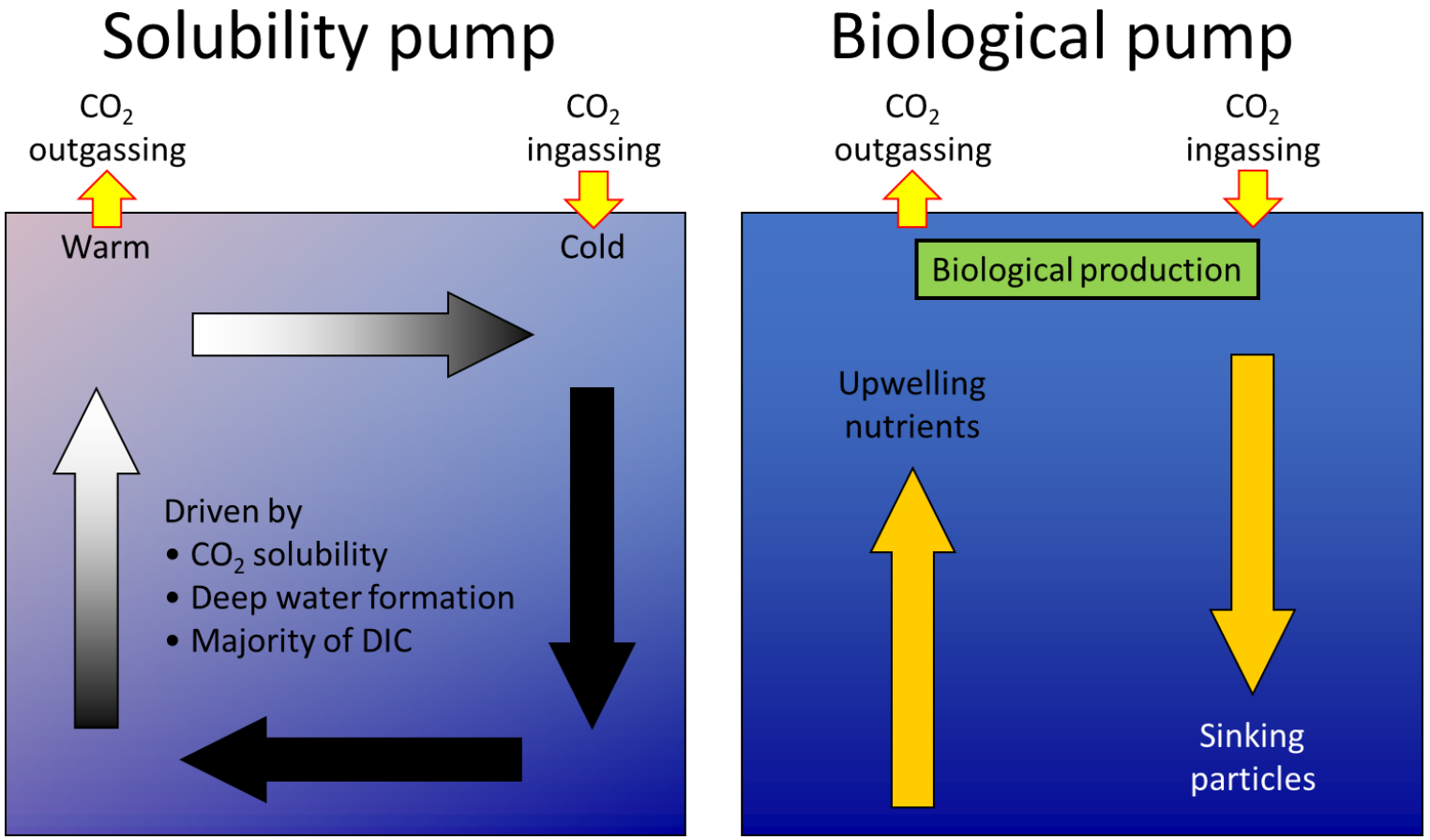
GFDL

Met Office

Max-Planck-Institut für Meteorologie

Outline

- Biological pump
- CMIP6 model configurations
- Primary and export production
- MLD horizons
- Going forwards



- Ocean is the largest active reservoir of CO2 because of two “pumps”
- Anthro CO2 uptake is driven by the physico-chemical “Solubility pump”
- Because biology is limited by nutrients, not CO2, the “Biological pump” is secondary
- However, by increasing biological rates, decreasing nutrient supply, etc., climate change may alter the Biological pump and affect future ocean carbon storage

CMIP6 models

- Models used here are:
  - CESM2-WACCM
  - EC-Earth-CC
  - GFDL-ESM4
  - IPSL-CM6A-LR
  - MPI-ESM1-2-LR
  - UKESM1-0-LL

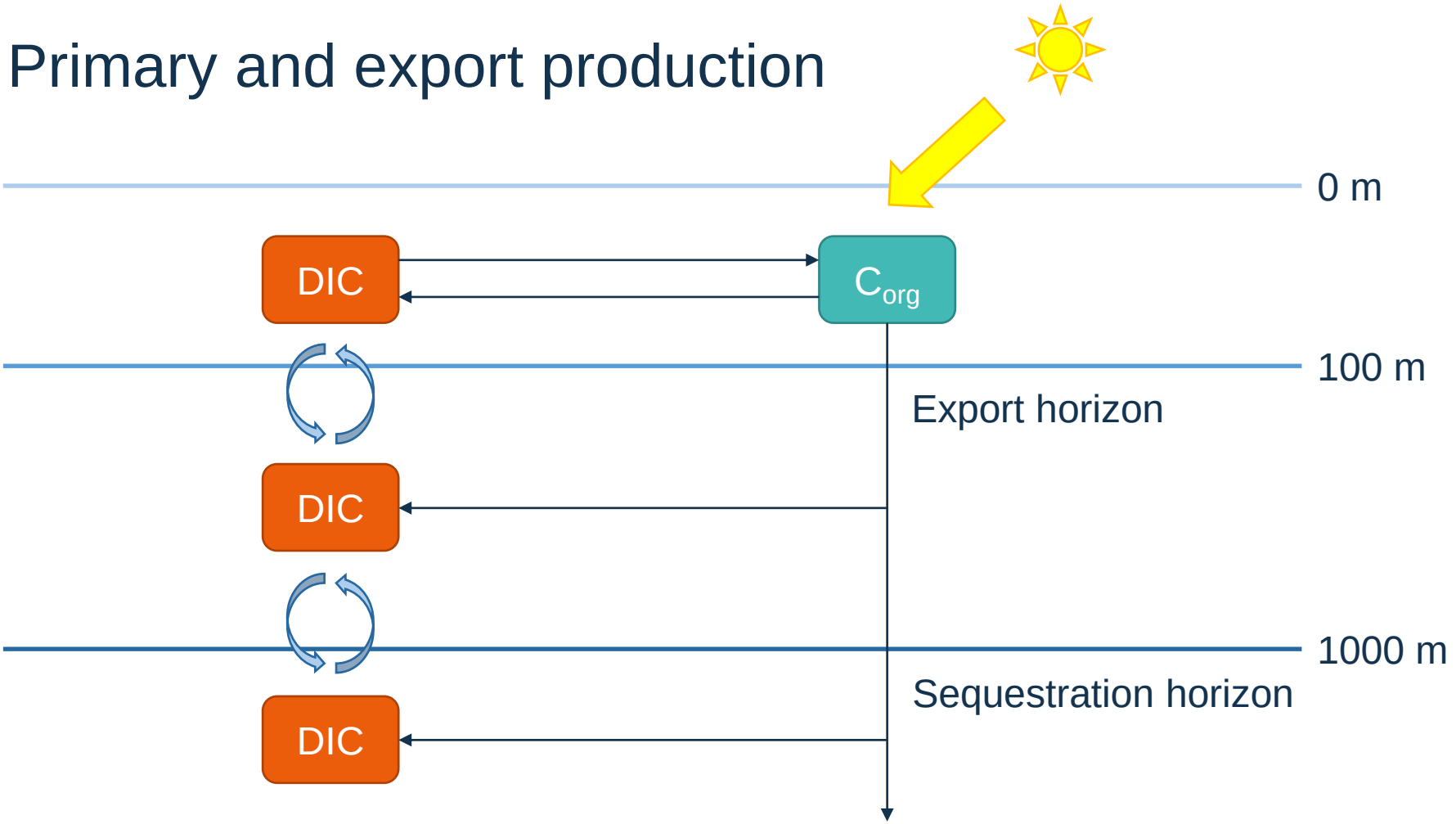
- Fields used are:
  - `intpp`, `mlotst`, `expc`, (`remoc`)
- SSP 585 future scenarios
- Currently there is limited availability of output from CMIP6 simulations on the ESGF (even UKESM1!)

Model configurations

Model	Ocean	Sea-ice	Marine BGC	Resolution
CESM2-WACCM	POP2	CICE5.1	MARBL	320x384x60
EC-Earth-CC	NEMO3.6	LIM3	PISCES v2	362x292x75
GFDL-ESM4	MOM6	SIS2.0	COBALT-v2	720x576x75
IPSL-CM6A-LR	NEMO3.6	LIM3	PISCES v2	362x332x75
MPI-ESM1-2-LR	MPI OM1.63	“unnamed”	HAMOCC6	256x220x40
UKESM1-0-LL	NEMO3.6 (GO6)	CICE (GSI8)	MEDUSA2	360x320x75

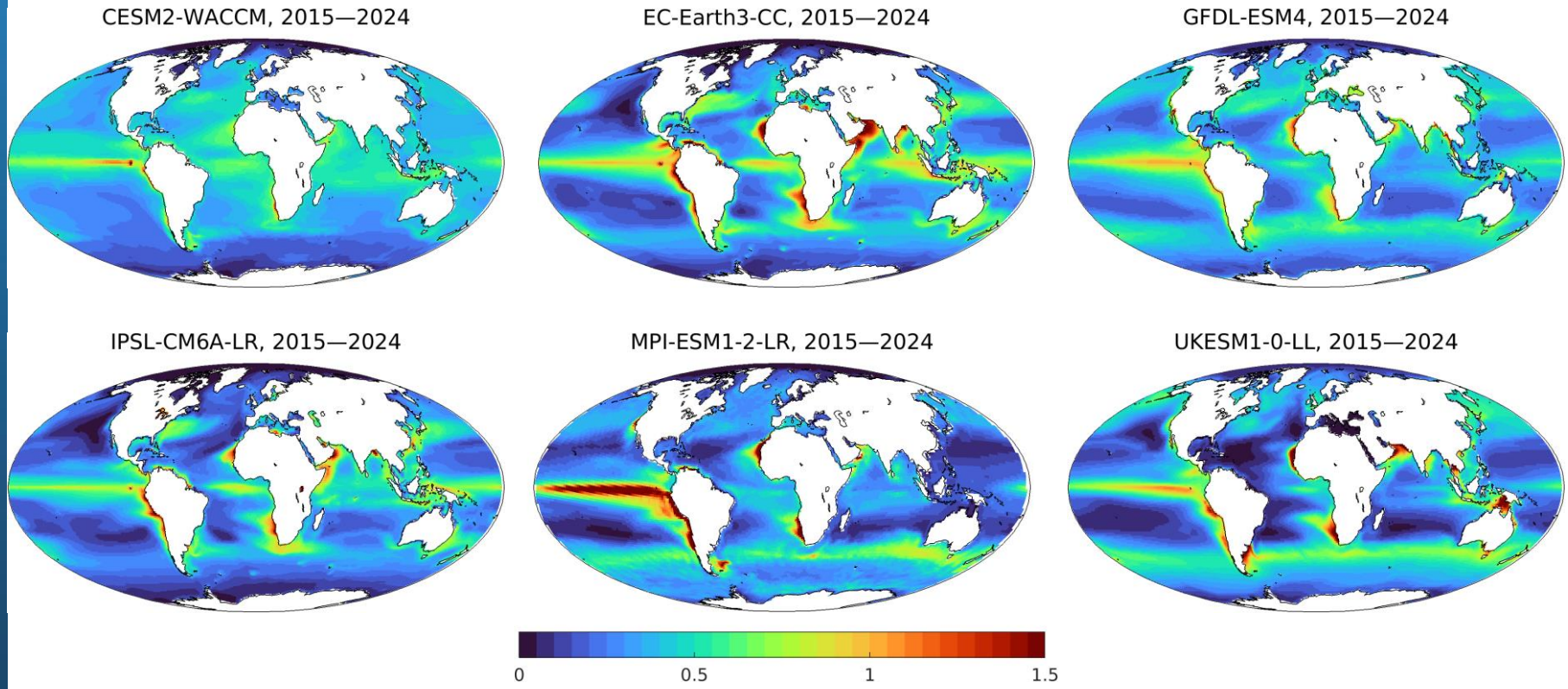
- Only single ensemble members used so far
- 4 ocean models, 4 sea-ice models, 5 marine BGC models
- Two models (EC-Earth and IPSL) share a similar but not identical configuration
- Resolution typically ~1°, with GFDL at ~0.5°

Primary and export production



- Dissolved DIC incorporated in particulate (and sinking) organic carbon
- This exits the productive layer via an arbitrary export horizon (here 100 m)
- Some of this sinks further to be “sequestered” (here 1000 m; IPCC definition)
- Mixing and circulation eventually return the DIC to the surface and atmosphere

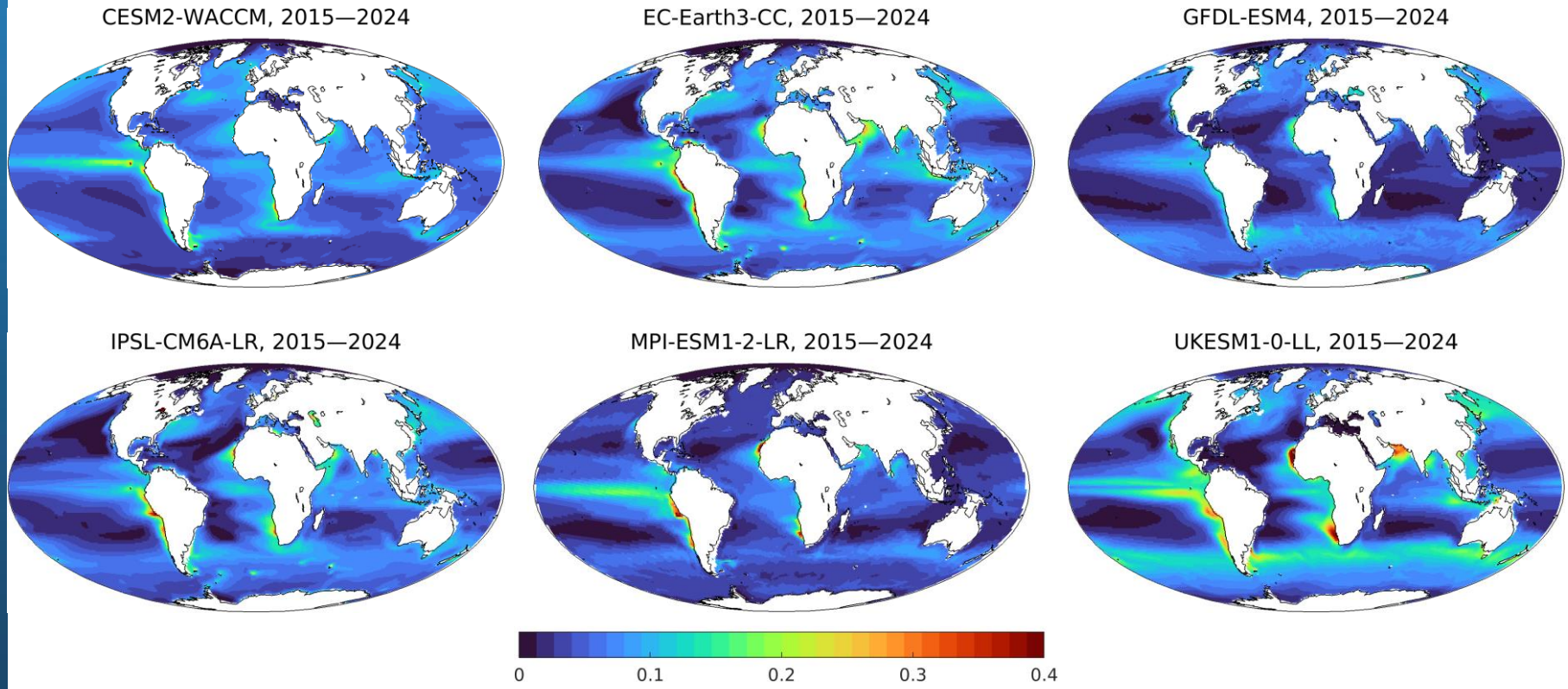
Mean integrated primary production (2015-2024)



[g C m^{-2} d^{-1}]

- Many common features, but significant divergence between models
- Excessive Southern Ocean production a common (3/6) bias
- Disagreement in productivity of oligotrophic gyres, the ocean's largest biome

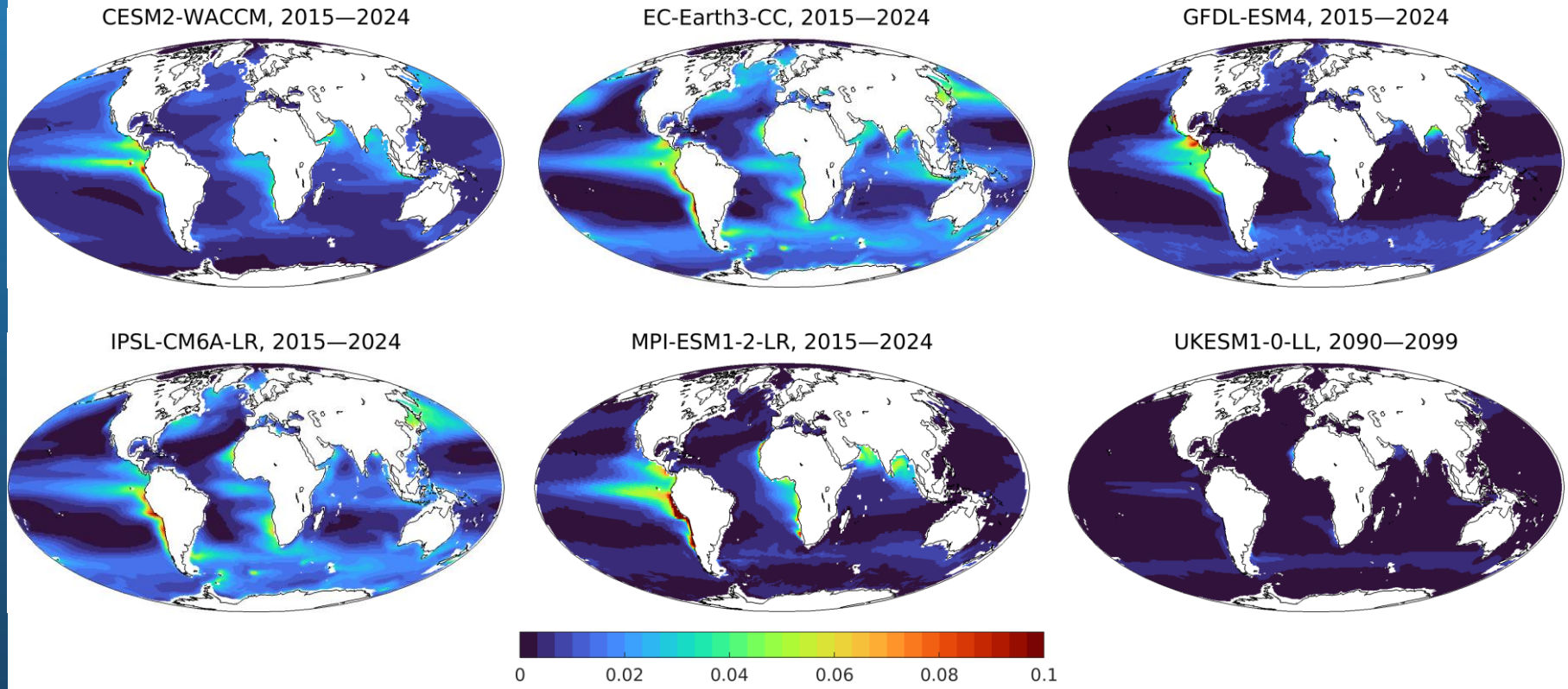
Mean 100m export production (2015-2024)



[g C m^{-2} d^{-1}]

- Export patterns generally track production (inevitably)
- Equatorial Pacific production less dominant an export feature; upwelling regions generally remain important

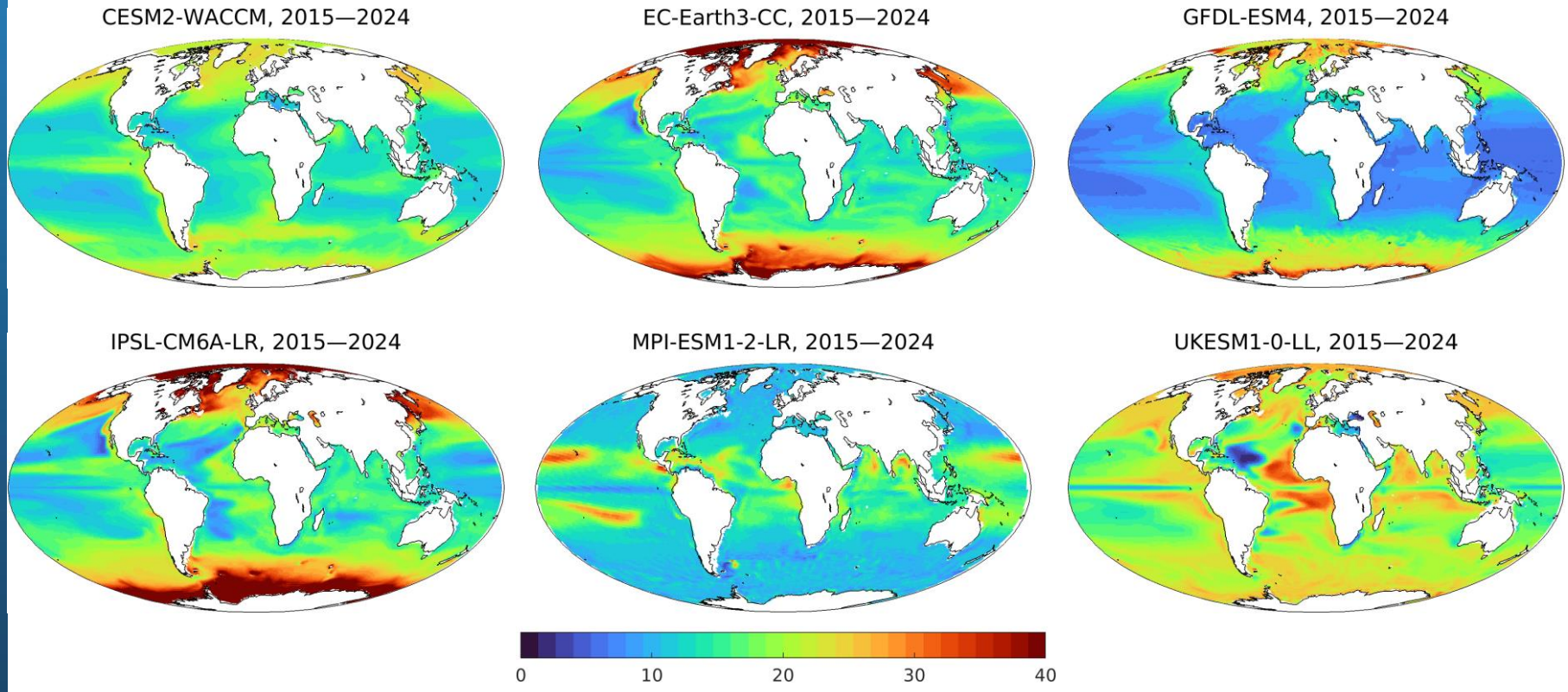
Mean 1000m export production (2015-2024)



[g C m^{-2} d^{-1}]

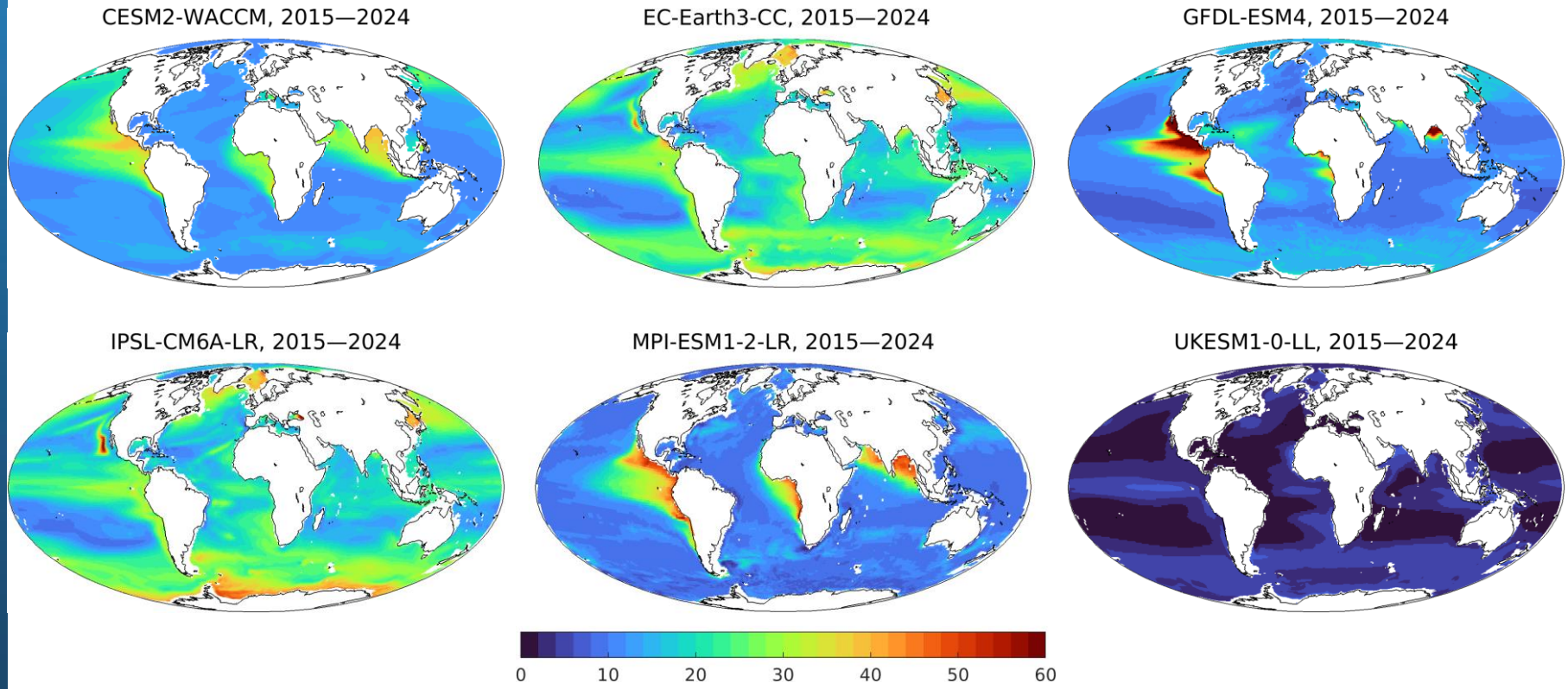
- Sequestration efficiency generally greater at low latitudes
- Extreme attenuation of export flux in UKESM1 a known bias with consequences for interior nutrient and oxygen distributions

Export fraction (2015-2024)



- Strong divergence in export efficiency with models ranging between extremes of efficiency in polar, tropical, equatorial regions
- Most suggest efficiency generally latitude dependent, MPI reverses this

Sequestration fraction (2015-2024)



- High equatorial sequestration efficiency clear in 3 models; related to oxygen minimum zones
- Other models show less focused efficiency; UKESM1 biased to inefficiency as noted

Primary to Export production

Model	IntPP 2015s	IntPP 2090s	Δ	E 100 2015s	E 100 2090s	Δ	E 1000 2015s	E 1000 2090s	Δ
	PgC/y	PgC/y	%	PgC/y	PgC/y	%	PgC/y	PgC/y	%
CESM2-WACCM	46.58	46.79	0.44	7.25	6.82	-5.96	1.1	1.11	1.13
EC-Earth-CC	47.25	49.68	5.13	7.79	7.57	-2.87	1.64	1.46	-11.09
GFDL-ESM4	49.41	46	-6.91	5.92	5.24	-11.41	0.8	0.57	-28.67
IPSL-CM6A-LR	39.34	41.62	5.79	6.92	6.77	-2.26	1.5	1.31	-12.92
MPI-ESM1-2-LR	45.3	41.5	-8.38	5.7	5.01	-12.1	0.82	0.67	-18.27
UKESM1-0-LL	41.48	36.38	-12.3	8.9	7.62	-14.38	0.32	0.17	-46.05

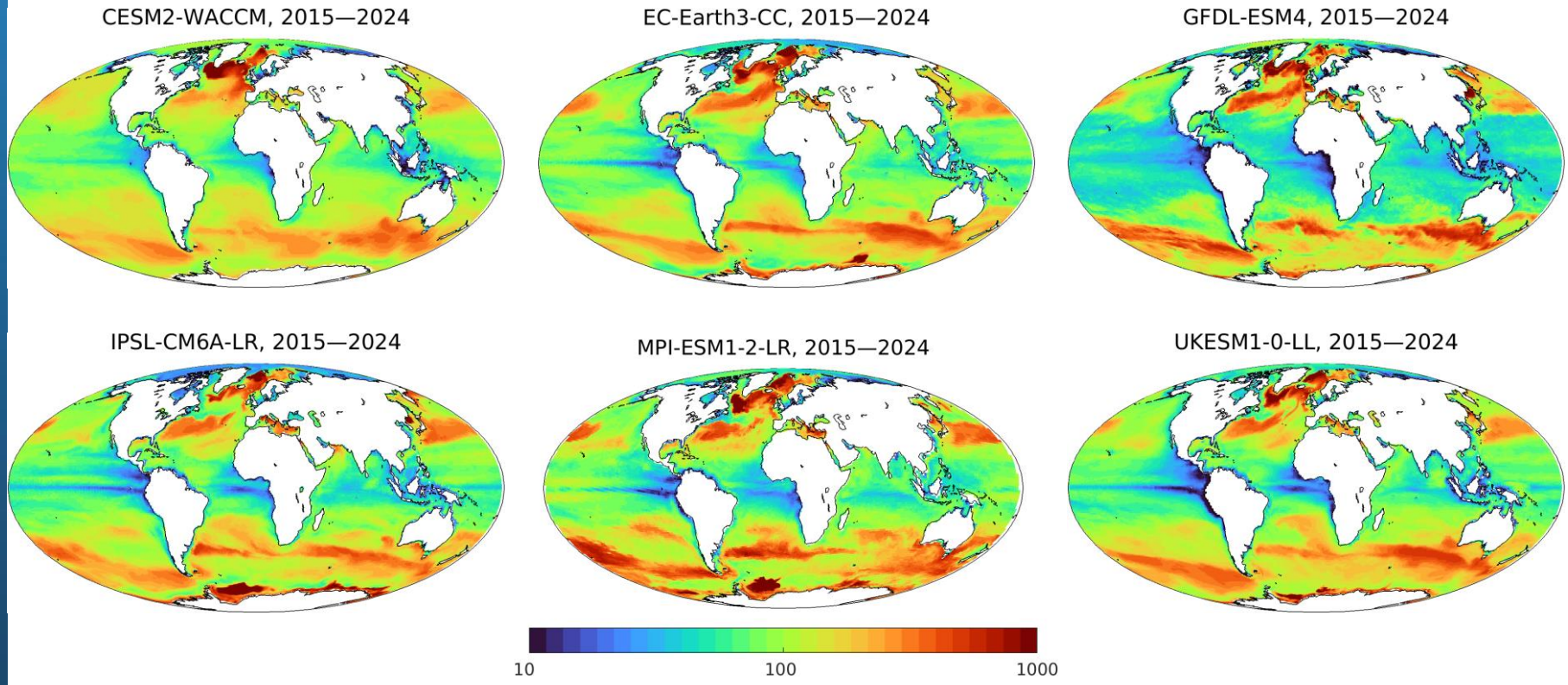
- Half of the models examined show increasing / decreasing production by the 2090s
- Increases are generally smaller than decreases
- However, all models show a decrease in 100 m export by the 2090s
- All, bar one, show a more significant decrease in 1000 m export by the 2090s

Efficiency of transfer

Model	Export 2015s	Export 2090s	Sequest. 2015s	Sequest. 2090s	Overall 2015s	Overall 2090s
	%	%	%	%	%	%
CESM2-WACCM	15.56	14.57	15.13	16.27	2.35	2.37
EC-Earth-CC	16.49	15.23	21.09	19.31	3.48	2.94
GFDL-ESM4	11.98	11.4	13.45	10.83	1.61	1.23
IPSL-CM6A-LR	17.59	16.26	21.68	19.32	3.81	3.14
MPI-ESM1-2-LR	12.58	12.06	14.42	13.41	1.81	1.62
UKESM1-0-LL	21.45	20.94	3.58	2.26	0.77	0.47

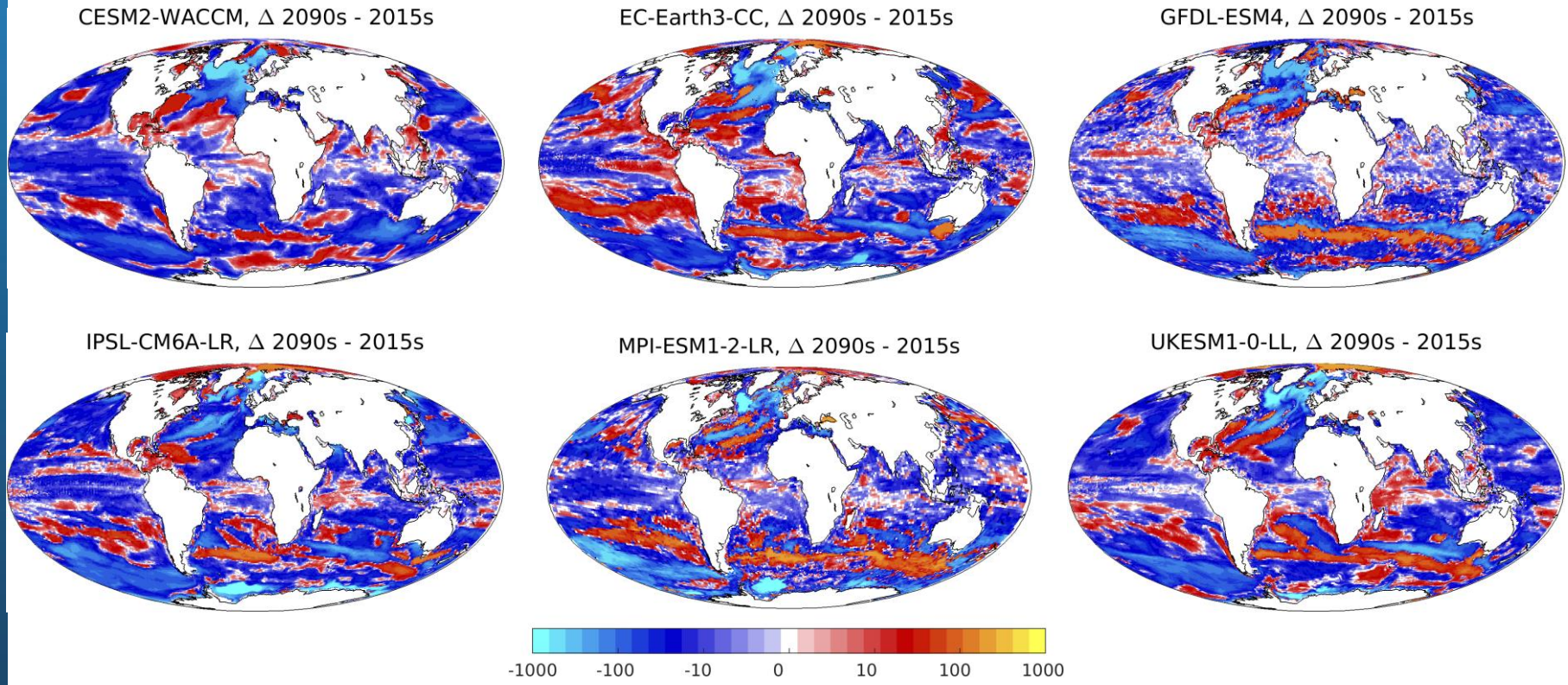
- All of the models examined show a decreasing fraction of production being exported at 100 m by the 2090s
- All, bar one, show decreasing fractions of production being exported (100 m) and sequestered (1000 m) by the 2090s
- Variability in model efficiency >> change between 2015s and 2090s

Maximum mixed layer depth (2015-2024)



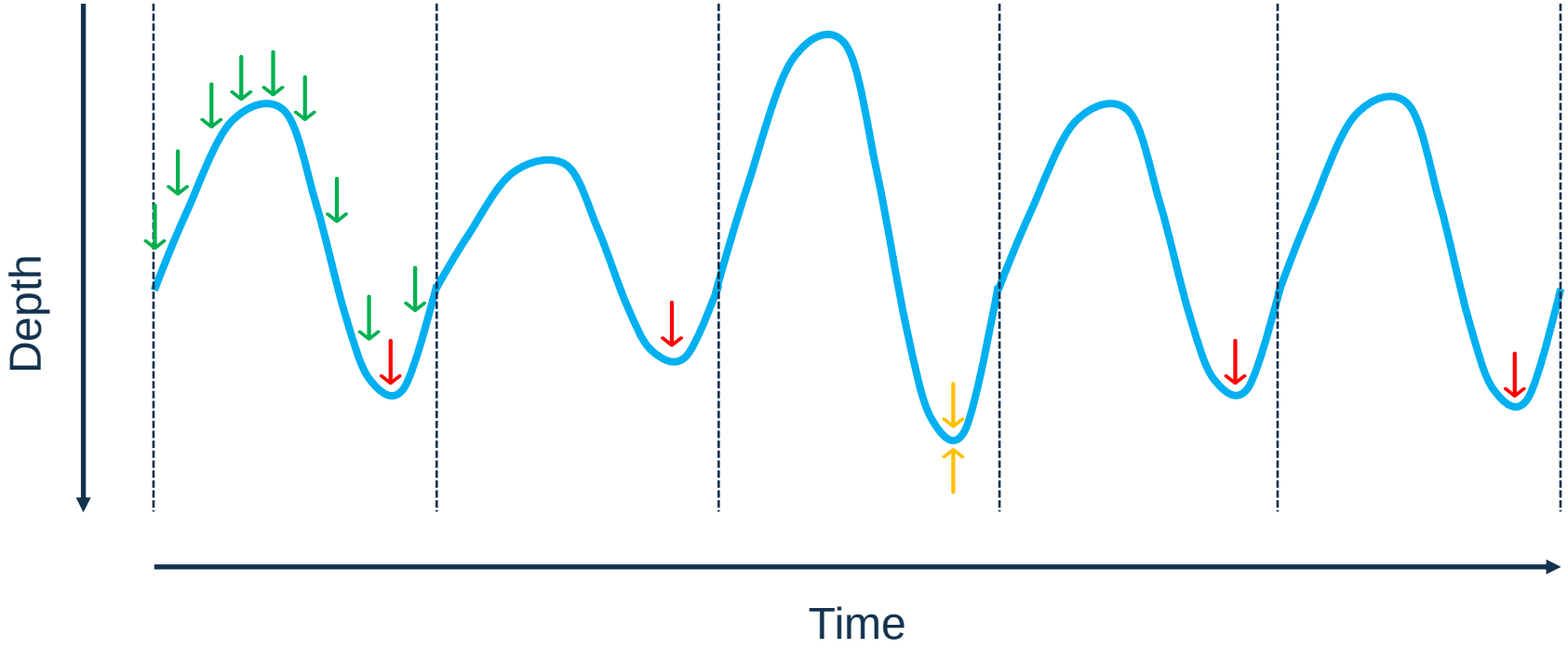
- General agreement in spatial patterns and magnitude of mixing
- Systematically lower tropical mixing in high resolution GFDL model
- Diversity in deepest mixing, esp. in Southern Ocean

Change, (2090-2099) – (2015-2024)



- Agreement on change in Southern Ocean and North Atlantic
- Divergence elsewhere, even between NEMO-using EC-Earth and IPSL
- No clear impact of high resolution for change in GFDL

Which export depth matters?



- How far does export production have to sink to be “exported”?
- Exiting the mixed layer is not enough if subsequent seasonal mixing simply re-entrains DIC later (i.e. it hasn’t been pumped deep enough)
- Recalculate efficiency and change using:
- 1. monthly, 2. mean annual, 3. annual max, 4. mean decadal, 5. decadal max

MLD metrics

Model	Mon	Δ	*Mavg*	*Δ*	Mmax	Δ	*Davg*	*Δ*	Dmax	Δ
	PgC/y	%	*PgC/y*	*%*	PgC/y	%	*PgC/y*	*%*	PgC/y	%
CESM2-WACCM	6.39	-8.58	*7.02*	*-8.32*	6.68	-3.55	*7.02*	*-8.41*	6.38	-2.45
EC-Earth-CC	5.5	-10.91	*5.93*	*-11.56*	6.28	-5.8	*5.94*	*-11.73*	6.3	-2.11
GFDL-ESM4	5.67	-13.38	*5.94*	*-12.91*	5.71	-10.68	*5.95*	*-12.89*	5.39	-10.12
IPSL-CM6A-LR	4.62	-12.33	*4.98*	*-12.21*	5.33	-8.56	*4.99*	*-12.3*	5.24	-7.01
MPI-ESM1-2-LR	6.73	-15.67	*6.9*	*-15.05*	6.02	-13.25	*6.92*	*-15.07*	5.39	-11.62
UKESM1-0-LL	7.23	-19.76	*7.9*	*-18.53*	7.38	-16.5	*7.91*	*-18.5*	6.91	-15.39

- Via these metrics, export / sequestration always declines
- Monthly statistics distorted by production of C_{org} below mixed layer
- Generally, selection of a deeper horizon reduces the apparent scale of change across the 21st century
- Results currently confounded by spatial aliasing of deep mixing and production

Conclusions

- Global magnitude of production consistent, but spatial patterns (and biases) divergent between models
- Export largely tracks production with common decrease in relative importance of equatorial upwelling
- Models diverge in fate of primary production over 21st century
- Export and sequestration at fixed horizons almost universally decline over the 21st century
- Models show good agreement for magnitude and pattern of ocean mixing, but disagree on spatial change in future
- Factoring in deeper mixing horizons tends to decrease apparent scale of change
- Mixing metrics can be confounded by vertical C_{org} production and mixing / production aliasing

Going forwards

- Widen analysis as more results arrive at ESGF (let me know if your data is coming)
- Widen analysis to use more ensemble members and end member scenarios
- Factor in change patterns to model processes (i.e. role of temperature, oxygen, biominerals)
- Happy to collaborate!

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