Southern hemisphere circulation shifts in a warming climate

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Separating forcings using AM2 & CM2

We examine:

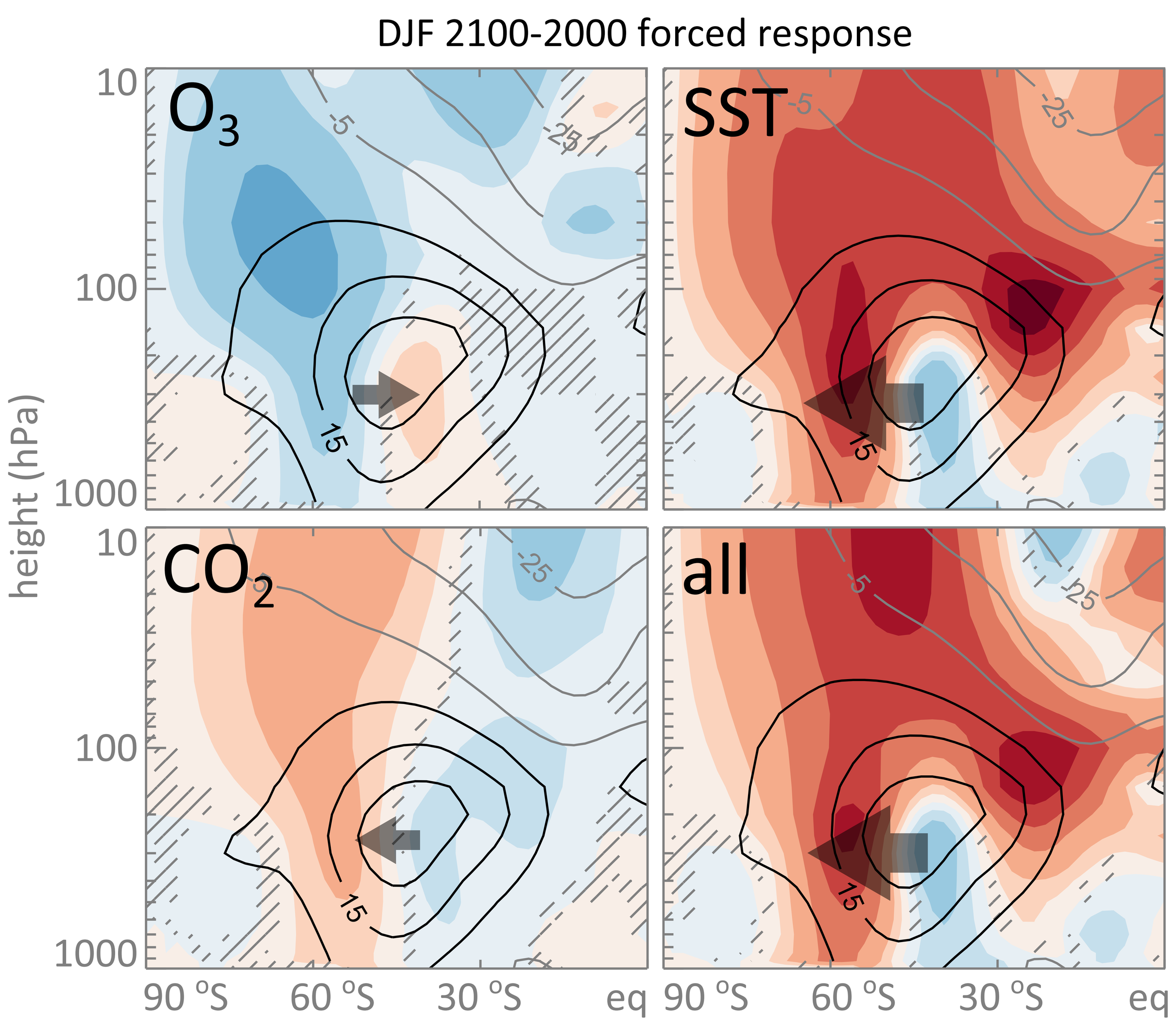
- 3000-year coupled CM2.1 control
- 3000-year uncoupled AM2.1 control
- 500-year time-slice simulations with varied forcings:
  - CO_2: 143, 286, 380, 720, or 1120 ppm
  - SSTs: from years 1870, 2000, 2050, or 2100
  - O_3: 0.4x reverse depletion, control, 1x or 2x depletion

We ask:

- What is the effect of each forcing?
- How will the circulation change in the 21st century?
- How do various forced shifts relate to each other?
- How do forced shifts compare to interannual variability?
- What mechanisms are involved?

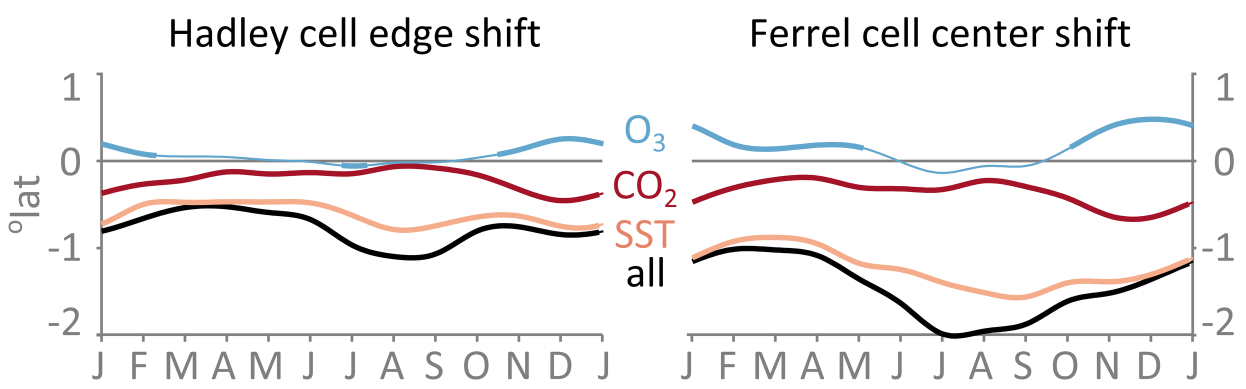
21st century circulation shifts

DJF circulation changes



- Moderate O_3 response + strong SST response = continued poleward jet shift in AM2.1 (even during 2000-2050).
- These results are likely model dependent, as studies using CMAM (e.g. Kang *et al.*, 2011; McLandress *et al.*, 2011), and other models (e.g. Polvani *et al.*, 2010, Son *et al.*, 2010) suggest a tighter 'competition' between ozone recovery and other forcings during the coming decades.

The seasonality of shifts

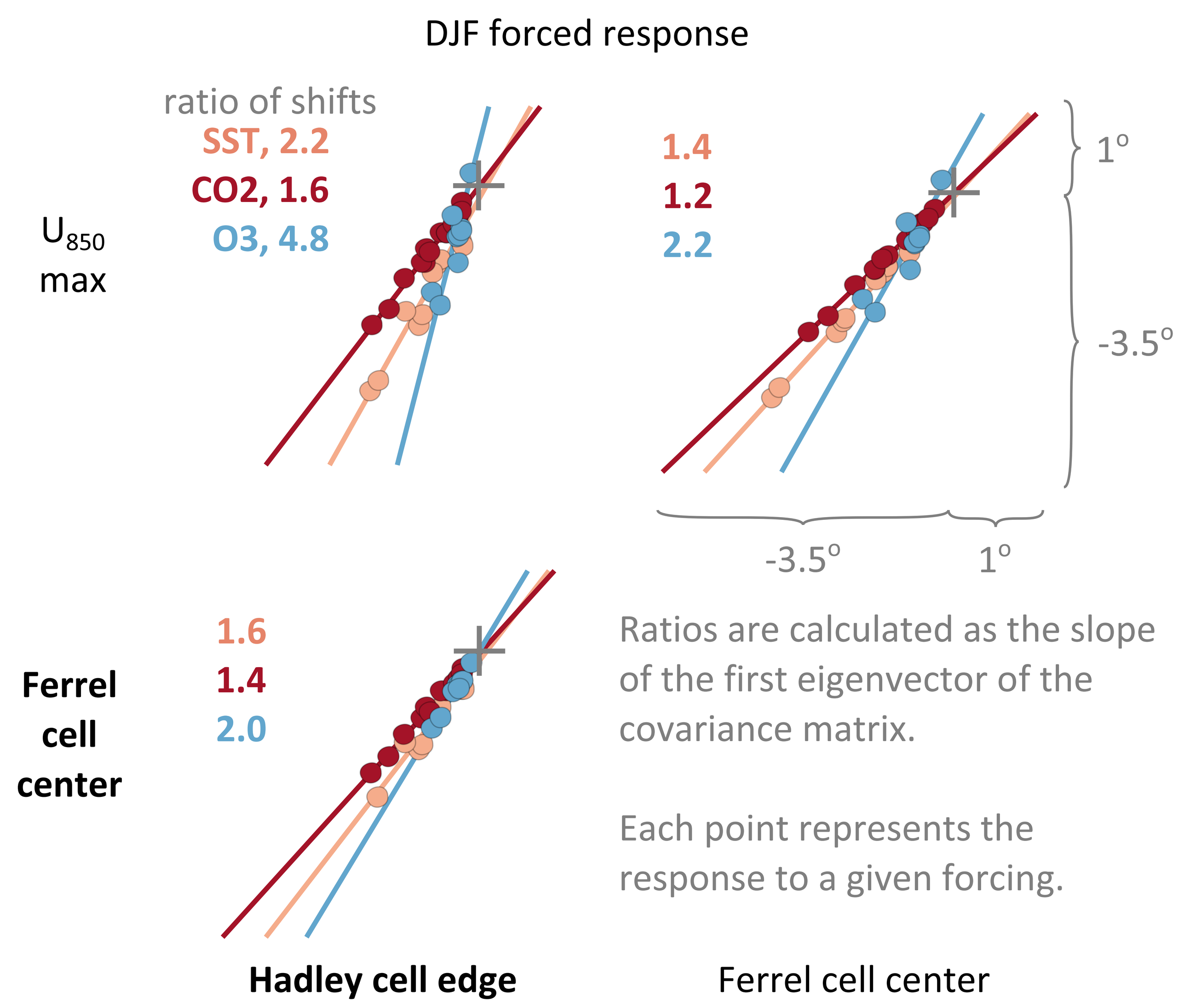


- Poleward shifts due to SST warming consistently overpower equatorward shifts due to O_3 recovery.
- The Ferrel cell shifts more strongly than the Hadley cell almost all year for all forcings.
- This strong SST effect is in contrast to Kang *et al.* (2011), who show relatively little dependence of circulation shifts on SSTs.

The Ferrel cell vs. Hadley cell shift ratio

FC/HC ratio due to external forcings

We investigate whether the Ferrel cell shift / Hadley cell shift ratio (FC/HC) seen during the 21st century is dependent on the strength of the forcing, type of forcing, or the background climatology.



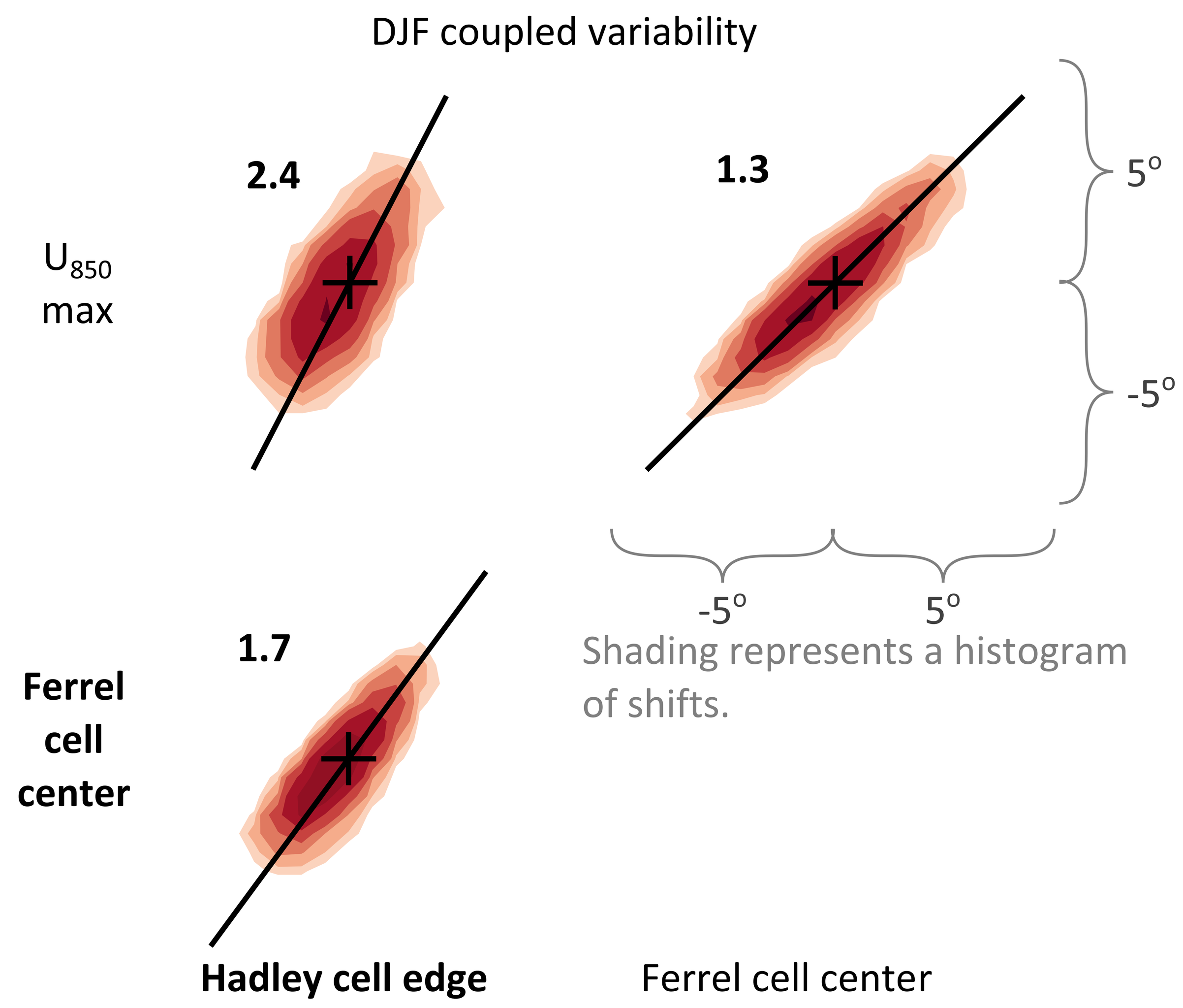
Ratios are calculated as the slope of the first eigenvector of the covariance matrix.

Each point represents the response to a given forcing.

- The FH/HC ratio varies by forcing.
- For a given forcing, shifts vary approximately linearly, and are insensitive to the background climatology. Kang & Polvani (2010), examining the interannual U_{850}/HC slope, also find little dependence on background climatology.
- Shifts vary by hemisphere and season (not shown).

FC/HC ratio due to coupled variability

Having examined forced shifts, we now examine year-to-year shifts in the coupled CM2.1 control simulation.



Shading represents a histogram of shifts.

- The interannual FC/HC ratio is similar to the forced FC/HC slopes above.
- Scatter makes it difficult to say whether interannual ratios most closely match changes from any particular forcing.
- Our results are similar to and extend those by Kang & Polvani (2010) for our model. For example, we calculate slopes for both hemispheres and for DJF (not shown). We find correlations above 0.6 for the FC/HC ratio during both seasons, and over both hemispheres.

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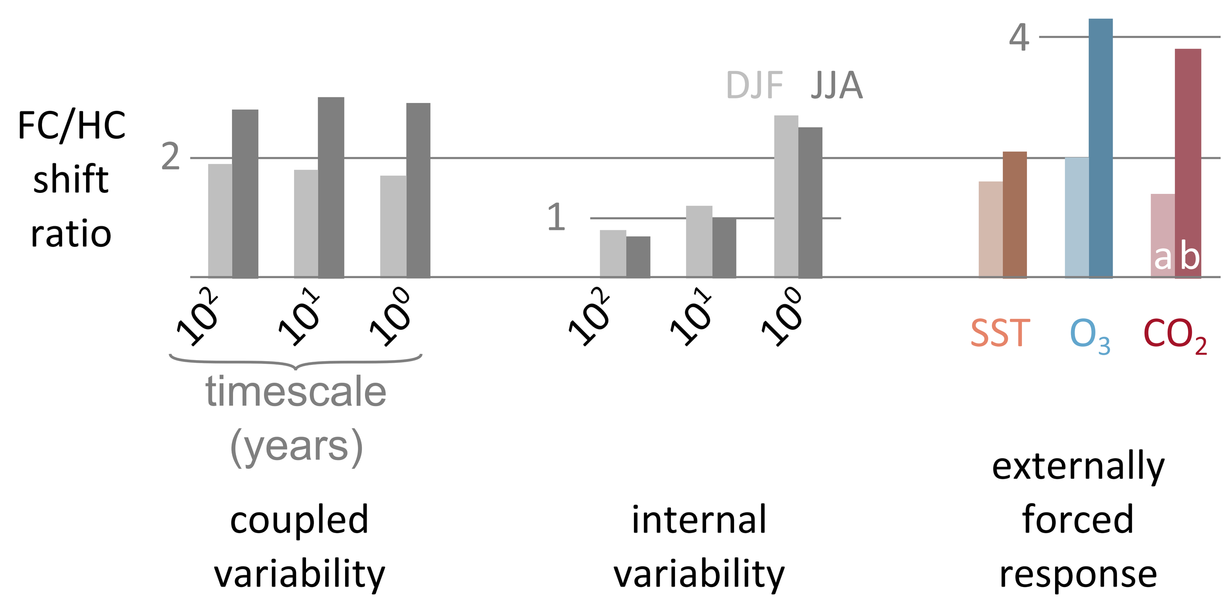
FC/HC ratio overview

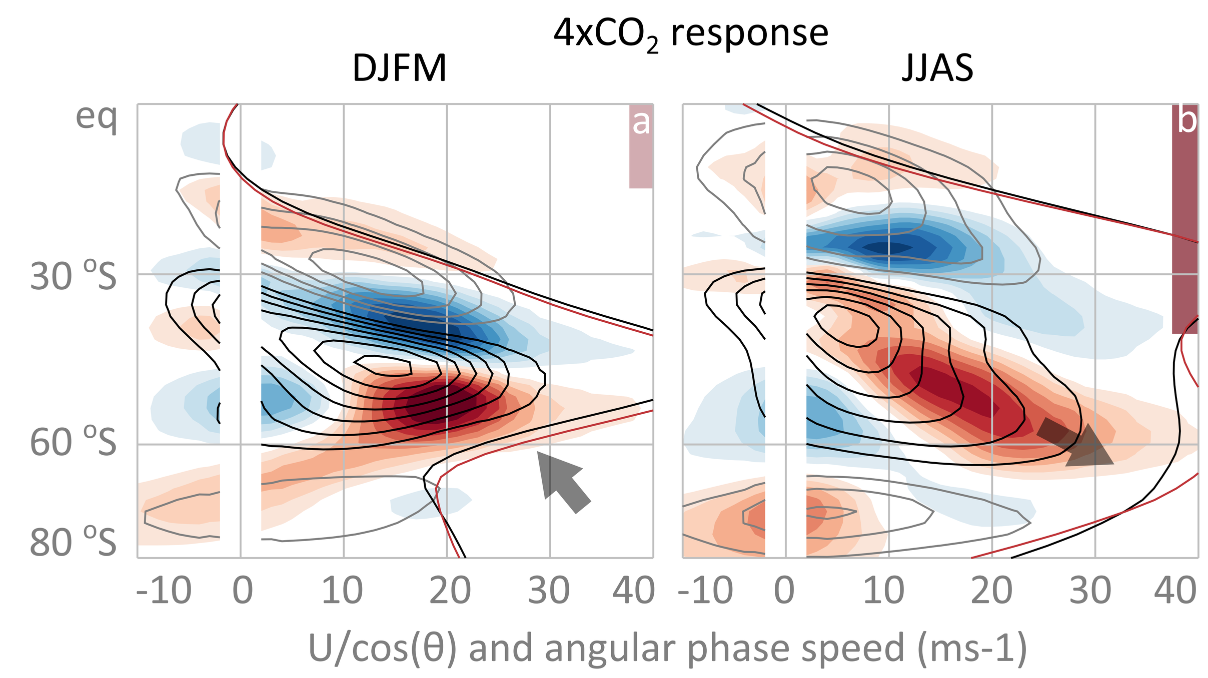
Here we examine the FC/HC ratio as a function of timescale and season, investigating the role of ocean coupling.



- Shift ratios are consistent across time scales in the coupled simulation, and are larger for the summer.
- This pattern breaks down when oceanic variability is omitted, but holds for the uncoupled forced responses.

Speculating on mechanisms– a flux convergence view

We calculate the eddy momentum flux convergence (EMFC) after Chen & Held (2007), and discuss their proposed mechanism whereby increased phase speeds are posited to result in a poleward shift in wave activity.



- During DJFM, weak westerlies at high latitudes limit deposition of momentum except near the subtropical jet core, keeping the Hadley and Ferrel cells more tightly coupled in spite of increased phase speeds.
- While linear wave behavior seems clearly evident, the contraction of the jet from both sides due to increased phase speeds is not, suggesting other mechanisms may also be work (see McLandress *et al.*, 2011).
- During JJAS, increased phase speeds are associated with a poleward shift in eddy activity. Strong high latitude westerlies allow wave activity to extend far polewardof Hadley cell.
- SST warming (not shown) produces more EMFC at low latitudes and slow phase speeds, and less at high latitudes. Perhaps this is why SST warming doesn't 'favor' the Ferrel cell so strongly, even during JJAS, when the polar vortex makes the Ferrel cell more 'sensitive'.

Conclusions

- In the GFDL model, the SST response dominates the O_3 response, producing a poleward jet shifts during the 21st century.
- The Ferrel cell generally shifts more than the Hadley cell.
- We find no definitive FC/HC shift ratio, even within one model.
- The FC/HC shift ratio for different forcings, seasons, and time-scales may yield insights into underlying mechanisms.
- The Chen and Held (2007) phase speed mechanism may explain some of the differences between season and forcing.