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Covariability of Southern Hemisphere tropical edge metrics with the SAM

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1) Motivation and Aim

The tropics are expanding. Models capture the expansion but the rate is much slower than observations. Metrics for the tropical edge include the subtropical (ST) jet and ST ridge. The tropical edge interacts with extratropical variability, specifically the Southern Annular Mode (SAM).

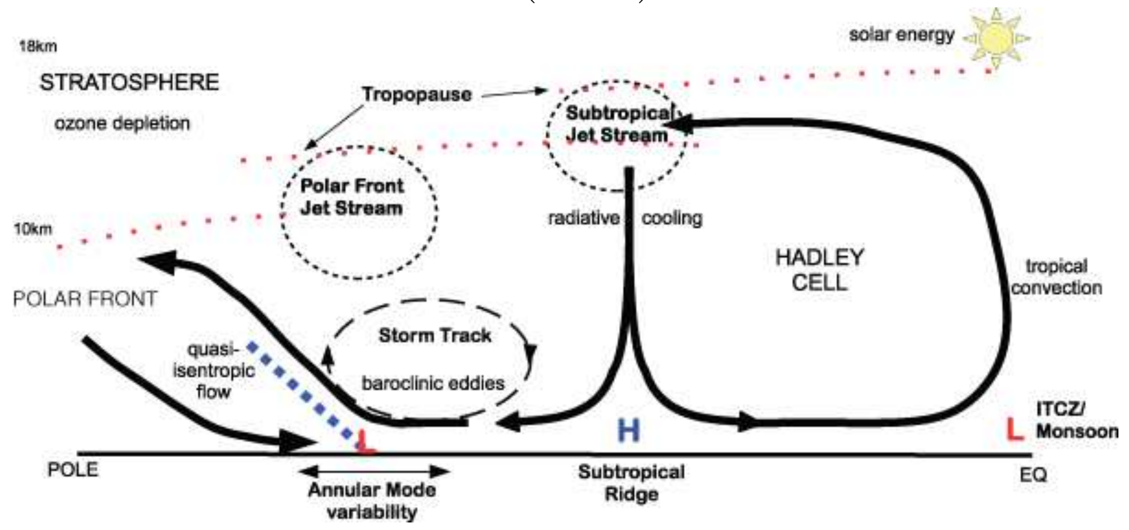

Fig. 1: Troposphere mean meridional circulation [1].

Aim: to identify observed relationships between Southern Hemisphere tropical edge metrics and test if CMIP5 models can reproduce the observed relationships in order to identify potential reasons for why the modelled expansion rate is slow. We focus on unforced interannual variability and the annual cycle. We do not consider the forced greenhouse gas response.

2) Idealised models of Hadley Circulation

Two limiting cases are widely used to explain the Hadley cell (HC) behaviour and to interpret changes in circulation.

The nearly inviscid limit of Held and Hou (1980) [2]:

- local $R_0 \approx 1$ (eddy momentum flux divergence ≈ 0)
- assumes thermal wind balance and conservation of absolute angular momentum
- HC edge occurs where radiative heating balances cooling

The eddy permitting limit of Held (2000) [3]:

- local $R_0 \approx 0$
- assumes momentum gained in tropics (easterly eddies) balanced by mid-latitude momentum loss (westerly eddies)
- HC edge where shear becomes baroclinically unstable

3) Expected Relationships

Winter:

- inviscid limit applies [4]
- poleward displaced HC edge linked to *stronger* ST jet in order to conserve momentum
- eddy and subtropical jets are well separated due to equatorward edge of HC in seasonal cycle favouring a double jet structure

Summer:

- eddy-driven limit applies [4]
- poleward displaced HC edge linked to *weaker* ST jet due to surface drag strengthening HC and reducing shear to maintain baroclinicity
- eddy and subtropical jets *not* well separated and HC edge nearer mid-lats favouring a single jet structure

Annually:

- poleward ST jet, poleward ridge and +SAM (contracted westerlies) associated with a poleward HC edge
- strong ridge associated with poleward ridge
- idealised study shown during +SAM a fast single jet is favoured and SAM describes pulsing of the single jet [5]. Likewise, -SAM linked to slower and double jet structure and SAM describes the eddy-driven jet position.
- +SAM linked to weak ST jet

4) Method and Data

The relationships are investigated using a multivariate linear independence approach [6]. The method:

- select candidate time series,
- calculate the partial correlation matrix,
- set the smallest non-significant element to zero, and
- recalculate the matrix until all links are significant.

The resulting partial matrix distinguishes between direct and indirect interactions between input timeseries (metrics). Non-significant links are conditionally independent.

The multivariate linear independence model is applied to 30 years of monthly Era–Interim and a subsets of CMIP5 models:

- UK: HadGEM2-ES (H)
- AUS: ACCESS1.0 (A)
- USA: CCSM4.0 (C)
- RUS: INM-CM4.0 (I)

5) Key Results: Covariability

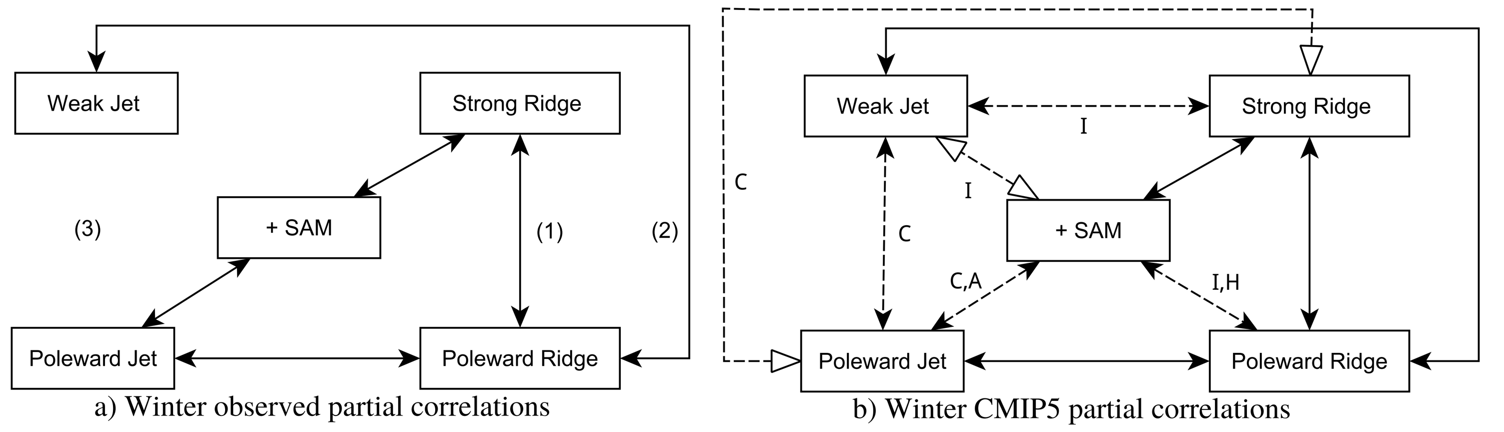

Fig. 2: Partial correlations between tropical edge metrics in Austral winter (JJA). Dashed lines are links only found in some CMIP5 models. Open arrows indicate reverse relationship.

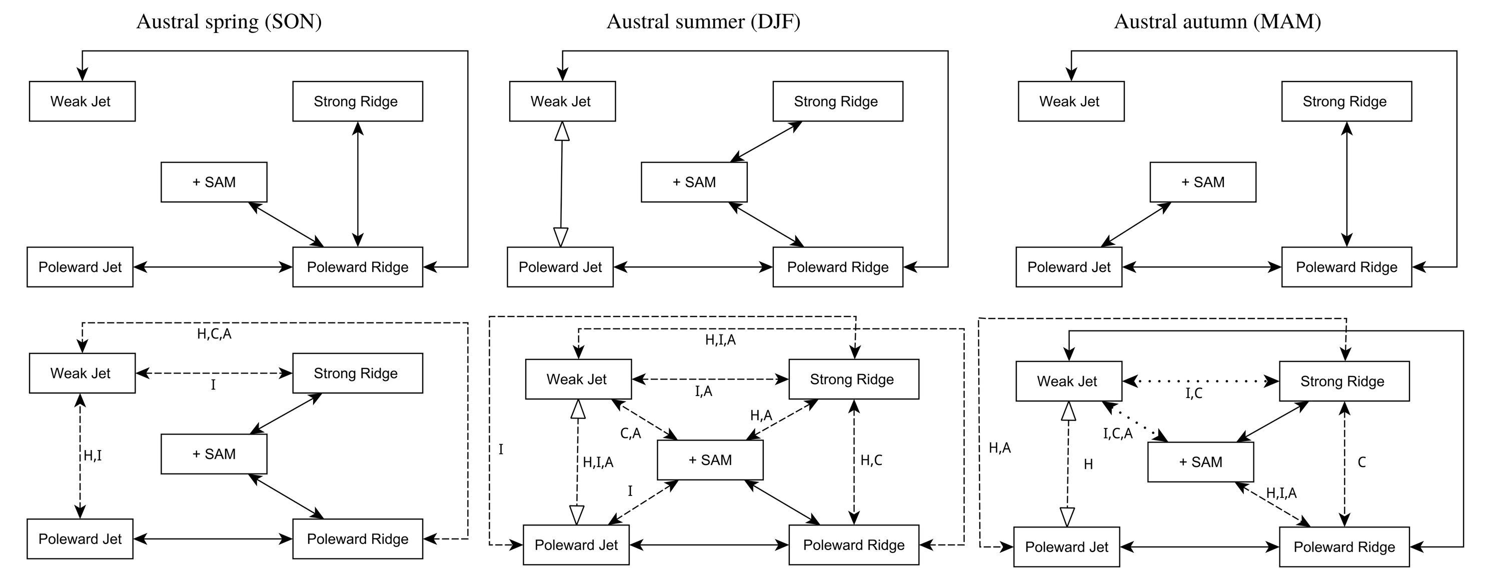

Fig. 3: As in Fig. 2 for seasons other than winter. Dotted lines link nodes with inconsistent signs for the model partial correlations. Panel arrangement transposed.

1. Ridge position plays a central role in joining tropical edge metrics
   (a) poleward ridge is strong (link 1) only captured models during JJA
   (b) poleward ridge and weak ST jet (link 2)
   (c) ST jet intensity is conditionally independent of its position (link 3) suggests no dominant interaction (likely opposing correlations)
   (d) intensities of ST jet and ridge are conditionally independent suggests variability is not, to first order, due to variability in the HC strength
   (e) the above are found in all seasons and generally well captured by each model
2. ST jet intensity is conditionally independent of the SAM in all seasons
3. SAM interactions with ST jet and ridge vary seasonally and modelled SAM accounts for too much variability (excessive links)

6) Interpretation

Q1. Why is a weak ST jet linked to a poleward ridge but not a poleward ST jet (links 2 and 3)?

– Poleward HC edge associated with weakening of ST jet in eddy–driven limit but this is expected in summer. Why is this found in all seasons and what is different in summer?

– This work is ongoing. We plan to look at the baroclinic instability at the latitude of the ST jet.

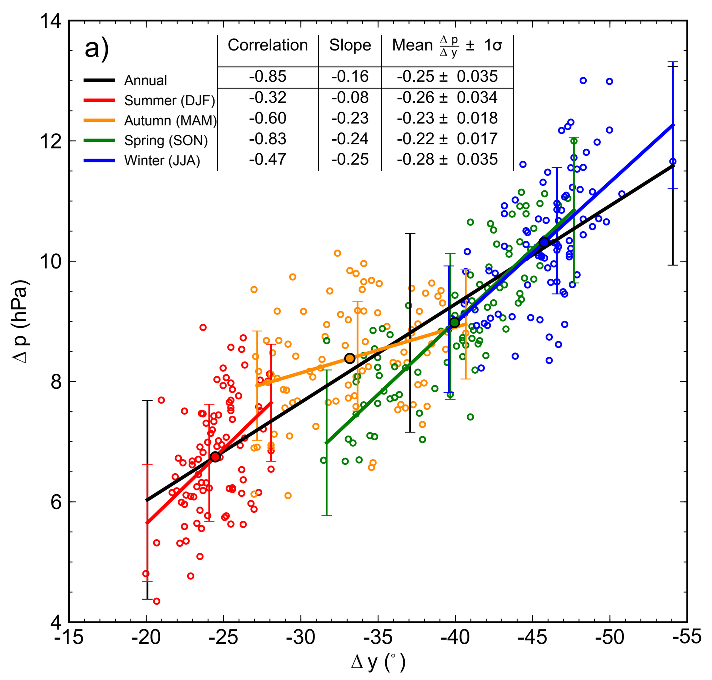

Fig. 4: Pressure difference (Δp) between ITCZ and ridge positions (Δy). Closed markers are seasonal mean. This figure relates to Q2.

Q2. Why is a poleward ridge strong (link 1)?

Hypothesis: Meridional momentum balance alone can explain why a poleward ridge is strong. Test a scaling relation assuming a meridional steady state, Rayleigh friction and no eddies:

$$\frac{dv}{dt} = -\frac{1}{\rho_0}\frac{\partial \bar{p}}{\partial y} - f\bar{u} - \alpha\bar{v} = 0$$

Assume overturning and zonal wind are unrelated to HC width, integrate wrt y and taking the total derivative gives:

$$\frac{Dp_r}{Dy_r} = \frac{\Delta p}{\Delta y} = \frac{\bar{p}_r - \bar{p}_i}{\bar{y}_r - \bar{y}_i}$$

The change in pressure (Dp_r) and position of ridge (Dy_r) is given by HC pressure difference (Δp) and width (Δy).

- Annual mean $\frac{\Delta p}{\Delta y} = -0.25$ hPa$^{\circ -1}$
- Seasonal slopes not significantly different to annual
- Seasonal means located on annual mean slope
- Scaling does a good job of predicting the pressure difference between the ITCZ and ridge based on their latitude

7) Conclusions

1. Ridge position joins tropical edge metrics. A strong ridge is located poleward in observations but poorly represented in models (except winter). Their relationship is explained using a simple scaling mechanism based on meridional momentum balance.
2. CMIP5 models capture many aspects of observed variability. Some model specific problems exist especially in summer autumn.
3. Weakening of ST jet with a poleward HC is consistent with eddy-driven limit in all seasons but with subtle summer difference.
4. Links with SAM vary with season. The SAM does not interact with ST jet intensity in any season. SAM accounts for too much of the tropical edge variability in the models.

References

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