Towards ocean hindcasts in coupled climate models: AMOC variability in a partially coupled model at eddying resolution.

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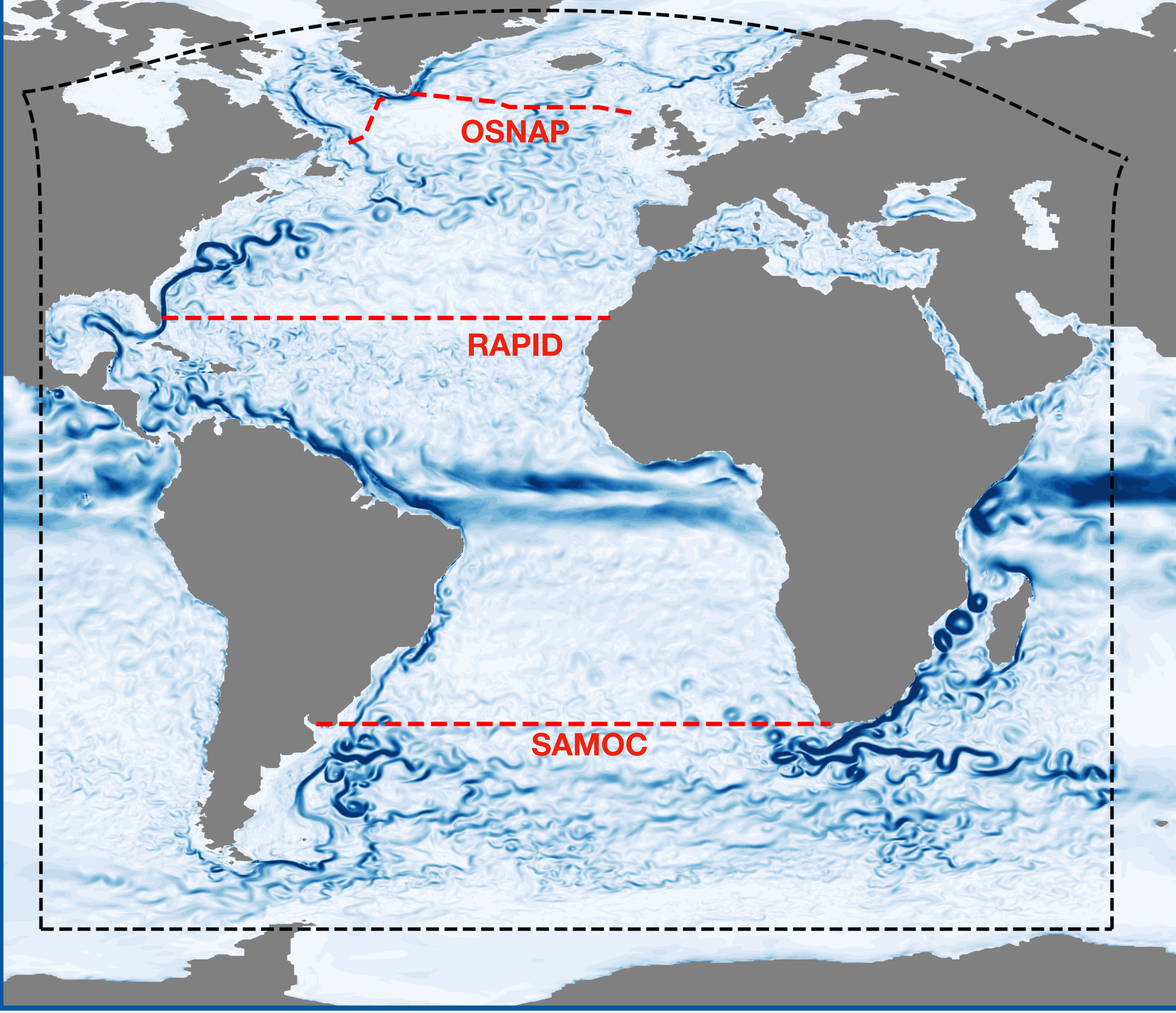
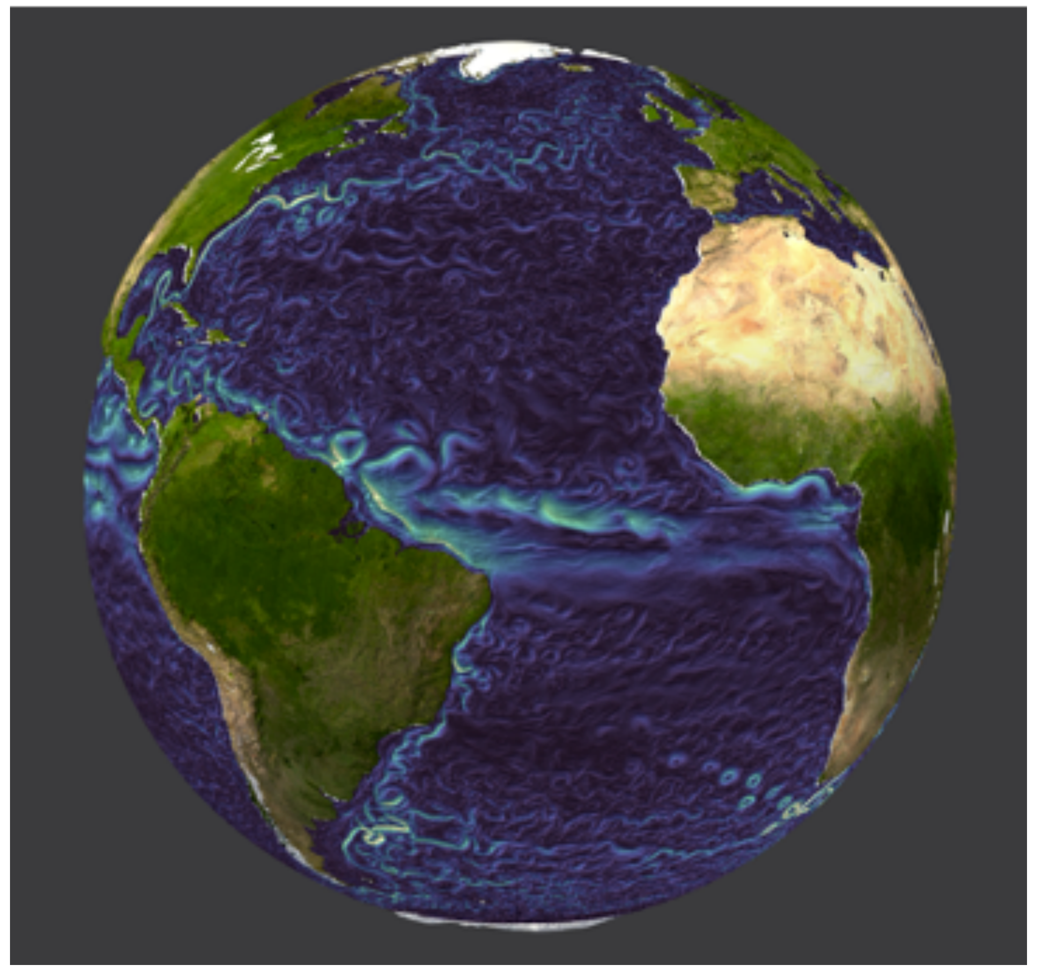
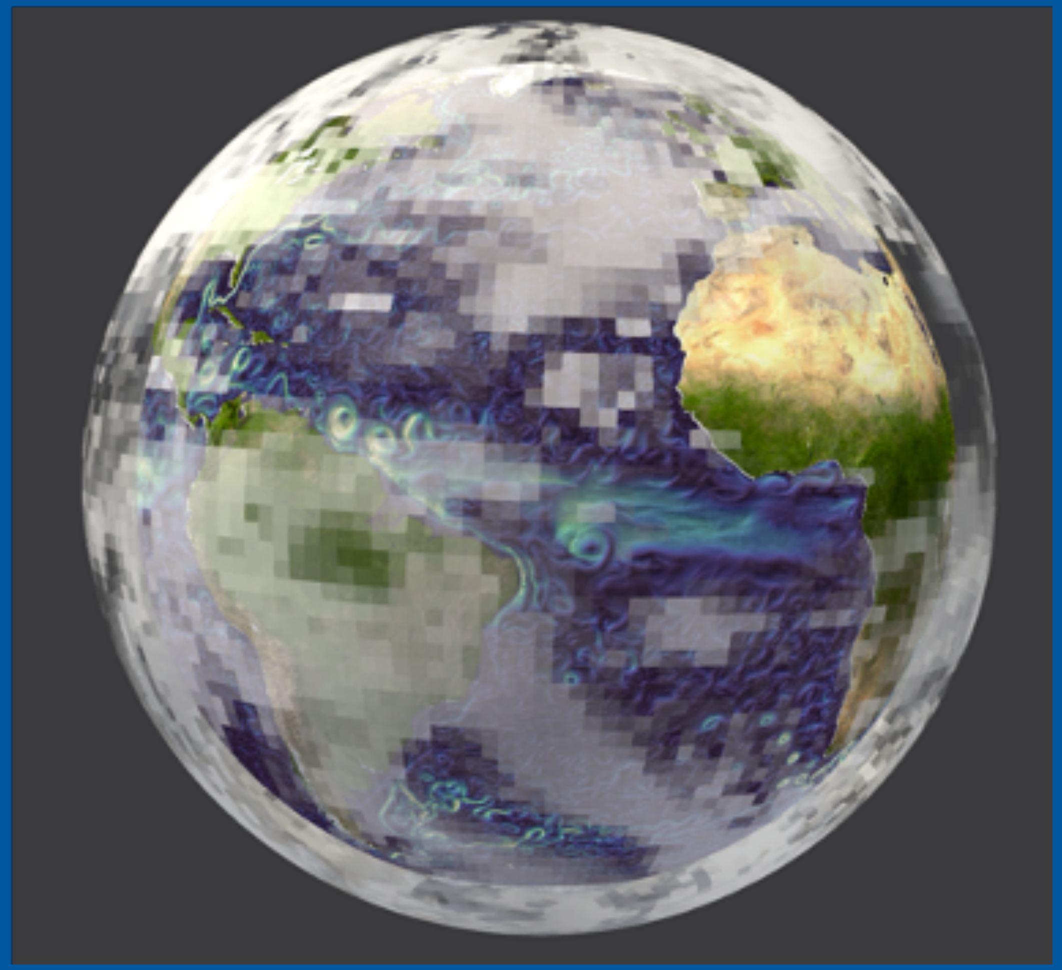


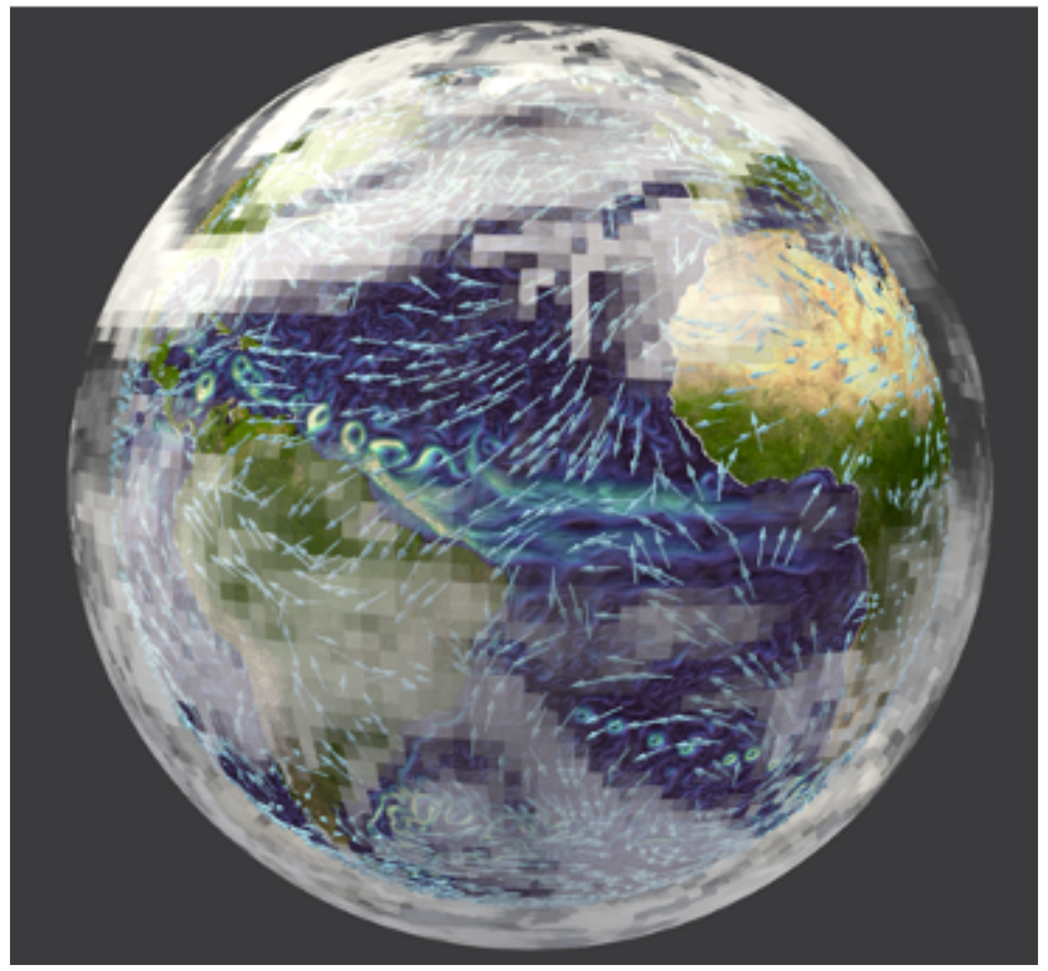
Motivation

- **Ocean-only** simulations of the past climate ("hindcasts")
  - Miss ocean-atmosphere feedbacks
  - Need restoring and budget corrections
    - AMOC sensitive to these choices[1]

- **Coupled** climate models:
  - Simulate feedbacks and have (nearly) closed budgets
  - Lack the correct timing of (AMOC) variability
    - Often ensembles are needed







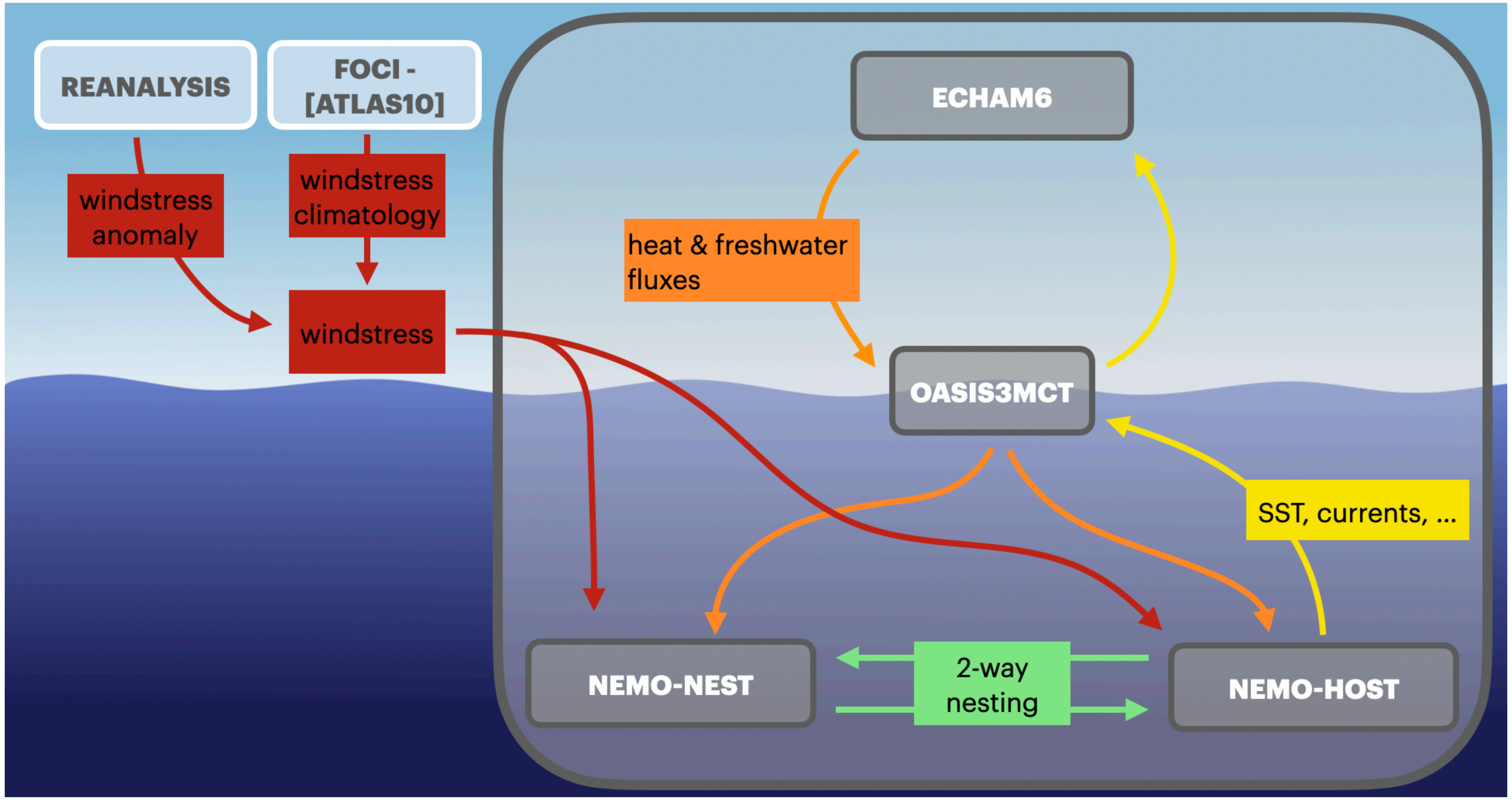
- Is it possible to combine the advantages of the two modelling strategies to improve the AMOC in models?
  - Does a **partially coupled** model reproduce the observed large-scale ocean circulation, including it's timing of variability?
  - On which timescales is AMOC variability caused by wind stress variability

Partial Coupling (PCPL)

- The ocean component of a coupled model is forced with reanalysed wind stress[2,3]
  - anomaly forcing (replaced monthly climatology):

$$\vec{\tau}^{af}(t) = \vec{\tau}^{re}(t) - \vec{\tau}^{re}_{clim} + \vec{\tau}^{FOCI}_{clim}$$

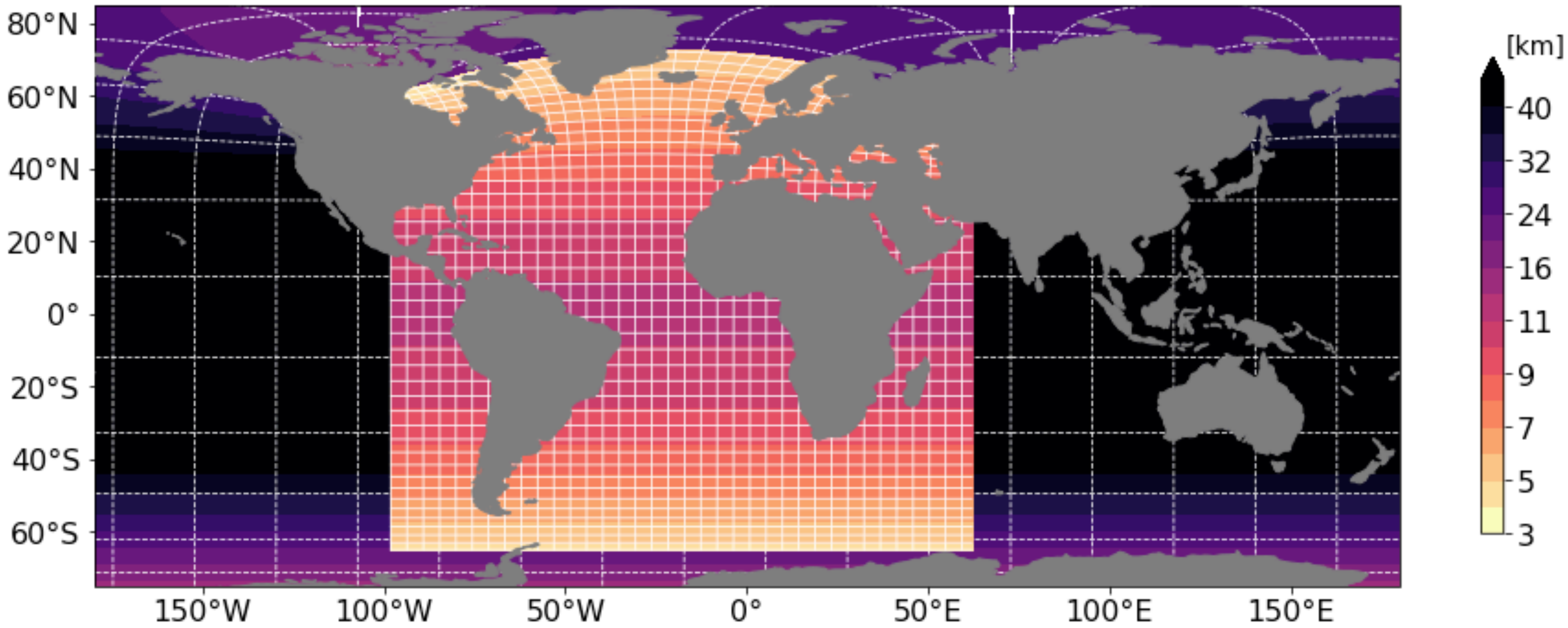
- Surface winds in the atmosphere model (ECHAM6) are not replaced
  - heat & freshwater fluxes are calculated using the ECHAM6 wind
    - not directly affected by PCPL



Schematic diagram of the implementation of partial coupling in the coupled climate model FOCI[4]. The wind stress, that would be provided by ECHAM6 in a fully coupled configuration, is replaced in NEMO with a reanalysis based forcing.

FOCI - ATLAS10: model configuration

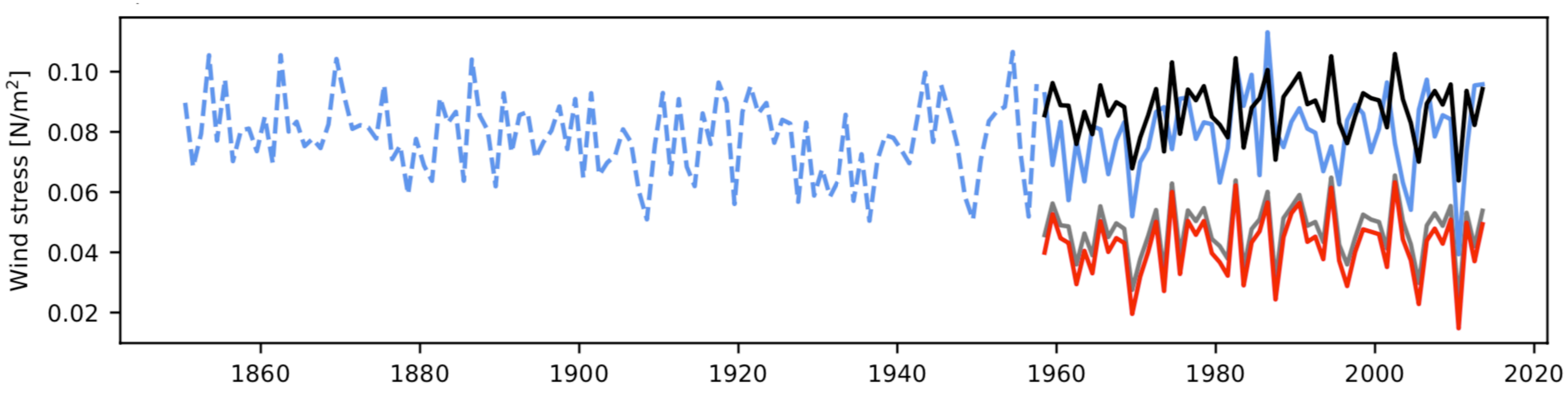
- Flexible Ocean and Climate Infrastructure (FOCI)[4]
  - Atmosphere:
    - ECHAM6: T63 resolution
  - Land model:
    - JSBACH
  - Ocean component - ATLAS10:
    - All-Atlantic nested configuration
    - NEMO v3.6 & LIM2
    - ORCA05 (0.5°) global host grid
    - 1/10° nest grid
      - AGRIF 2-way exchange
    - 46 z-levels
  - Coupler:
    - OASIS3MCT



Ocean component of FOCI-ATLAS10: Shading shows the zonal distance between grid points. Every 45th grid line of the host and nest grids are visualised.

Experiments

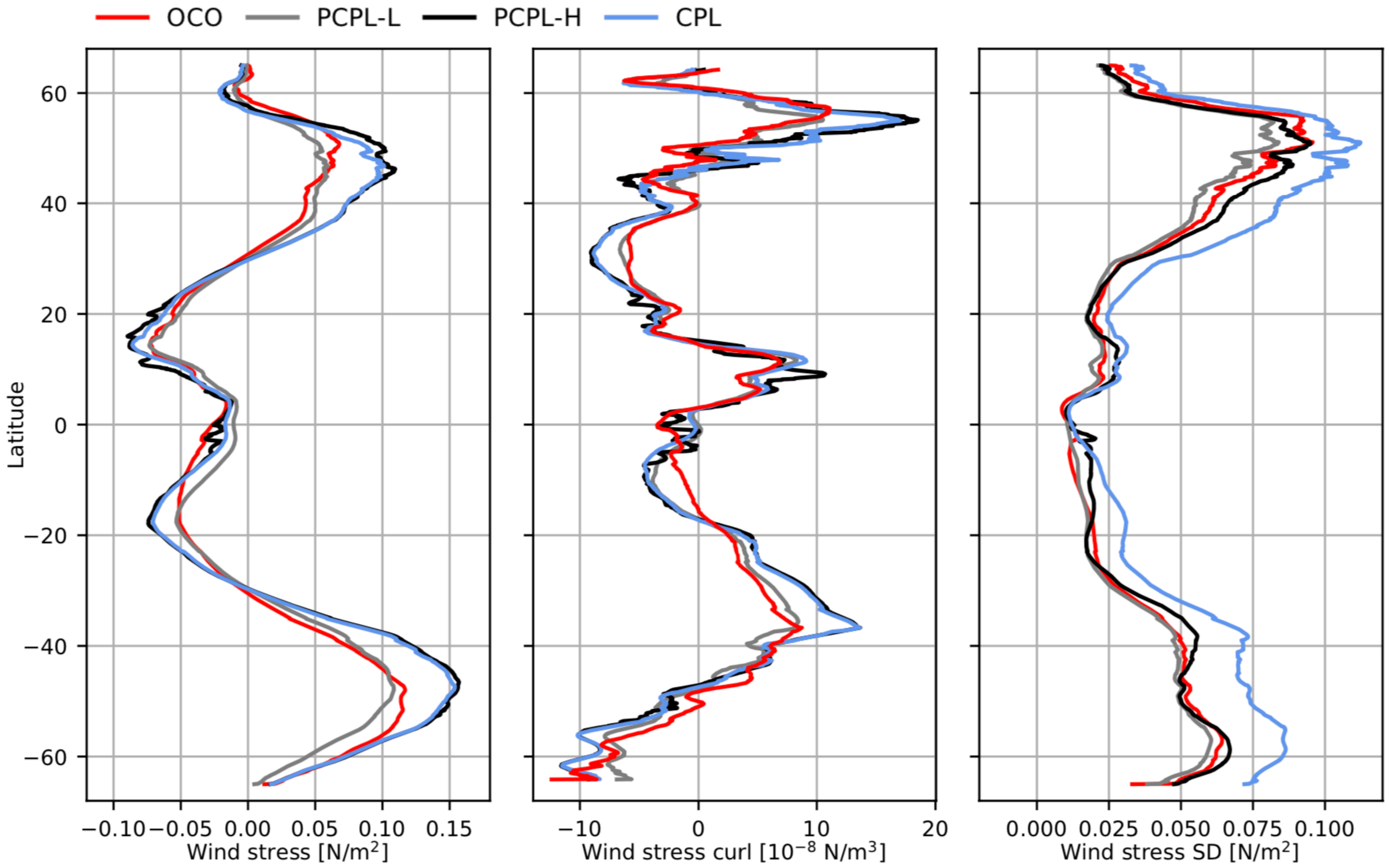
- FOCI-ATLAS10 is run:
  - Fully coupled (**CPL**)
  - Partially coupled:
    - high mean wind stress comparable to CPL (**PCPL-H**)
    - low mean wind stress comparable to OCO (**PCPL-L**)
- For comparison, the ocean-component (ATLAS10) is run un-coupled (**OCO**)



Zonal mean zonal windstress at 47°N

Experiment	Mode	Heat/Freshwater forcing	Wind stress anomalies (climatology)	Initialisation	Years
CPL	Fully coupled	ECHAM6 / JSBACH	ECHAM6 (ECHAM6)	FOCI-piCTRL	1850 - 2013
PCPL-H	Partially coupled	ECHAM6 / JSBACH	JRA55-do (FOCI-Ensemble)	CPL	1958 - 2013
PCPL-L	Partially coupled	ECHAM6 / JSBACH	JRA55-do (CPL)	CPL	1958 - 2013
OCO	Ocean-only	JRA55-do (v1.5)	JRA55-do (JRA55-do)	WOA13 / rest	1958 - 2013

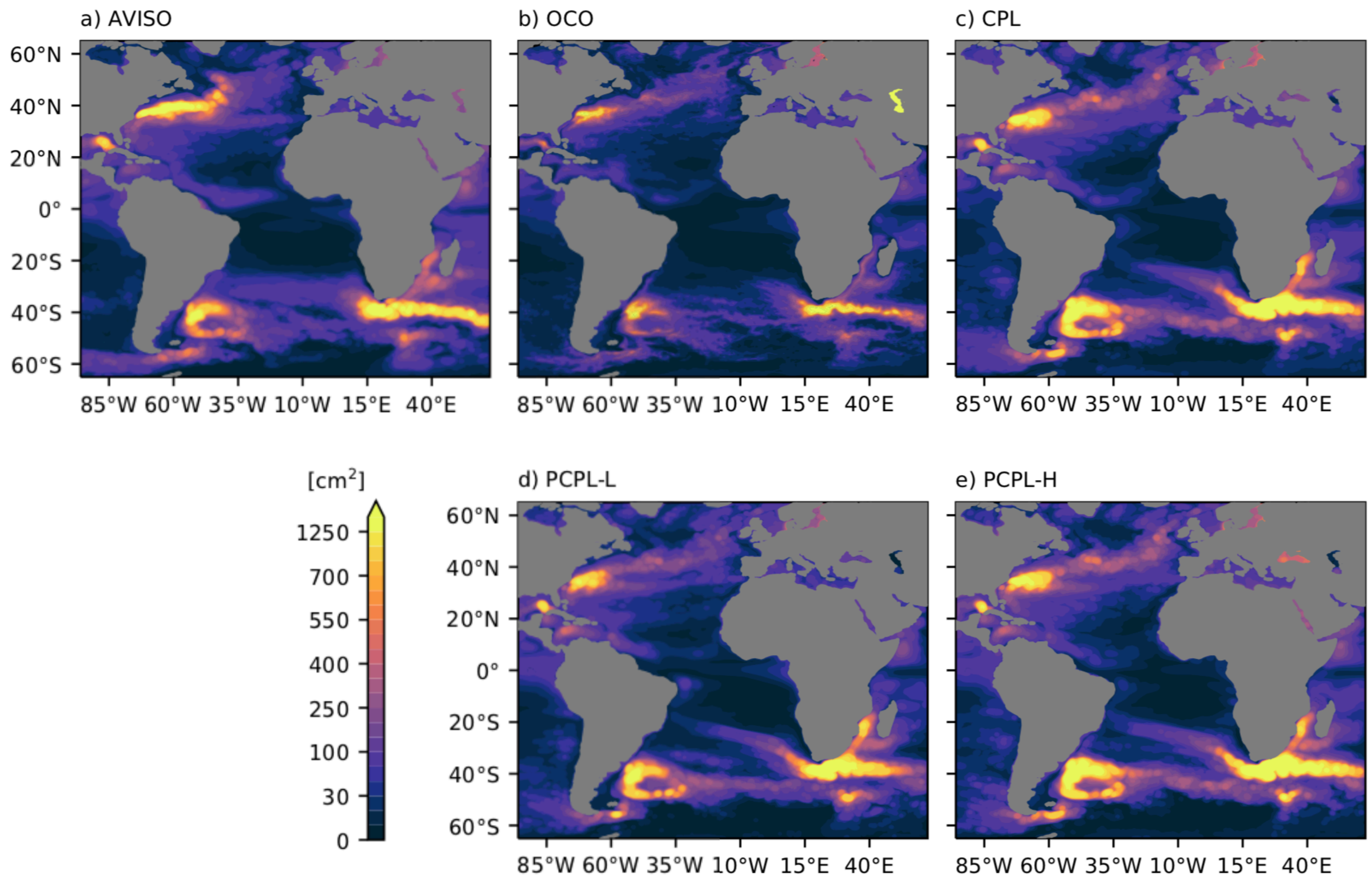
Wind Stress Forcing



Atlantic (including Southern Ocean - Atlantic sector) zonal mean zonal wind stress, wind stress curl and wind stress standard deviation (1970-2013).

- Meridional structure (position of minima/ maxima) is the same in CPL & PCPL-H/L by construction
- PCPL-L mean wind stress (magnitude) similar to OCO
- PCPL-H mean wind stress (magnitude) similar to CPL
- Mean wind stress curl stronger in PCPL-H / CPL than in PCPL-L / OCO
- Wind stress variability is similar in PCPL & OCO, but lower than in CPL
  - due to higher mean wind stress & simulation of feedbacks involving a transfer of momentum in CPL

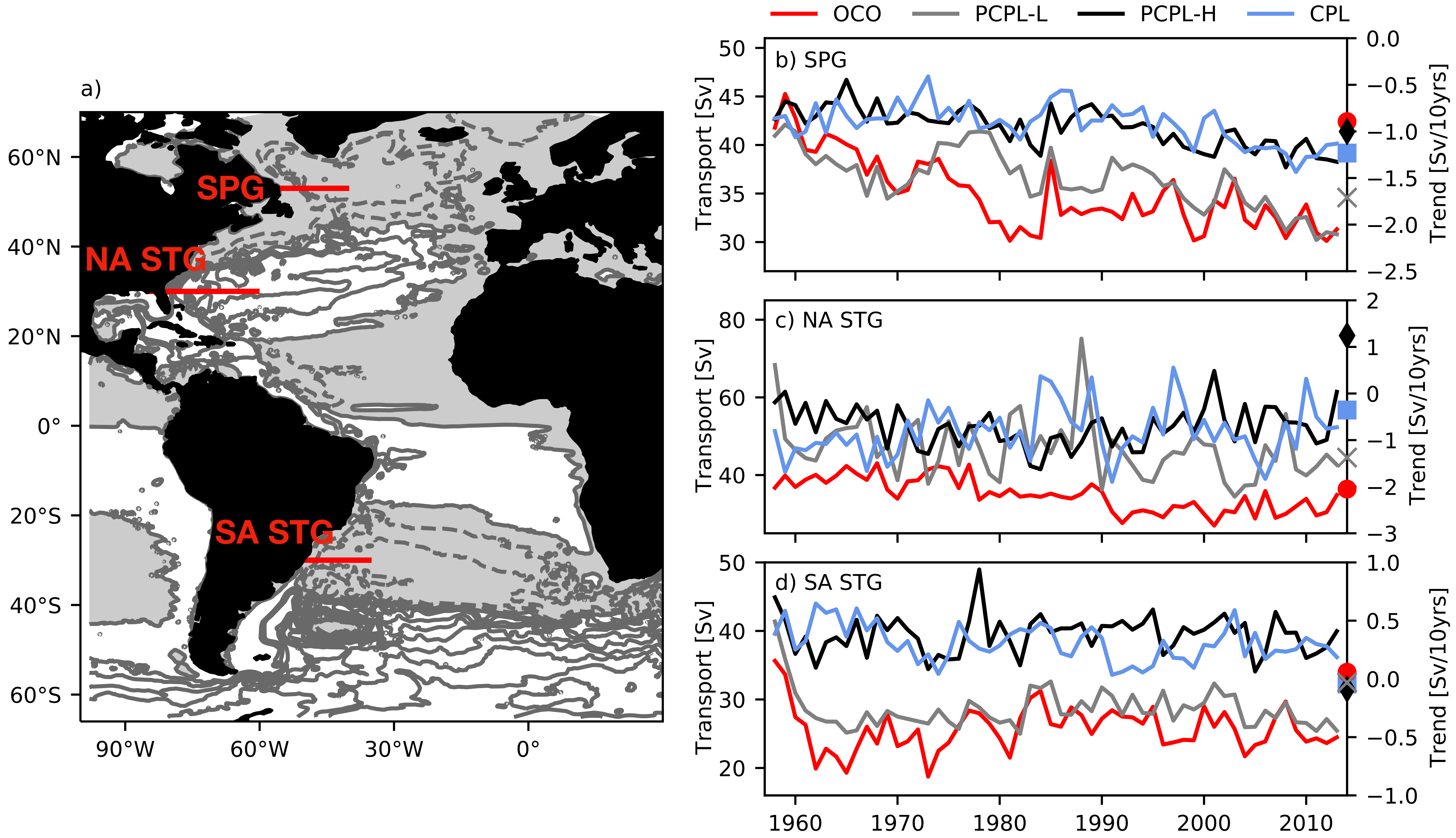
SSH Variance



SSH variance from satellite observations (AVISO)[5] and the ATLAS10 nest grid (1993-2013).

- Resolving mesoscale eddies in large areas of the Atlantic is a main motivation to run the nested configuration
- Overall realistic variance pattern in FOCI-ATLAS10 with two exceptions:
  - Agulhas Ring path too regular
    - coarse atmospheric resolution
    - more realistic in OCO
  - Northwest Corner not well established
    - no-slip boundary conditions on nest grid
- SSH variance in PCPL mode is depended on the mean wind stress (higher in PCPL-H than in PCPL-L)

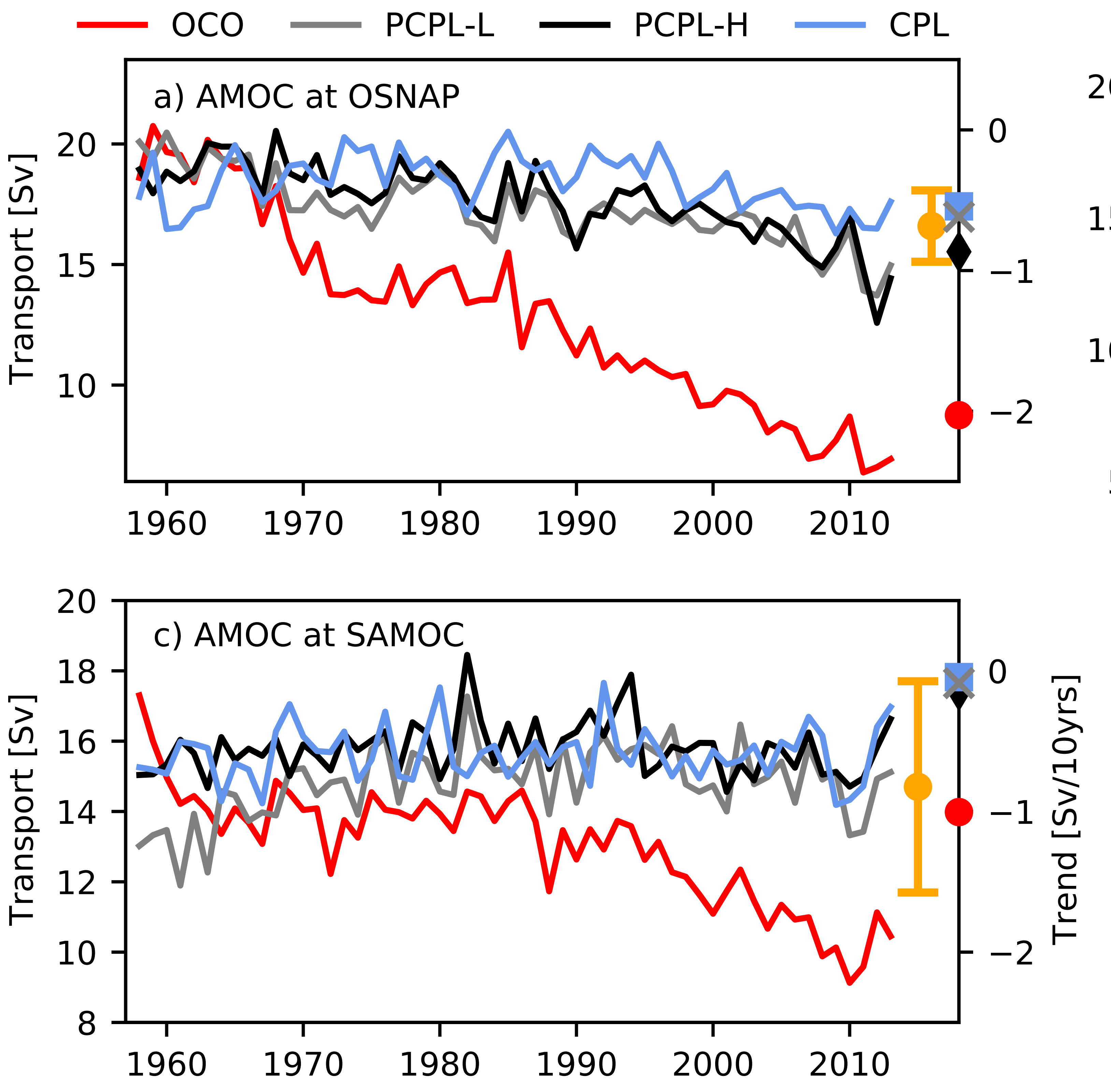
Horizontal Circulation: Gyre Transports



Barotropic streamfunction (1970-2013) in CPL (a). Sections used to calculate the gyre strengths are shown red. b) Subpolar gyre, c) North Atlantic subtropical gyre and d) South Atlantic subtropical gyre transport. Linear trends (1970-2013) are marked on the right y-axis.

- General structure of the horizontal circulation in agreement with other high-resolution models[6,7]
- Mean gyre transport mostly determined by mean wind stress curl
  - higher in PCPL-H/CPL than in PCPL-L/OCO
  - NA STG estimate strongly influenced by mesoscale activity
- Multidecadal trends in the subpolar gyre transport possibly linked to the AMOC (see following slides) and historic atmospheric boundary conditions

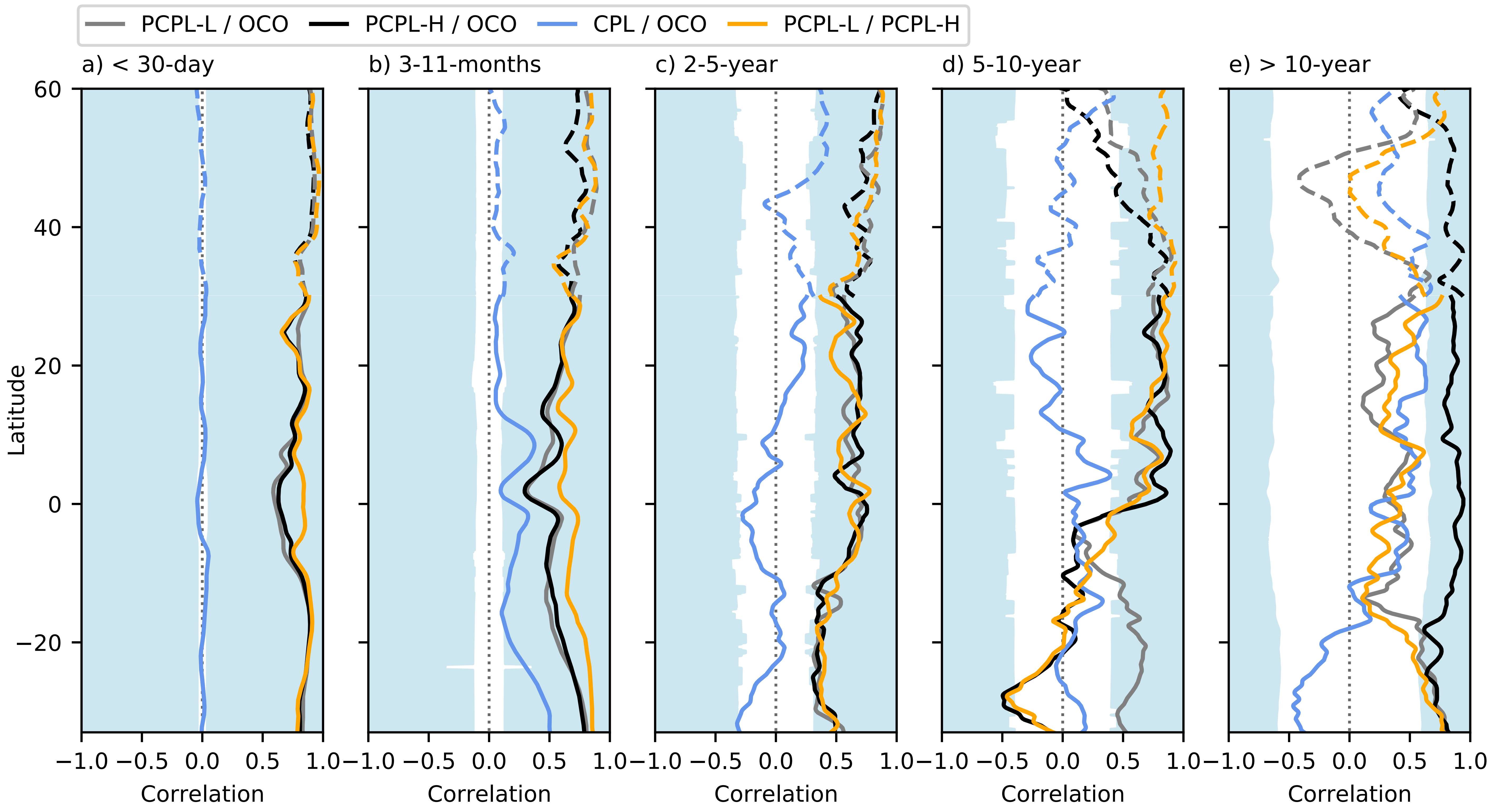
Overturning Circulation: Mean & Trends



AMOC transport across the OSNAP (a), RAPID (26.5°N; b) and SAMOC (34.5°S; c) sections. Observational estimates[8,9,10] are shown in orange (mean and interannual standard deviation).

- Strong negative trend in OCO at all latitudes as a result of insufficient tuning
  - a stable AMOC in OCO would be possible, but requires a subjective adjustment (e.g. of the restoring strength)
- Realistic mean transports in CPL, PCPL-L & PCPL-H
  - less sensitive to the mean wind stress compared to the gyre transports
- Stable AMOC in CPL and PCPL-L/H
  - significant negative trend at the OSNAP section in PCPL and CPL likely caused by atmospheric boundary conditions
  - necessary ocean-atmosphere feedbacks maintained in PCPL mode

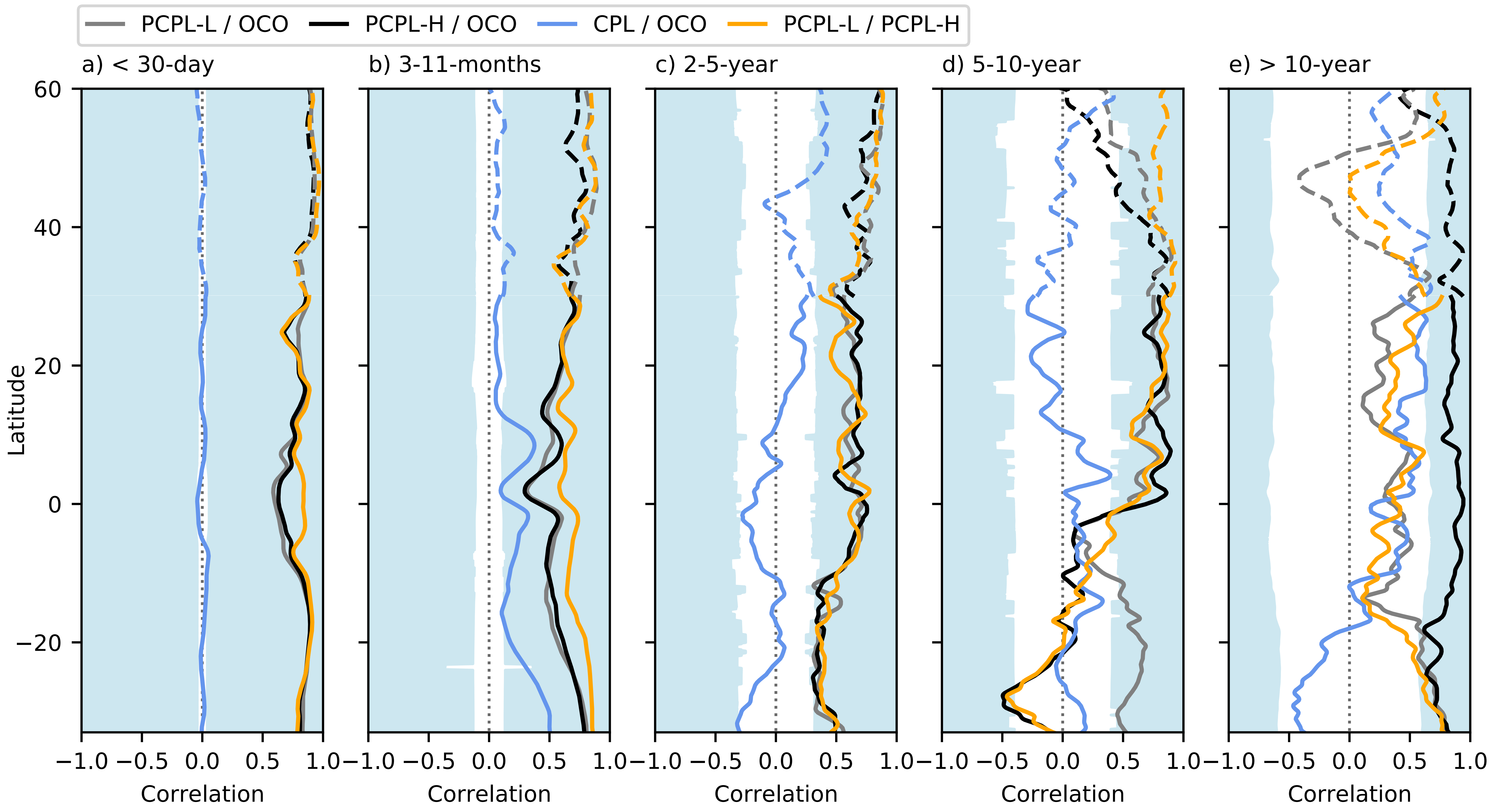
Overturning Circulation: Timing of Variability



AMOC correlation on different timescales:
a) 30-day highpass, b) 3-11 month bandpass, c) 2-5 year bandpass,
d) 5-10-year bandpass and e) 10-year lowpass filtered.
Significant correlations (95% confidence) are shaded blue. South of 30°N the AMOC is calculated in depth space (solid), density coordinates are used further north (dashed).

- OCO is used as the reference
  - despite the strong negative trend, AMOC variability on subdecadal timescales is highly correlated with other ocean-only models
- High and significant correlation (PCPL / OCO) on timescales shorter than 5 years
  - consistent with known processes causing AMOC variability
  - meridional structure (2-5-year) agrees with an increasing fraction of intrinsic variability in the South Atlantic[11]
  - As expected, CPL and OCO are mostly uncorrelated
    - 3-11 months correlation in the SA caused by an in-phase semi-annual cycle

Overturning Circulation: Timing of Variability



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- **5-10 years:**
  - different water mass properties in the North Atlantic cause the PCPL \ OCO correlation to become insignificant
  - wind-driven deep mixing in the Southern Ocean with stronger mean wind stress causes anti-correlation south of 20°S (PCPL-H)
- **> 10 years:**
- significant correlation between PCPL-H and OCO could hint on a wind-driven component of decadal AMOC variability
- more experiments are needed to validate this hypothesis:
  - short timeseries compared to the filters cutoff period
  - only one ensemble member
  - weak decadal variability in OCO

Summary & Conclusion

- Is it possible to combine the advantages of forced and coupled modelling strategies to improve the AMOC in models?
  - Does a **partially coupled** model reproduce the observed large-scale ocean circulation, including it's timing of variability?
  - On which timescales is AMOC variability caused by wind stress variability
    - The gyre strengths strongly depend on the applied mean wind stress
    - The AMOC is stable in the fully coupled and partially coupled experiments without artificial restoring, or budget corrections
      - important ocean-atmosphere feedbacks are simulated in PCPL mode
    - Sub-monthly to pentadal AMOC variability is dominated by wind forcing
      - the timing of variability is improved in PCPL mode for timescales shorter than 5 years at all latitudes
      - on longer timescales processes other than wind forcing (e.g. buoyancy forcing & density stratification) become increasingly important
    - Partial coupling is successful in simulating a stable AMOC with the correct timing of variability even on interannual timescales, but its applicability on decadal timescales seems to be limited

References

[1] Biastoch et al. (2021): Regional imprints of changes in the Atlantic Meridional Overturning Circulation in the eddy-rich ocean model VIKING20X. Ocean Sci., 17(5), 1177–1211. doi: 10.5194/os-17-1177-2021

[2] Ding et al. (2013): Hindcast of the 1976/77 and 1998/99 Climate Shifts in the Pacific. J. Climate, 26(19), 7650–7661. doi: 10.1175/JCLI-D-12-00626.1

[3] Thoma et al. (2015): Partially coupled spin-up of the MPI-ESM: implementation and first results. Geosci. Model Dev., 8(1), 51–68. doi: 10.5194/gmd-8-51-2015

[4] Matthes et al. (2020):The Flexible Ocean and Climate Infrastructure Version 1 (FOCI1): Mean State and Variability. Geosci. Model Dev. Discuss., 2020, 1–53. doi: 10.5194/gmd-2019-306

[5] The Ssalto/Duacs altimeter products were produced and distributed by the Copernicus Marine and Environment Monitoring Service (CMEMS), http://www.marine.copernicus.eu

[6] Hirschi et al. (2020): The Atlantic Meridional Overturning Circulation in High-Resolution Models. Journal of Geophysical Research: Oceans, 125(4), e2019JC015522. doi: 10.1029/2019JC015522

[7] Schwarzkopf et al. (2019): The INALT family – a set of high- resolution nests for the Agulhas Current system within global NEMO ocean/sea-ice configurations. Geosci. Model Dev., 12(7), 3329–3355. doi: 10.5194/gmd-12-3329-2019

[8] Lozier et al. (2019):

[9] McCarthy et al. (2015): Measuring the Atlantic Meridional Overturn- ing Circulation at 26°N. Progress in Oceanography, 130, 91–111. doi: 10.1016/j.pocean.2014.10.006

[10] Meinen et al. (2018): Meridional Overturning Circulation Transport Variability at 34.5°S During 2009–2017: Baroclinic and Barotropic Flows and the Dueling Influence of the Boundaries. Geophysical Research Letters, 45(9), 4180–4188. doi: 10.1029/2018GL077408

[11] Grégorio et al. (2015): Intrinsic Variability of the Atlantic Meridional Overturning Circulation at Interannual-to-Multidecadal Time Scales. Journal of Physical Oceanography, 45(7), 1929–1946. doi: 10.1175/JPO-D-14-0163.1