To What Extent Can Bjerknes Compensation Explain a Weak AMOC in GC5-LFRic?

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1. The Problem

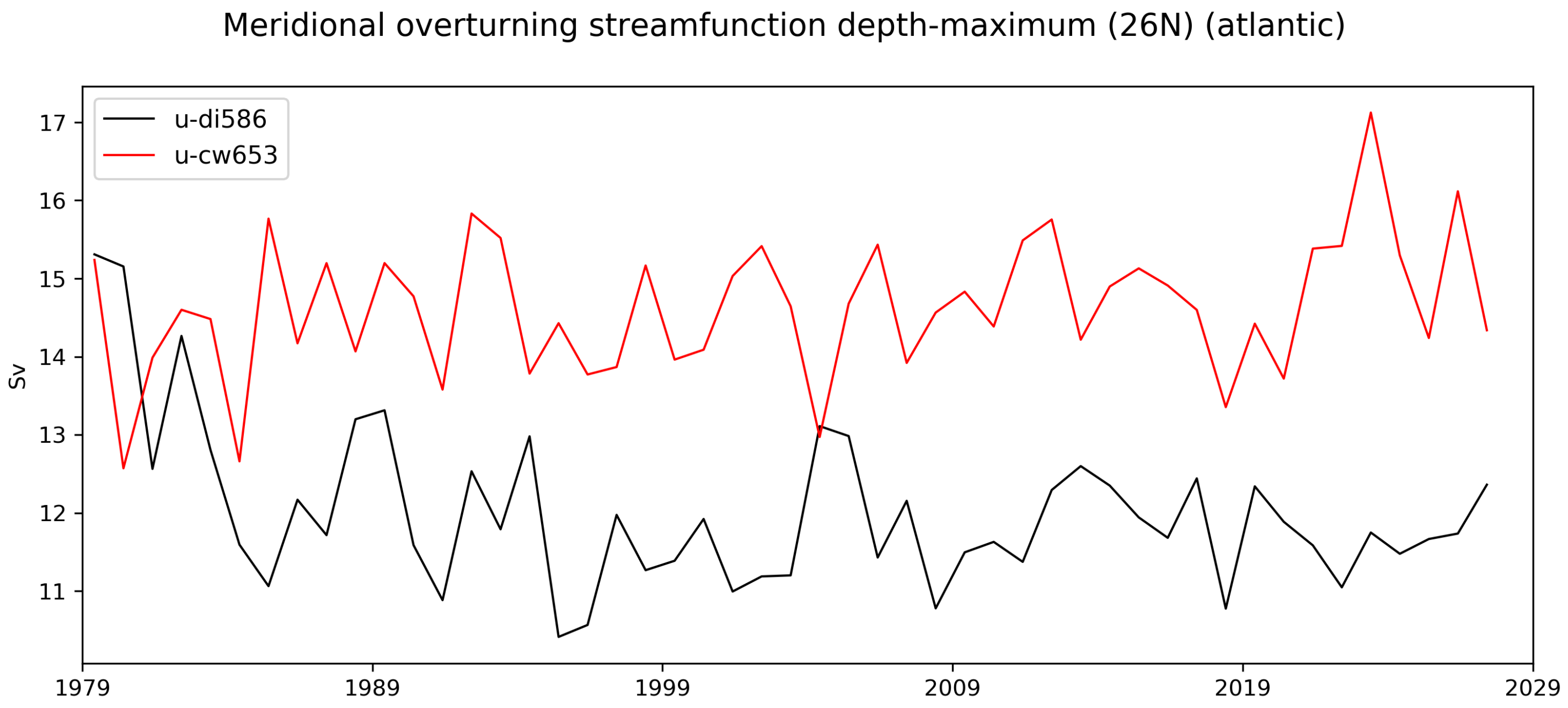

Figure 1: Time series of modelled North Atlantic AMOC strength; UM in red and LFRic in black.

- As part of its new Momentum modelling system, the Met Office is developing a new coupled configuration based on the LFRic modelling infrastructure, which incorporates the new GungHo dynamical core.
- The Atlantic Meridional Overturning Circulation (AMOC) in LFRic (black line in Figure 1) **is several Sverdrups lower than in the currently-operational Unified Model** (UM; red line in Figure 1).
- This means the LFRic AMOC is much weaker than observational estimates, making it unsuitable for research on how AMOC might change in a warming climate.

Box 1: Method - Implied Heat Transport Calculation

We can calculate implied atmospheric heat transports from the energy divergence σ (the sum of net downwelling TOA radiative fluxes and net upwelling surface heat & radiative fluxes) as follows (Pearce and Bodas-Salcedo, 2023):

1. Define horizontal heat transport $\boldsymbol{T} = q\boldsymbol{v}$; q is the heat carried by an air parcel with velocity $\boldsymbol{v}$.
2. Recognise continuity equation $\boldsymbol{\nabla} \cdot \boldsymbol{T} = \sigma - \frac{\partial q}{\partial t}$. Here, $\sigma = NTOA + NSHF$
3. Write IHT as $\boldsymbol{T} = \boldsymbol{T_{div}} + \boldsymbol{T_{sol}}$ where $\boldsymbol{\nabla} \times \boldsymbol{T_{div}} = 0$ and $\boldsymbol{\nabla} \cdot \boldsymbol{T_{sol}} = 0$
4. Define IHT potential φ via $\boldsymbol{T_{div}} = \boldsymbol{\nabla}\varphi$
5. Substitute 3 and 4 into 2 to get $\boldsymbol{\nabla}^2\varphi = \sigma$. Solve for potential.

The global mean of the RHS is subtracted off before solving to remove any average storage effect from (e.g.) global warming.

2. Direct Driver: Too-Small Sea-Air Heat Fluxes from the Labrador Sea

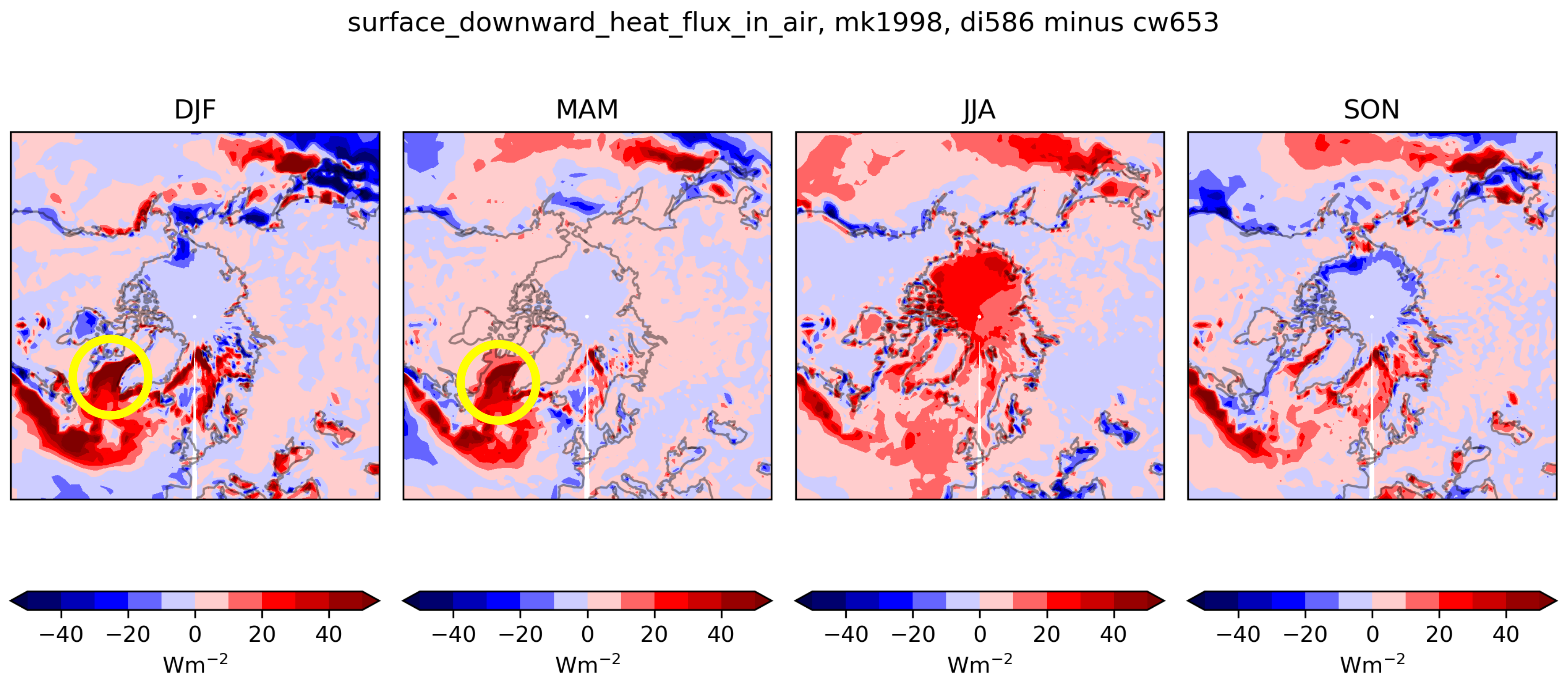

Figure 2: Difference LFRic minus UM (both coupled) in downward net surface heat flux. 20-year seasonal means. Labrador Sea deep-water formation region highlighted.

- One of the driving mechanisms of AMOC is **deep water formation** in the seas surrounding Greenland. Water loses buoyancy either by **heat loss to the cold atmosphere** or by wintertime **brine rejection** from growing sea ice (Figure 3).
- In winter (DJF) and spring (MAM), the **ocean in the LFRic coupled model loses much less heat to the atmosphere in deep water formation regions** than the UM ocean (Figure 2).
- Usually, ocean heat loss in these areas is driven by very cold air flowing out from the Arctic. This **air is much warmer in LFRic** than in the UM.
- This suggests that the AMOC issue is either **caused or exacerbated by a separate issue in LFRic : The model loses its sea ice too quickly**. The albedo feedbacks involved in sea ice loss increase Arctic air temperatures significantly (~5K).
- However, atmosphere-only simulations with prescribed oceans and sea ice exhibit similar (but smaller in magnitude) Labrador Sea heat flux biases to those shown in Figure 2. **Is there another mechanism driving the too-small heat fluxes, and therefore the too-weak AMOC in LFRic?**

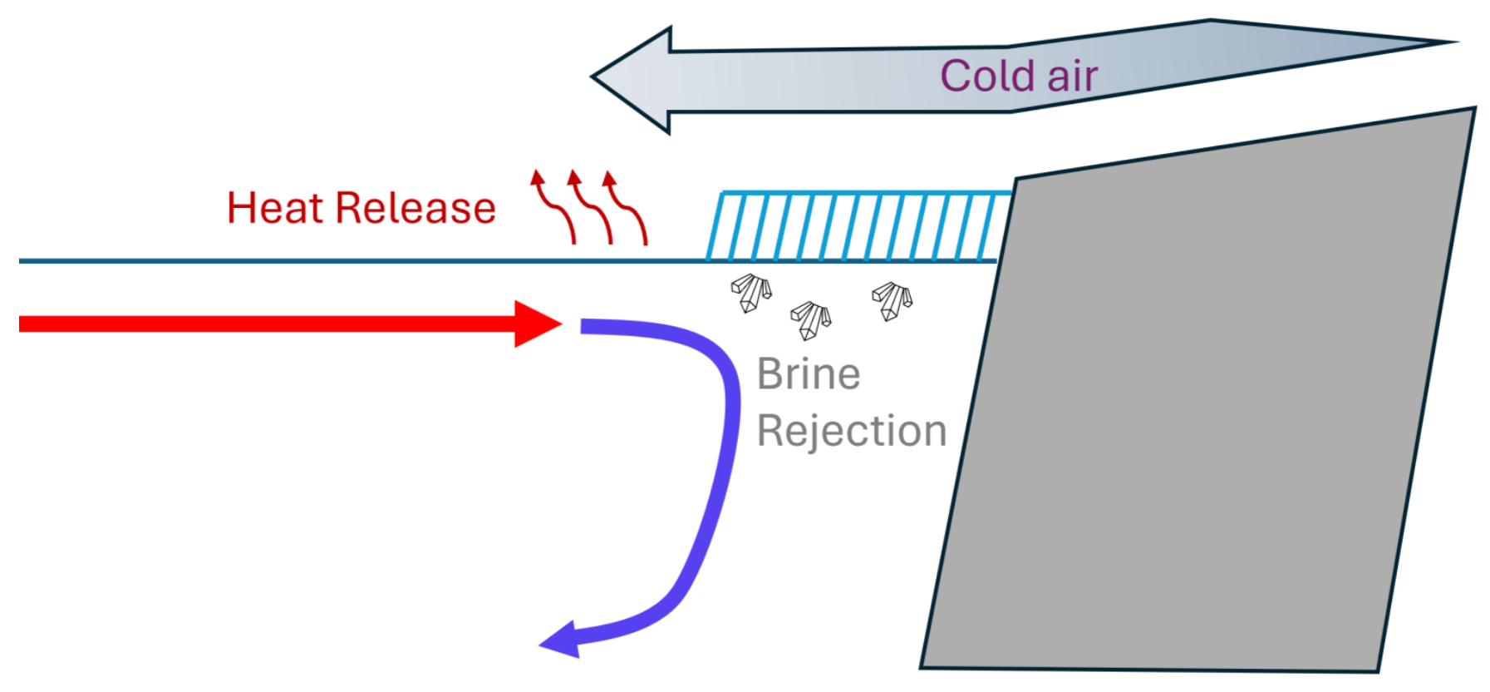

Figure 3: Mechanisms for deep water formation in the North Atlantic.

3. A Remote Driver of the Weak AMOC?

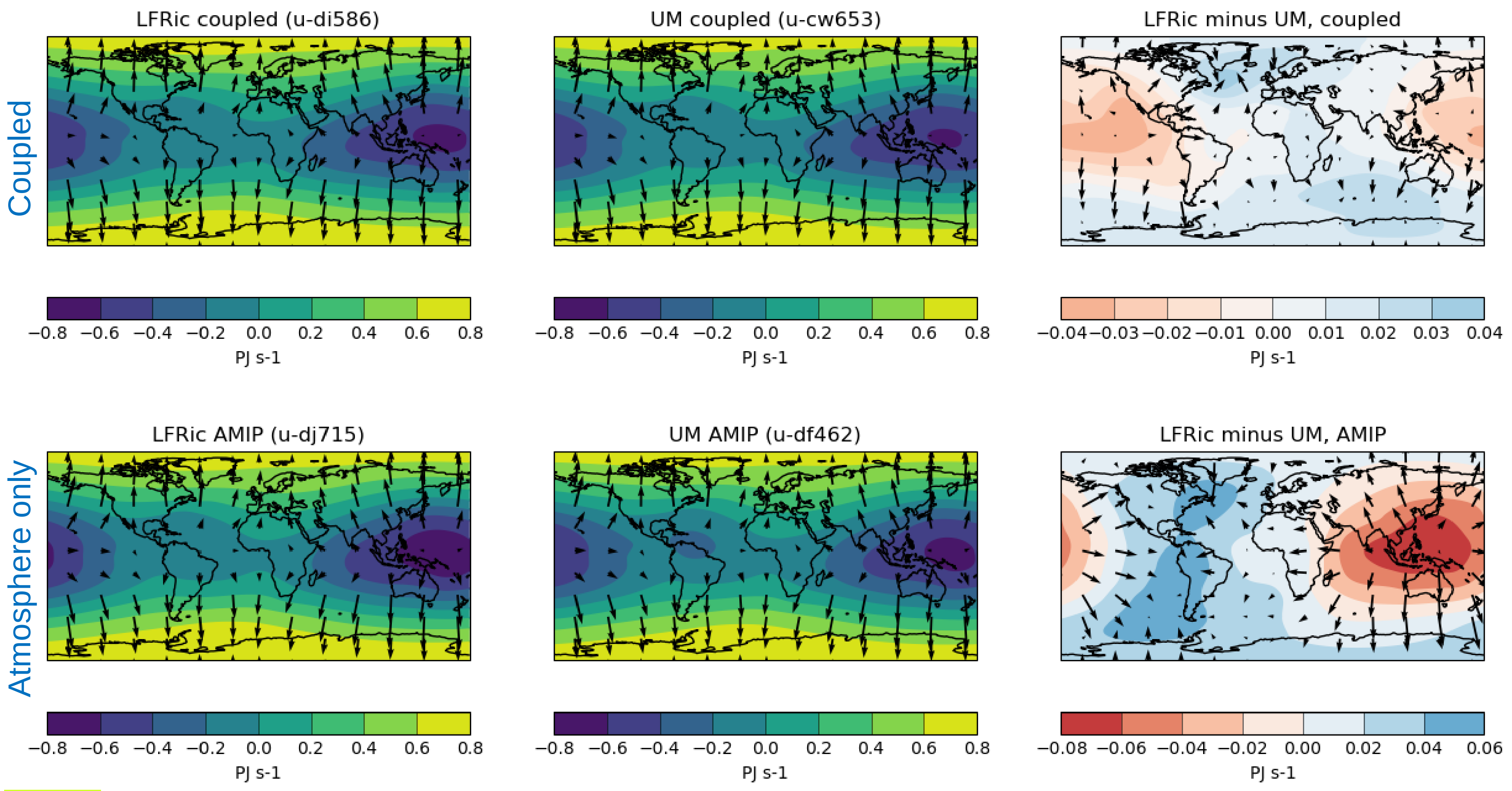

Figure 4: Implied Heat Transports calculated from 20-year annual means of net surface heat fluxes and net TOA fluxes.

If the top-of-atmosphere (TOA) energy balance does not change, **meridional heat transport changes in the ocean and atmosphere cancel each other out**. This is known as Bjerknes compensation (Bjerknes, 1964).
The divergent component of atmospheric heat transports implied by net TOA and net surface heat fluxes can be calculated using the method in Box 1.
The resulting heat transport potentials are shown in Figure 4. Figure 4 shows **that in atmosphere-only experiments, the LFRic atmosphere is implied to transport about 10% more heat away from the tropical maritime continent than the UM.** The total increase in atmospheric heat transport from the equator to the poles implied by the Atmosphere-only part of Figure 4 is about 0.12 PW, which is roughly 10% of the heat carried by AMOC at 26N (Trenberth et al., 2019).

4. Excess Latent Heat Release Over the Maritime Continent

Why does LFRic export more heat from the maritime continent (Section 3)**?**

- Splitting up the heat transport calculation into contributions from individual fluxes shows that the **surface latent heat flux contributes most of the additional energy in LFRic** (Figure 5).
- Figure 6 shows that maritime continent latent **heat flux differences** between LFRic and the UM are **focused around coastlines** in atmosphere-only simulations.
- This suggests the **origin of the excess latent heat could be related to the handling of the land-sea contrast.**
- **In coupled experiments, the response is more complicated** but still seems dominated by latent heat – however further east, in the ‘open’ Pacific. We will focus on easier-to understand atmosphere-only simulations.

To better understand these LFRic-UM discrepancies, we note the bulk equation for the latent heat flux:

$$E = L_v \rho c_H U \Delta q$$

where L_v is the latent heat of evaporation, ρ is the density of air, c_H is a dimensionless exchange coefficient, U is the wind speed at 10m height and Δq is the surface gradient in specific humidity.
This means that **changes in latent heat flux over the ocean can come from three places:** Different screen-level **humidity** (given equal SSTs), different near-surface **wind speed**, or different surface **stability** (feeding into the stability function and thus the exchange coefficient).
Inspecting 20-year means of the ocean-only points immediately adjacent to land we find:

- **Differences in humidity and wind speed explain 77% of the observed variance in latent heat flux difference** across these points, making stability a less likely culprit (Figure 8).
- LFRic consistently has higher wind speeds in coastal areas, while humidity is on average similar to the UM (Figure 7). **This suggests higher winds are the main driver of the larger latent heat release.**
- This supports the hypothesis that **the enhanced latent heat flux may be due to enhanced sea breezes. Investigations on why this might happen are ongoing** (see section 5).

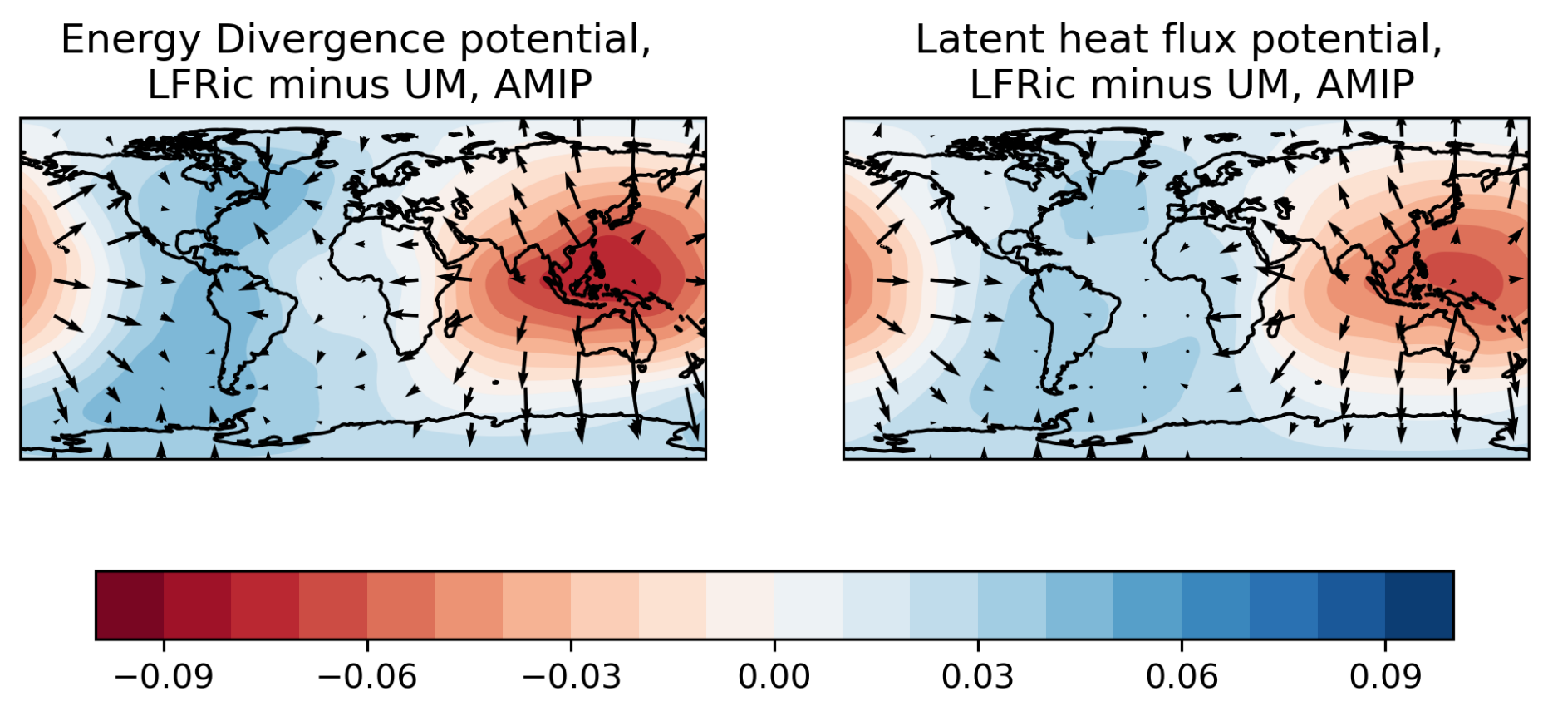

Figure 5: Heat Transport potential difference (LFRic-UM) calculated using only the latent heat flux (right), with the full solution for reference on the left. 20-year annual means.

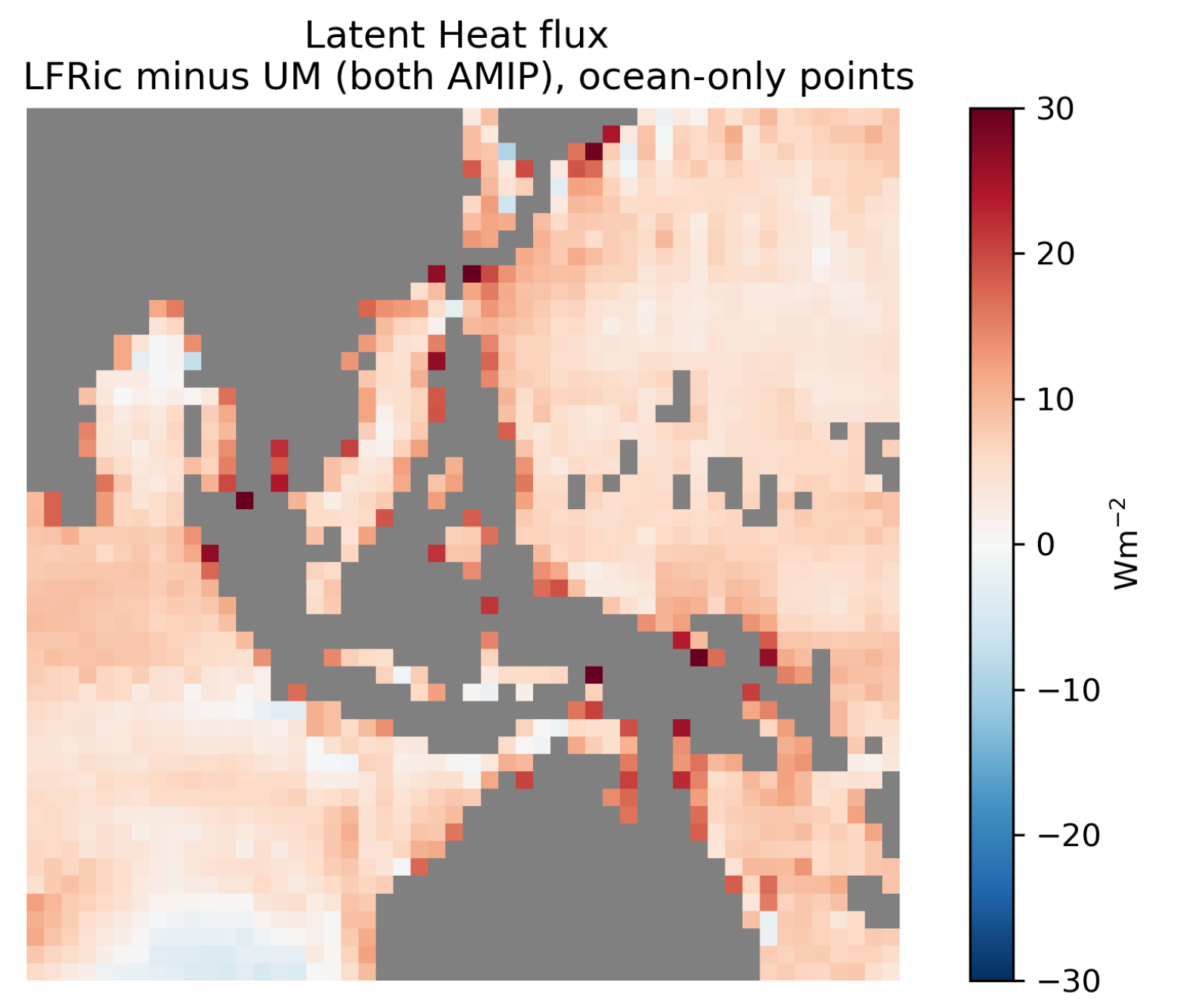

Figure 6: 20-year annual mean latent heat fluxes over ocean-only points, atmosphere-only experiments, LFRic minus UM.

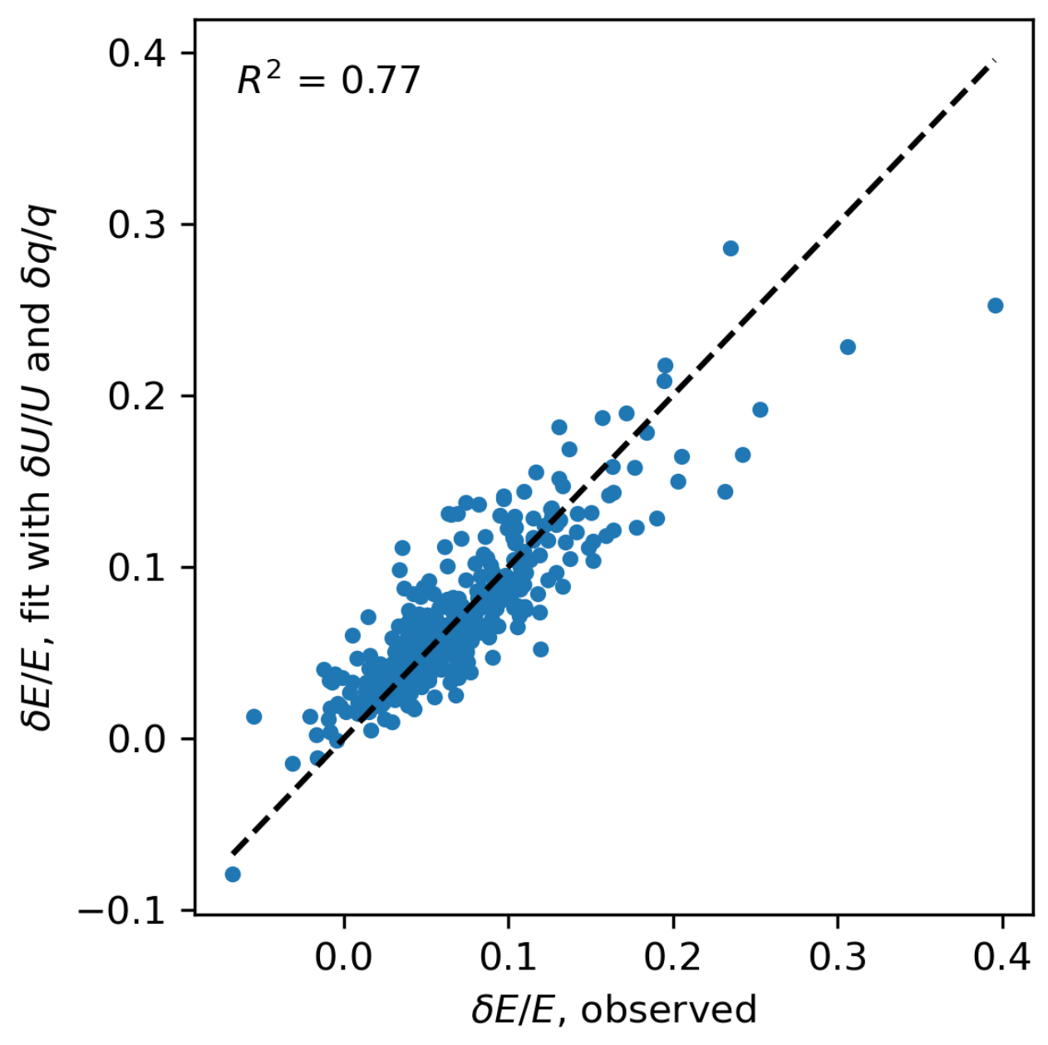

Figure 8: Linear Regression of normalised latent heat flux difference between LFRic and UM against humidity and wind speed differences; all 20-year means of coastal points. Predictions on the y-axis scattered against the observed latent heat flux difference on the x-axis.

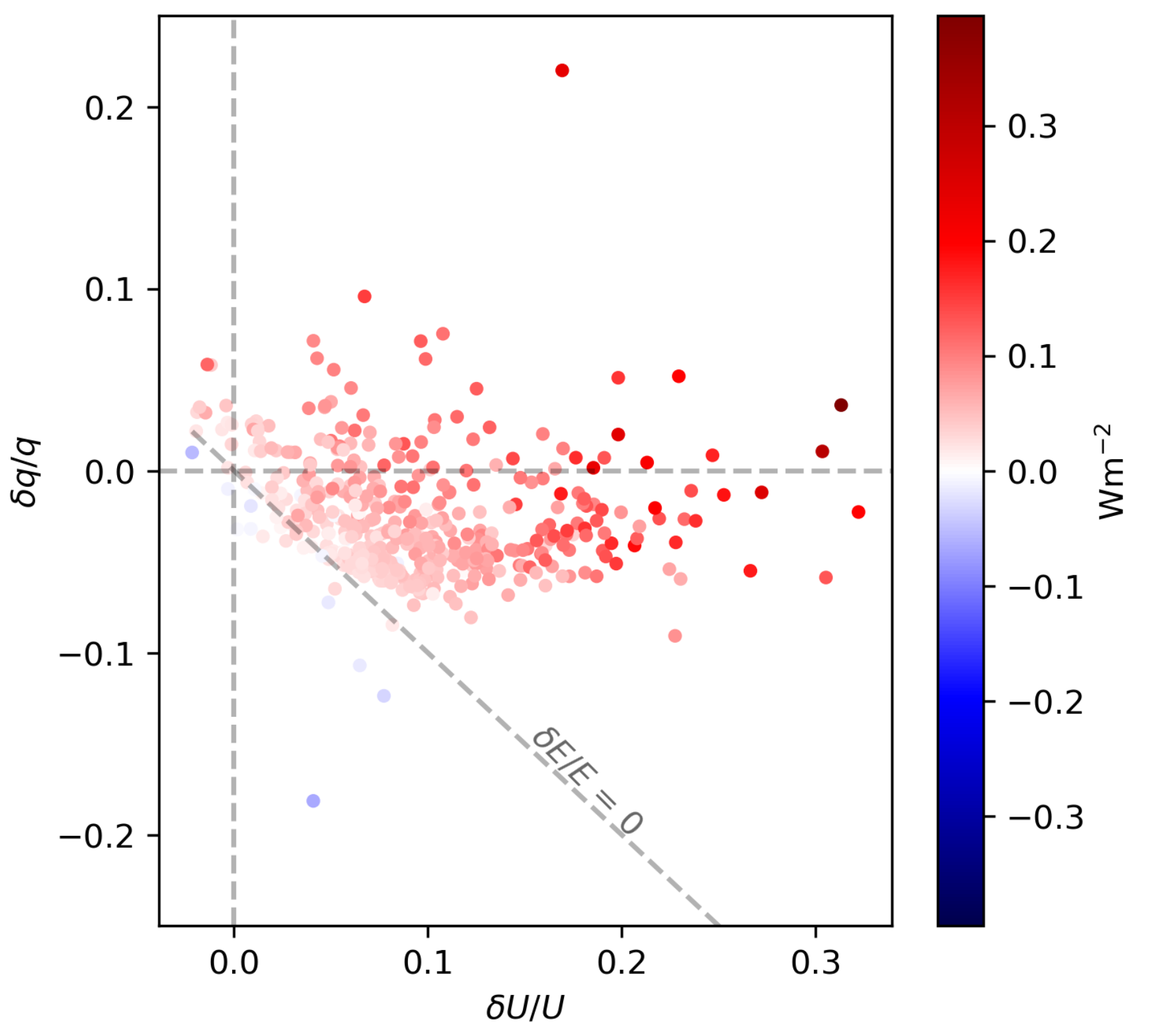

Figure 7: Scatterplot of LFRic-minus-UM wind speed and humidity gradient differences – both normalised by UM values – across all ocean points directly adjacent to the coast. Coloured by latent heat flux differences normalised by UM values. 20-year annual means.

6. References

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5. Further Work: Sensitivity Experiments

We are testing two hypotheses for why near-coastal winds and hence latent heat fluxes in LFRic may be different:

- the current LFRic orography is interpolated from the UM grid, making it too smooth. Sensitivity experiments with recently-available native mean orography suggest it does not make a big difference, but sub-grid terms might still do.
- The GungHo dynamics have different conservation properties. We are trying to reproduce this effect in the UM by tweaking the ‘fountain-buster’ setting in the convection scheme.

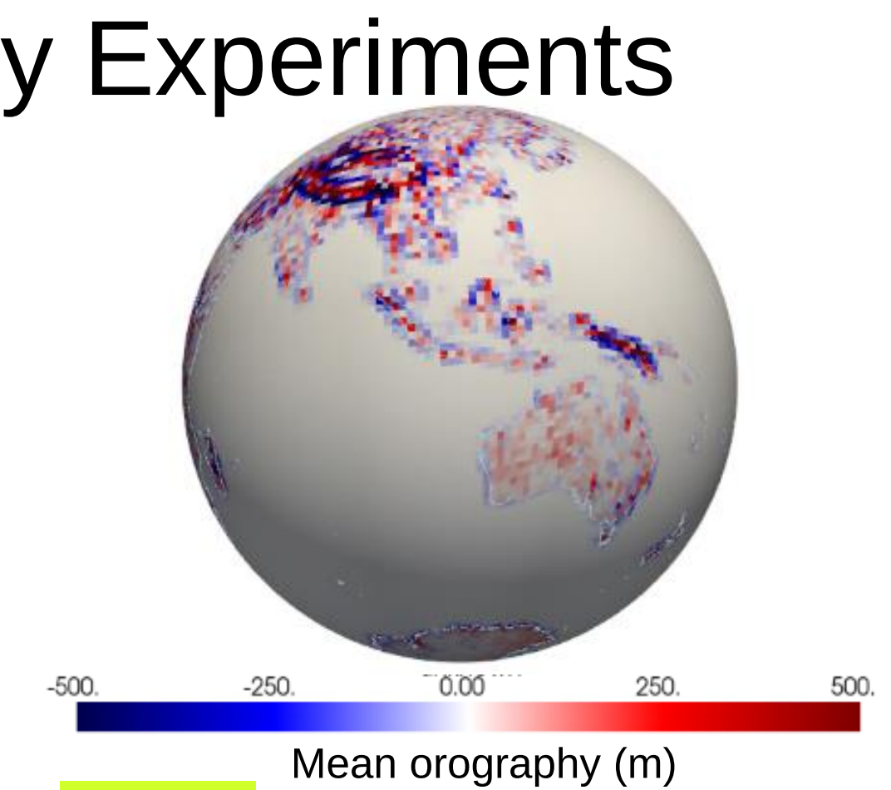

Figure 9: native minus interpolated mean orography

6. Summary & Conclusions

- During development of the first coupled configuration to incorporate the new LFRic model infrastructure, it was found that LFRic has an unacceptably weak AMOC.
- The weakening is caused by too-warm air flowing out from the Arctic, an effect caused or exacerbated by a separate LFRic issue (rapid sea ice loss). We investigate whether too-strong atmospheric heat transport may also contribute via Bjerknes compensation.
- LFRic atmosphere-only simulations export too much heat from the maritime continent, creating a difference in meridional heat transport that could account for a roughly 10% drop in the heat transported by AMOC (half of the observed weakening in LFRic).
- In atmosphere-only simulations, the excess heat transport is driven by larger latent heat fluxes around tropical coastlines, possibly driven by stronger land-sea breezes.
- Further work is needed to understand the coupled response and the origin of the stronger coastal winds.

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