ESM systematic biogeochemical biases and uncertainties

Chris Jones

1st Aug. 2017

Complexity, realism and cost

- Consider atmosphere-only vs coupled atmosphere-ocean GCMs

- Which is ***cheaper***?

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- Which is ***cheaper***?
  - A-GCM
- Which ***evaluates better***?

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Complexity, realism and cost

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- Which ***should you use*** for 21st century projection?
  - AO-GCM

- Why?
  - Because processes and feedbacks operate which are leading order drivers of long-term transient and equilibrium changes

Complexity, realism and cost

- Now consider "physical" / AO GCMs vs biogeochemistry / ESMs

- Which is ***cheaper***?
  - AO-GCM
- Which ***evaluates better***?
  - AO-GCM
- Which ***should you use*** for 21st century projection?
  - ESM

- Why?
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So the complexity is required…

- At least, that's what we believe and have been arguing for 20 years…

- Can we demonstrate it?
  - A) in principle – are there processes required to answer the questions we want?
  - B) in reality – are the models good enough to justify doing it?

- I'll try to show that the answer to (A) is clearly "YES"
- Challenge to ESM community to demonstrate (B) is "YES" too - that detriments in terms of cost, complexity and performance are worth it
  - **Important framing to keep in mind to ensure we don't lose track**

Complexity, realism and cost

- Four key BGC areas
- Carbon cycle (land / ocean)
  -
  -
- Land-use / biophysical effects
  -
  -
- Aerosols
  -
  -
- Atmospheric chemistry
  -
  -

Complexity, realism and cost

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- Four key BGC areas

- Carbon cycle (land / ocean)
  - Strong, uncertain, regionally-specific feedbacks/processes
  - Determine future carbon budgets to hit climate targets
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Complexity, realism and cost

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Complexity, realism and cost

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  - Global radiative forcing and uncertainty
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Complexity, realism and cost

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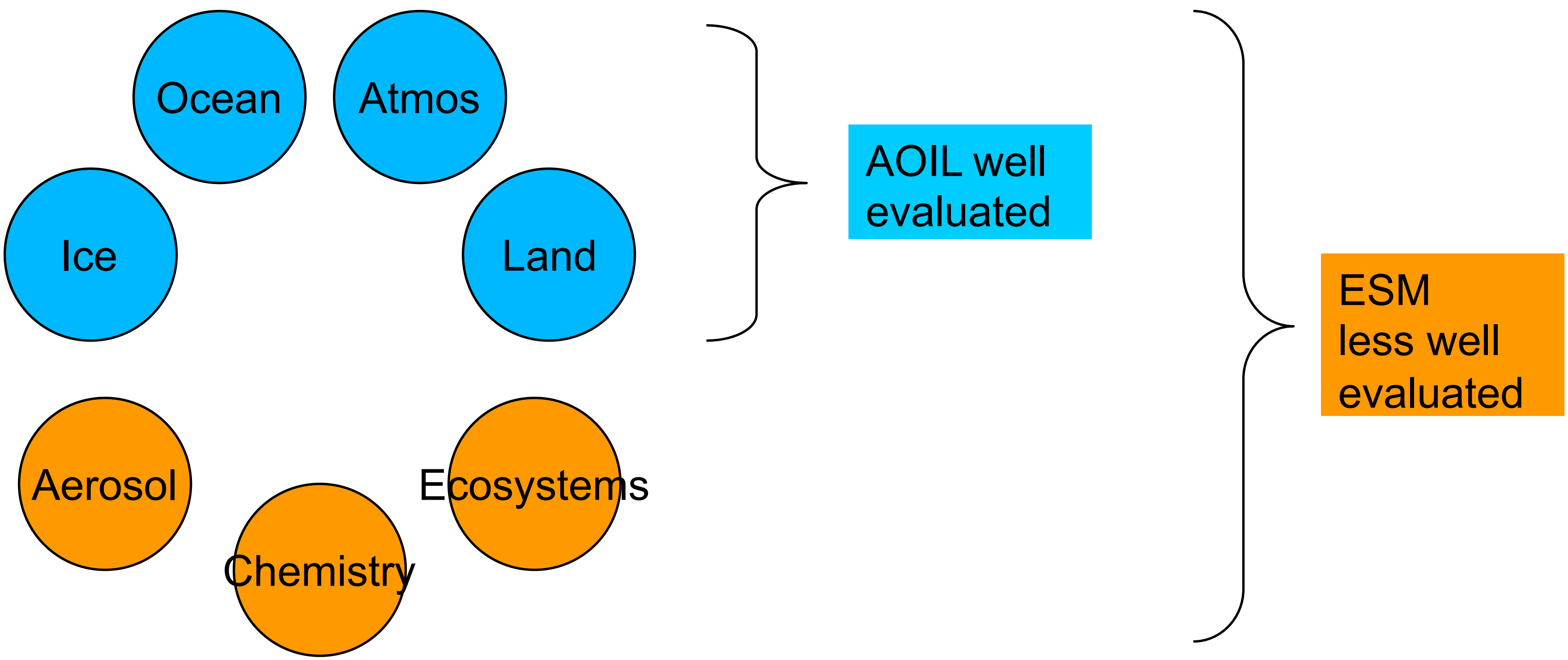
  - Global radiative forcing and uncertainty
  - Strong regional effects on weather
- Atmospheric chemistry
  - CH_4, Ozone lifetime, stratospheric ozone recovery and radiative forcing
  - AQ and impacts on ecosystems/crops

Background

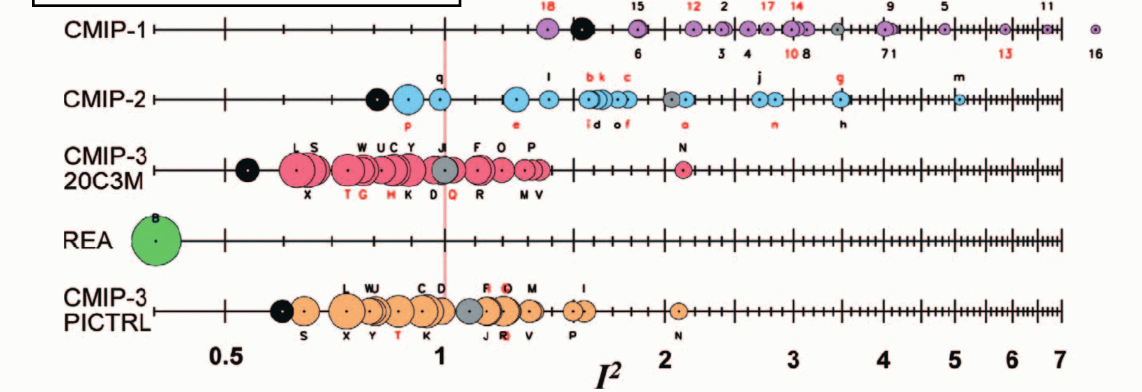
- Model development has moved towards greater complexity
  - Carbon-cycle, chemistry, more interactive aerosols now common place in CMIP5-class models
- Evaluation not necessarily kept apace

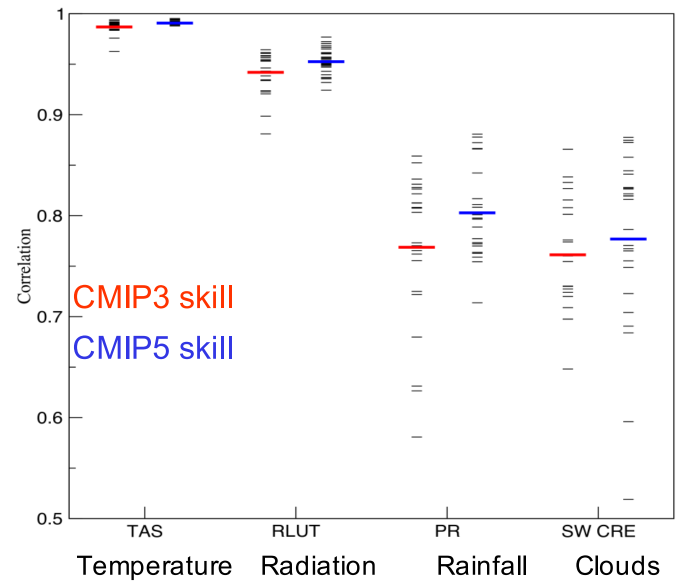


CMIP6 vision

- Need to show ***demonstrable*** progress in ES components
    - CMIP1-2-3-5 progress for climate models

Reichler and Kim, 2008





- What will CMIP6 look like?
- Emergent behaviour/response/sensitivity might not converge
    - E.g. climate sensitivity
- But basic properties must get better

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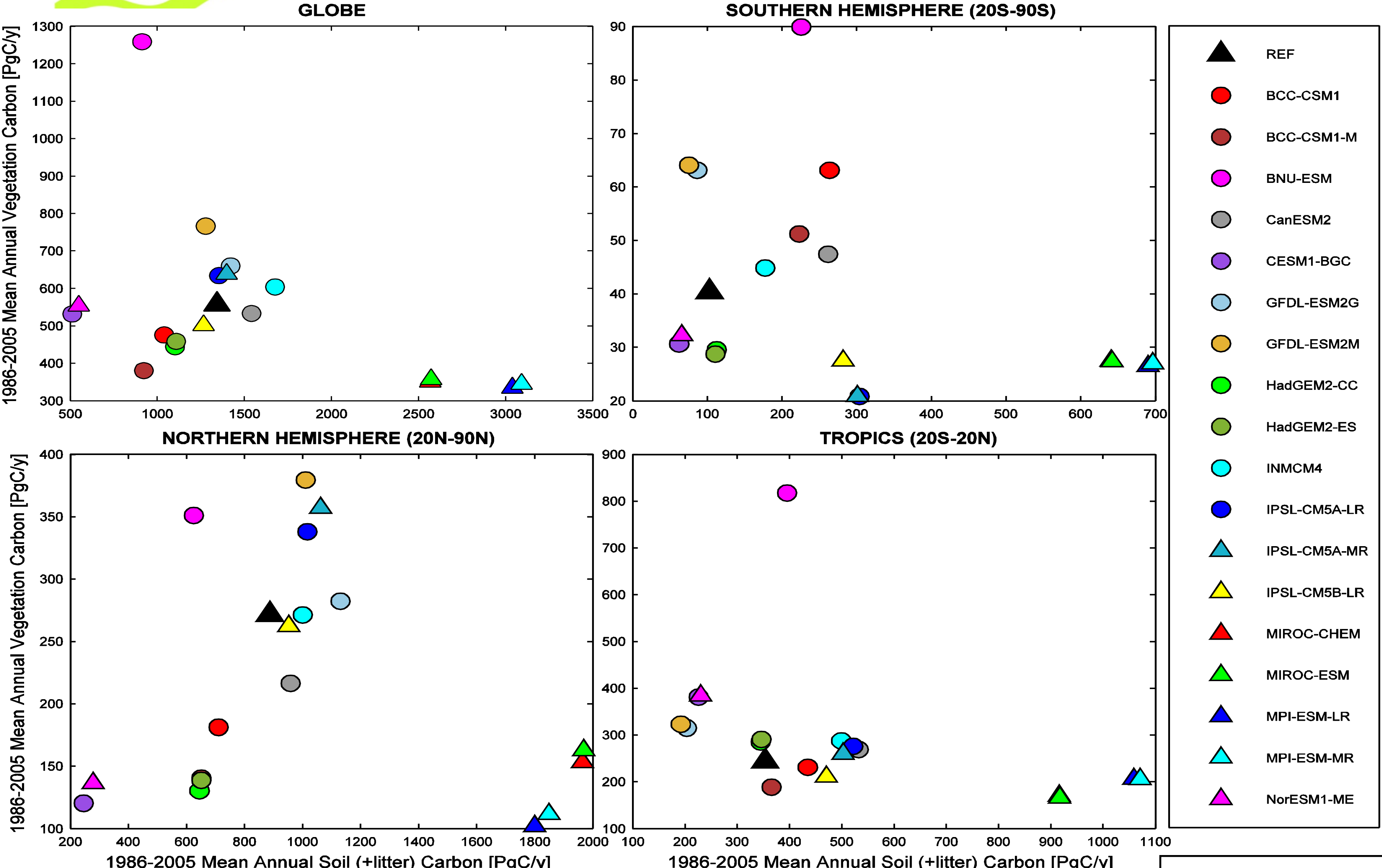
Examples:

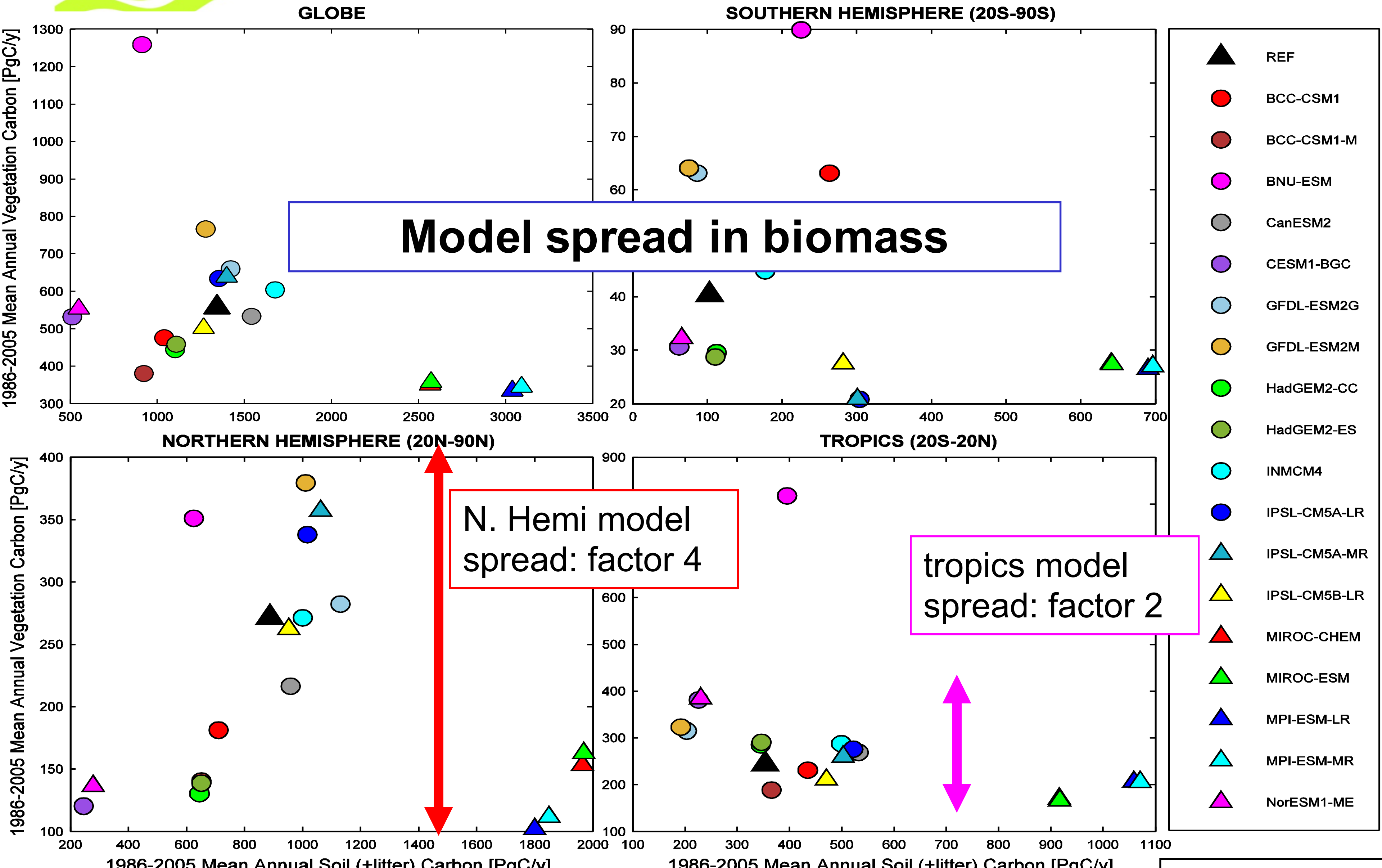
- Carbon cycle
  - Land
    - Evaluating existing processes
    - Missing processes
  - Ocean
    - Global vs. regional

Global soil and biomass carbon stores



Anav et al, 2013

Global soil and biomass carbon stores



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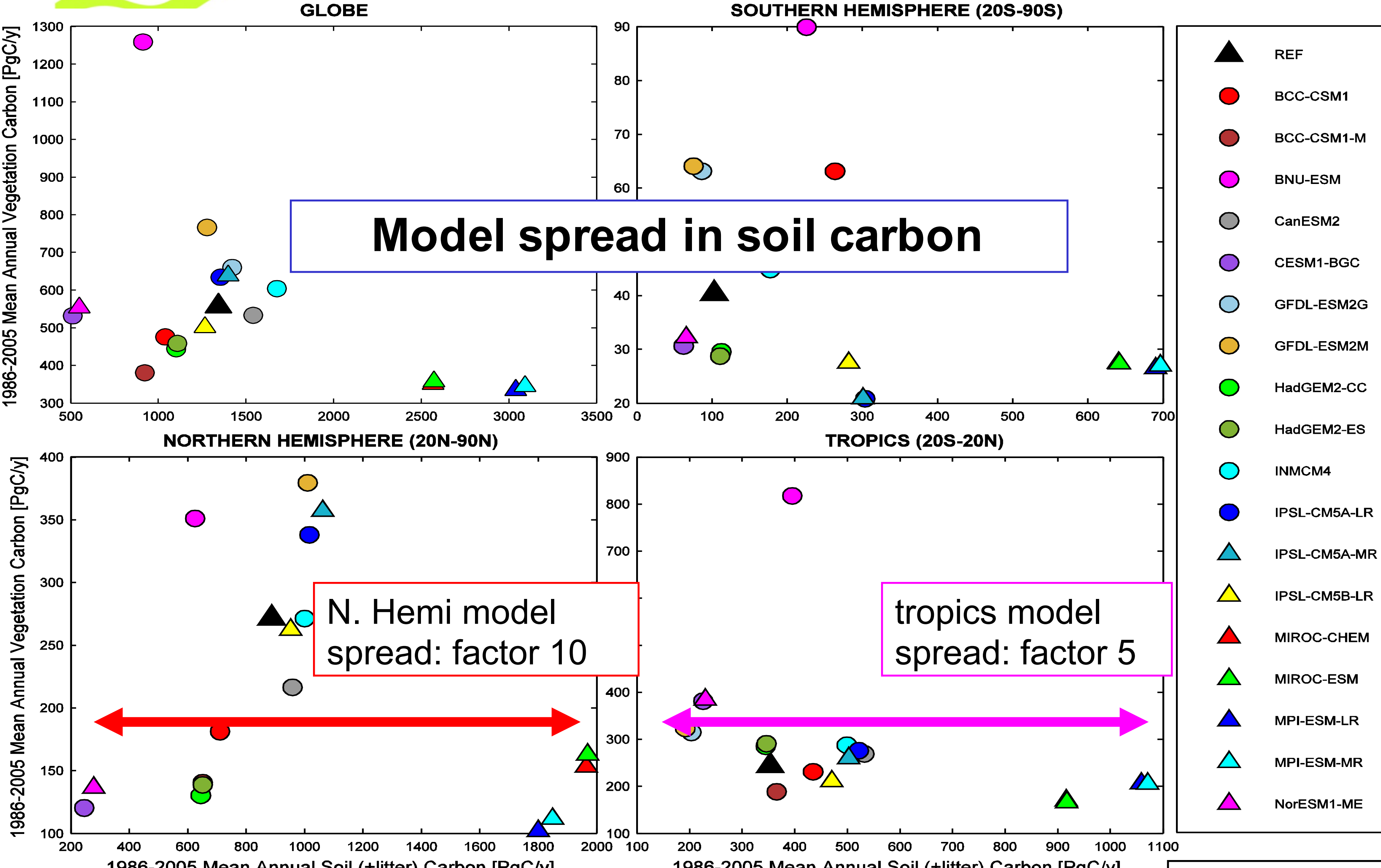
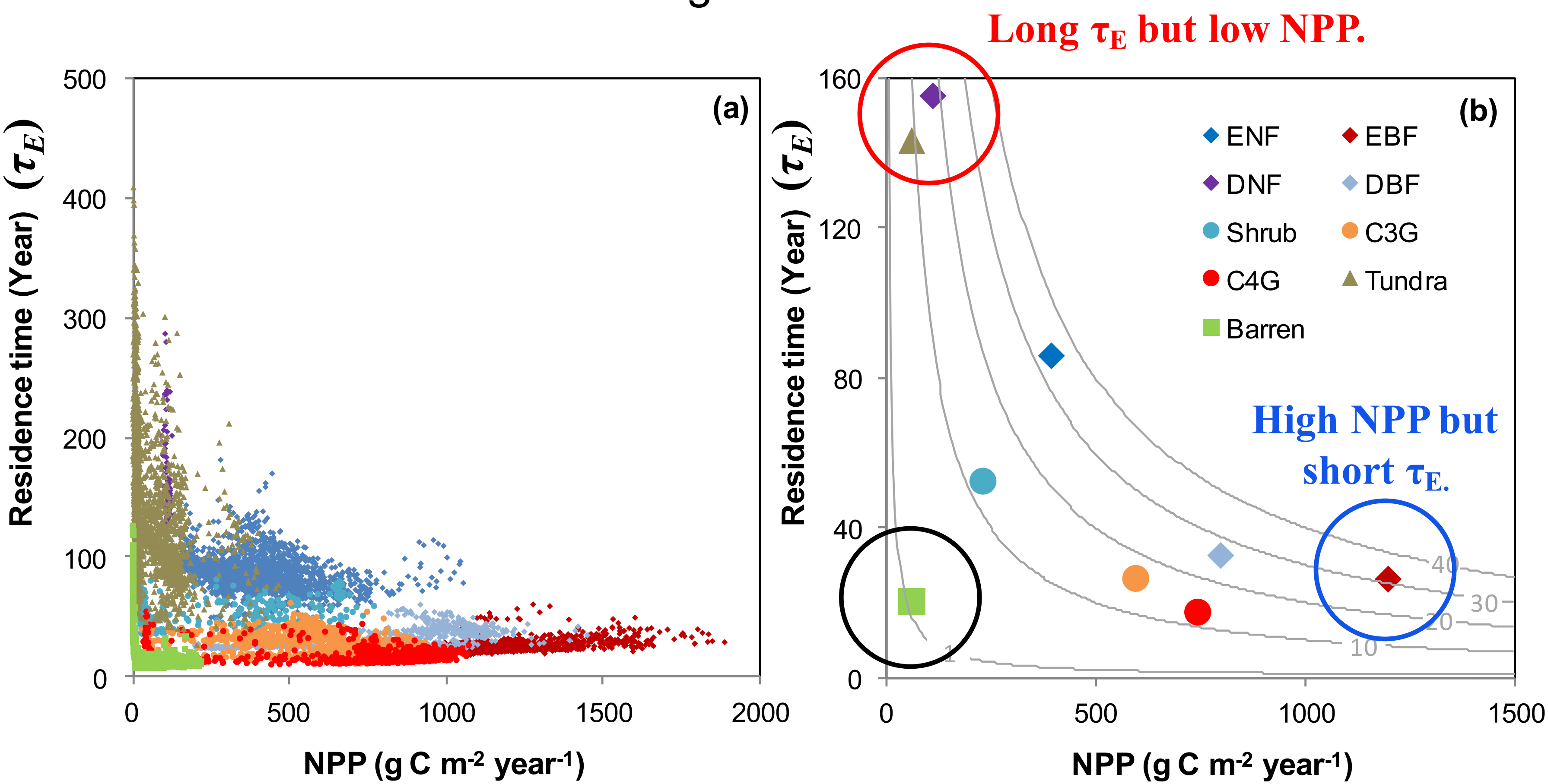


Anav et al, 2013

Traceability for differences among biomes

- How can models be factor 2-10 out in carbon stores when within 20% on gross fluxes?
  - •Residence time been forgotten about



Based on spin-up results from CABLE with 1990 forcings

Xia et al. 2013 GCB

Slide courtesy Yiqi Luo

ILAMB: CMIP5 ESM assessment

http://redwood.ess.uci.edu/mingquan/www/ILAMB/index.html

Global Variables (Info for Weightings)

	MeanModel	bcc-csm1-1-m	BNU-ESM	CanESM2	CESM1-BGC	GFDL-ESM2G	HadGEM2-ES	inmcm4	IPSL-CM5A-LR	MIROC-ESM	MPI-ESM-LR	MRI-
Live Biomass Carbon	0.73	0.68	0.33	0.65	0.60	0.62	0.72	0.50	0.56	0.62	0.58	0.
Burned Area	0.38	-	-	-	0.37	-	-	-	-	-	0.38	-
Carbon Dioxide	0.85	-	0.65	0.65	0.78	0.65	-	-	-	0.79	0.68	0.
Gross Primary Productivity	0.77	0.72	0.73	0.64	0.70	0.67	0.68	0.70	0.67	0.69	0.69	0.
Leaf Area Index	0.66	0.66	0.41	0.60	0.53	0.49	0.59	0.68	0.66	0.62	0.68	0.
Global Net Ecosystem Carbon Balance	0.58	-	0.38	0.27	0.38	0.18	-	0.46	0.25	0.38	0.42	0.
Net Ecosystem Exchange	0.49	0.47	0.47	0.39	0.48	0.49	0.46	0.44	0.53	0.48	0.50	0.
Ecosystem Respiration	0.75	0.72	0.72	0.65	0.67	0.71	0.66	0.70	0.67	0.68	0.68	0.
Soil Carbon	0.55	0.50	0.42	0.56	0.38	0.51	0.51	0.53	0.57	0.53	0.41	0.
Summary	0.64	0.62	0.51	0.55	0.55	0.54	0.60	0.56	0.55	0.59	0.55	0.
Evapotranspiration	0.75	0.73	0.72	0.72	0.73	0.70	0.74	0.69	0.75	0.70	0.73	0.
Evaporative Fraction	0.84	0.76	0.77	0.81	0.81	0.75	0.81	0.81	0.72	0.75	0.75	0.
Latent Heat	0.80	0.76	0.77	0.77	0.78	0.74	0.77	0.72	0.77	0.75	0.76	0.
Runoff	0.61	0.59	0.60	0.58	0.64	0.59	-	0.62	0.57	0.56	0.66	0.
Sensible Heat	0.76	0.69	0.70	0.71	0.75	0.69	0.75	0.66	0.69	0.69	0.69	0.
Terrestrial Water Storage Anomaly	0.38	0.37	0.36	0.38	0.38	0.38	-	0.38	0.37	0.38	0.38	0.
Summary	0.68	0.65	0.65	0.66	0.67	0.64	0.77	0.64	0.64	0.63	0.66	0.

ILAMB: CMIP5 ESM assessment

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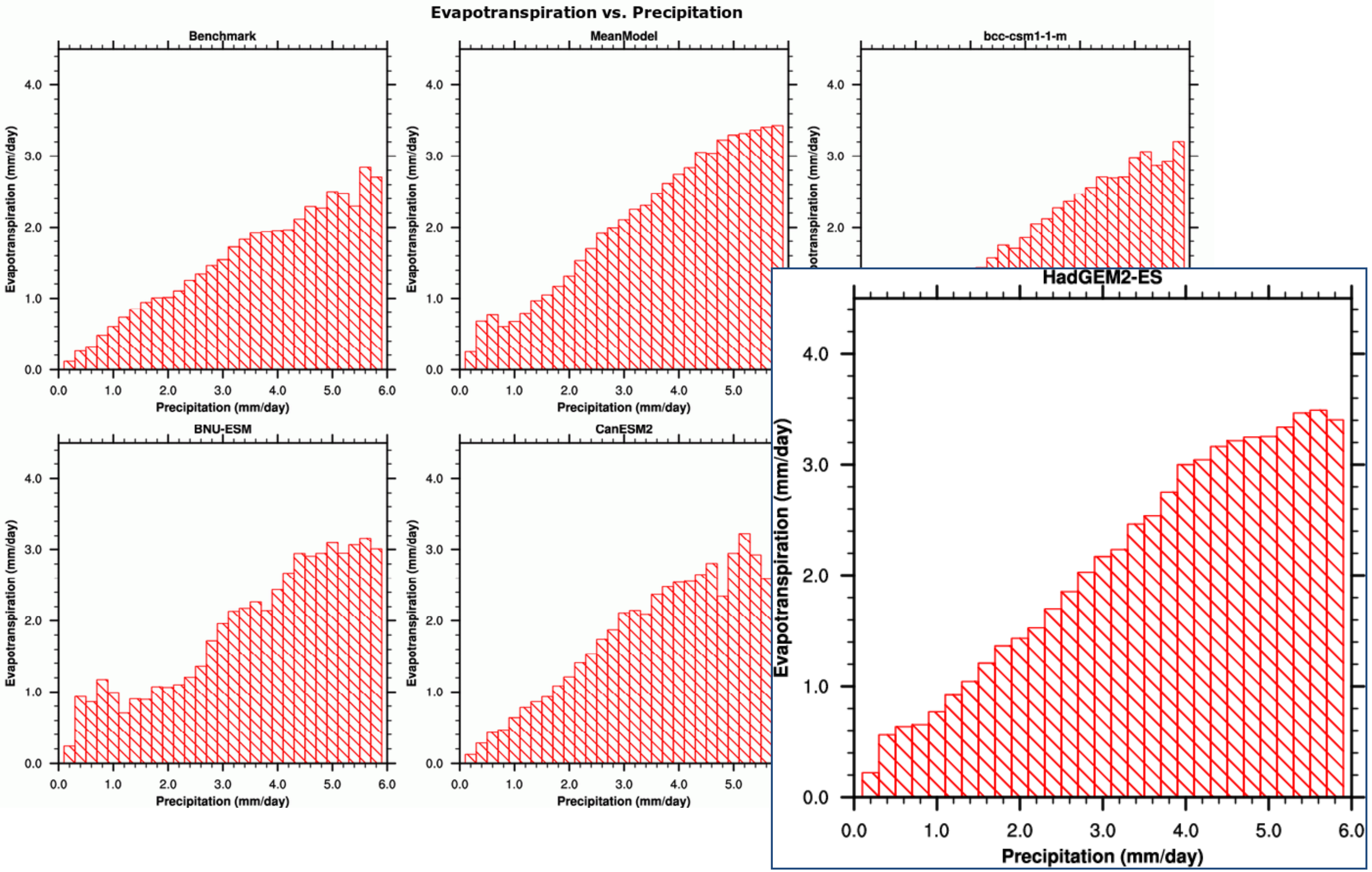
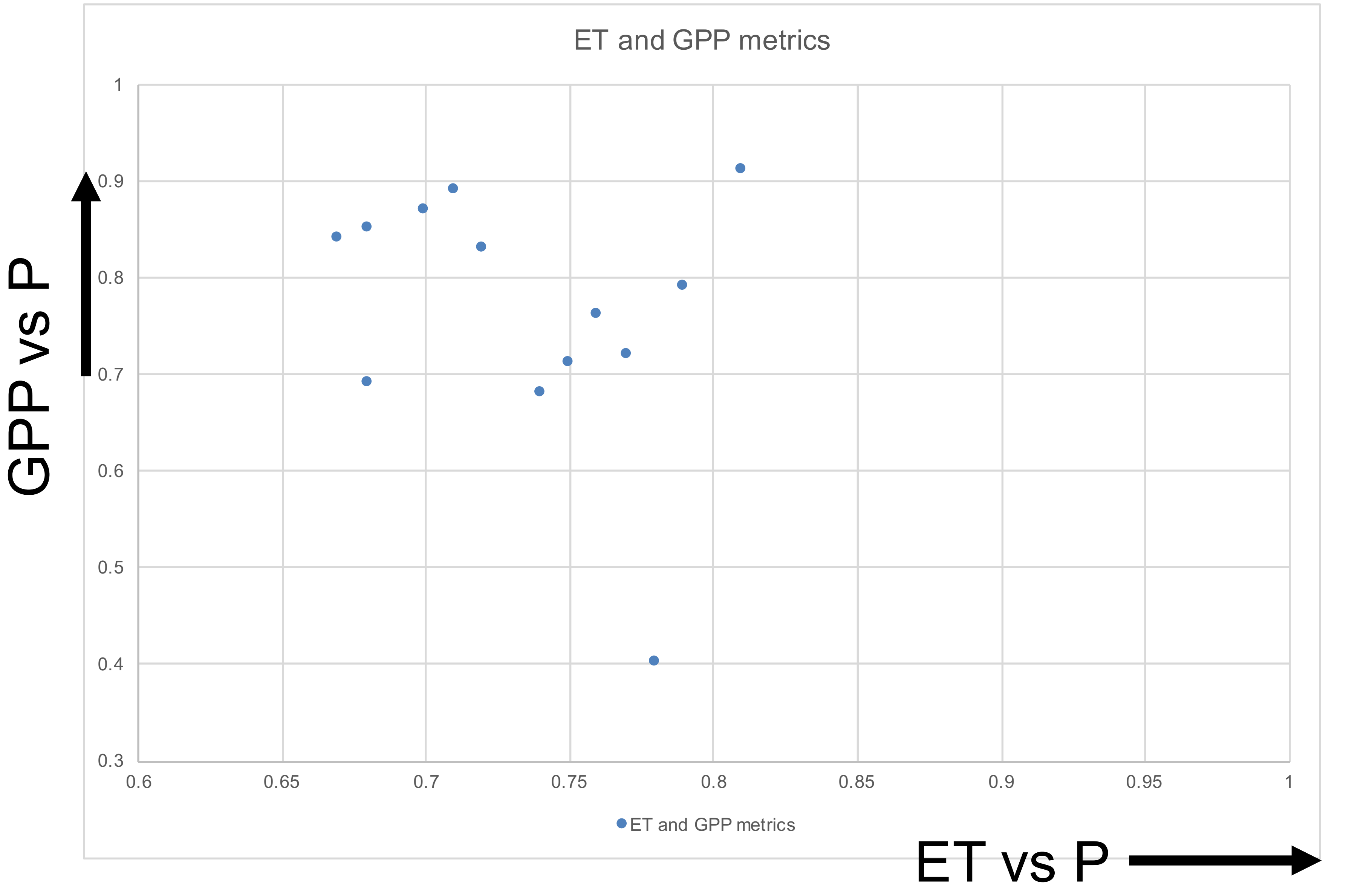
Variable to Variable Relationships (Info for Weightings)

	Relationship	Benchmark	MeanModel	bcc-csm1-1-m	BNU-ESM	CanESM2	CESM1-BGC	GFDL-ESM2G	HadGEM2-ES	inmcm4	IPSL-CM5A-LR	MIROC-ESM	MPI-ESM-LR
Evapotranspiration vs. Gross Primary Productivity	function_bar	1	0.81	0.79	0.61	0.84	0.73	0.90	0.85	0.69	0.87	0.74	0.88
Precipitation vs. Burned Area	function_bar	1	0.45	-	-	-	0.46	-	-	-	-	-	0.43
Precipitation vs. Evapotranspiration	function_bar	1	0.71	0.81	0.77	0.79	0.70	0.76	0.68	0.68	0.75	0.72	0.74
Precipitation vs. Gross Primary Productivity	function_bar	1	0.89	0.91	0.72	0.79	0.87	0.76	0.69	0.85	0.71	0.83	0.68
Precipitation vs. Leaf Area Index	function_bar	1	0.62	0.68	0.34	0.58	0.55	0.42	0.47	0.84	0.60	0.67	0.76
Surface Downward SW Radiation vs. Gross Primary Productivity	function_bar	1	0.74	0.80	0.77	0.64	0.72	0.60	0.65	0.75	0.47	0.66	0.53
Surface Net SW Radiation vs. Gross Primary Productivity	function_bar	1	0.77	0.83	0.63	0.67	0.77	0.64	0.76	0.78	0.60	0.62	0.59
Surface Air Temperature vs. Burned Area	function_bar	1	0.42	-	-	-	0.44	-	-	-	-	-	0.44
Surface Air Temperature vs. Evapotranspiration	function_bar	1	0.68	0.75	0.63	0.82	0.64	0.65	0.65	0.59	0.74	0.65	0.76
Surface Air Temperature vs. Gross Primary Productivity	function_bar	1	0.78	0.77	0.65	0.75	0.70	0.67	0.76	0.62	0.62	0.73	0.56

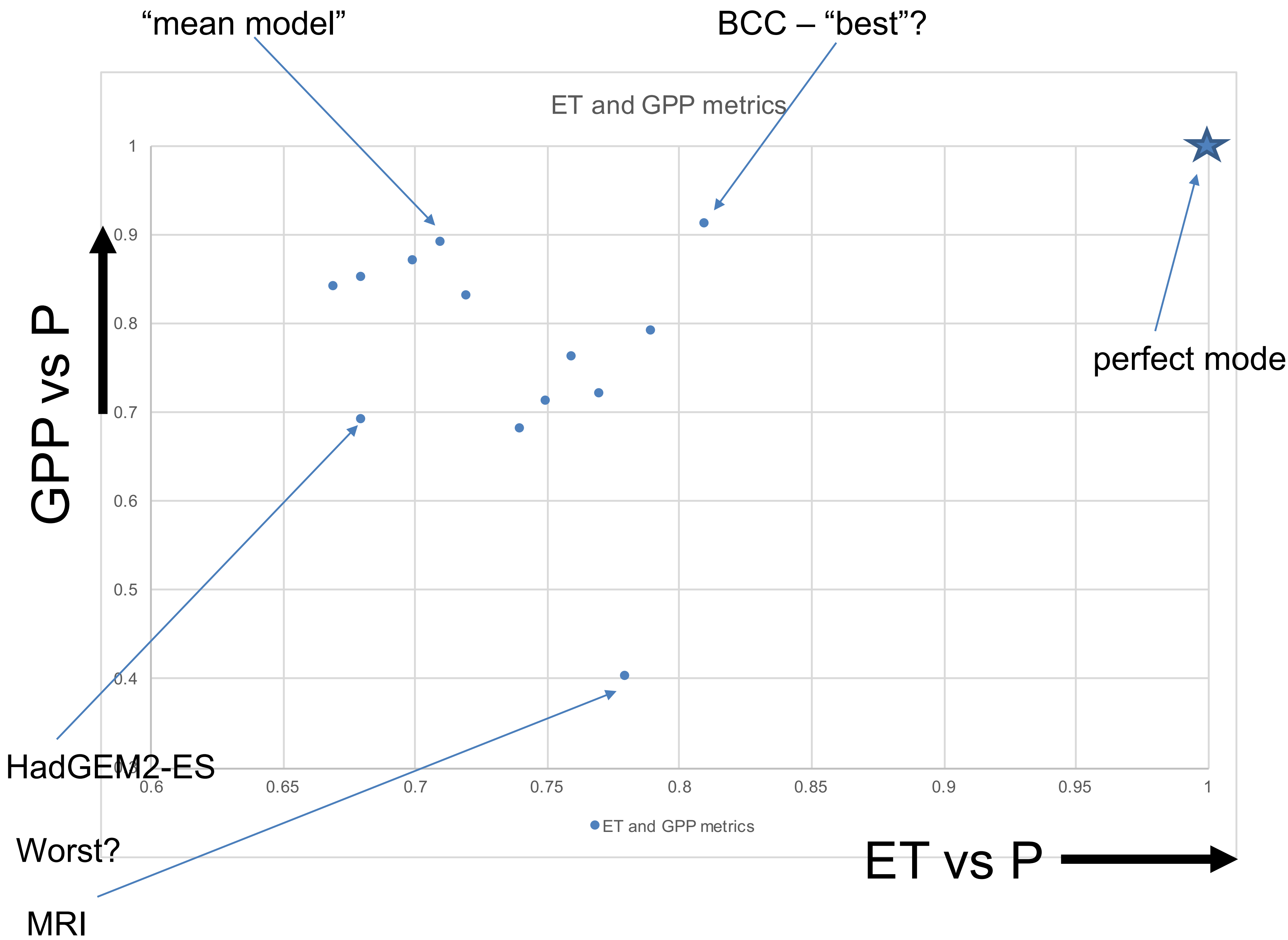
So HadGEM2 has about best ET and precip individually, but worst relationship between them...

ILAMB: CMIP5 ESM assessment
http://redwood.ess.uci.edu/mingquan/www/ILAMB/index.html





ET and GPP metrics
GPP vs P
ET vs P
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
ET and GPP metrics



"mean model"
BCC – "best"?
ET and GPP metrics
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0.9
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GPP vs P
perfect model
HadGEM2-ES
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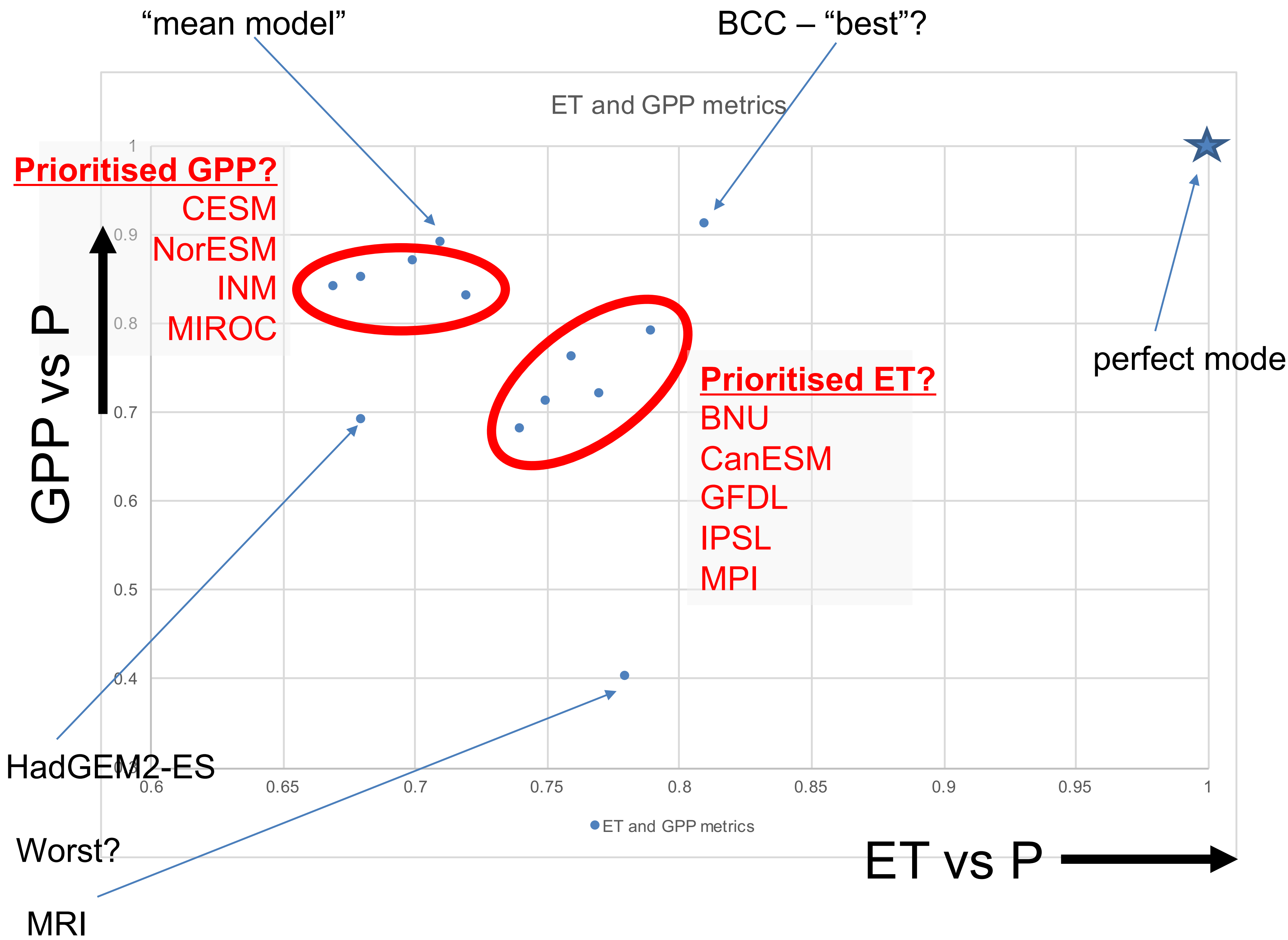
0.85
0.9
0.95
1
ET and GPP metrics
Worst?
ET vs P
MRI


"mean model"
BCC – "best"?
ET and GPP metrics
Prioritised GPP?
CESM
NorESM
INM
MIROC
GPP vs P
Prioritised ET?
BNU
CanESM
GFDL
IPSL
MPI
perfect model
HadGEM2-ES
Worst?
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ET vs P
1
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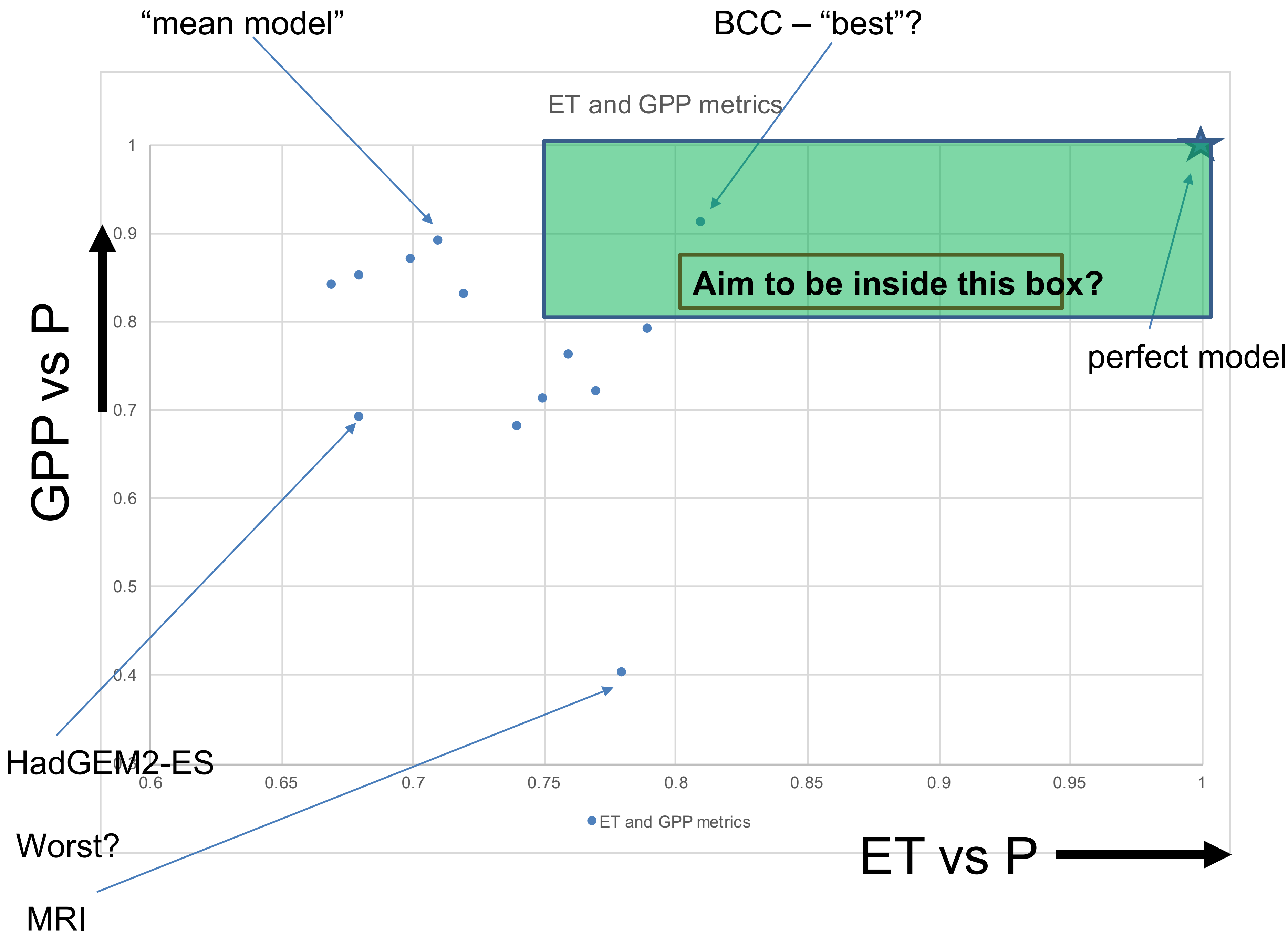
1
ET and GPP metrics



"mean model"
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ET and GPP metrics
Aim to be inside this box?
perfect model
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MRI
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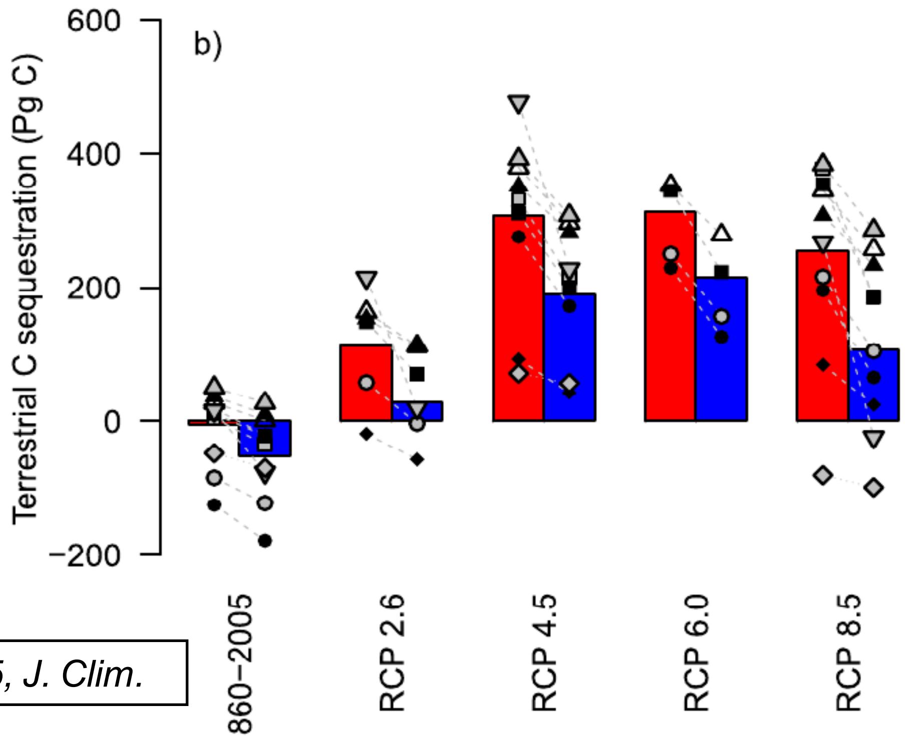
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1

Key missing processes

- Most CMIP5 models do not include the fact that carbon storage in vegetation requires sufficient nutrients to enable plant growth.
- Limitation of nutrients, mainly reactive nitrogen, would therefore reduce carbon storage on land and leave more in the atmosphere as CO2

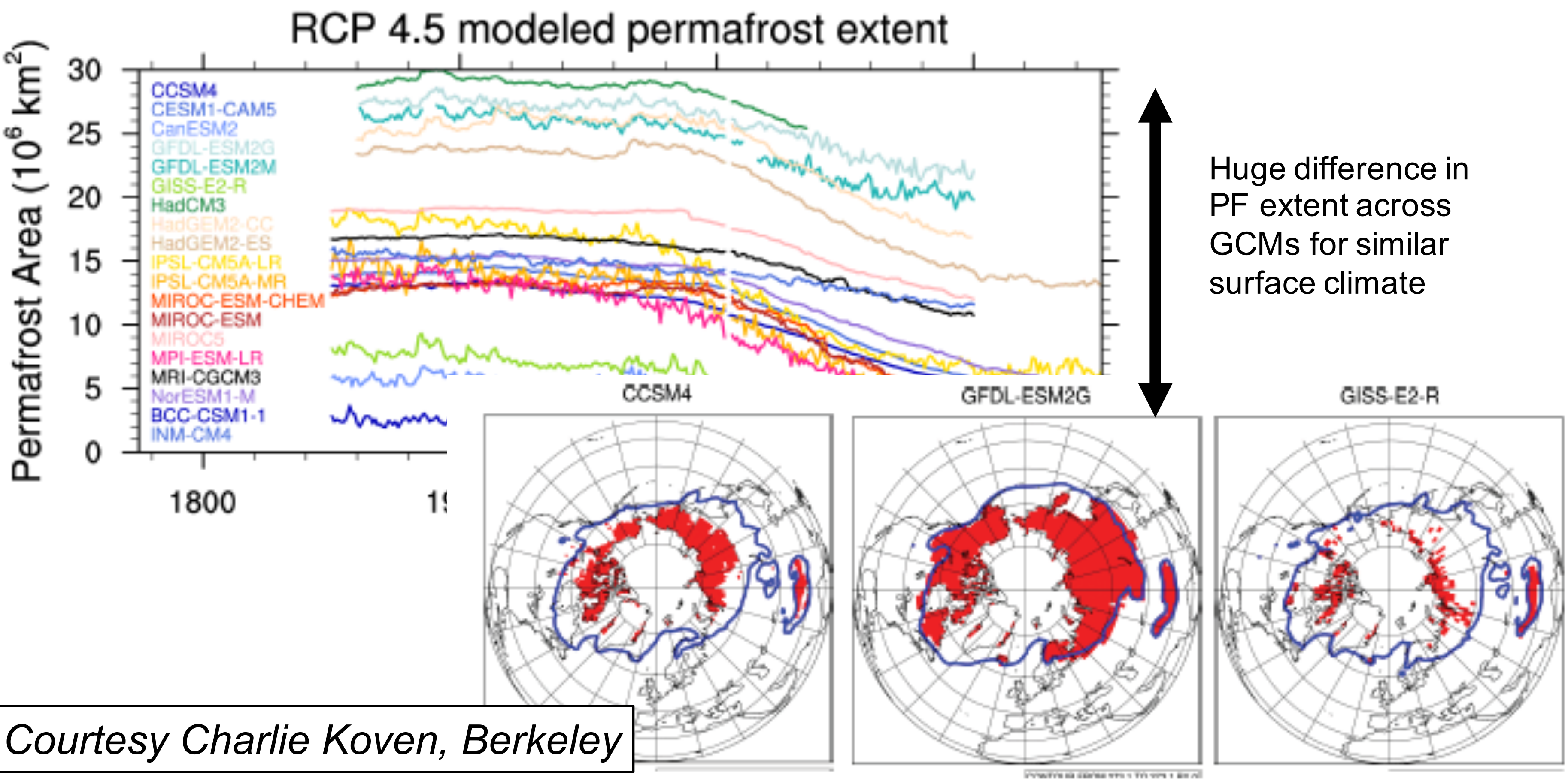
- This is apparent in CMIP5 models: consistent overestimate of carbon sequestration for all RCP scenarios



Zaehle et al., 2015, J. Clim.

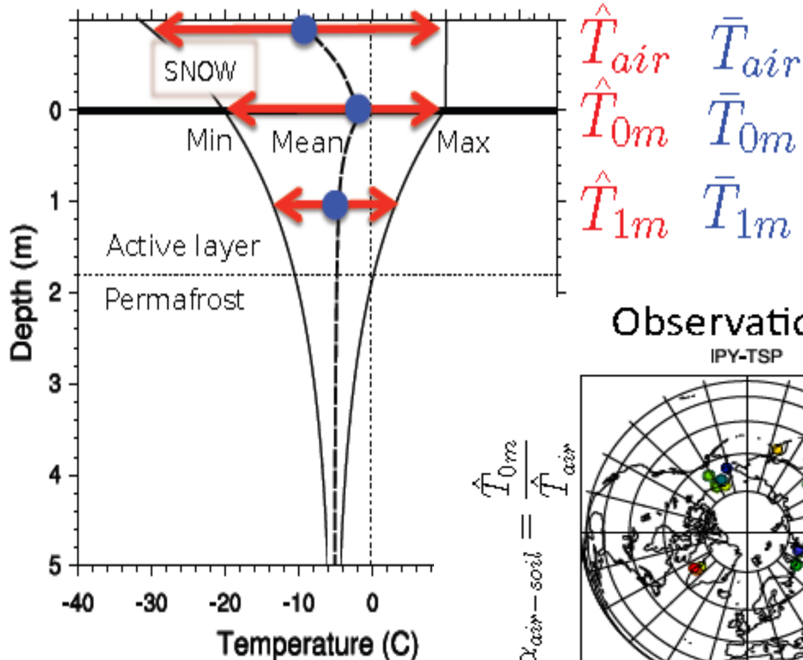
Permafrost case study

- No CMIP5 models represent carbon loss from permafrost thawing
- Can't even represent soil physics properly yet!
    - But we're starting to understand it…



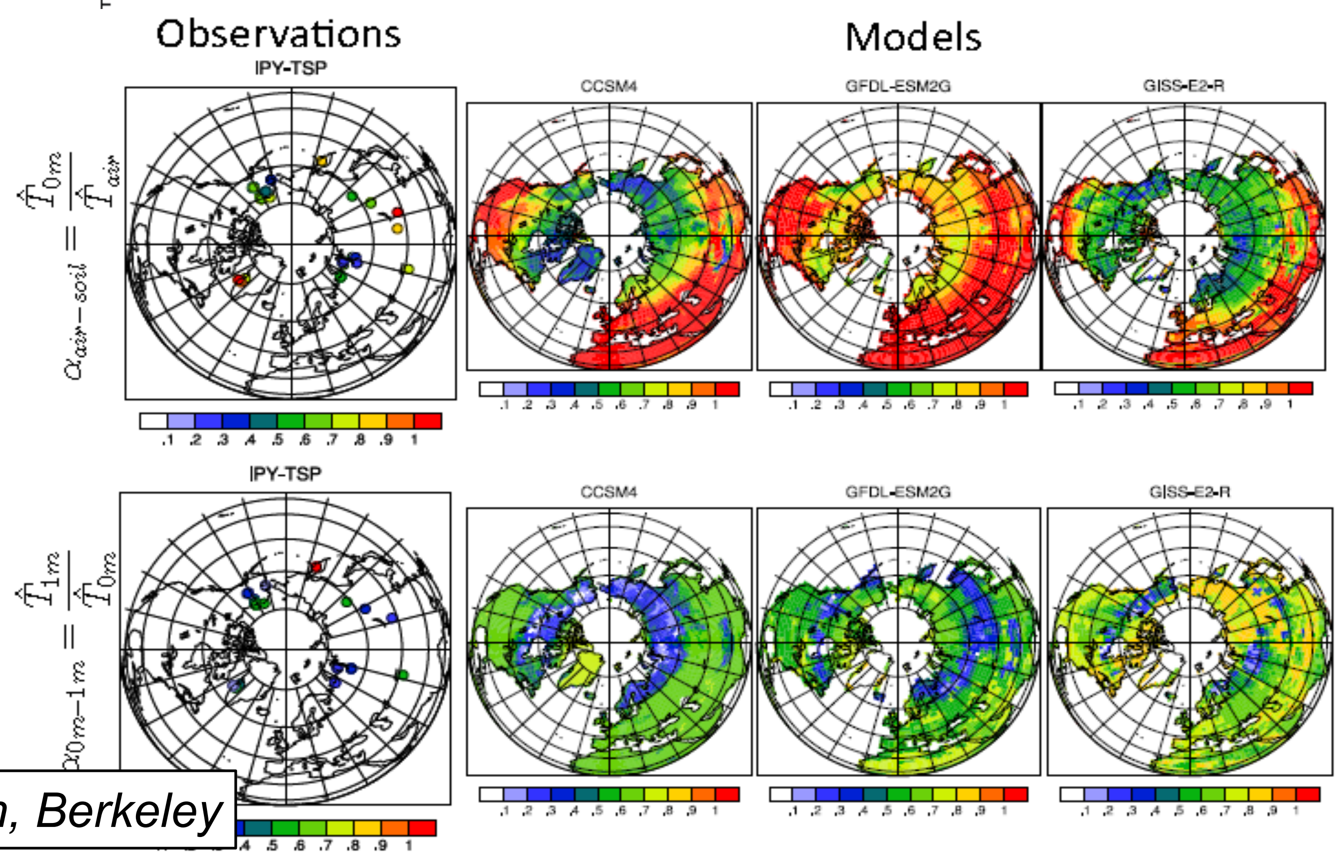
Courtesy Charlie Koven, Berkeley

Bottom-up process-based evaluation



Snow and soil physics determine seasonal cycle magnitude by depth

Observations tell us about specific



Courtesy Charlie Koven, Berkeley

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quality of biomass datasets

ESA mission planned (2021?)

Newly available obs?

Sensitivity datasets

Warming, drou

Global Change Biology

Explore this jo

Primary Research Article

An integrated pan-tropical biomass ma
reference datasets

Valerio Avitabile, Martin Herold, Gerard B. M. Heuvelink,

nature International weekly journal of science

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NATURE | LETTER

日本語要約

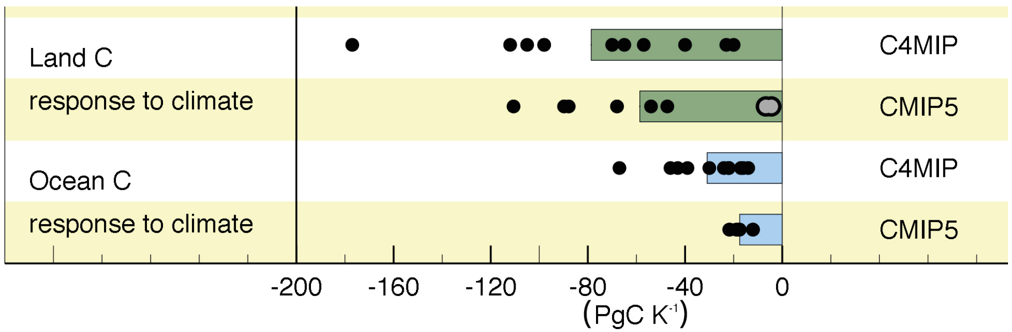
Quantifying global soil carbon losses in response to warming

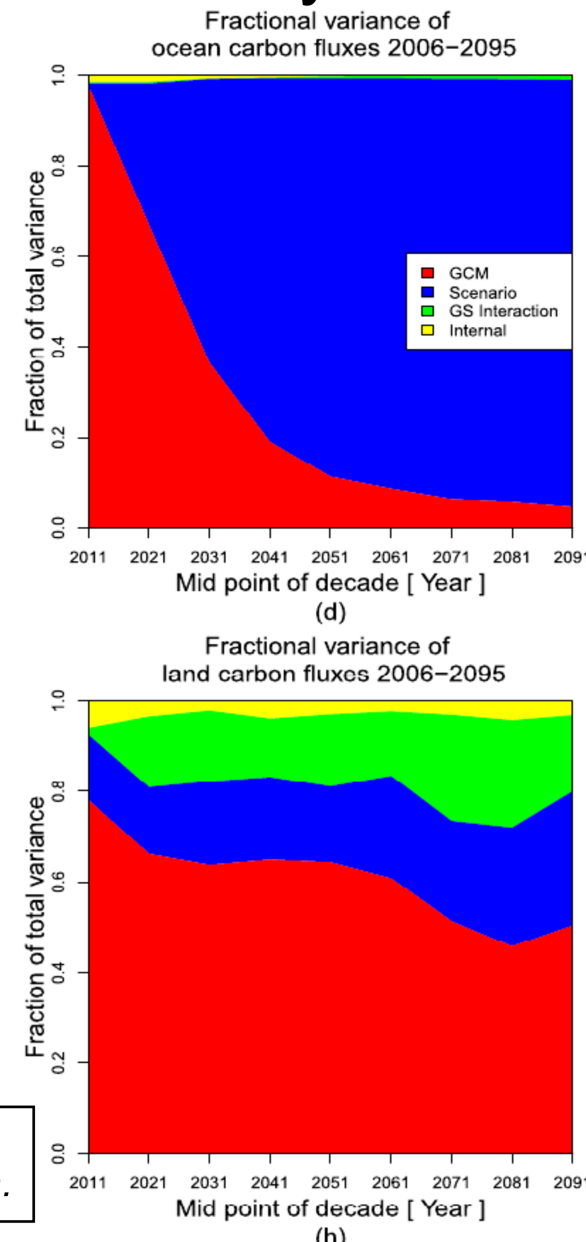
T. W. Crowther, K. E. O. Todd-Brown, C. W. Rowe, W. R. Wieder, J. C. Carey, M. B. Machmuller, B. L. Snoek, S. Fang, G. Zhou, S. D. Allison, J. M. Blair, S. D. Bridgham, A. J. Burton, Y. Carrillo, P. B. Reich, J. S. Clark, A. T. Classen, F. A. Dijkstra, B. Elberling, B. A. Emmett, M. Estiarte, S. D. Frey, J. Guo, J. Harte, L. Jiang et al.

AMAZONFACE

- Ocean Carbon
  - Global vs. regional

Ocean carbon – have models really converged?





- Model spread in future projections can come from differences between models, differences between scenarios, or sensitivity to initial conditions
- The relative importance of these aspects differs for land and ocean carbon uptake

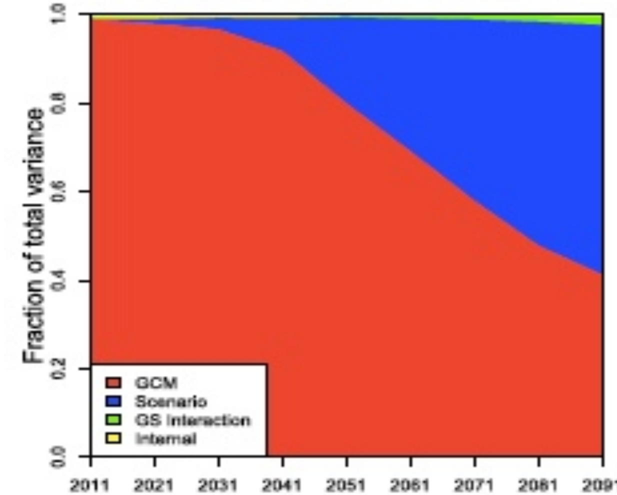
- Land carbon uptake is dominated by model uncertainty
- Ocean carbon uptake (globally) is dominated by differences across scenarios

Hewitt et al., 2016, J. Clim.

Ocean carbon – have models really converged?

- But clearly not true at basin scale
- Southern ocean and N. Atlantic still dominated by model differences

- Combination of present day uptake as well as changes into future



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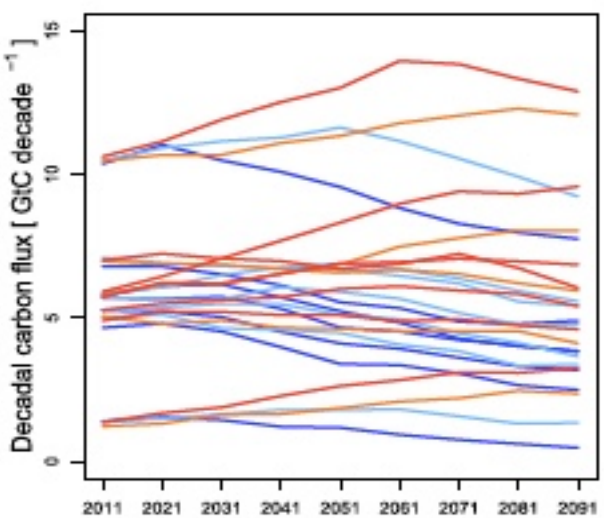
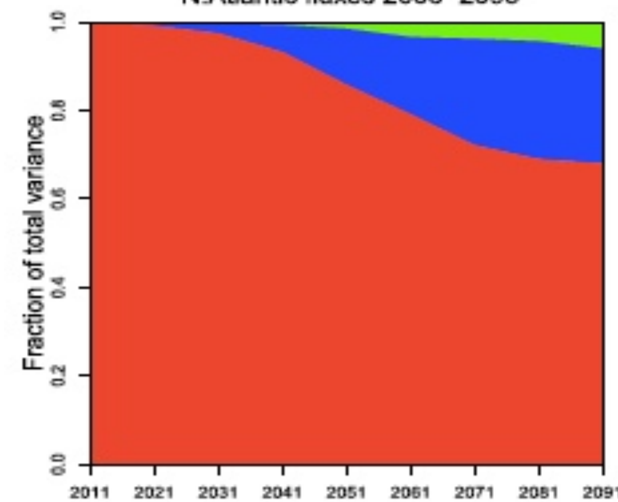


(e)

Hewitt et al., 2016, J. Clim.



(h)

Ocean carbon – have models really converged?

- Southern ocean carbon related to heat uptake?
    - Similarities and differences…
    - Can learn about one from the other, so joint use of heat and carbon obs
        - Surface exchange and at depth

- Vertical distribution of carbon / role of biology

- Circulation, upwelling of DIC / nutrients

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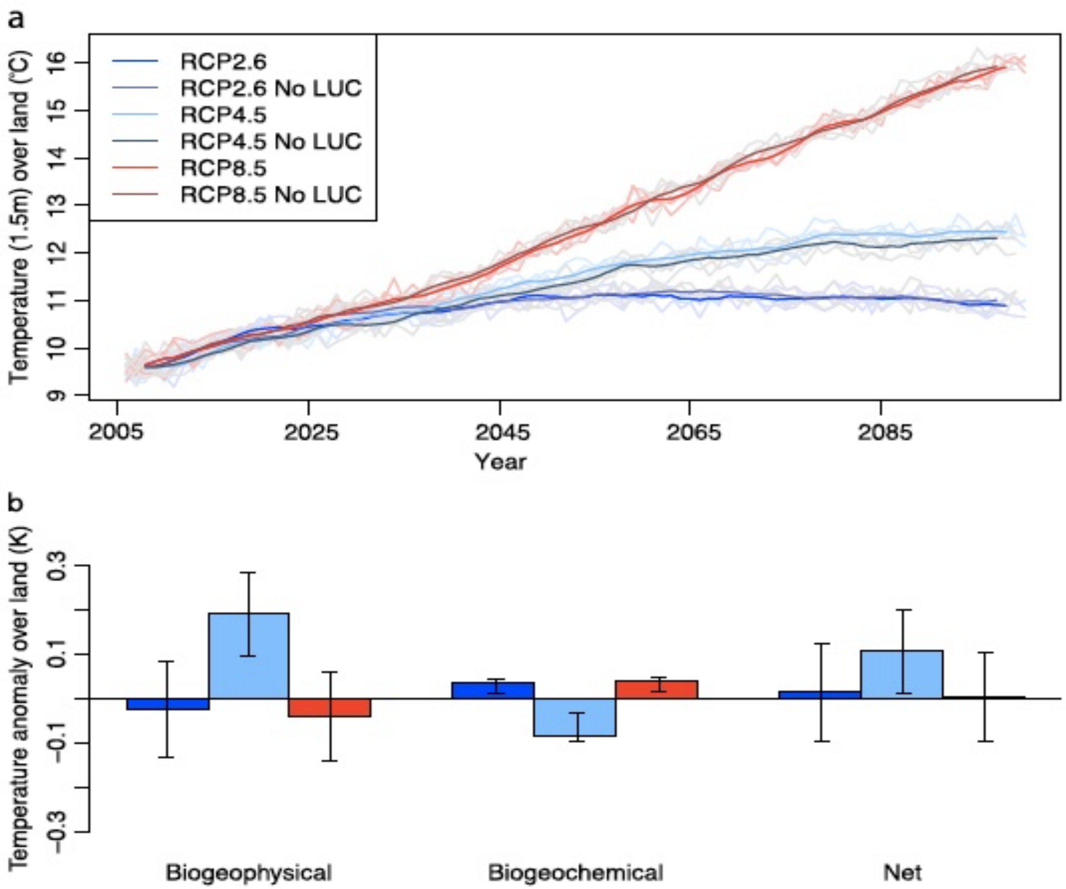
- Land-use
  - Biophysical effects
  - CO_2 emissions

Land-use

- Biophysics
  - Often offsets carbon emissions



Davies-Barnard et al., 2014, ERL

Land-use

- Biophysics
    - Often offsets carbon emissions

(c) Tropical

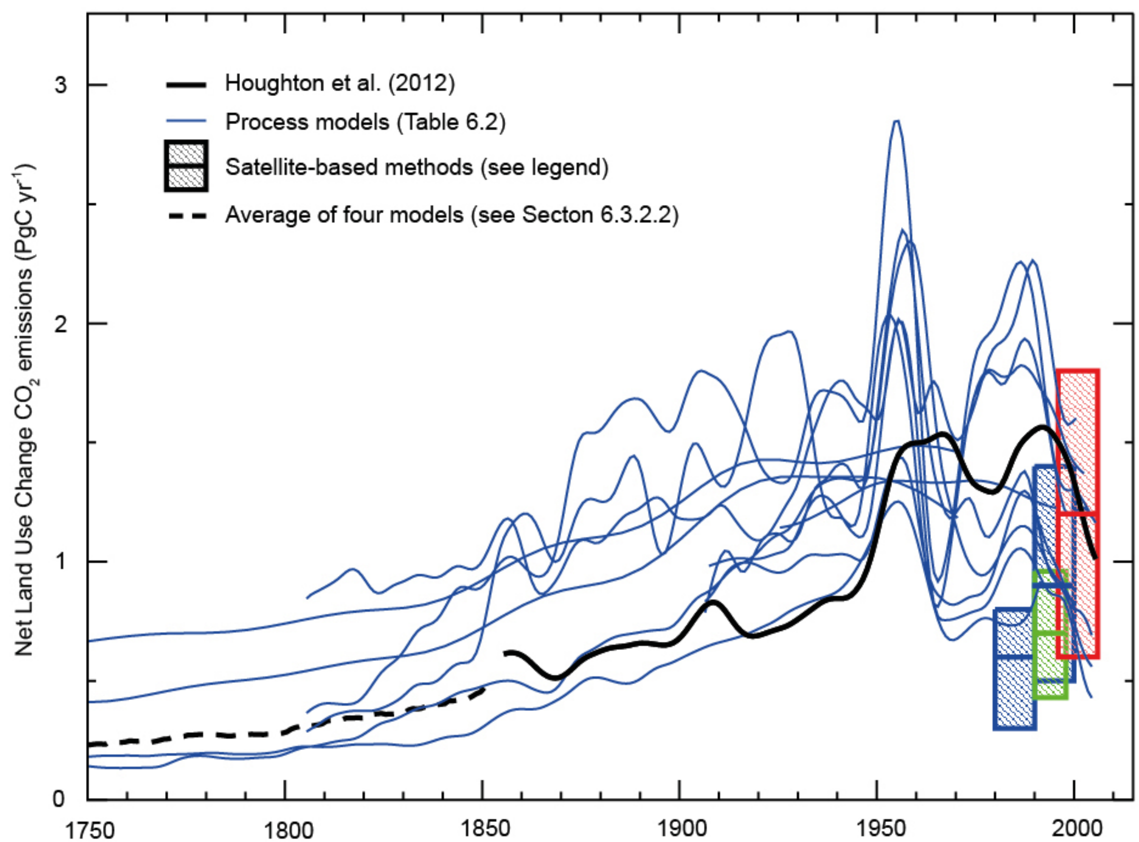
MODELLED						
Shrubland	*Bare land*	0.55	0.62	1.20	−0.40	5[6]
Shrubland	*Cropland*	0.50*	—	—	—	1[5]
Forest	*Cropland*	1.02	0.71	2.00	0.29	5[5,11,12]
Forest	*Grassland*	0.33	0.76	2.50	−0.30	21[2,4,9,13–17]
Forest	*Bare land*	1.06	0.23	1.50	0.80	8[6,18]
Grassland	*Forest*	−0.17	0.12	−0.10	−0.40	6[1,9]
Deforestation		0.60	0.74	2.5	−0.30	34[2,4–6,11–18]
Forestation		−0.17	0.12	−0.10	−0.40	6[1]
OBSERVED						
Deforestation		0.41	0.57	1.06	−0.23	4[7–9]
Forestation		−0.87	—	−0.67	−1.06	2[8,9]

Just beginning to develop observational estimates of biophysical effects

Perugini et al., 2017, ERL

Land-use

- Can models contribute to estimates of land-use emissions?
  - Hindered by large spread (blue lines)
  - Surely must be related to standing biomass
    - (which we saw above was horrible)



IPCC AR5 WG1, fig 6.10

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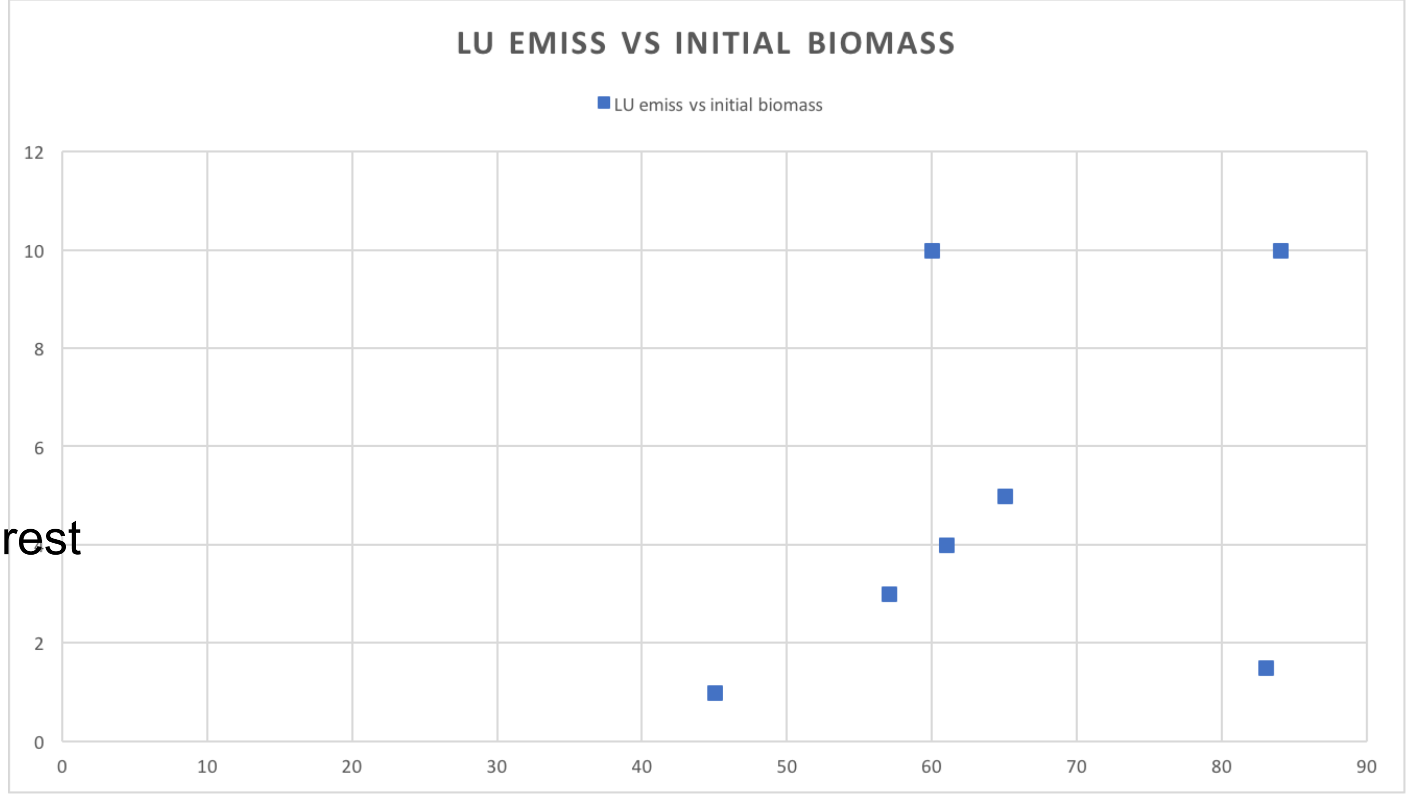

TRENDY Amazon forest land-use emissions depend on initial simulated biomass

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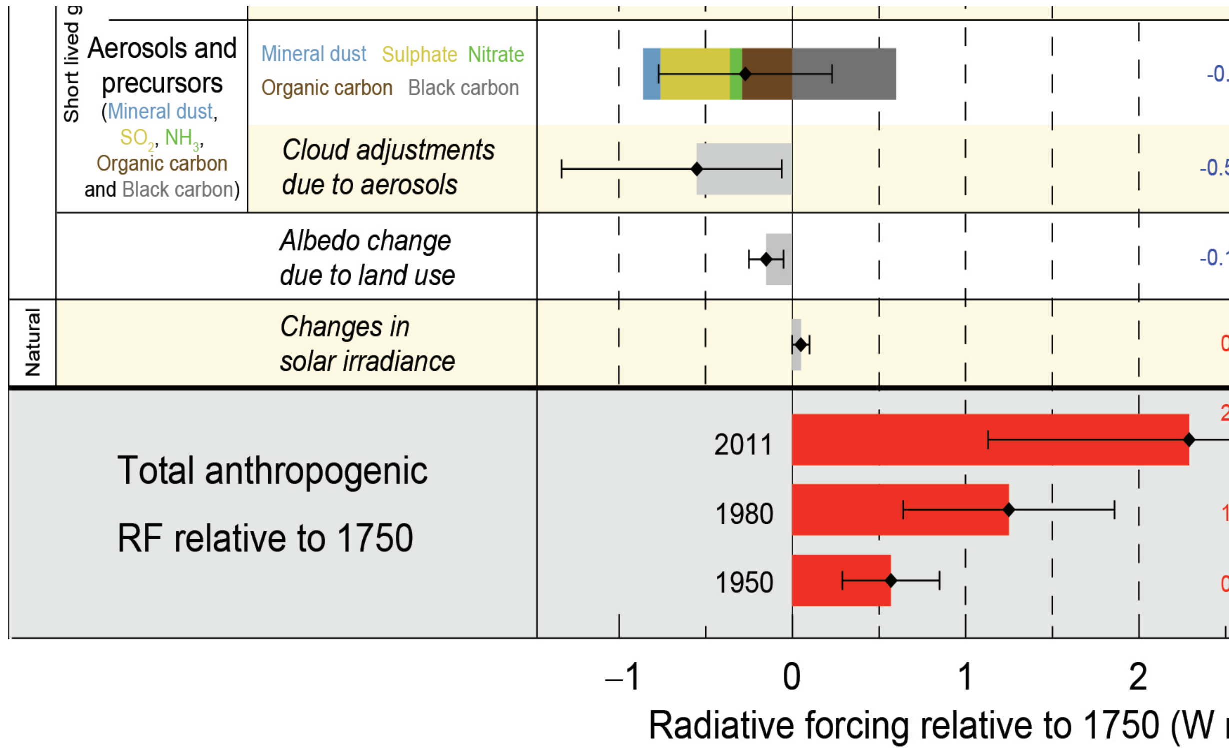
- Aerosols
  - Global forcing
  - Regional impacts

Aerosols

- Global radiative forcing
  - Remains one of biggest uncertainties
  - Reason we can't determine climate sensitivity from 20th-century T record



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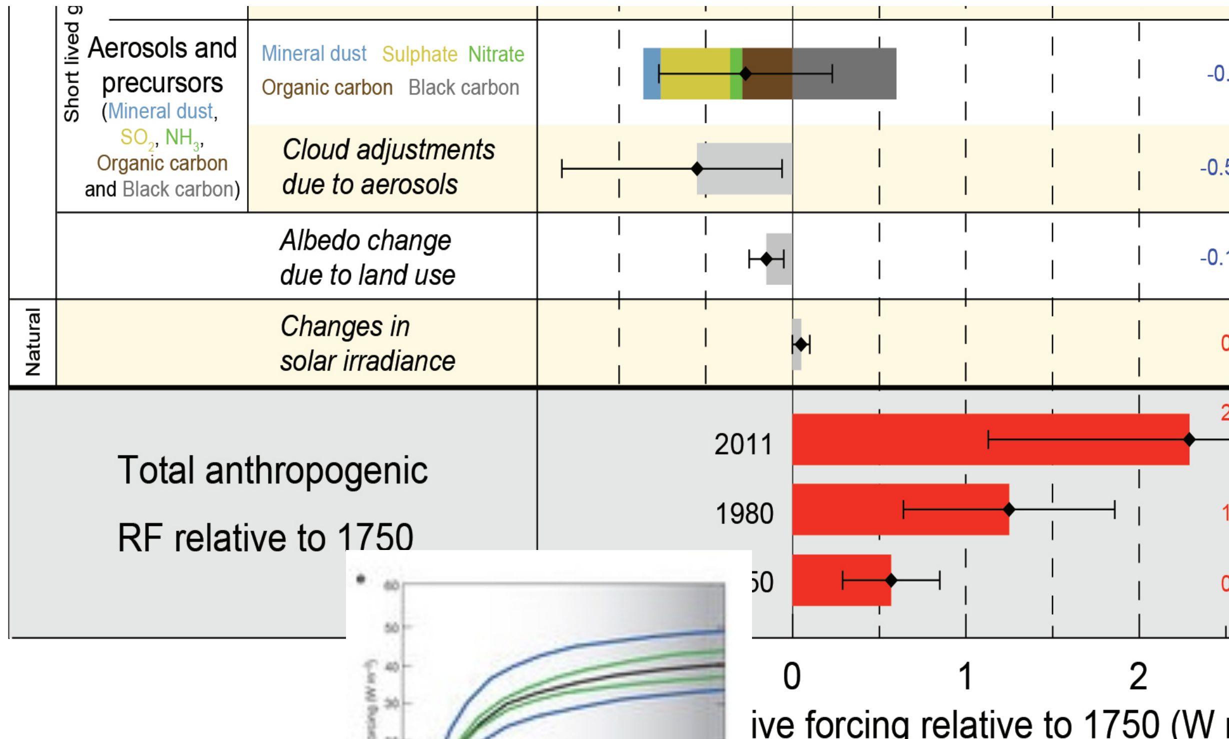
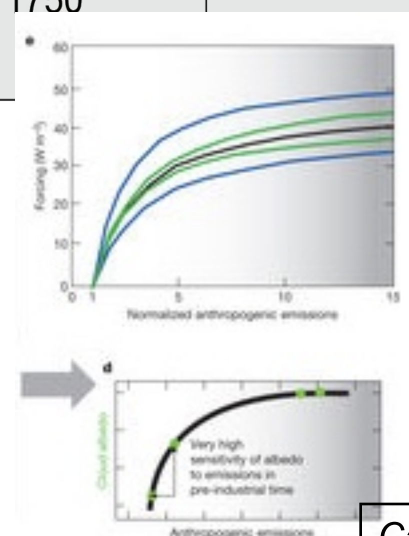
  - Reason we can’t determine climate sensitivity from 20th-century T record

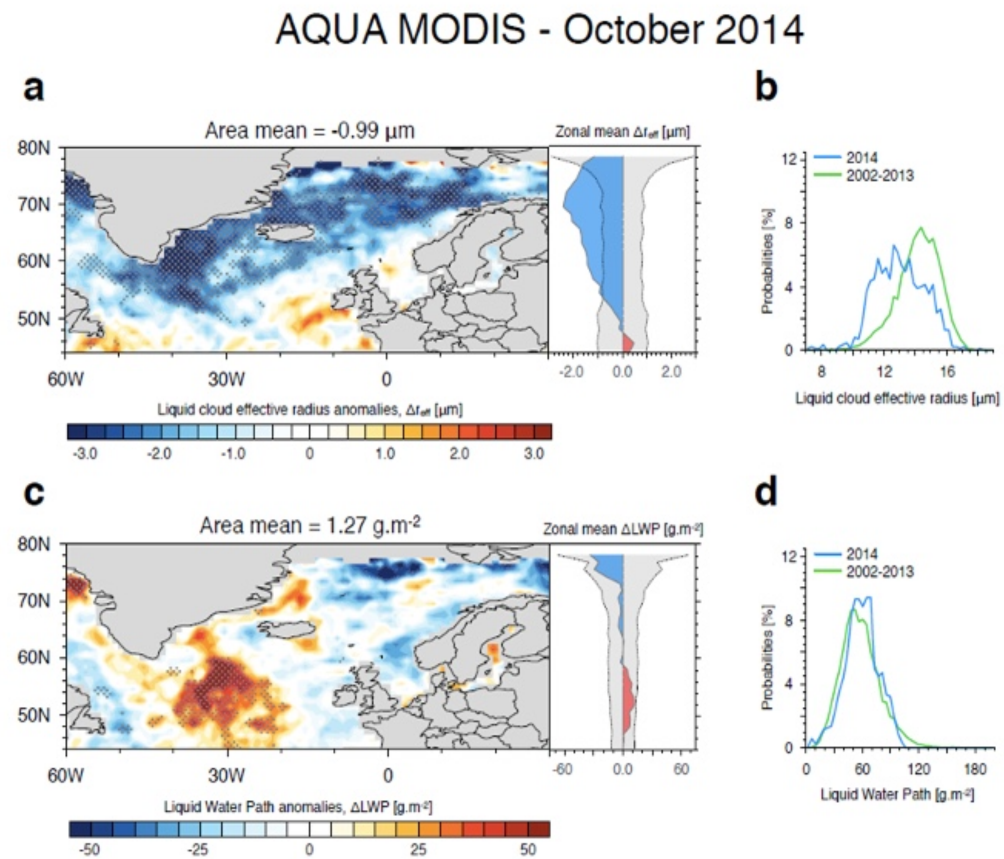




- Aerosol-cloud interaction processes at microphysics scale
- Role of natural aerosols / pristine environments

Carslaw et al., 2013, Nature

Aerosols



- Using volcanic eruption as test case of (tropospheric) aerosol emission
- Can measure response of clouds from remote sensing and evaluate ESM response
- Two Indirect effects –
  - clouds brighter – due to smaller water droplets. This is observed clearly in the observations
  - clouds longer lived – due to slower rain-out of smaller drops. This is NOT observed

Malavelle et al., 2017, Nature

Testable aerosol-cloud evaluation metric

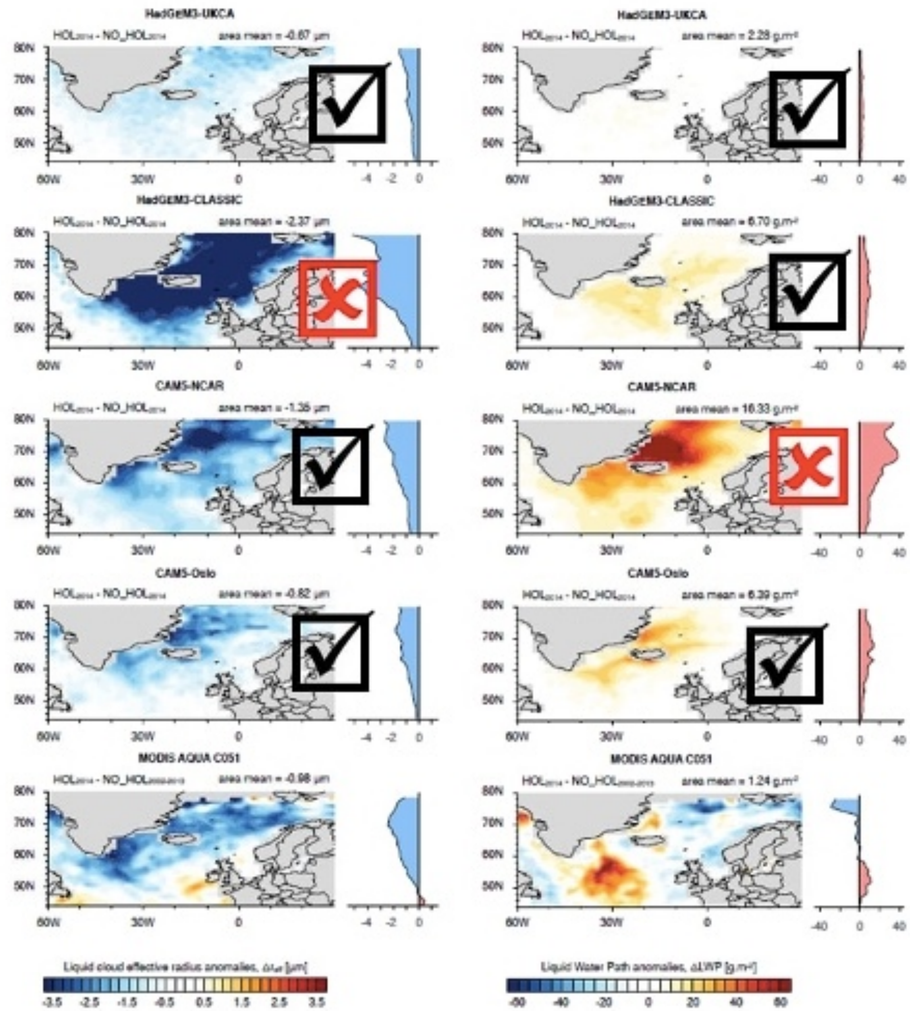
HadGEM3-UKCA:

HadGEM3-CLASSIC

CAM5.4:

CAM5-Oslo:

MODIS:



Malavelle et al., 2017, Nature

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- Chemistry / composition
  - Global forcing
  - AQ and impacts

Tropospheric O_3 Forcing: Climatology & Budget

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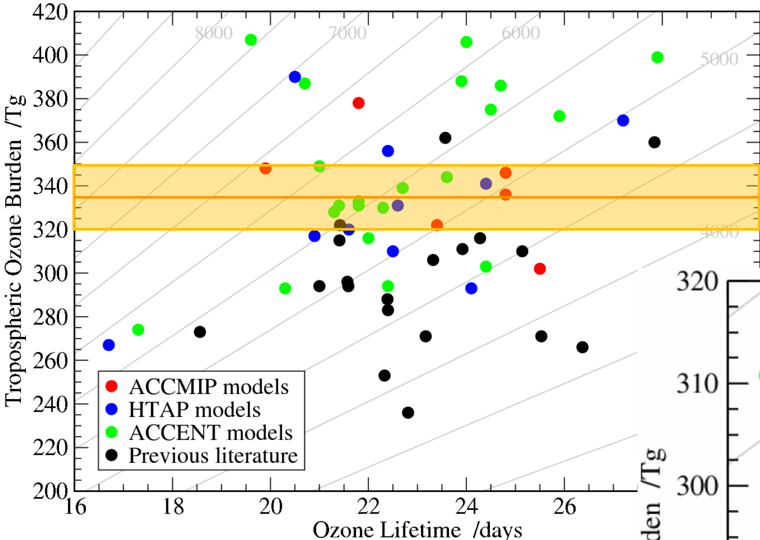


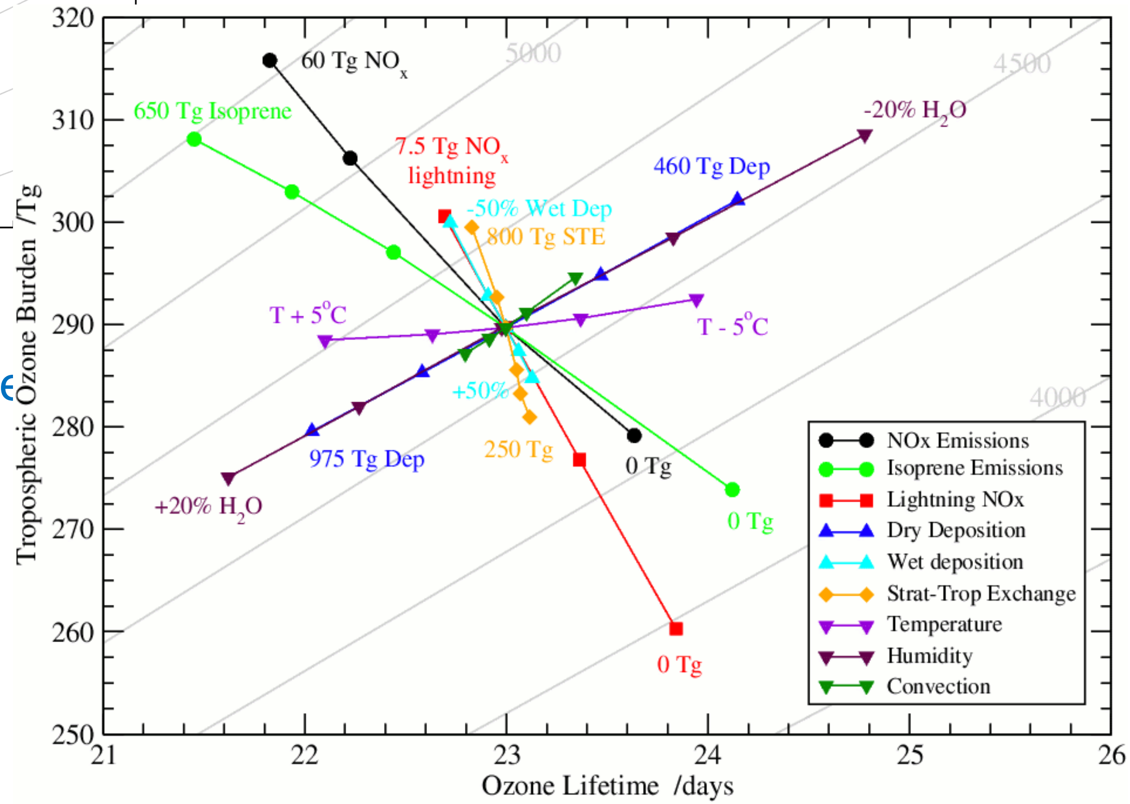
335±15 Tg (Obs.)

22.4 days

Tropospheric O_3 lifetime not well constrained…

Key variables: emissions, humidity & dry deposition

Some fraction of scatter explained

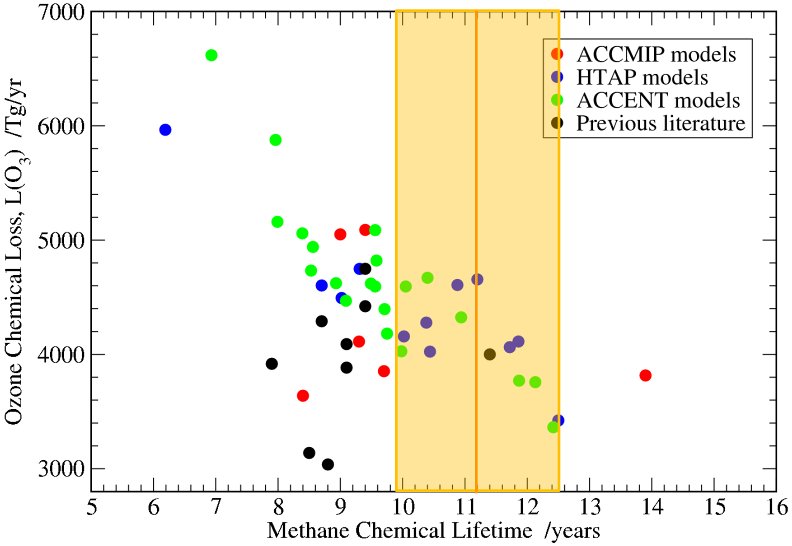


Model studies

ACCENT: 344±39 Tg

HTAP: 328±41 Tg

PD Global CH_4 Lifetime



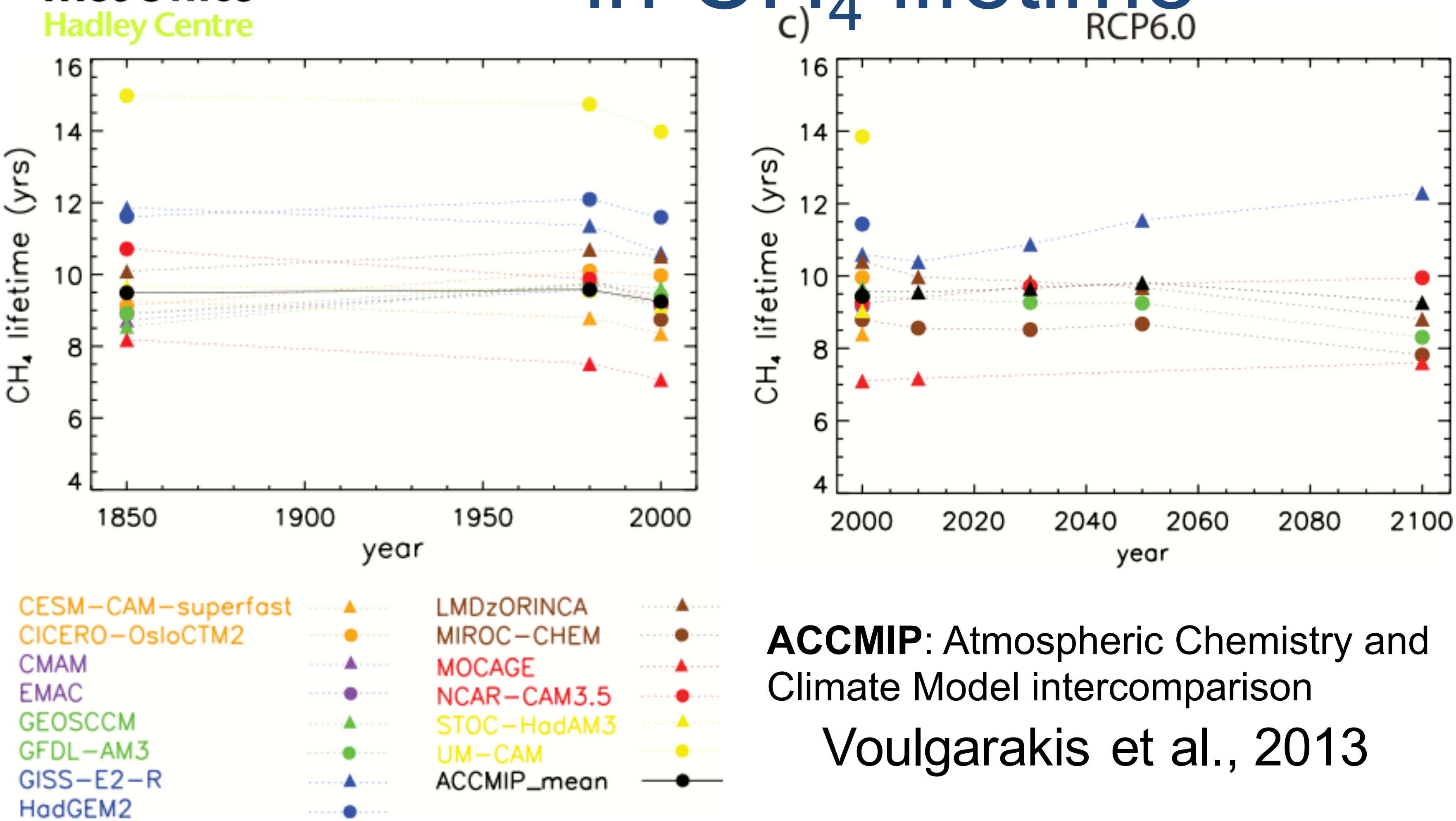
11.2±1.3 yr (Obs)

Major implications for O_3 and CH_4 trends, CH_4 interannual variability, radiative forcing estimates, etc.

CH_4 chemical lifetime:

ACCENT:	9.6 yr	(τ_{CH4} ~8.5 yr)
HTAP:	10.2 yr	(τ_{CH4} ~8.8 yr)
ACCMIP:	9.7 yr	(τ_{CH4} ~8.6 yr)
Obs:	11.2 yr	(τ_{CH4} ~9.1 yr)

Past and Future Changes in CH_4 lifetime



ACCMIP: Atmospheric Chemistry and Climate Model intercomparison

Voulgarakis et al., 2013

- Factor of two differences in CH_4 lifetime
- Differences in sign of modelled changes

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Impact of Climate Change on Composition & AQ

O_3

↑ Temperature
Impacts:
a) increases chemical reaction rates for O_3 production and destruction notably: Less PAN more NO_x locally near emission source
b) b) increases emissions of: biogenic VOCs; wildfires; CH_4 from wetlands; NO_x from lightning and soils

↓ Rainfall
Impacts: Reduced soil moisture and O_3 dry deposition

↑ Water vapour
Impacts: enhanced O_3 destruction in unpolluted areas

↑ Water vapour
Impacts: enhanced O_3 production in polluted regions

↓ Cloud amounts
Impacts: reduced photolysis of NO_2, that leads to O_3 production

↑Ventilation/mixing depth
Impacts: less pollution build-up

↑ Stratospheric tropospheric O_3 exchange
Impacts: high O_3 transported to lower altitudes

↑ Blocking highs/stagnation
Impacts: more pollution build-up

PM

↑ Temperature
Impacts:
a) higher biogenic VOC, wildfire emissions and NO_x emissions from lightning and soils
b) greater oxidation to sulphate aerosol

↑ Temperature
Impacts: increased gas to aerosol partitioning

↑ Water vapour
Impacts: increased oxidation to sulphate and nitrate aerosol

↓ Cloud amounts
Impacts: reduced photolysis of SO_2

↑Ventilation/mixing depth
Impacts: less pollution build-up

↑ Blocking highs/stagnation
Impacts: more pollution build-up

↑ Rainfall
Impacts: increased wet deposition

Summary – BGC systematic errors and/or evaluation priorities

- Land carbon
  - carbon stocks and residence time
  - sensitivity to drivers, variability
    - response to CO_2
  - physical state (of soil)
  - role of nutrient limitations

- Ocean carbon
  - basin scale uptake
  - joint analysis of heat and carbon

Summary – BGC systematic errors and/or evaluation priorities

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- Land-use:
  - biophysical forcing. Latent heat/albedo trade-off
  - importance of simulated biomass
- Aerosols:
  - pre-industrial pristine state
  - aerosol-cloud interactions
- Chemistry:
  - burden and lifetime (changes) of ozone and CH_4
  - processes and feedbacks that determine AQ

Conclusions

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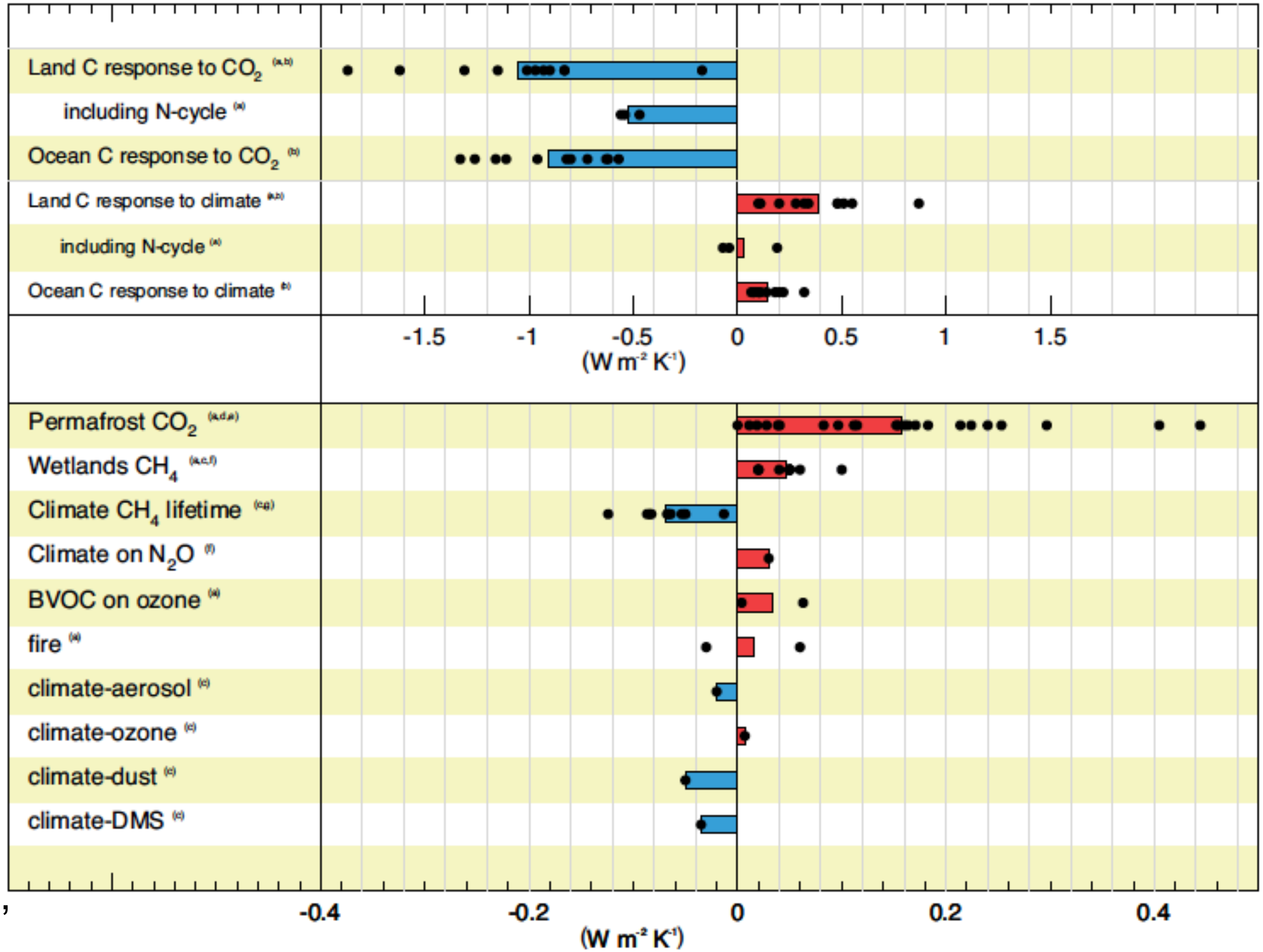
We need an agreed top-level set of metrics for biogeochemistry

at the moment we don't even know if we've made progress or not

Will allow better cost-benefit discussion around justification of added complexity

How to prioritise? Global feedback metrics



IPCC AR5, WG1, fig 6.20