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Ocean biogeochemistry projections from CMIP5 to CMIP6: what's new and have we learnt anything?

The initial trickle of CMIP6 marine biogeochemistry papers…

Twenty-first century ocean warming, acidification, deoxygenation, and upper-ocean nutrient and primary production decline from CMIP6 model projections

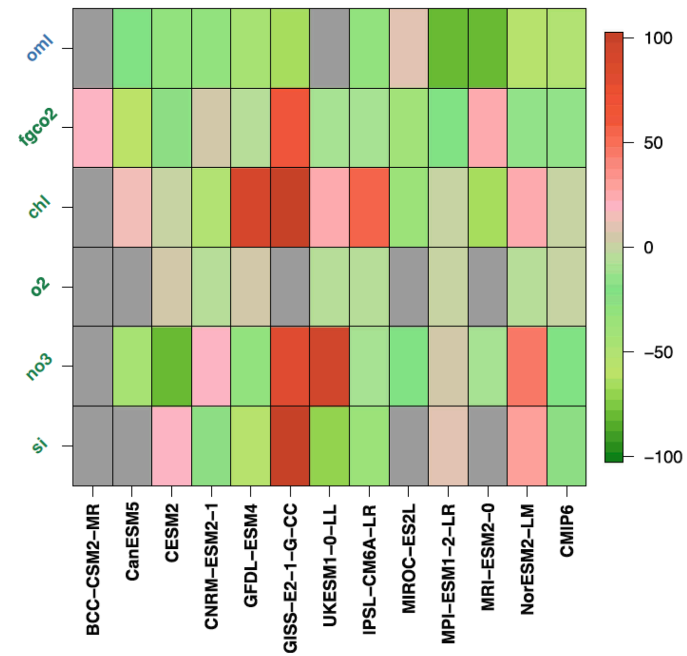
Lester Kwiatkowski[1], Olivier Torres[2], Laurent Bopp[2], Olivier Aumont[1], Matthew Chamberlain[3], James R. Christian[5], John P. Dunne[6], Marion Gehlen[7], Tatiana Ilyina[8], Jasmin G. John[6], Andrew Lenton[3,4], Hongmei Li[8], Nicole S. Lovenduski[9], James C. Orr[7], Julien Palmieri[10], Yeray Santana-Falcón[11], Jörg Schwinger[12], Roland Séférian[11], Charles A. Stock[6], Alessandro Tagliabue[13], Yohei Takano[8,14], Jerry Tjiputra[12], Katsuya Toyama[15], Hiroyuki Tsujino[15], Michio Watanabe[16], Akitomo Yamamoto[16], Andrew Yool[10], and Tilo Ziehn[3]

Tracking Improvement in Simulated Marine Biogeochemistry Between CMIP5 and CMIP6

Roland Séférian[1] • Sarah Berthet[1] • Andrew Yool[2] • Julien Palmiéri[2] • Laurent Bopp[3] • Alessandro Tagliabue[4] • Lester Kwiatkowski[5] • Olivier Aumont[5] • James Christian[6] • John Dunne[7] • Marion Gehlen[8] • Tatiana Ilyina[9] • Jasmin G. John[7] • Hongmei Li[9] • Matthew C. Long[10] • Jessica Y. Luo[7] • Hideyuki Nakano[11] • Anastasia Romanou[12] • Jörg Schwinger[13] • Charles Stock[7] • Yeray Santana-Falcón[1] • Yohei Takano[9,14] • Jerry Tjiputra[13] • Hiroyuki Tsujino[11] • Michio Watanabe[15] • Tongwen Wu[16] • Fanghua Wu[16] • Akitomo Yamamoto[15]

CMIP6 ocean biogeochemical performance (mean state and trends) gives us some confidence in future projections

Decent representation of OBGC mean states (typically at least as good as CMIP5)



Ocean warming, acidification and deoxygenation in broad agreement with historical observations

Variable	Years	Observed trend and reference	CMIP6 trend
SST	1901–2012	+0.06 (°C decade^{-1}; Hartmann et al., 2013)	$+0.055 \pm 0.015$ (°C decade^{-1})
SST	1979–2012	+0.095 (°C decade^{-1}; Hartmann et al., 2013)	$+0.152 \pm 0.042$ (°C decade^{-1})
Surface pH	1991–2011	−0.018 (units decade^{-1}; Lauvset et al., 2015)	-0.016 ± 0.0003 (units decade^{-1})
Subsurface O_2	1970–2010	−0.30 to −1.52 (mmol m^{-3} decade^{-1}; Helm et al., 2011; Schmidtko et al., 2017; Ito et al., 2017; Bindoff, et al., in press)	-0.49 ± 0.097 (mmol m^{-3} decade^{-1})

Séférian et al., (2020), Kwiatkowski et al., (2020)

What have we looked at? More of the same "stressors" and a little bit more

Projected 21st century decrease in marine productivity: a multi-model analysis

M. Steinacher[1,2], F. Jo
K. Lindsay[5], J. K. Mo

Oxygen and indicators of stress for marine life in multi-model global warming projections

V. Cocco[1,2], F. Joos[1,
A. Oschlies[9], B. Sch

Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models

L. Bopp[1], L. Resplandy[1], J. C. Orr[1], S. C. Doney[8], J. P. Dunne[2], M. Gehlen[1], P. Halloran[3], C. Heinze[6,9,10], T. Ilyina[4], R. Séférian[1,5], J. Tjiputra[6,9,10], and M. Vichi[7]

Updated projections of:
-surface ocean warming
-surface ocean acidification
-subsurface (100-600m) deoxygenation
-upper ocean/euphotic (0-100m) $[NO_3^-]$
-Integrated net primary production (NPP)

+ projections of:
-benthic ocean warming, acidification, deoxygenation
-Seasonal cycles of temperature and carbonate chemistry

What's changed in the ocean BGC projections?

Compared to CMIP5, under the same radiative forcing in CMIP6 there is…

Higher prescribed atmospheric CO_2 concentrations
(radiative forcing derived from the MAGICC6)

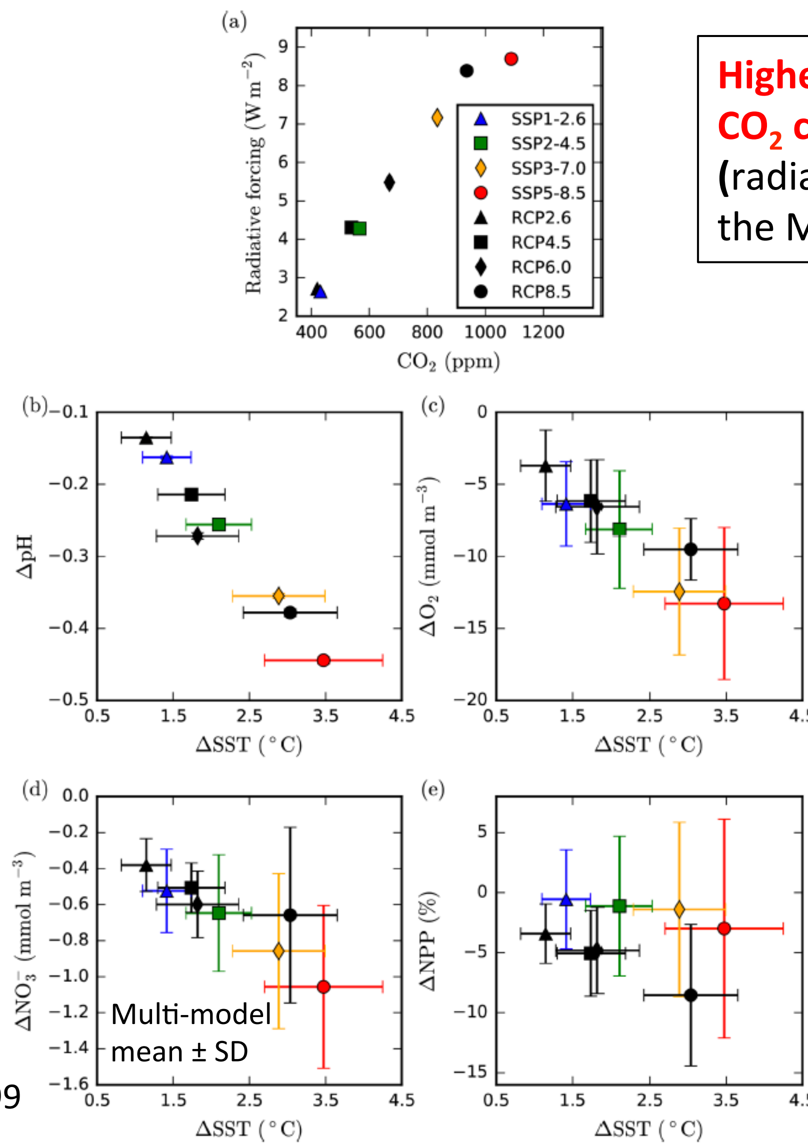
Greater ocean warming

Greater ocean acidification
(the only significant change)

Greater deoxygenation

Greater NO_3^- declines

Lesser NPP declines



Anomalies are 2080–2099 values relative to 1870–1899

Kwiatkowski et al., (2020)

What's changed in the ocean BGC projections?

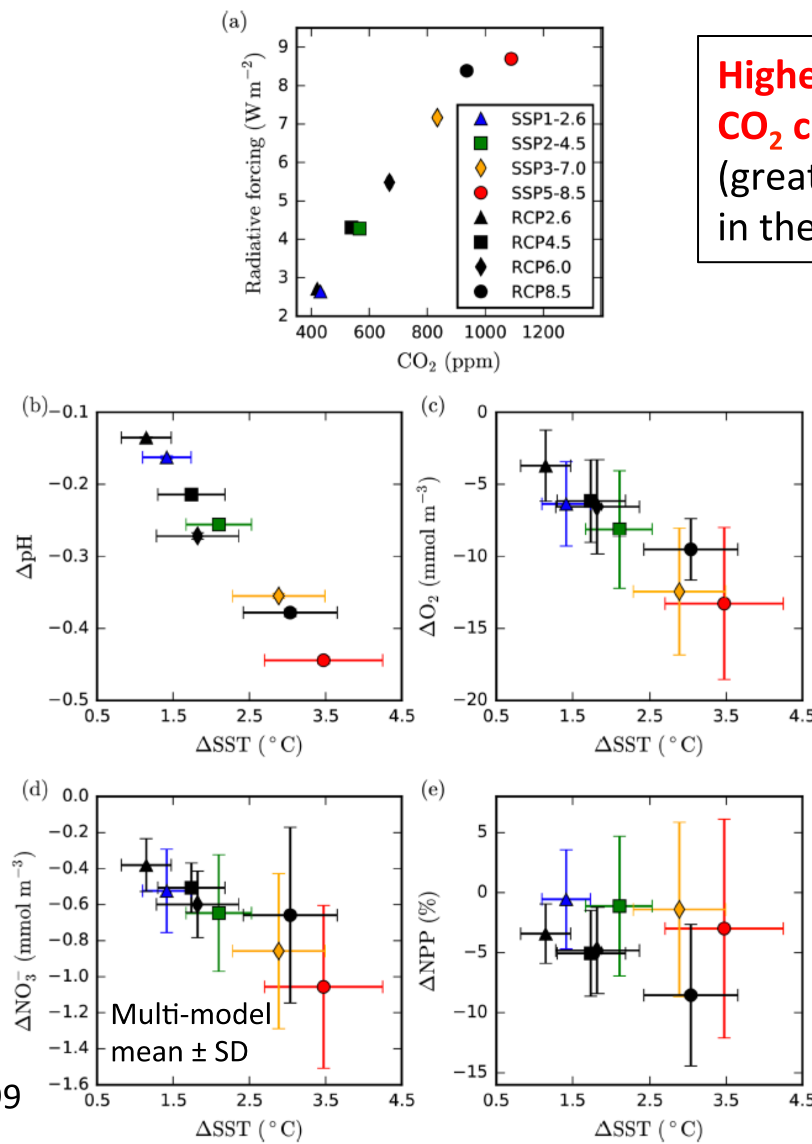
Compared to CMIP5, under the same radiative forcing in CMIP6 there is…

Greater ocean warming
(increase in ECS/TCR)

Greater ocean acidification
(higher atmospheric CO_2)

Greater NO_3^- declines
(enhanced stratification)

Anomalies are 2080–2099 values relative to 1870–1899



Higher prescribed atmospheric CO_2 concentrations
(greater coal reliance assumed in the SSPs esp. SSP5-8.5)

Greater deoxygenation
(reduced solubility & changes in AOU)

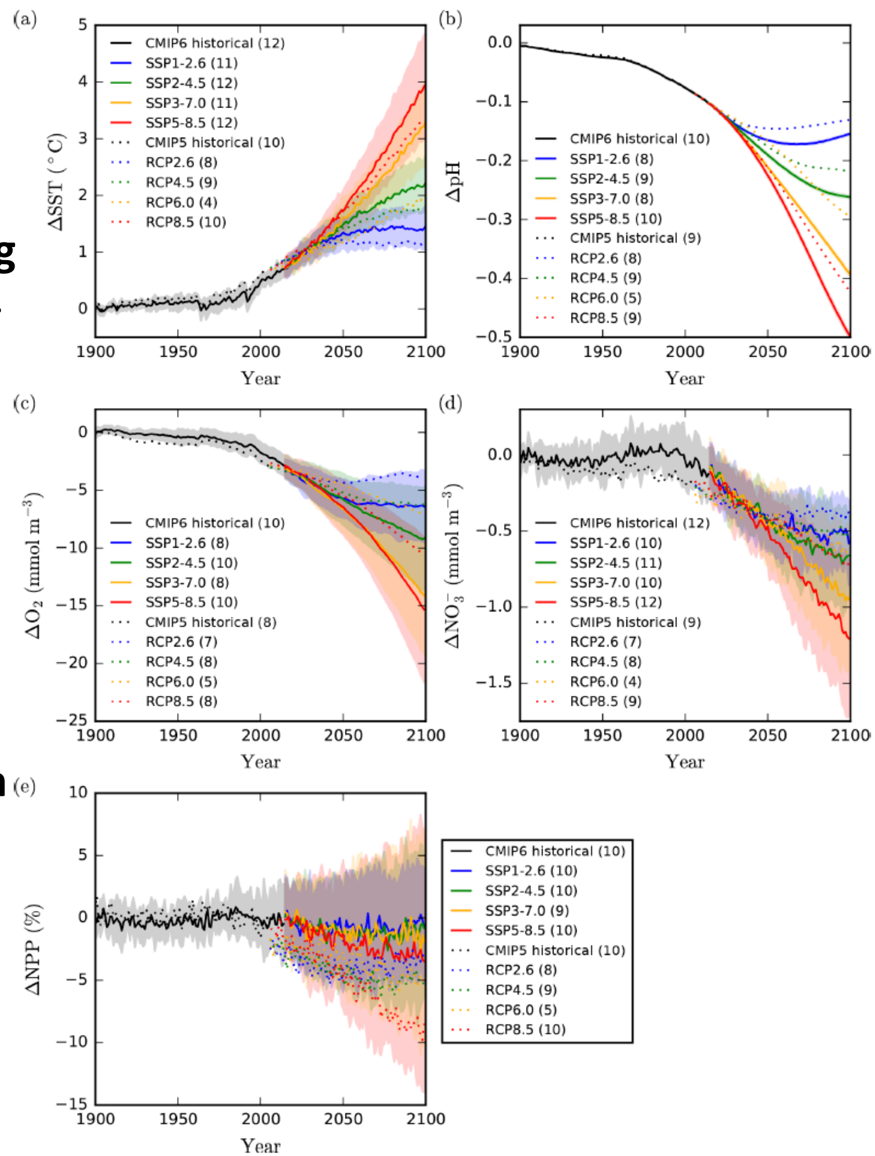
Lesser NPP declines
(uncertain why, more diverse model response, Nfix partly responsible)

Kwiatkowski et al., (2020)

What's changed in the ocean BGC projections?

Lesser confidence in surface ocean warming
(scenario uncertainty > model uncertainty)

Very low confidence in NPP projections
(model uncertainty > scenario uncertainty)
<u>-not even confident of sign of change!</u>



Highest confidence in surface OA projections
(scenario uncertainty >> model uncertainty)

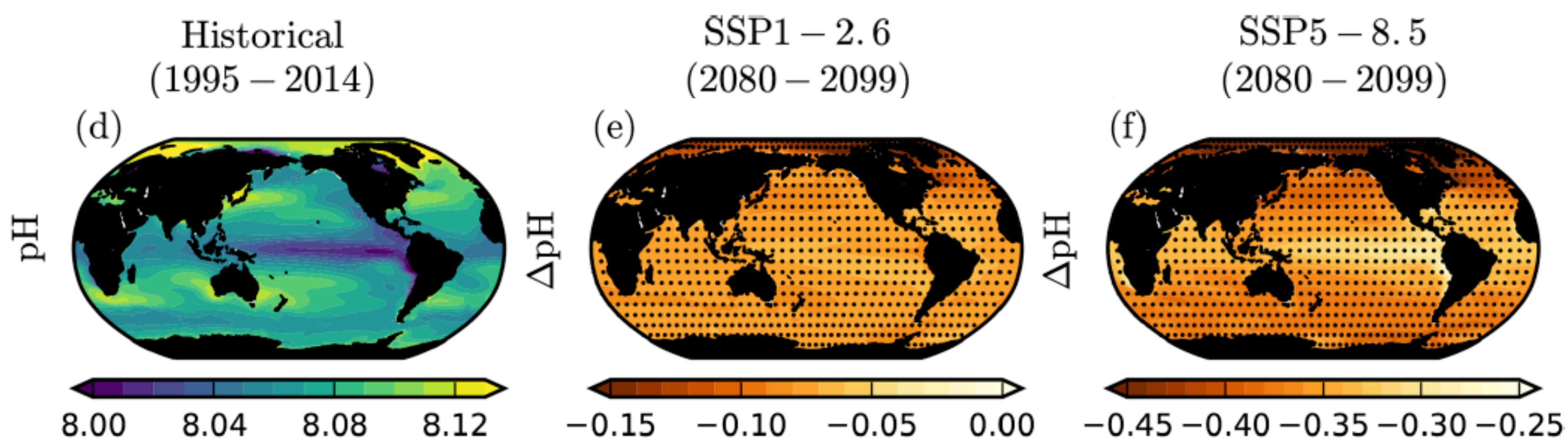
Subsurface deoxygenation & euphotic NO_3^-
(scenario uncertainty ≈ model uncertainty)

Kwiatkowski et al., (2020)

Greater surface ocean acidification due to higher atmospheric [CO_2]

Year 2100 concentrations

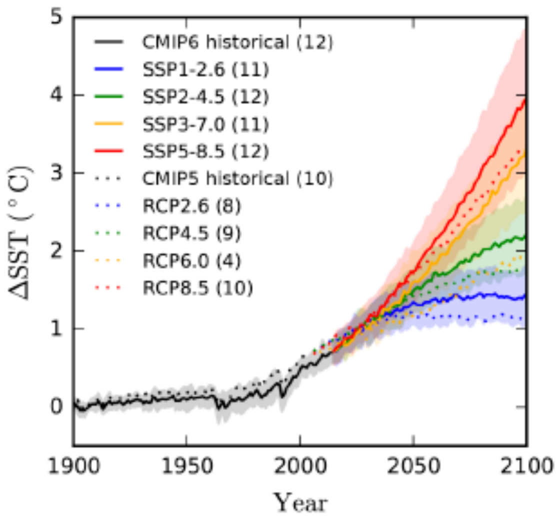
Radiative Forcing	2.6 W m^{-2}		4.5 W m^{-2}		8.5 W m^{-2}	
Scenario	SSP1-2.6	RCP 2.6	SSP2-4.5	RCP 4.5	SSP5-8.5	RCP 8.5
CO_2 (ppm)	445.6	421	602.8	538	1135.2	936
CH_4 (ppb)	1056.4	1254	1683.2	1576	2415.3	3751
N_2O (ppb)	353.9	344	377.3	372	391.8	435



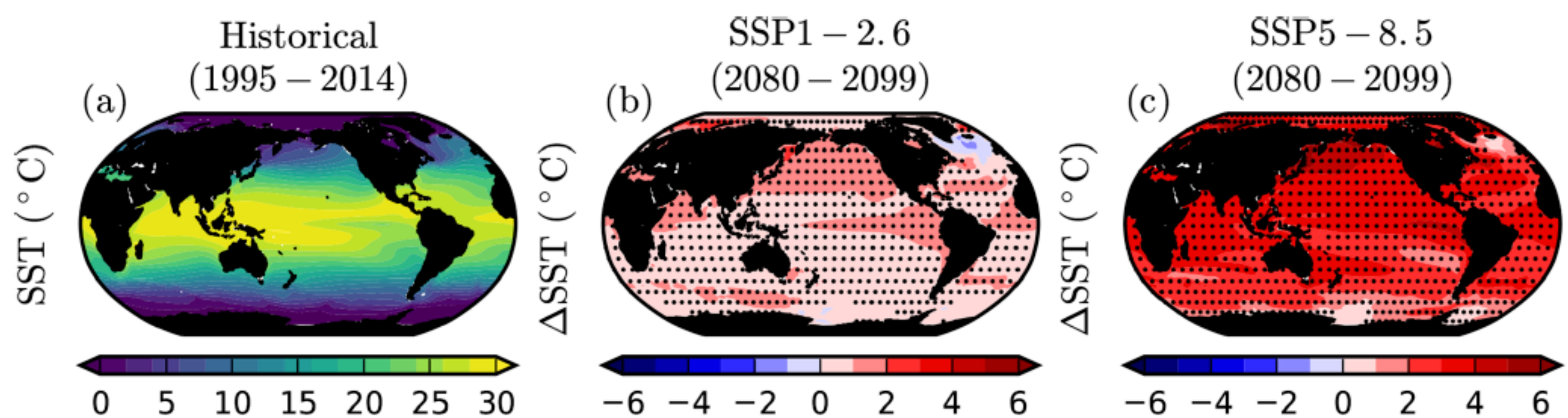
Stippling = mean anomaly > inter-model SD (robustness)

Kwiatkowski et al., (2020)

Enhanced surface ocean warming



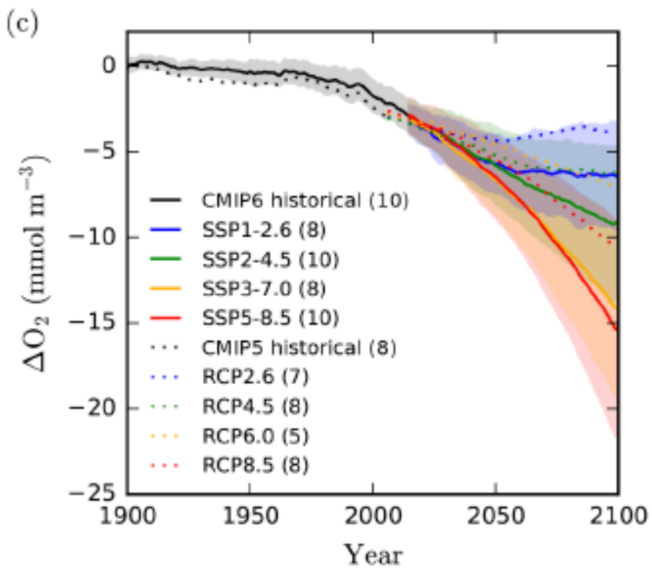
- Greater warming due to higher ECS in CMIP6 (stronger positive cloud feedbacks, Zelinka et al., 2020)
- Spatial projections of surface warming very similar between CMIP6 and CMIP5
- Warming near ubiquitous with high confidence (North Atlantic "warming hole" still present)
- Arctic amplification still apparent



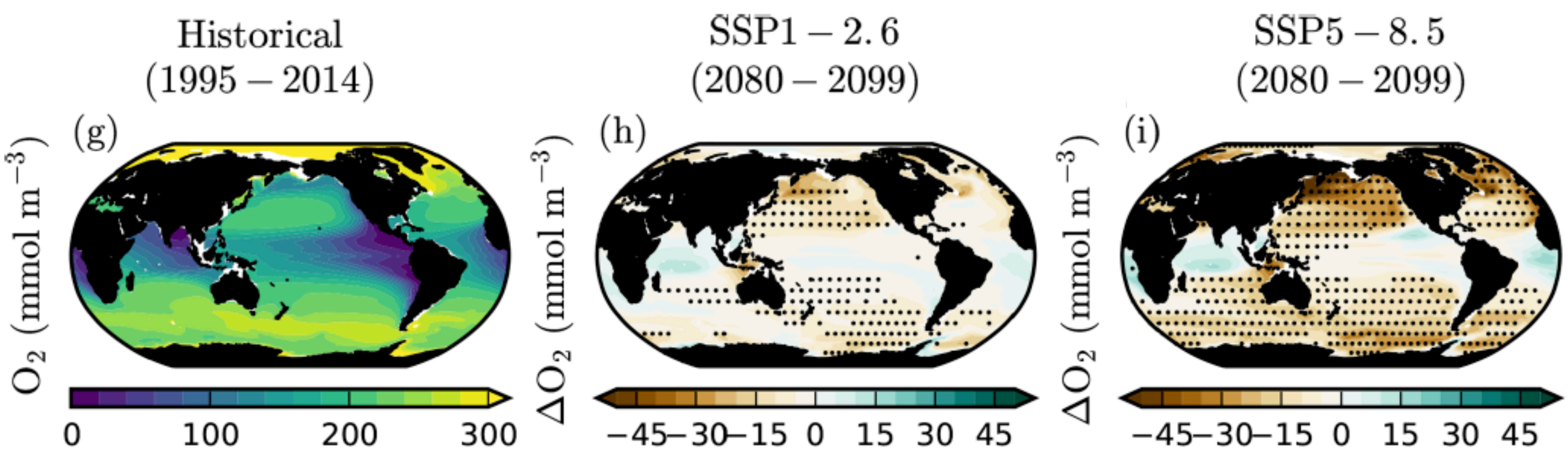
Stippling = mean anomaly > inter-model SD (robustness)

Kwiatkowski et al., (2020)

Enhanced subsurface (100-600m) deoxygenation



- Spatial projections of deoxygenation similar between CMIP6 and CMIP5
- Subsurface O_2 generally declines
- Increases in certain low latitude regions (<u>but not robustly</u>)

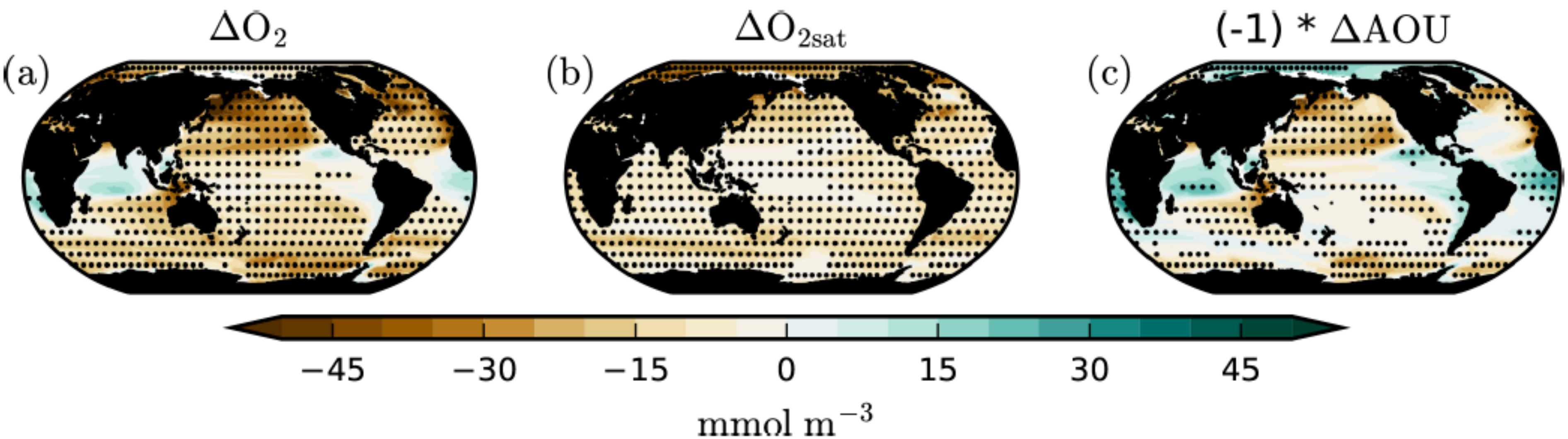


Stippling = >80% model sign agreement

Kwiatkowski et al., (2020)

Enhanced subsurface (100-600m) deoxygenation: the role of the

$\Delta O_2 = \Delta O_{2sat} - \Delta AOU$



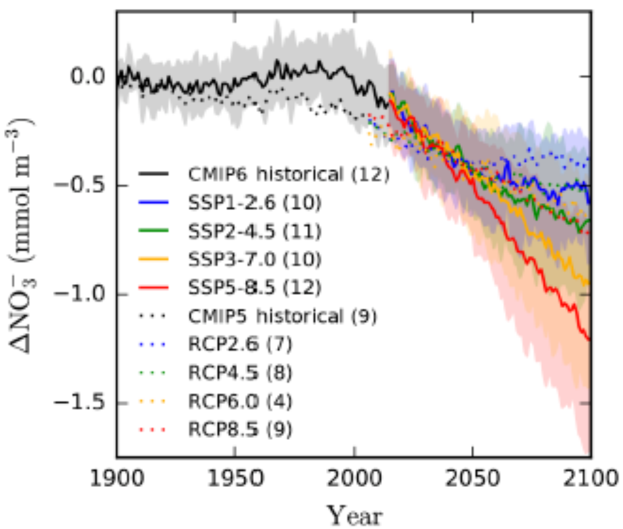
Reductions in subsurface oxygen due to

1. Temperature driven reductions in solubility (O_{2sat})
2. Mediated by Apparent Oxygen Utilisation (AOU) increases and decreases

- same analysis not performed for CMIP5 but thermal solubility decline presumably enhanced in CMIP6

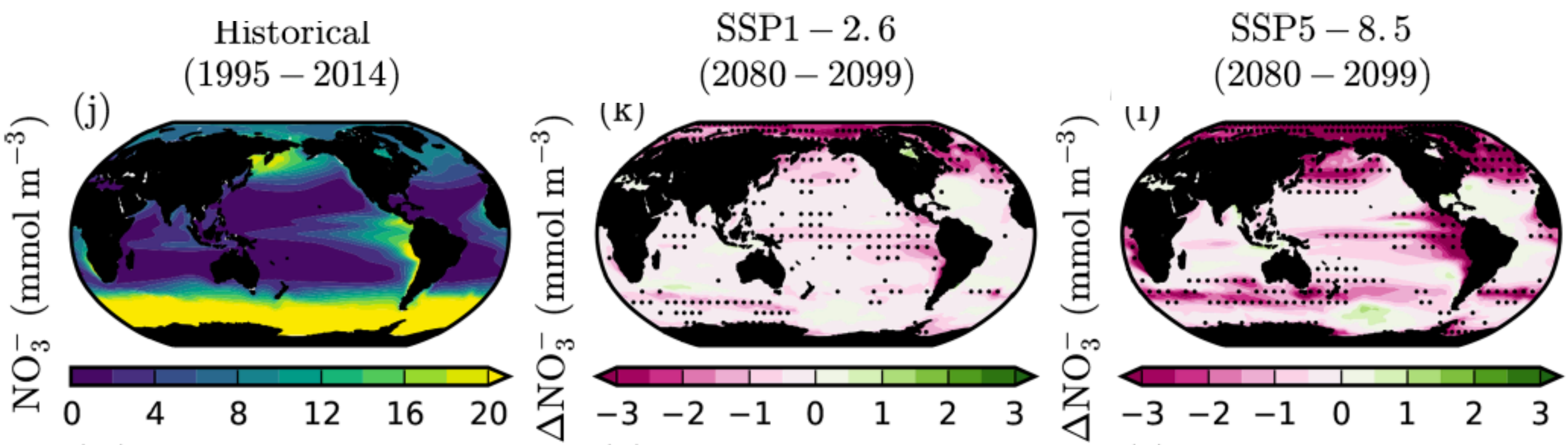
Kwiatkowski et al., (2020)

Enhanced upper ocean (0-100m) NO_3^- declines



- NO_3^- declines largest in Arctic, Eastern Pacific, North Atlantic/Pacific

- Enhanced CMIP6 declines consistent with the enhanced stratification (biological processes can't be ruled out)



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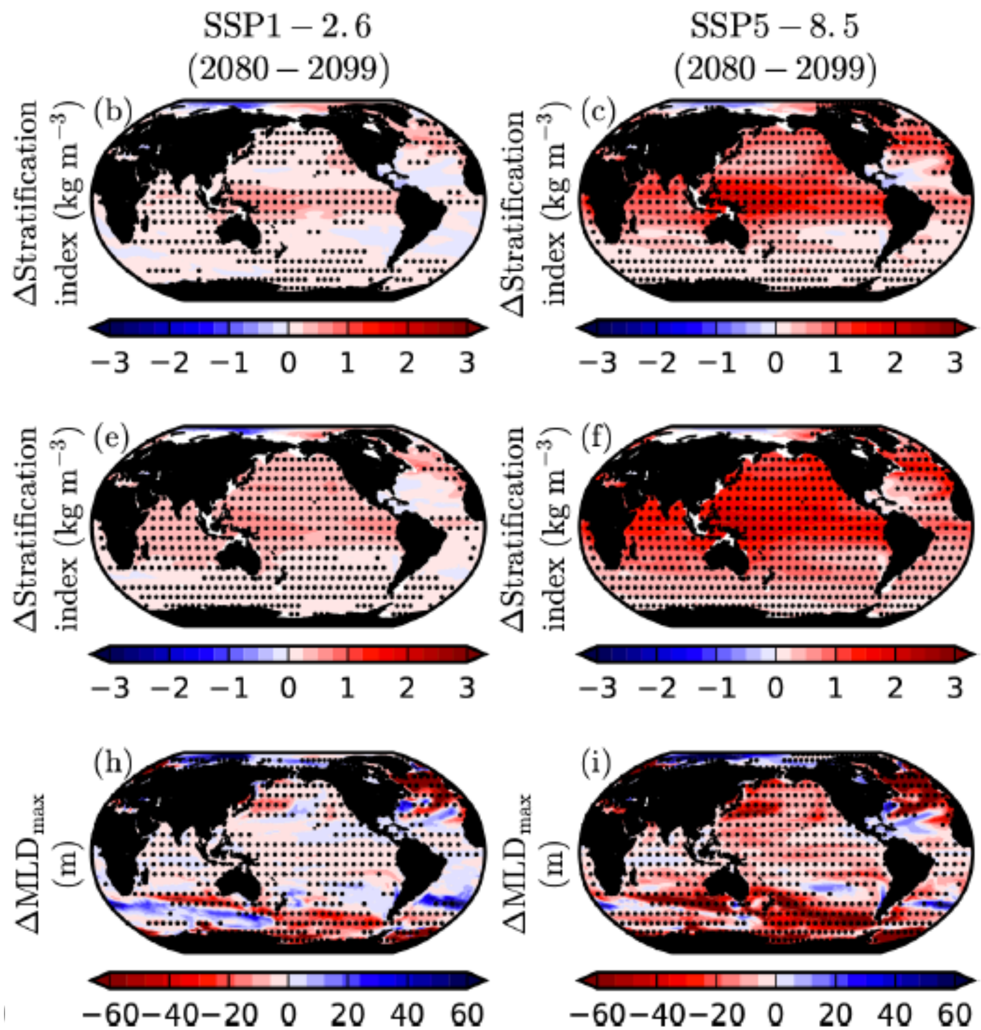
Kwiatkowski et al., (2020)

Enhanced upper ocean (0-100m) NO_3^- declines

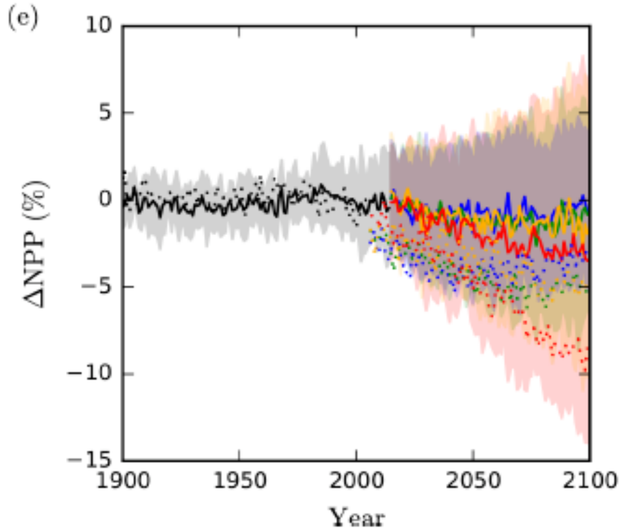


- Stratification Indices increase in SSPs (greater density gradients due to upper ocean warming)
- Mixed layer depth (MLD) is reduced
- Increases in stratification are enhanced relative to comparative CMIP5 simulations (Cabré et al., 2014; Fu et al., 2016)

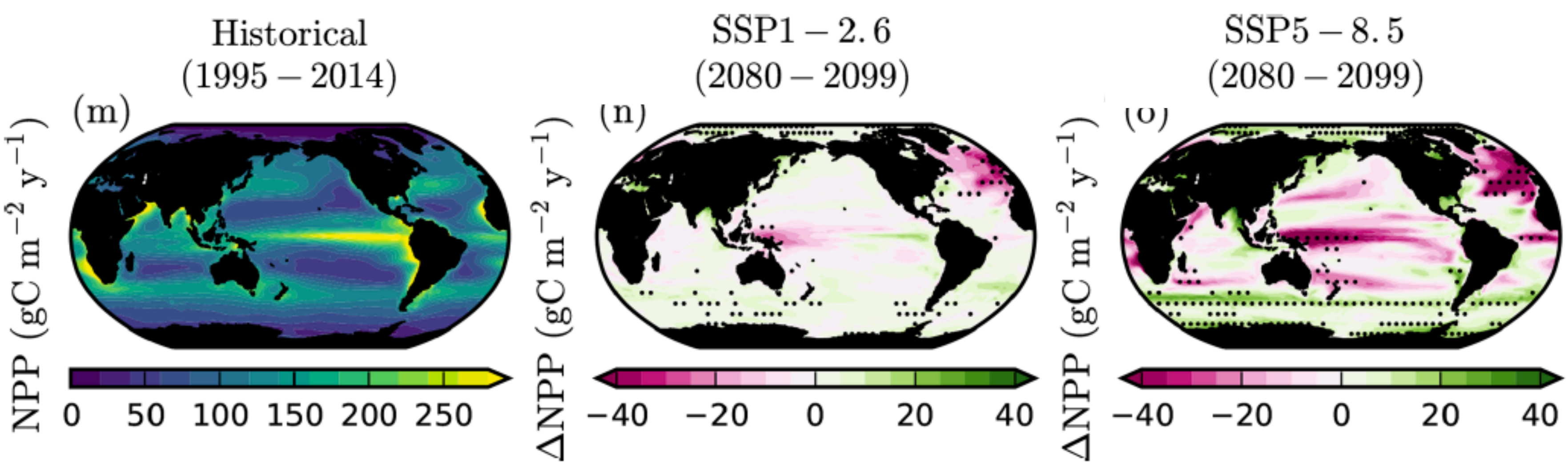
➔ Enhanced global-scale reduction in vertical supply of nutrients to the upper ocean in CMIP6

Kwiatkowski et al., (2020)

Lesser NPP declines with striking increases in uncertainty



- Global NPP projections driven by declines in low-mid latitudes and increase in high latitudes (as in CMIP5)
- Declines in the Indian Ocean and North Pacific much reduced in CMIP6
- The conventional narrative: Low-mid lat declines (nutrient driven), high lat increases (light driven)



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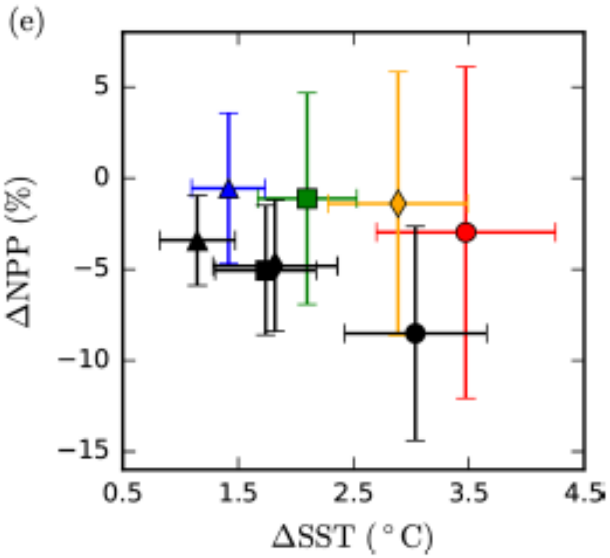
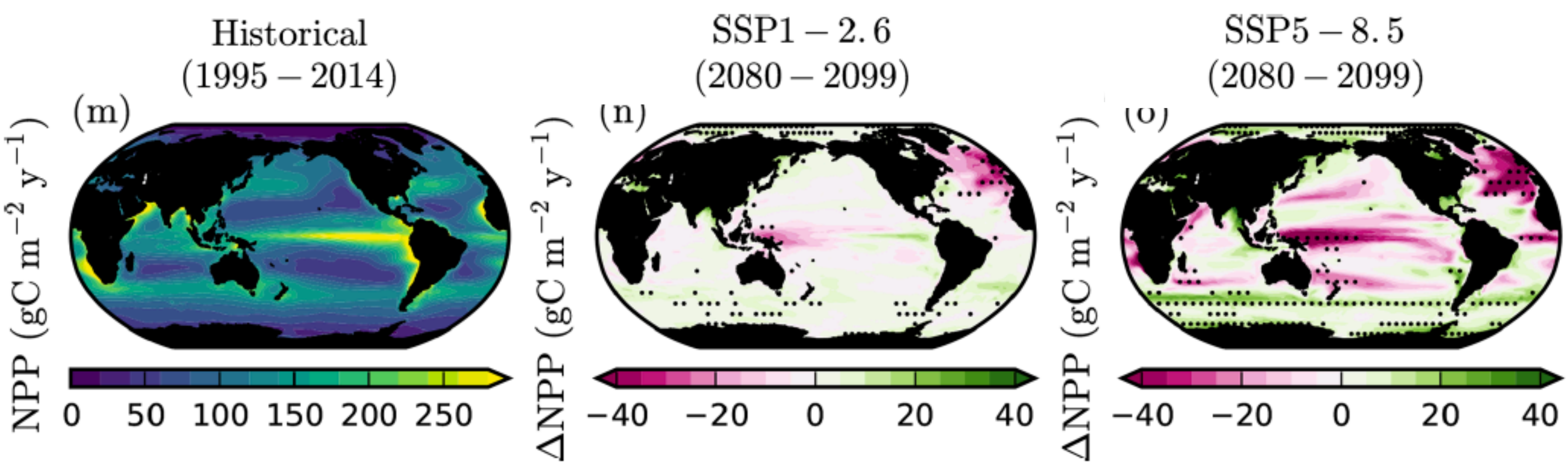
Kwiatkowski et al., (2020)

But NO_3^- declines are greater in CMIP6 and NPP declines are reduced with 2x the uncertainty…



- Evolution of phytoplankton resource limitation and/or grazing pressure under climate change has altered in ESMs
- Temperature driven intensification of the microbial loop increasing regenerated production? (Schmittner et al., 2008; Taucher and Oschlies, 2011)
- Nitrogen fixation parameterisation choices in Redfieldian models?

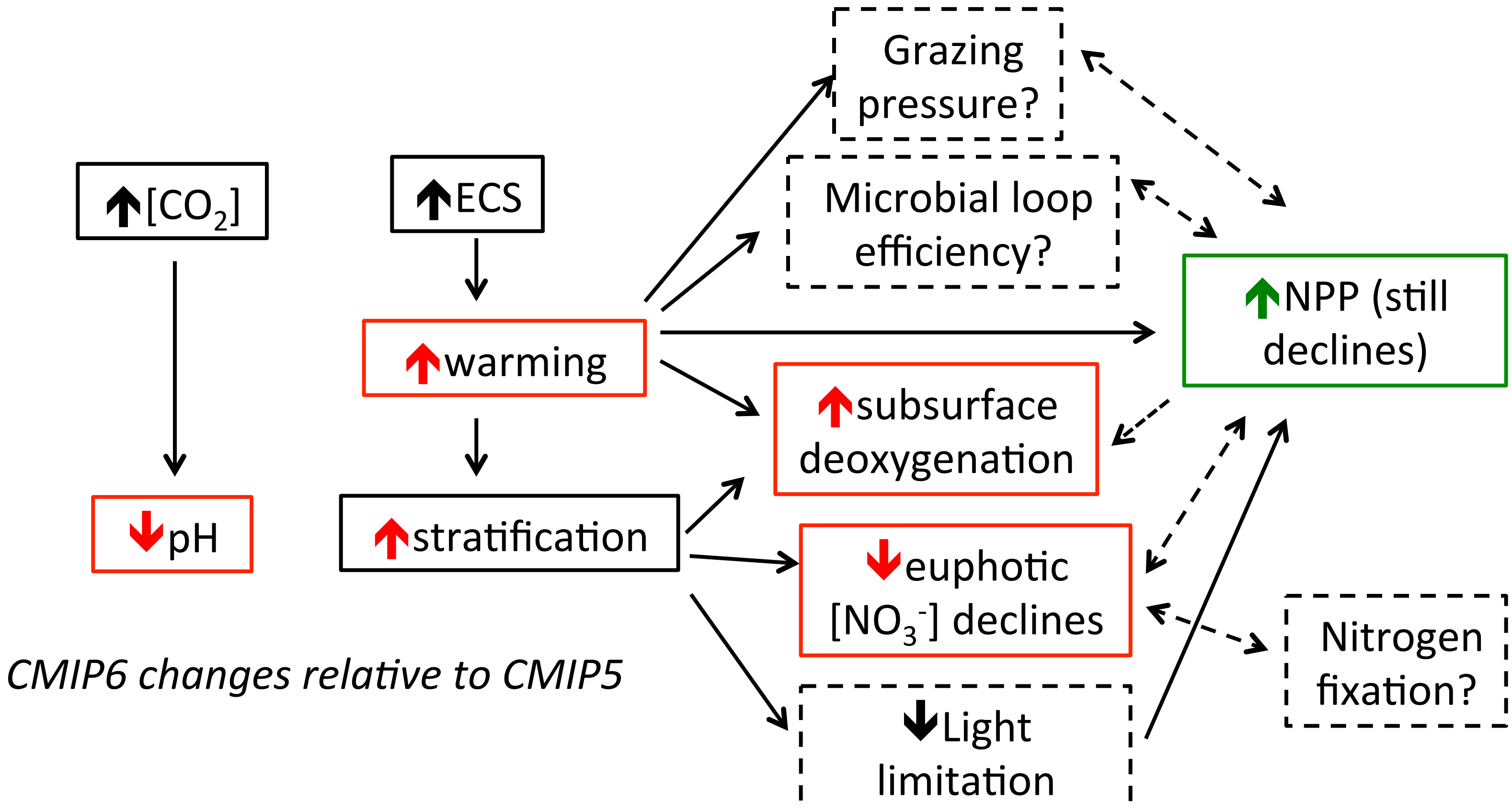


Stippling = >80% model sign agreement

Kwiatkowski et al., (2020)

Conclusions

- CMIP6 warming, acidification, deoxygenation, nutrient and NPP decline largely depends on the extent of future emissions, <u>consistent with previous studies</u>



- We are not reducing projection uncertainties and in certain cases they are increasing! (maybe we're learning we don't know as much as we thought we did)

Thanks to all the authors and model developers

Any questions?

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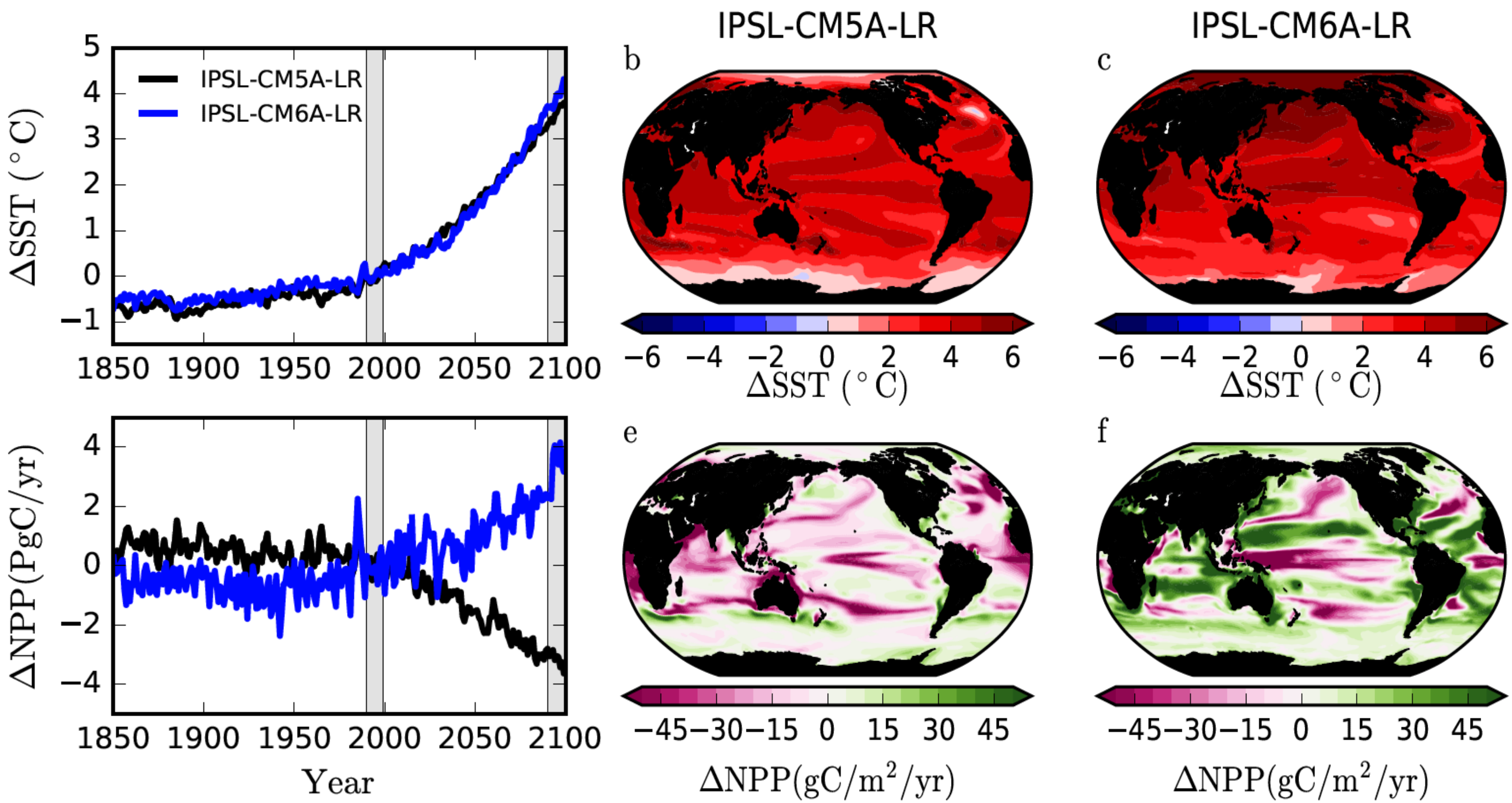
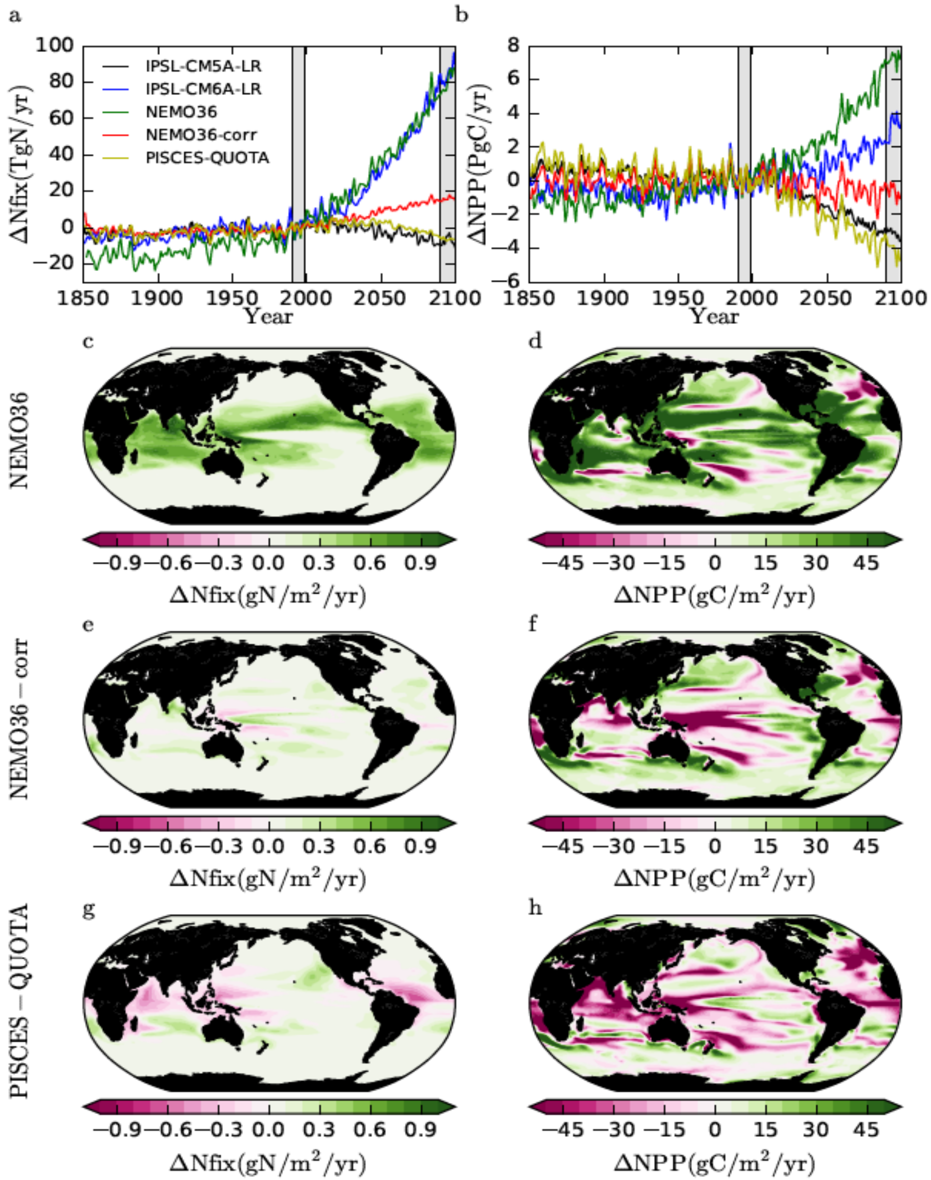
Ongoing work…unravelling the dramatic change in NPP response in IPSL-CM5/6



Bopp et al., (in prep)

Ongoing work…unravelling the dramatic change in NPP response in IPSL-CM5/6



Nitrogen fixation is key:

It's parameterisation is non-trivial in Redfield models without an explicit DOP pool

Mean N/P state and the balance between future T↑ and P↓ in Nfix drives the future low-latitude NPP response

The latest version of NEMO-PISCES and a NEMO-PISCESQUOTA project more conventional/traditional NPP declines

Bopp et al., (in prep)

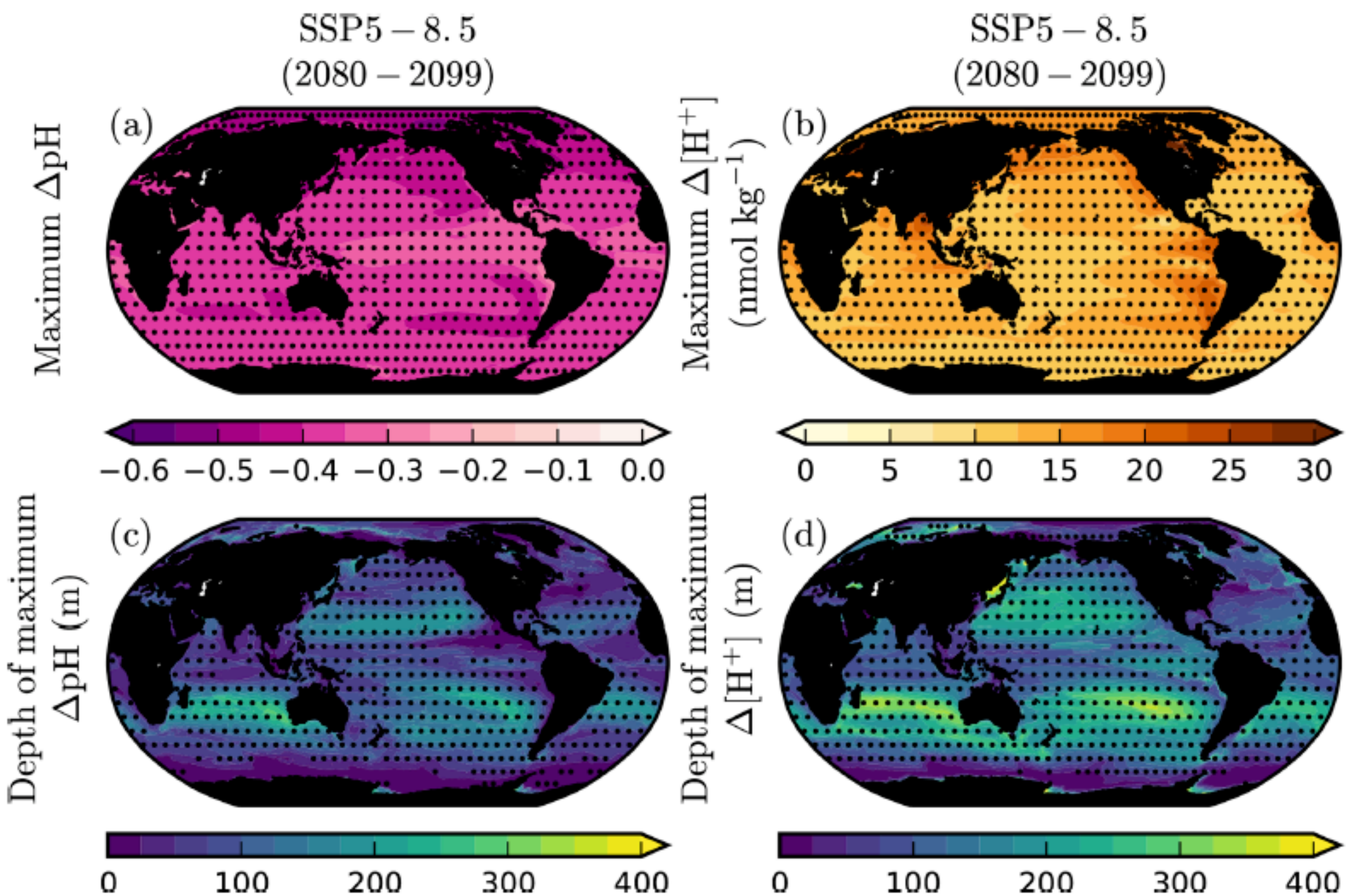
CMIP6 models

Model and reference	Ocean and sea ice	Marine biogeo-chemistry	Drivers	Simulations	Data DOI
ACCESS-ESM1.5 (Ziehn et al., 2020)	MOM5, CICE4	WOMBAT	T, pH, O_2, NO_3^-, NPP	Historical, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5	Ziehn et al. (2019a, b)
CanESM5 (Swart et al., 2019a)	NEMO 3.4.1-LIM2	CMOC	T, pH, O_2, NO_3^-	Historical, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5	Swart et al. (2019b, c)
CESM2	POP2-CICE5	MARBL-BEC	T, pH, NO_3^-, NPP	Historical, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5	Danabasoglu (2019a, b)
CESM2-WACCM	POP2-CICE5	MARBL-BEC	T, pH, NO_3^-, NPP	Historical, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5	Danabasoglu (2019c, d)
CNRM-ESM2-1 (Séférian et al., 2019)	NEMOv3.6-GELATOv6	PISCESv2-gas	T, pH, O_2, NO_3^-, NPP	Historical, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5	Séférian (2018, 2019)
GFDL-CM4 (Held et al., 2019; Dunne et al., 2020a)	MOM6, SIS2	BLINGv2	T, pH, O_2, NO_3^-	Historical, SSP2-4.5, SSP5-8.5	Guo et al. (2018a, b)
GFDL-ESM4 (Dunne et al., 2020b; Stock et al., 2020)	MOM6, SIS2	COBALTv2	T, pH, O_2, NO_3^-, NPP	Historical, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5	Krasting et al. (2018); John et al. (2018)
IPSL-CM6A-LR (Boucher et al., 2020)	NEMOv3.6-LIM3	PISCESv2	T, pH, O_2, NO_3^-, NPP	Historical, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5	Boucher et al. (2018, 2019)
MIROC-ES2L (Hajima et al., 2020)	COCO	OECO2	T, pH, O_2, NO_3^-, NPP	Historical, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5	Hajima et al. (2019); Tachiiri et al. (2019)
MPI-ESM1.2-HR (Müller et al., 2018; Mauritsen et al., 2019)	MPIOM	HAMOCC6	T, pH, O_2, NO_3^-, NPP	Historical, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5	Schupfner et al. (2019); Jungclaus et al. (2019)
MRI-ESM2 (Yukimoto et al., 2019a)	MRICOM4	NPZD	T, pH, O_2, NO_3^-	Historical, SSP5-8.5	Yukimoto et al. (2019b, c)
NorESM2-LM (Tjiputra et al., 2020)	BLOM- CICE5	iHAMOCC	T, pH, O_2, NO_3^-, NPP	Historical, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5	Seland et al. (2019a, b)
UKESM1-0-LL (Sellar et al., 2019)	NEMO v3.6, CICE	MEDUSA-2	T, pH, O_2, NO_3^-, NPP	Historical, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5	Good et al. (2019); Tang et al. (2019)

CMIP5 models

Model and reference	Ocean and sea ice	Marine biogeochemistry	Simulations
CESM1-BGC (Gent et al., 2011)	POP2-CICE4	BEC	Historical, RCP4.5, RCP8.5
CMCC-CESM (Vichi et al., 2011; Cagnazzo et al., 2013)	OPA8-2-LIM2	PELAGOS	Historical, RCP8.5
GFDL-ESM2G (Dunne et al., 2012)	GOLD	TOPAZ2	Historical, RCP2.6, RCP4.5, RCP6.0, RCP8.5
GFDL-ESM2M (Dunne et al., 2012)	MOM5	TOPAZ2	Historical, RCP2.6, RCP4.5, RCP6.0, RCP8.5
HadGEM2-ES (Collins et al., 2011)	UM	Diat-HadOCC	Historical, RCP2.6, RCP4.5, RCP6.0, RCP8.5
IPSL-CM5A-LR (Dufresne et al., 2013)	NEMOv3.2-LIM2	PISCES	Historical, RCP2.6, RCP4.5, RCP6.0, RCP8.5
IPSL-CM5A-MR (Dufresne et al., 2013)	NEMOv3.2-LIM2	PISCES	Historical, RCP2.6, RCP4.5, RCP8.5
MPI-ESM-LR (Giorgetta et al., 2013)	MPIOM	HAMOCC5-2	Historical, RCP2.6, RCP4.5, RCP8.5
MPI-ESM-MR (Giorgetta et al., 2013)	MPIOM	HAMOCC5	Historical, RCP2.6, RCP4.5, RCP8.5
NorESM1-ME (Bentsen et al., 2013)	MICOM-CICE4	HAMOCC5.1	Historical, RCP2.6, RCP4.5, RCP6.0, RCP8.5

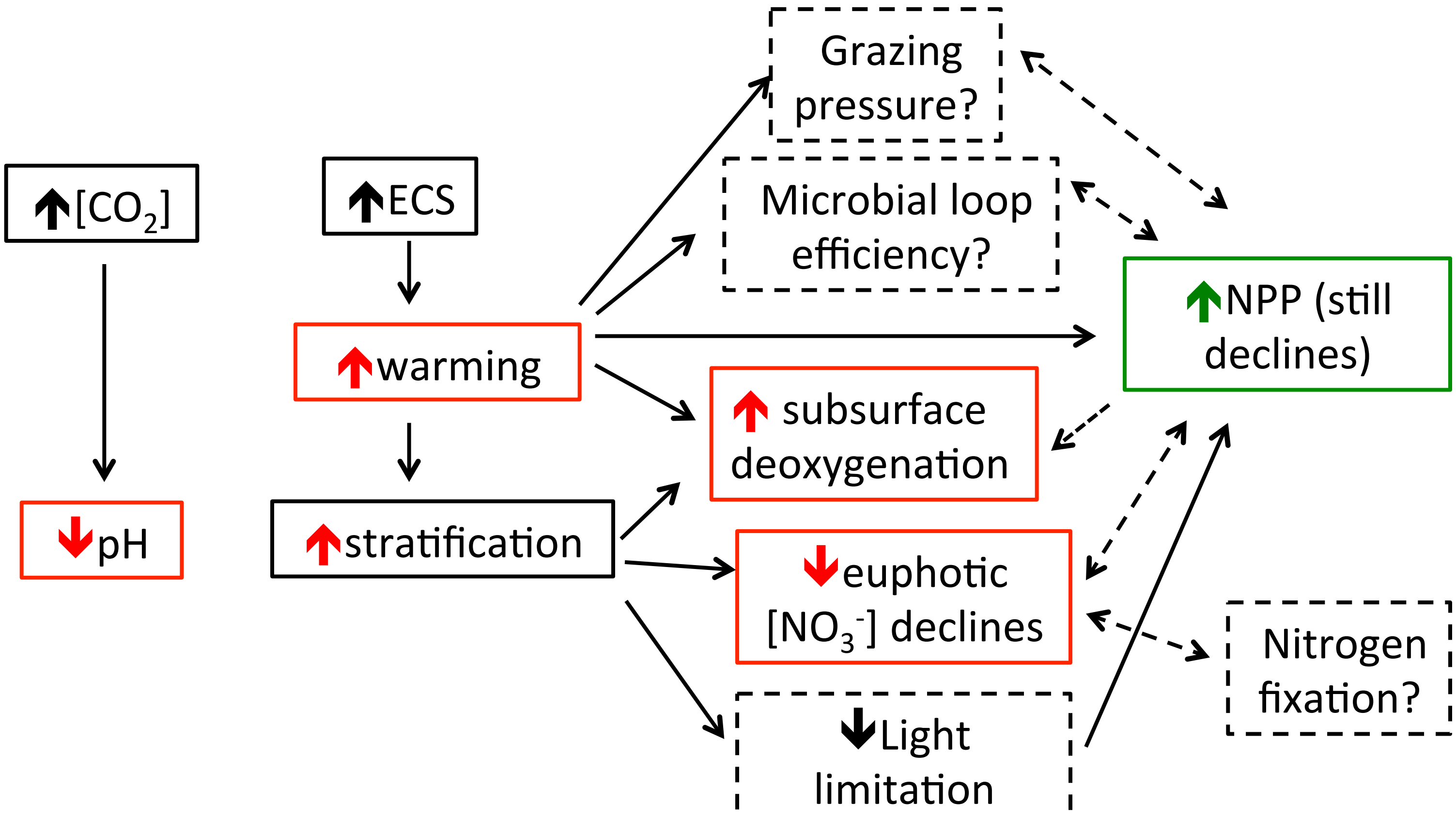
Subsurface acidification



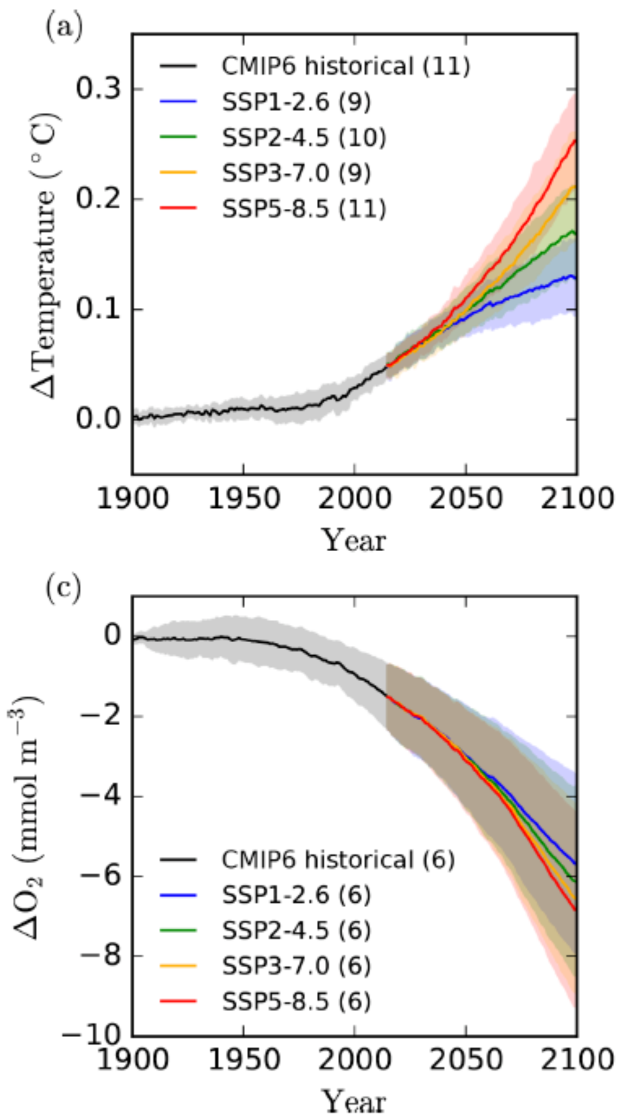
Anomalies are 2080–2099
values relative to 1995-2014

Kwiatkowski et al., (2020)

The dominant drivers of CMIP6 warming, acidification relative to CMIP5



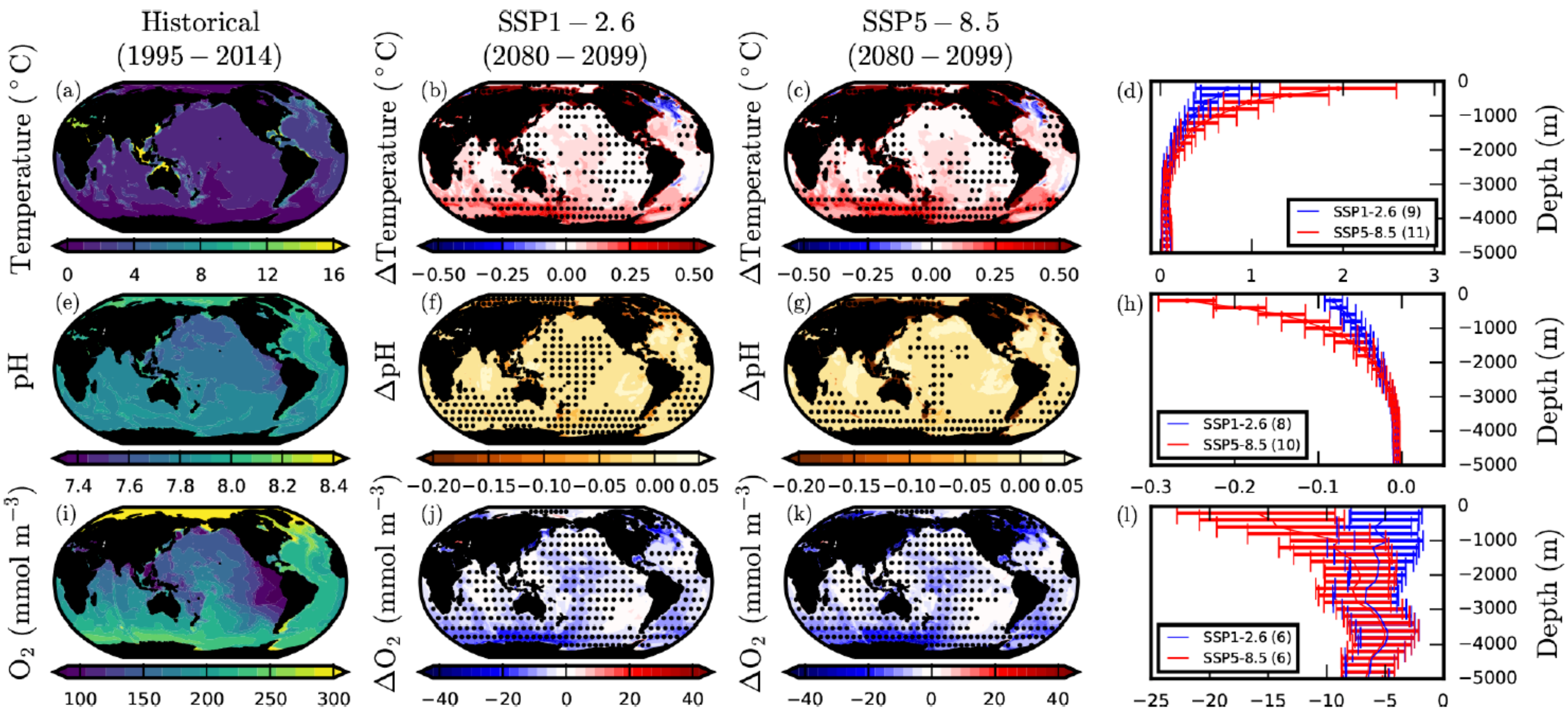
Benthic ocean projections of warming, acidification and deoxygenation



- Benthic = the bottom layer of each ESM
- Benthic warming, acidification & deoxygenation much reduced compared to the upper ocean
- Model uncertainty is increased in the benthic ocean (less separation of SSPs)

Kwiatkowski et al., (2020)

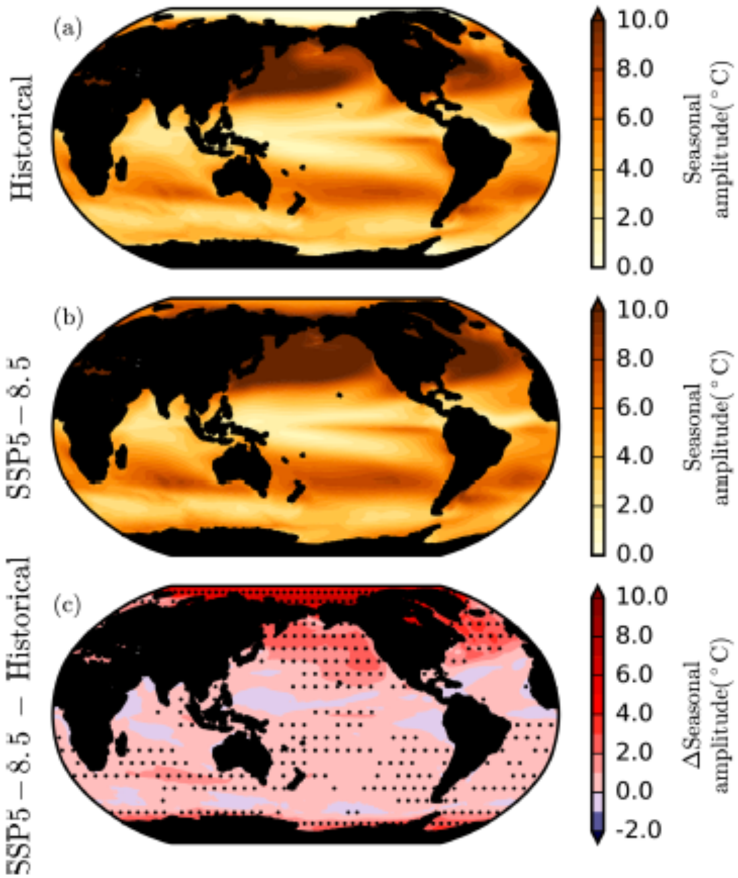
Benthic ocean projections of warming, acidification and deoxygenation



- ‘Shallow’ benthic waters and regions of deep water formation most affected (greater coupling to surface changes)
- Differences between SSPs confined to benthic waters in the upper 2000m

Kwiatkowski et al., (2020)

Amplification of seasonal surface ocean temperature variability

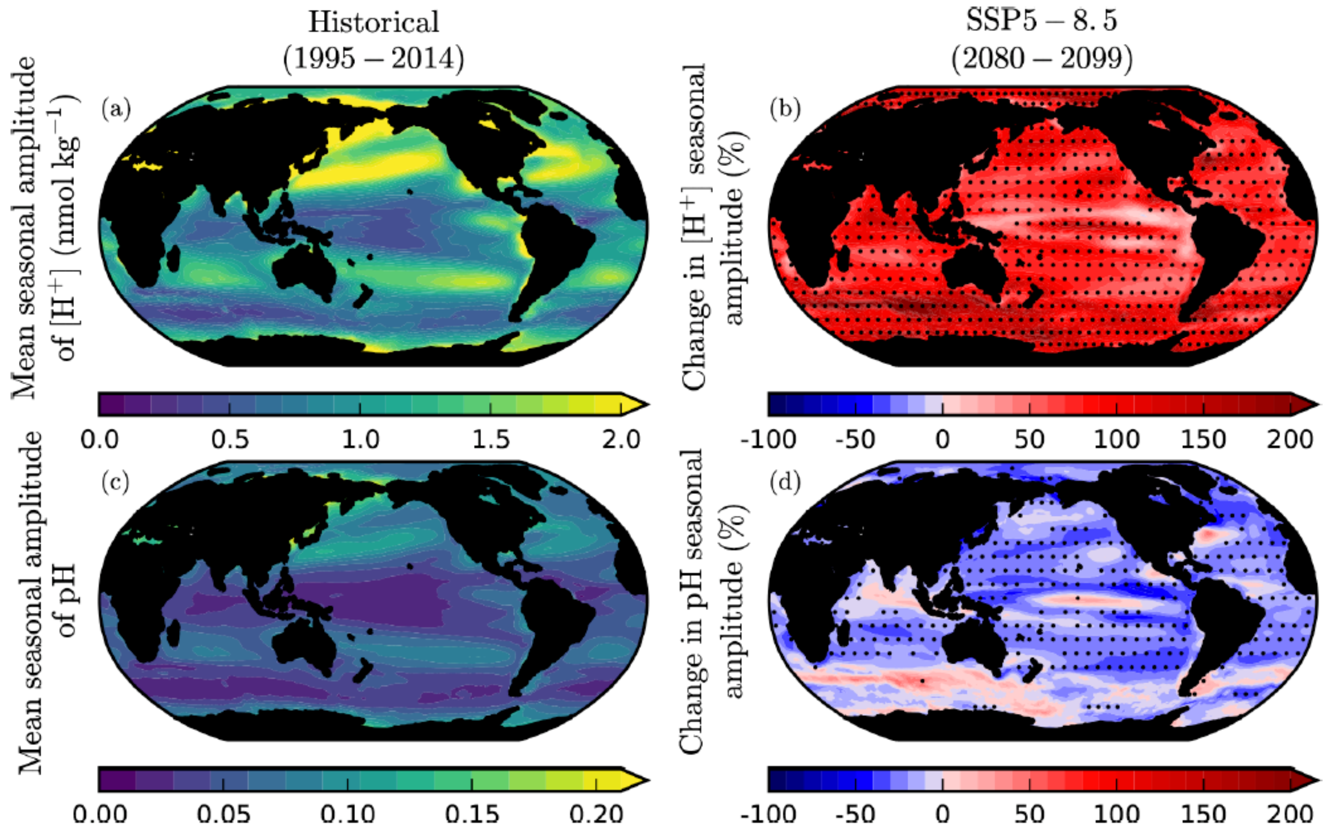


Stippling = >80% model sign agreement

- Seasonal amplitude of SST projected to increase <+0.5°C over most of the ocean,
- But, increases >+2°C in the North Atlantic/ Pacific and Southern Ocean
- and increases >+5°C in the Arctic!

Processes responsible: loss of sea ice, shoaling of summer MLD (Alexander et al., 2018; Carton et al., 2015)

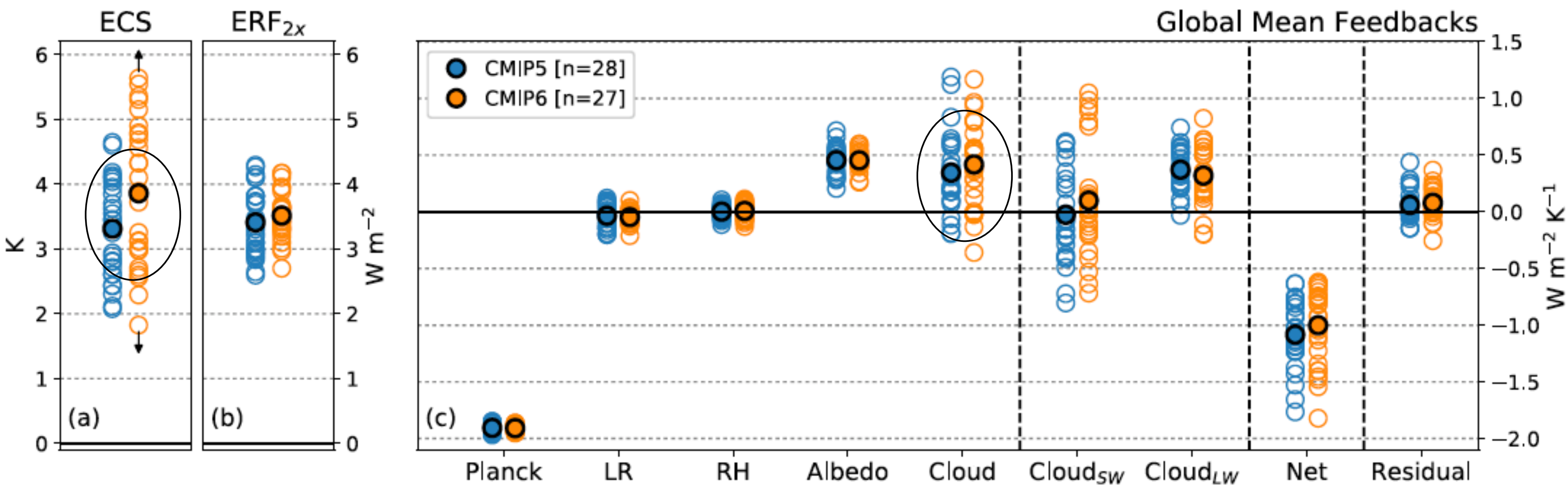
Seasonal amplification/attenuation of surface ocean $[H^+]$/pH



- Amplification of seasonal amplitudes of surface ocean pCO_2/$[H^+]$
- Attenuation of seasonal amplitudes of surface ocean pH
- In agreement with historical observations (Landshutser et al., 2018) and CMIP5 models (McNeil & Sasse, 2016; Gallego et al., 2018; Kwiatkowski & Orr, 2018)

Kwiatkowski et al., (2020)

Greater surface ocean warming, driven by higher equilibrium climate sensitivity



Increase in ECS is primarily due to **<u>stronger positive cloud feedbacks</u>** from decreasing extratropical low cloud coverage and albedo

Zelinka et al., (2020)