Impact of sub-seasonal atmosphere-ocean interactions in a large ensemble

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- Sea surface temperature (SST) emerges from air-sea interaction

$$\rho\, C_P h\, \frac{\partial T_s}{\partial t} = Q_s + Q_F$$

Net surface heat flux

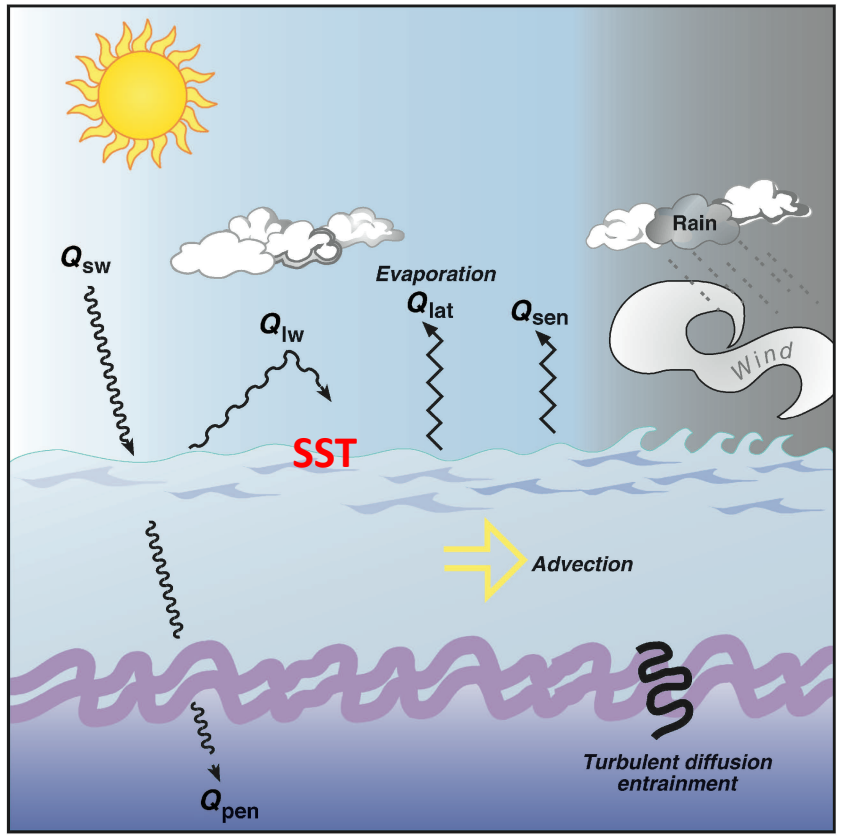
Net ocean heat flux

Surface layer thickness

→ Fluxes set SST

- Many attribution studies use atmospheric models with prescribed SST

→ SST sets fluxes



Cronin & Sprintall, 2001

- What is the impact of the feedback of air-sea heat fluxes on sea surface temperature?

Otto, 2017; Schaller et al., 2016; Mitchell et al., 2017; Christidis and Stott, 2014; Frankignoul et al., 2004; Park et al, 2005; Bishop et al., 2017; Patrizio and Thompson, 2022

Key result:

The feedback of surface fluxes on sea surface temperature

strongly **decreases the spread** of seasonal means

and

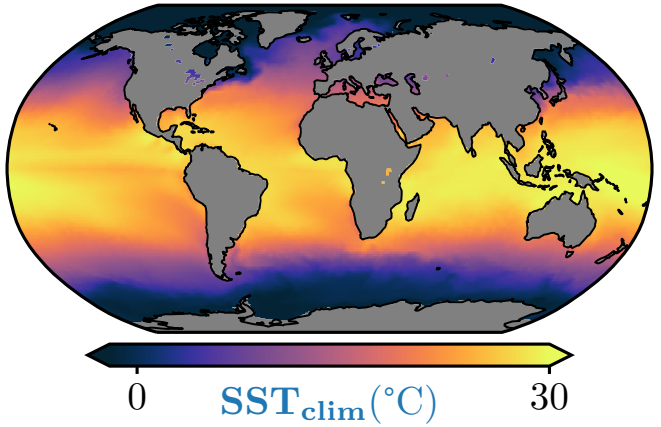
significantly **improves the realism** of air-sea interactions,

but

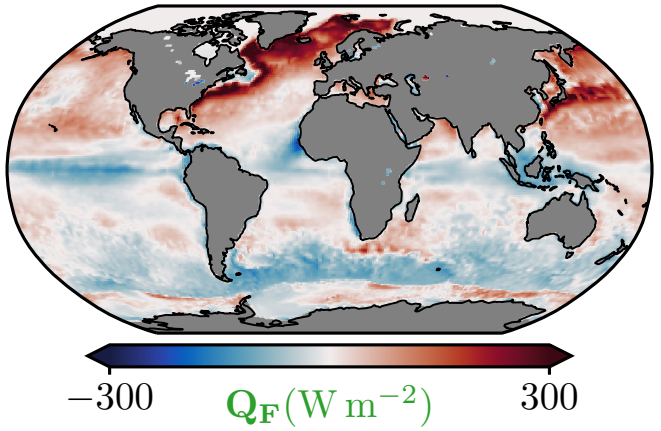
has only **limited consequences**
for **extratropical land** climate

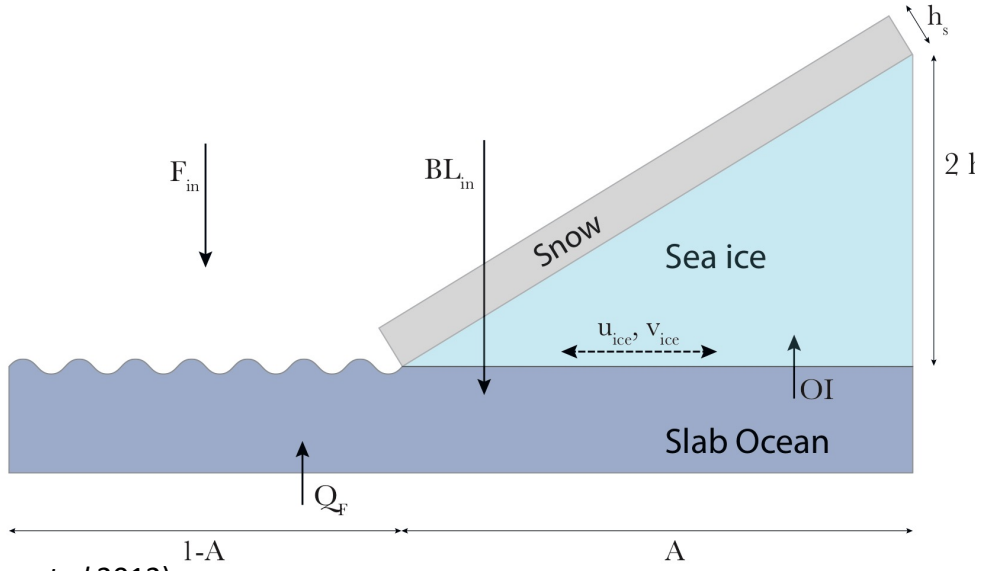
Modeling framework: HadSM4

- N144 atmosphere + Slab Ocean
  a) → more realistic air-sea interactions
  b) → imposing circulation anomalies
- Q_F is calibrated from observed SST[1]
- 30-year calibration run
- HadAM4 → HadSM4



$$Q_F(x,y,t) = (SST_{clim}(x,y,t) - SST(x,y,t)\frac{\rho C_P h}{\Delta t}$$

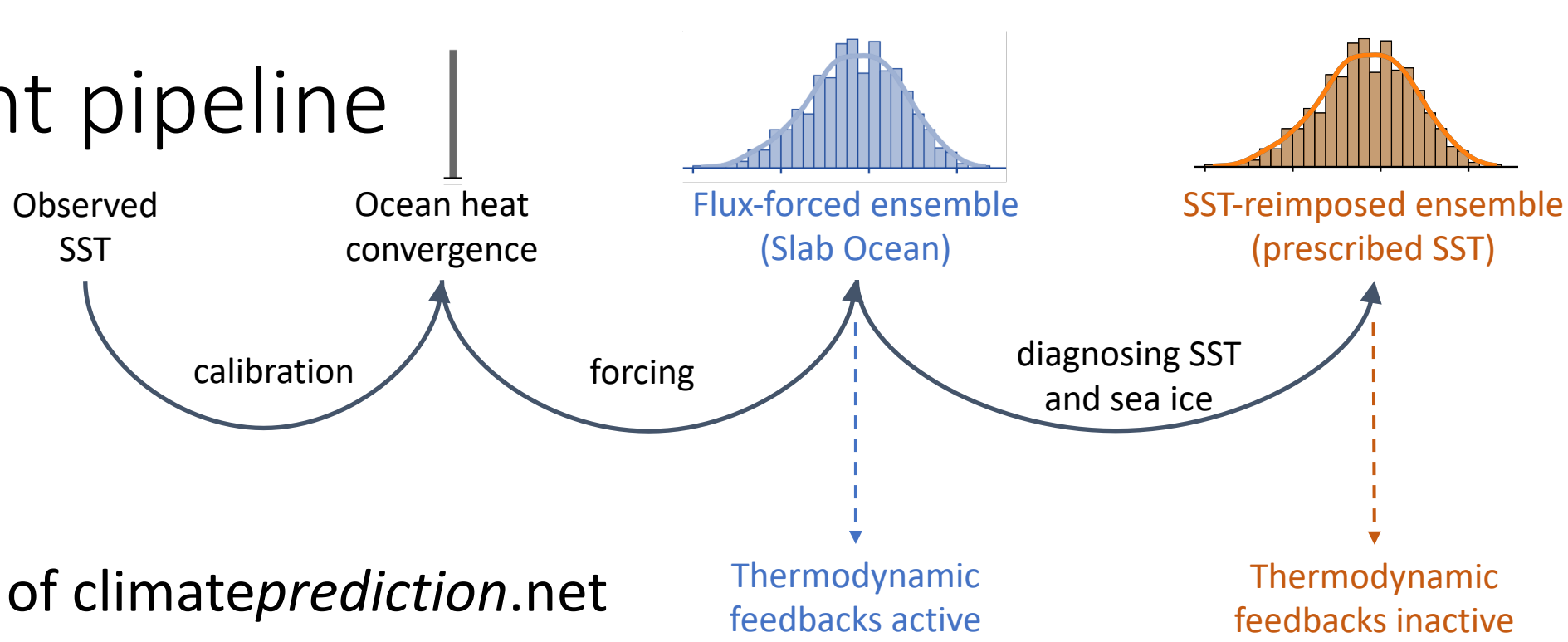




Bevacqua et al., 2021
Watson et al., 2020
Williams et al., 2003
Webb et al., 2001
Hewitt and Mitchell., 1997

[1]Operational Sea Surface Temperature and Sea Ice Analysis (Donlon *et al* 2012)

Experiment pipeline



- Infrastructure of climate*prediction*.net
- Two 578-member ensembles *with* and *without* active thermodynamic feedbacks
- SST, sea ice: 578 unique, identical trajectories
- → clear identification of impact of presence/absence of feedback

Guillod et al., 2017; Massey et al., 2015; Mitchell et al., 2017

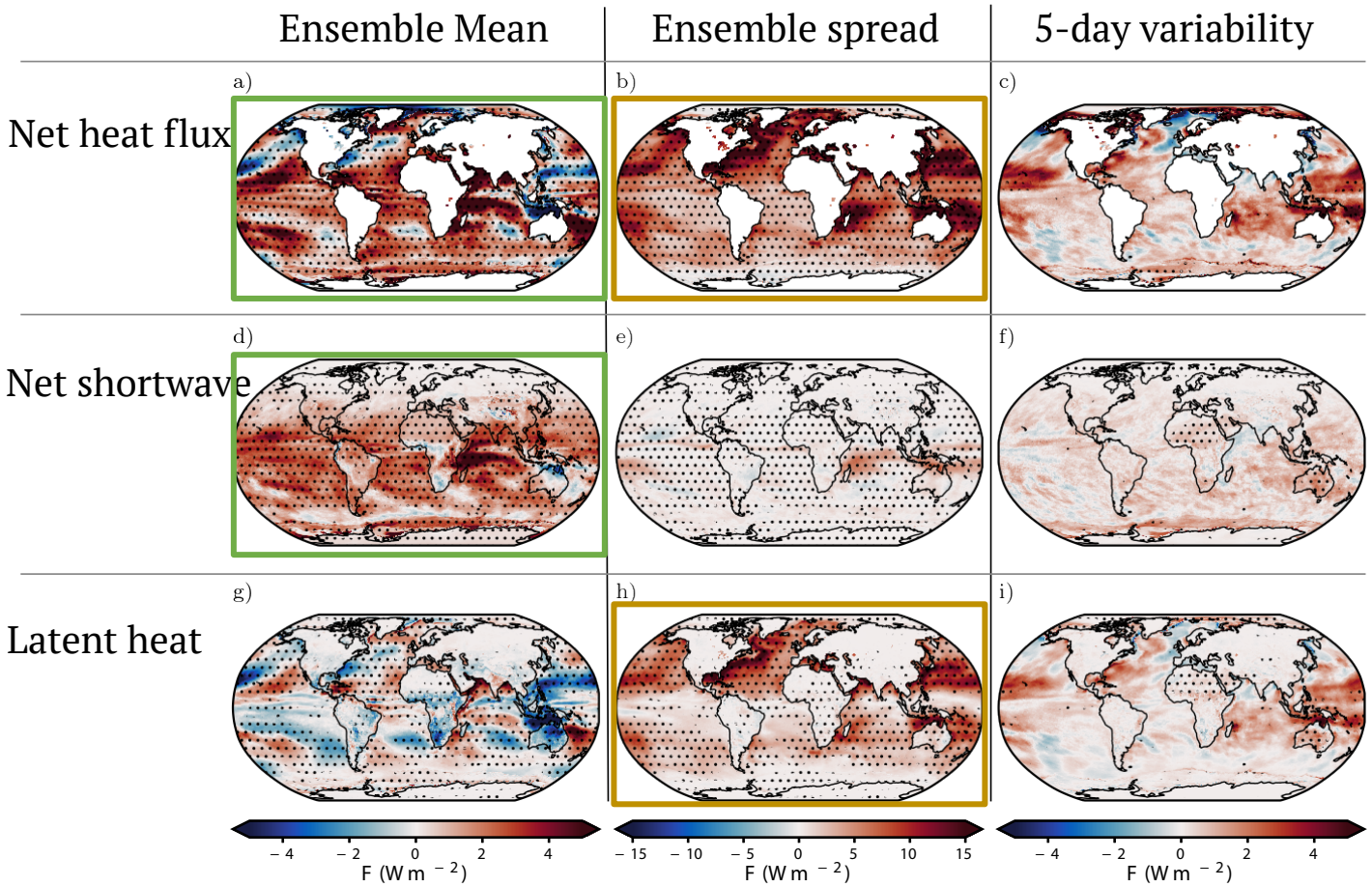
Global air-sea fluxes

	Net (W m^{-2}, %)	Shortwave	Longwave	Latent	Sensible
DJF mean	1.6 (16.9%)	1.6 (0.9%)	0.1 (-0.2%)	-0.1 (0.1%)	-0.1 (0.4%)
DJF spread	6.5 (46.8%)	0.5 (6.7%)	0.2 (4.7%)	3.7 (38.5%)	0.8 (27.1%)
5-daily anomalies	1.0 (1.8%)	0.4 (1.4%)	0.1 (0.7%)	0.5 (1.5%)	0.4 (3.3%)

- Disabling the feedback …
  - … increases ⬆ *mean* net heat flux due to shortwave radiation
  - … increases ⬆ *variability* due to latent heat flux

- → Thermodynamic feedbacks strongly constrain the seasonal variability of surface fluxes!

Feedback active → feedback inactive



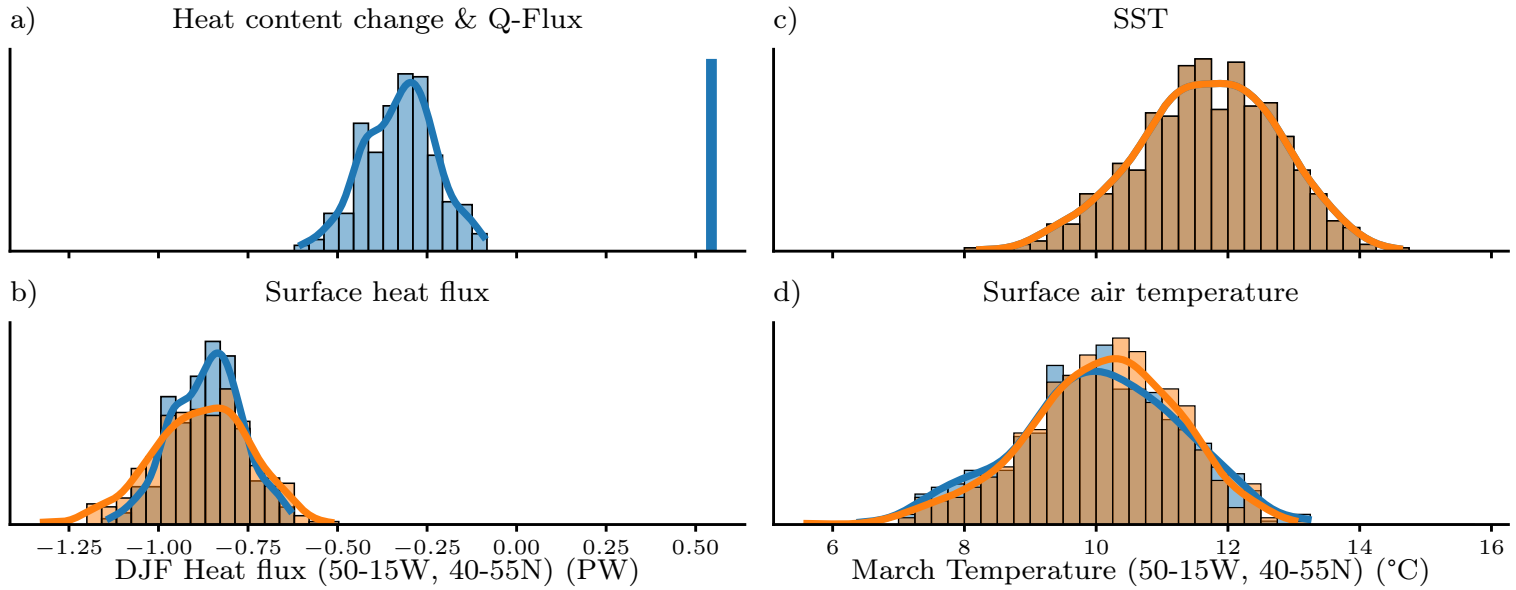
Why the increase in variability?

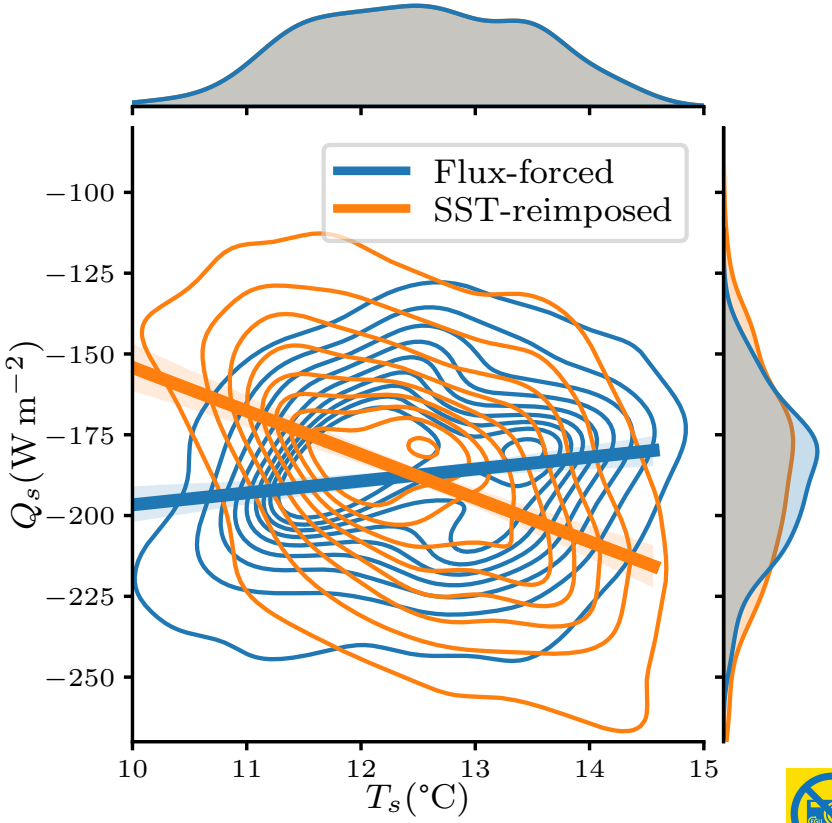
- Understand the local Slab-atmosphere system
- Increase in heat flux variance, decrease in the spread of surface air temperature
- Changed sign of SST-flux covariance

- **Atmosphere-driven** ⟺ **ocean-driven**

feedbacks active
variability *sink*

feedbacks inactive
variability *source*

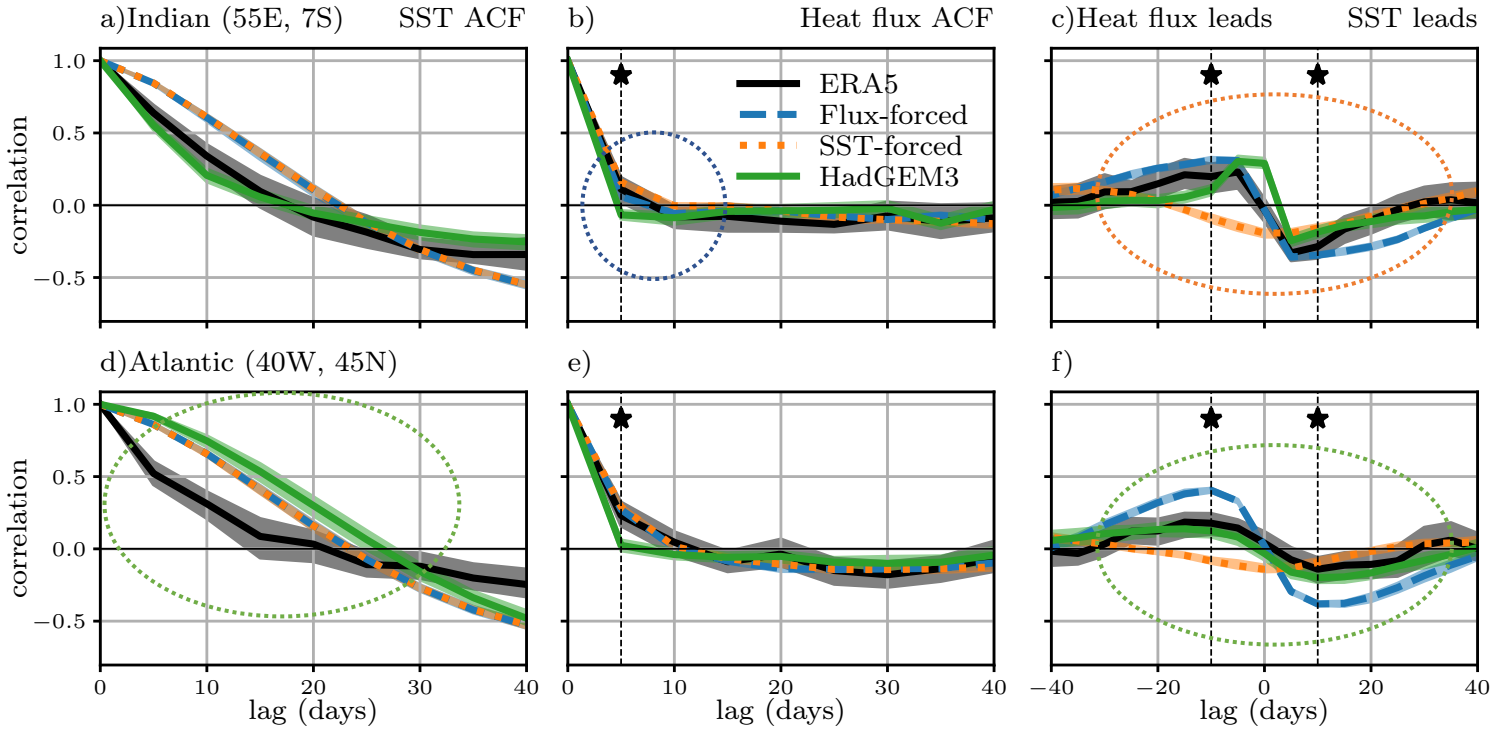


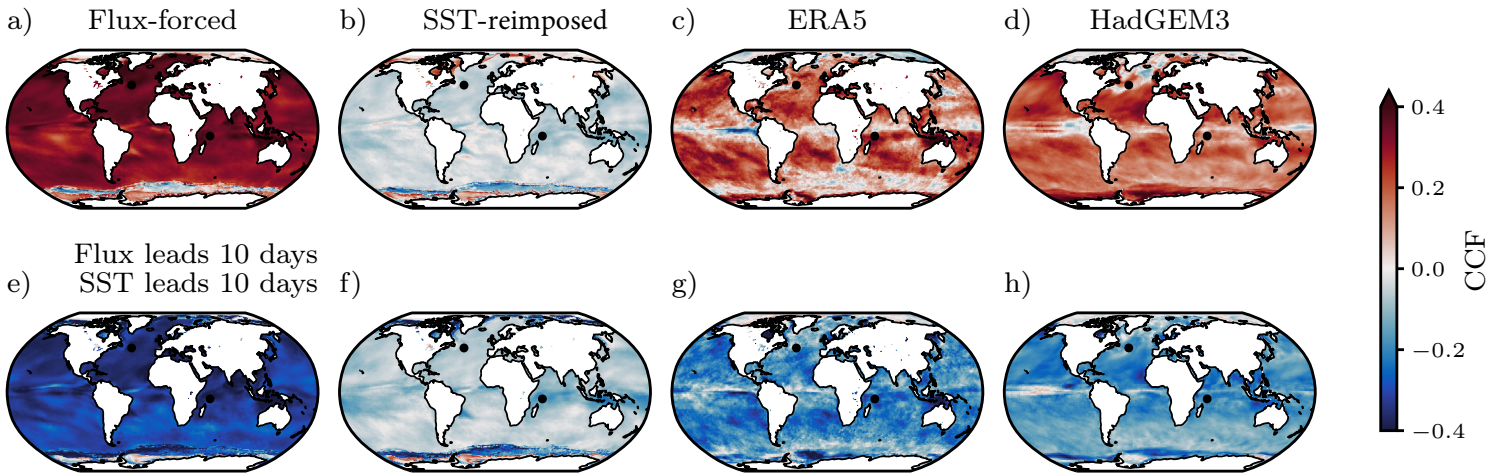


Time lag structure

- More flux memory without the feedback
- More realistic cross-correlation structure with feedback
- Constant mixed layer depth inflates CCF structure

- → Big improvement from including active feedback!

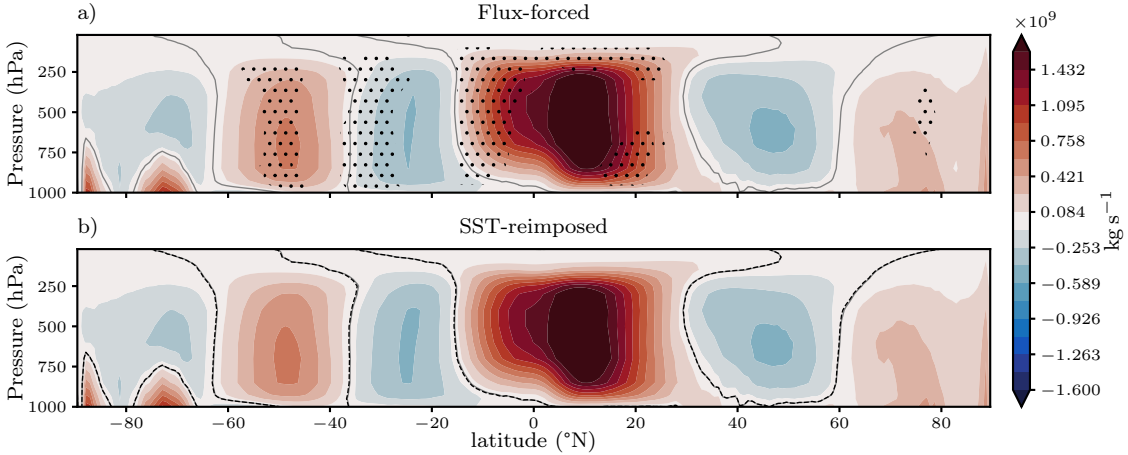


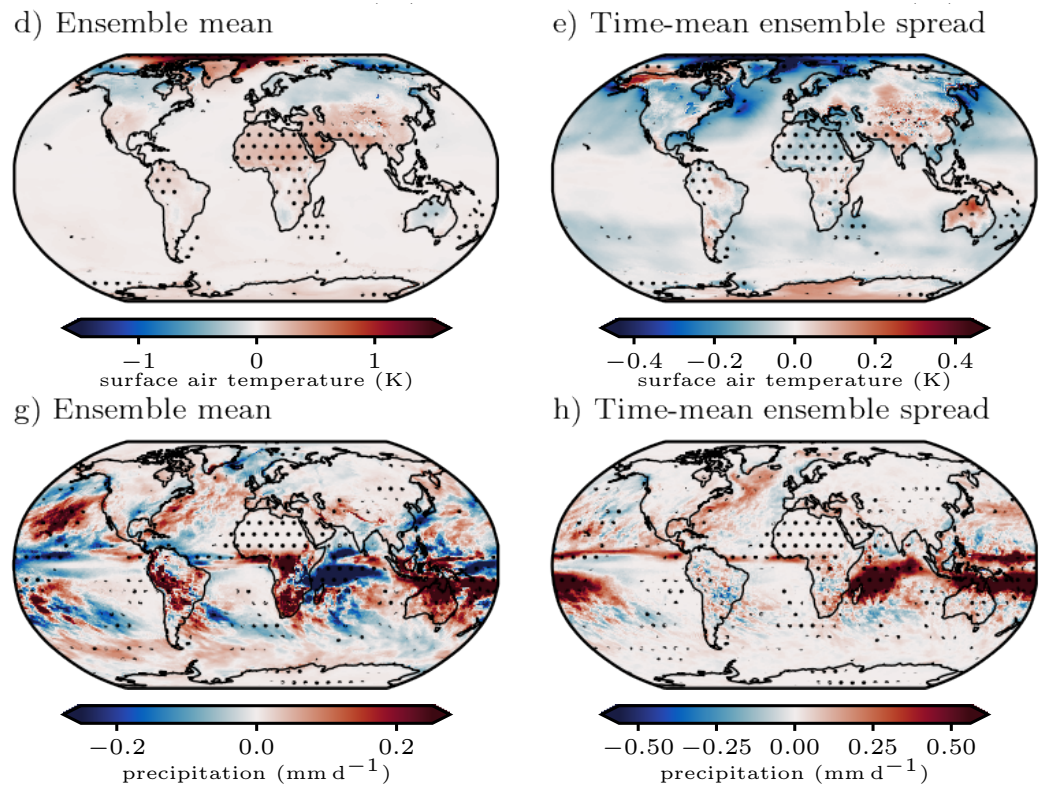


Impacts

- Disabling the feedback causes…
  - … little dynamical change
  - … low-latitude surface warming (increased heat flux)
  - … small signals in Northern extratropics over land
  - … increased precipitation mean and variance in (sub-) tropical Southern hemisphere
  - … DJF precipitation change up to 25% in Australia, Southern Africa

Hadley cell



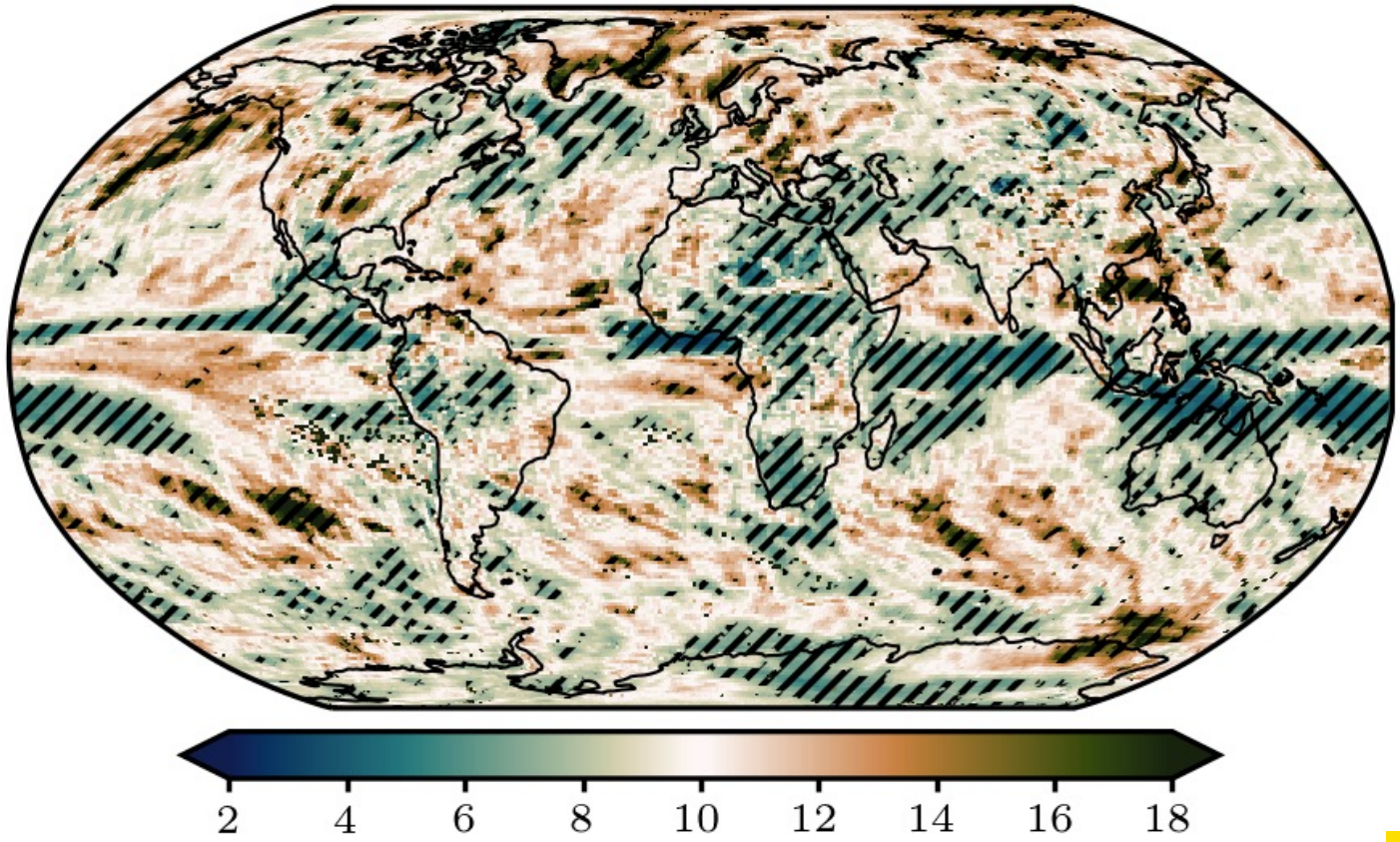


Extremes

$$F(X;\mu,\sigma,\xi) = \exp\left(-\left[1+\xi\left(\frac{X-\mu}{\sigma}\right)\right]^{-\frac{1}{\xi}}\right)$$

$$z_T = \mu - \frac{\sigma}{\xi}\left[1-\left(-\log\left[1-\frac{1}{T}\right]\right)^{-\xi}\right]$$

- 10-year extremely wet winters generally become more likely (increase in precipitation mean and/or variance)
- Most significant over the ocean
- Land regions: Australia, Southern Africa, Middle East



Return time of winter precipitation
(baseline: 10 years)

Conclusion

- New framework for investigating importance of thermodynamic air-sea feedbacks
  - Large ensemble study to investigate impact on extreme events
  - Big improvement in representing surface feedbacks
  - Important part of model hierarchy
- General increase in DJF mean ensemble spread of fluxes, precipitation, …
  - Regional changes in extremes
  - Changes most pronounced in (sub-)tropics, Southern hemisphere
- Limited dynamical effects (e.g. no evidence for changing SST-NAO relationship)
- Companion work investigates the impact of changing heat convergence on dynamics and impacts

Questions? Contact me: ***matthias.aengenheyster@physics.ox.ac.uk***

References

- Bevacqua E, Shepherd T G, Watson P A G, Sparrow S, Wallom D and Mitchell D 2021 Larger Spatial Footprint of Wintertime Total Precipitation Extremes in a Warmer Climate *Geophys Res Lett* **48**
- Bishop S P, Small R J, Bryan F O and Tomas R A 2017 Scale Dependence of Midlatitude Air–Sea Interaction *Journal of Climate* **30** 8207–21
- Christidis N and Stott P A 2014 Change in the Odds of Warm Years and Seasons Due to Anthropogenic Influence on the Climate *Journal of Climate* **27** 2607–21
- Donlon C J, Martin M, Stark J, Roberts-Jones J, Fiedler E and Wimmer W 2012 The Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) system *Remote Sensing of Environment* **116** 140–58
- Frankignoul C, Botzet M, Carril A F, Kestenare E, Drange H, Pardaens A, Terray L and Sutton R 2004 An intercomparison between the surface heat flux feedback in five coupled models, COADS and the NCEP reanalysis *Climate Dynamics* **22** 373–88
- Guillod B P, Jones R G, Bowery A, Haustein K, Massey N R, Mitchell D M, Otto F E L, Sparrow S N, Uhe P, Wallom D C H, Wilson S and Allen M R 2017 weather@home 2: validation of an improved global–regional climate modelling system *Geoscientific Model Development* **10** 1849–72
- Massey N, Jones R, Otto F E L, Aina T, Wilson S, Murphy J M, Hassell D, Yamazaki Y H and Allen M R 2015 Weather@Home-Development and Validation of a Very Large Ensemble Modelling System for Probabilistic Event Attribution *Quarterly Journal of the Royal Meteorological Society* **141** 1528–45
- Mitchell D, Davini P, Harvey B, Massey N, Haustein K, Woollings T, Jones R, Otto F, Guillod B, Sparrow S, Wallom D and Allen M 2017 Assessing mid-latitude dynamics in extreme event attribution systems *Climate Dynamics* **48** 3889–901
- Hewitt C D and Mitchell J F B 1997 Radiative forcing and response of a GCM to ice age boundary conditions: cloud feedback and climate sensitivity *Climate Dynamics* **13** 821–34
- Otto F E L 2017 Attribution of Weather and Climate Events *Annual Review of Environment and Resources* **42** 627–46
- Park S, Deser C and Alexander M A 2005 Estimation of the Surface Heat Flux Response to Sea Surface Temperature Anomalies over the Global Oceans *Journal of Climate* **18** 4582–99
- Patrizio C R and Thompson D W J 2022 Understanding the Role of Ocean Dynamics in Midlatitude Sea Surface Temperature Variability using a Simple Stochastic Climate Model *Journal of Climate* 1–62
- Schaller N, Kay A L, Lamb R, Massey N R, van Oldenborgh G J, Otto F E L, Sparrow S N, Vautard R, Yiou P, Ashpole I, Bowery A, Crooks S M, Haustein K, Huntingford C, Ingram W J, Jones R G, Legg T, Miller J, Skeggs J, Wallom D, Weisheimer A, Wilson S, Stott P A and Allen M R 2016 Human influence on climate in the 2014 southern England winter floods and their impacts *Nature Climate Change* **6** 627–34
- Watson P, Sparrow S, Ingram W, Wilson S, Marie D, Zappa G, Jones R, Mitchell D, Woollings T and Allen M 2020 Multi-thousand member ensemble atmospheric simulations with global 60km resolution using climateprediction.net *EGU General Assembly 2020, Online, 4–8 May 2020*
- Webb M, Senior C, Bony S and Morcrette J-J 2001 Combining ERBE and ISCCP data to assess clouds in the Hadley Centre, ECMWF and LMD atmospheric climate models *Climate Dynamics* **17** 905–22
- Williams K D, Ringer M A and Senior C A 2003 Evaluating the cloud response to climate change and current climate variability *Climate Dynamics* **20** 705–21