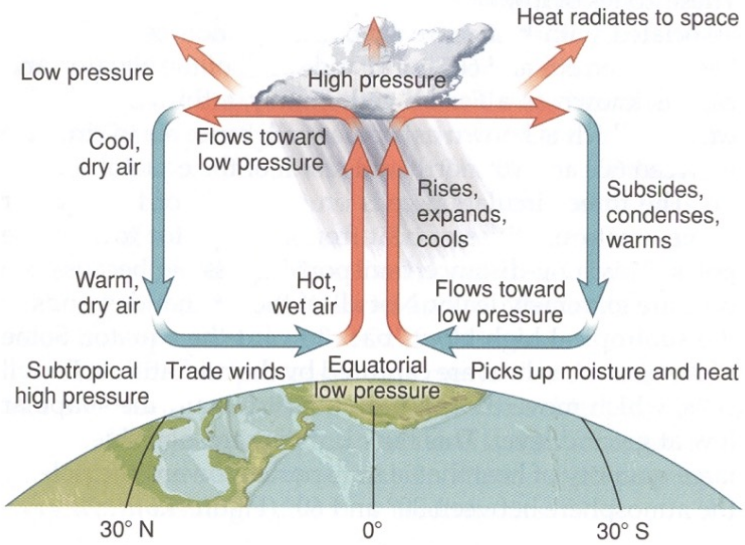
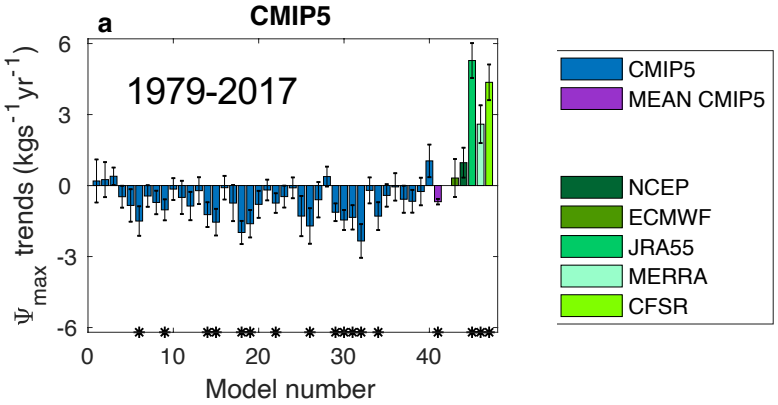
Historical Hadley circulation changes: resolving the model-reanalysis discrepancy



In collaboration with Janni Yuval (Google) and Kevin Grise (U. Virginia)

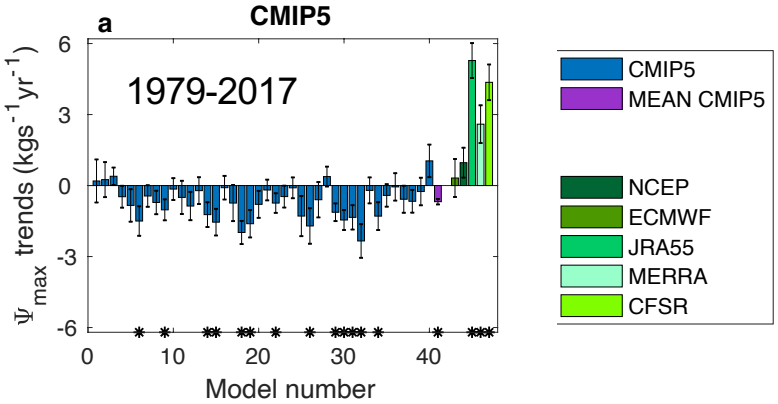
While CMIP5 models show a weakening of the circulation, all reanalyses show a strengthening over the last four decades



Chemke and Polvani, *Nature Geoscience*, 2019

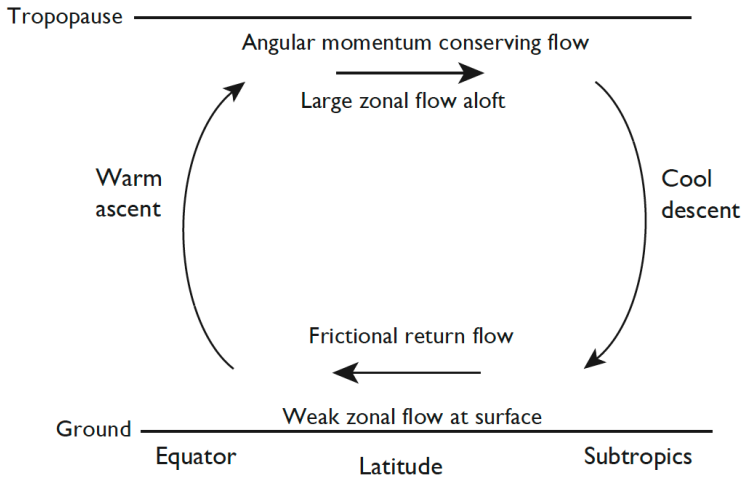
While CMIP5 models show a weakening of the circulation, all reanalyses show a strengthening over the last four decades

- Large uncertainty in recent Hadley cell changes
  - What is role of human emissions in recent Hadley cell changes?
  - How confident we are in tropical climate projections?



Chemke and Polvani, *Nature Geoscience*, 2019

Observational constraint on the Hadley cell strength



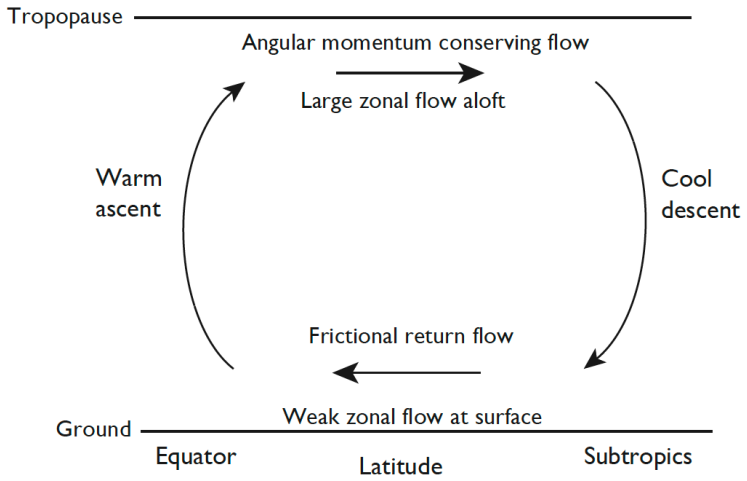
Vallis, 2006

Observational constraint on the Hadley cell strength

Lower branch of the HC

Zonal and time mean zonal momentum eq:

$$f\overline{v} \approx r\overline{u}$$



Vallis, 2006

Observational constraint on the Hadley cell strength

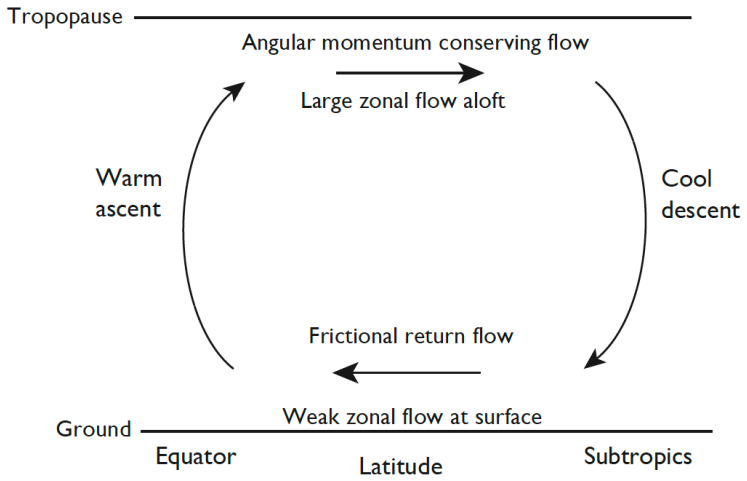
Lower branch of the HC

Zonal and time mean zonal momentum eq:

$$f\overline{v} \approx r\overline{u}$$

Vertical integral from the surface to 500mb:

$$f\Psi_{500} \propto -r\overline{u_{\mathrm{sfc}}}$$



Vallis, 2006

Observational constraint on the Hadley cell strength

Lower branch of the HC

Zonal and time mean zonal momentum eq:

$$f\overline{v} \approx r\overline{u}$$

Vertical integral from the surface to 500mb:

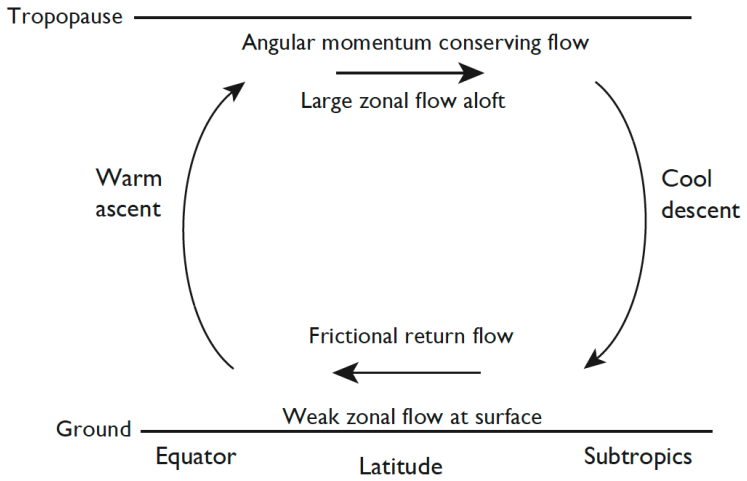
$$f\Psi_{500} \propto -r\overline{u_{\mathrm{sfc}}}$$

Near surface

Zonal and time mean of the meridional momentum eq

Frictional-geostrophic balance:

$$f\overline{u_{\mathrm{sfc}}} \approx -\frac{1}{\rho}\frac{\partial\overline{\mathrm{PSL}}}{\partial y} - r\overline{v_{\mathrm{sfc}}}$$



Vallis, 2006

Observational constraint on the Hadley cell strength

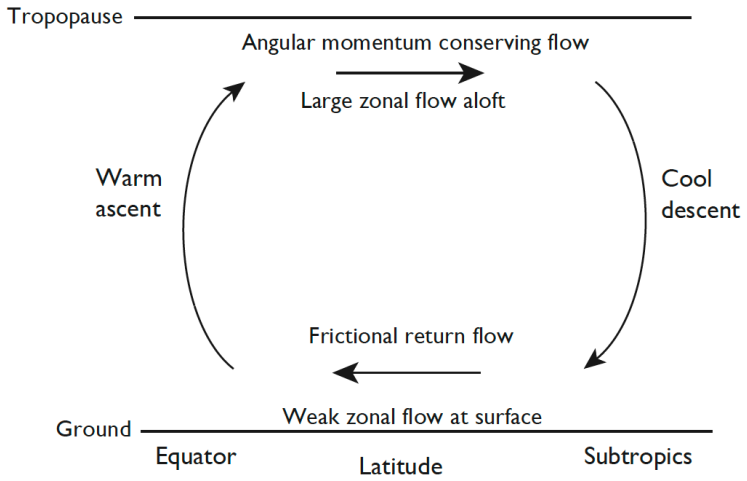
Lower branch of the HC

Zonal and time mean zonal momentum eq:

$$f\overline{v} \approx r\overline{u}$$

Vertical integral from the surface to 500mb:

$$f\Psi_{500} \propto -r\overline{u_{\mathrm{sfc}}}$$



Vallis, 2006

Near surface

Zonal and time mean of the meridional momentum eq

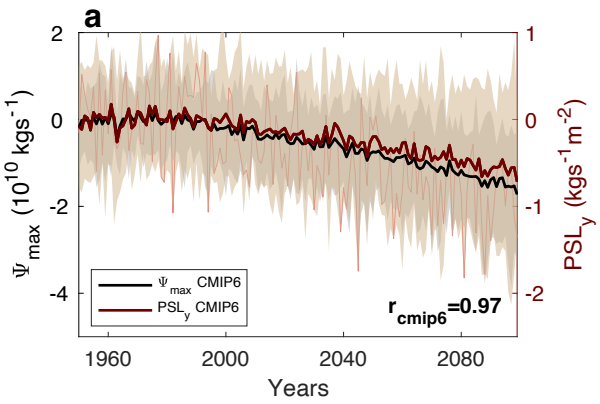
Frictional-geostrophic balance:

$$f\overline{u_{\mathrm{sfc}}} \approx -\frac{1}{\rho}\frac{\partial\overline{\mathrm{PSL}}}{\partial y} - r\overline{v_{\mathrm{sfc}}}$$

$$\Psi_{500} \propto \frac{1}{|f|}\frac{\partial \mathrm{PSL}}{\partial y}$$

Observational constraint on the Hadley cell strength

- The meridional gradient of sea-level pressure in models adequately captures the changes in the Hadley cell edge in recent and coming decades

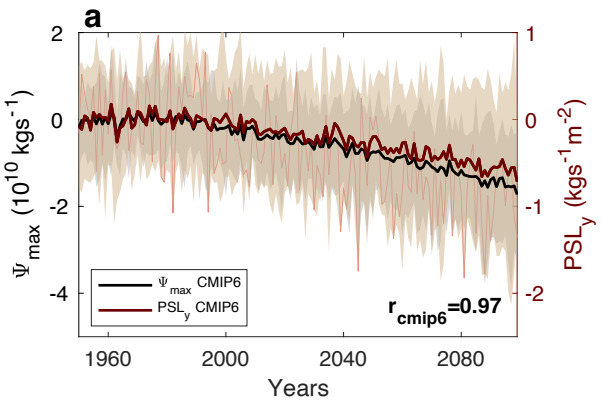


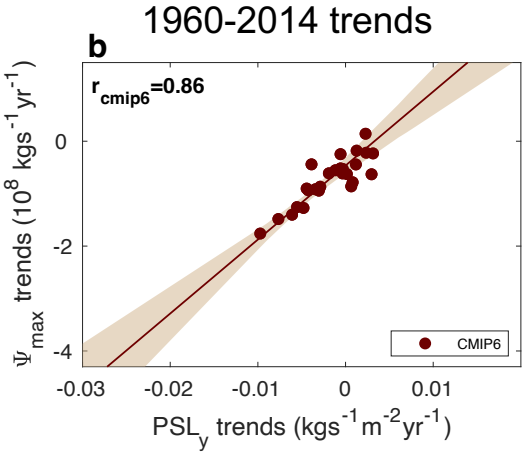
$$\Psi_{500} \propto \frac{1}{|f|}\frac{\partial \mathrm{PSL}}{\partial y}$$

Chemke and Yuval, Nature 2023

Observational constraint on the Hadley cell strength

- The meridional gradient of sea-level pressure in models adequately captures the changes in the Hadley cell edge in recent and coming decades





$$\Psi_{500} \propto \frac{1}{|f|}\frac{\partial \mathrm{PSL}}{\partial y}$$

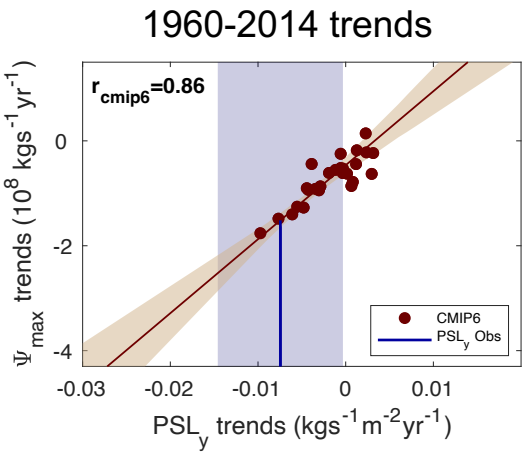
Chemke and Yuval, Nature 2023

Observational constraint on the Hadley cell strength

- Emergent constraint analysis

- Exploit the strong linear relation, which stems from the momentum equations, between the Hadley cell strength and sea level pressure gradient
- Use the observed trend to constrain the observed Hadley cell strength trend

Observations
CMIP6



$$\Psi_{500} \propto \frac{1}{|f|}\frac{\partial \mathrm{PSL}}{\partial y}$$

Chemke and Yuval, Nature 2023

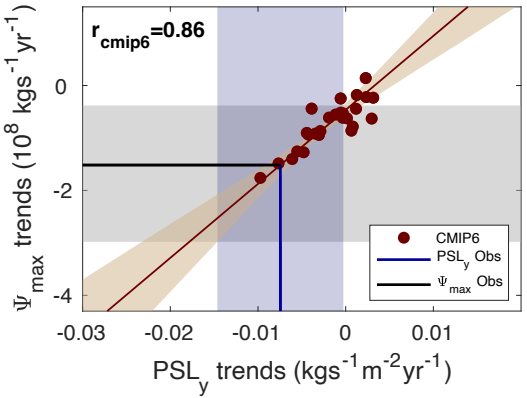
Observational constraint on the Hadley cell strength

Emergent constraint analysis

- Based on sea level pressure measurements, the Hadley cell has been weakening in recent decades
- The consistent weakening of the circulation as inferred from observations and climate models increases our confidence in the model-projected weakening of the flow in coming decades

Observations
CMIP6

1960-2014 trends



$$\Psi_{500} \propto \frac{1}{|f|}\frac{\partial \mathrm{PSL}}{\partial y}$$

Chemke and Yuval, Nature 2023

Could the recent weakening of the Hadley circulation be attributed to anthropogenic emissions?

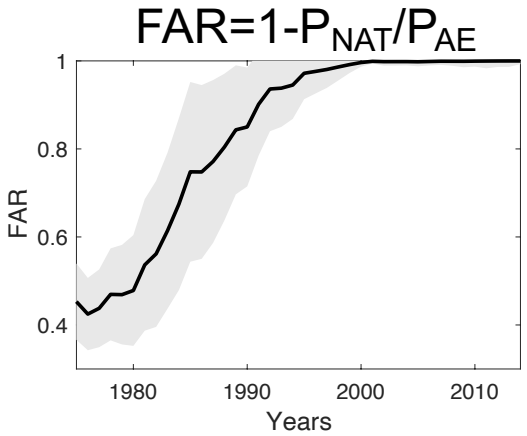
Fractional Attributional Risks (FAR) analysis

- Calculate, for each year, the observed trend since 1960
- Estimate the probability of having such a trend across CMIP6 simulations with (P_{AE}) and without (P_{NAT}) anthropogenic emissions

Could the recent weakening of the Hadley circulation be attributed to anthropogenic emissions?

Fractional Attributional Risks (FAR) analysis

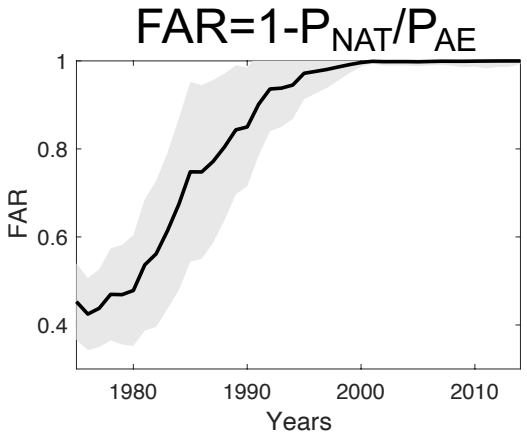
- Calculate, for each year, the observed trend since 1960
- Estimate the probability of having such a trend across CMIP6 simulations with (P_{AE}) and without (P_{NAT}) anthropogenic emissions
- Since the early 00's FAR has exceeded a value of 0.99



Could the recent weakening of the Hadley circulation be attributed to anthropogenic emissions?

Fractional Attributional Risks (FAR) analysis

- Calculate, for each year, the observed trend since 1960
- Estimate the probability of having such a trend across CMIP6 simulations with (P_{AE}) and without (P_{NAT}) anthropogenic emissions
- Since the early 00's FAR has exceeded a value of 0.99
- We have high confidence (of more than 99%) that the recent weakening is attributed to anthropogenic emissions
- Human emissions have increased the probability of observing such a trend by a factor of ~100 over this period



Observational constraint on the Hadley cell

Lower branch of the HC

Zonal and time mean zonal momentum eq:

$$f\overline{v} \approx r\overline{u}$$

Vertical integral from the surface to 500mb:

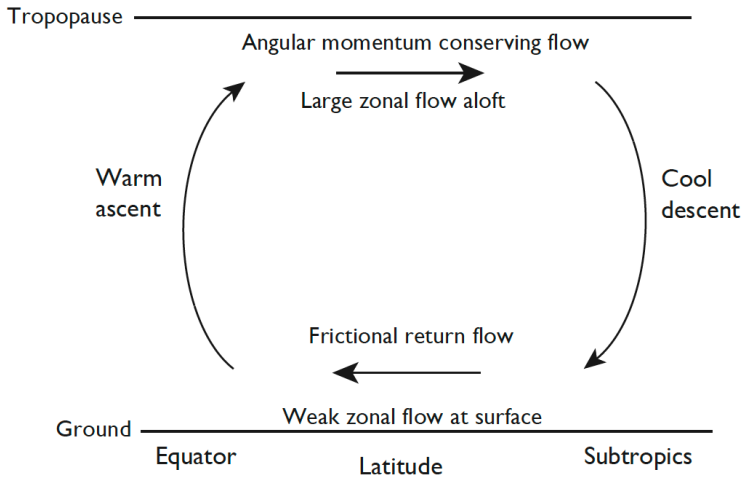
$$f\Psi_{500} \propto -r\overline{u_{\mathrm{sfc}}}$$

Near surface

Zonal and time mean of the meridional momentum eq

Frictional-geostrophic balance:

$$f\overline{u_{\mathrm{sfc}}} \approx -\frac{1}{\rho}\frac{\partial\overline{\mathrm{PSL}}}{\partial y} - r\overline{v_{\mathrm{sfc}}}$$

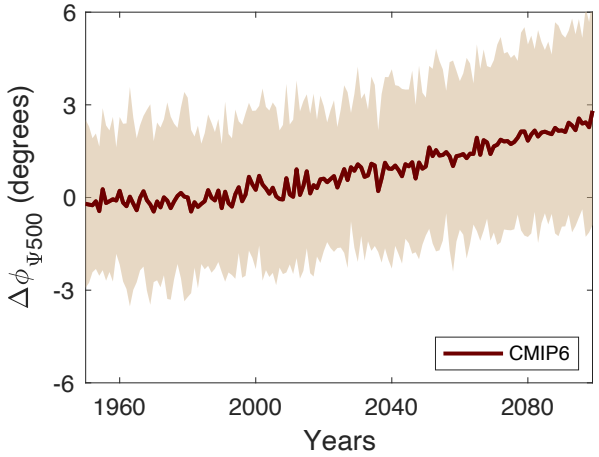


Vallis, 2006

$$\Psi_{500} \propto \frac{1}{|f|}\frac{\partial\mathrm{PSL}}{\partial y}$$

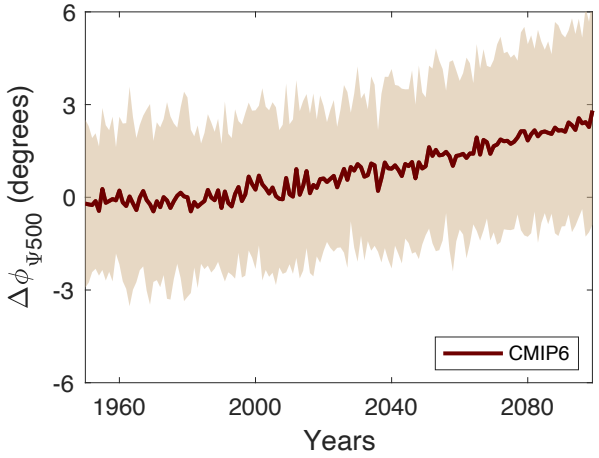
Constraining the Hadley cell edge

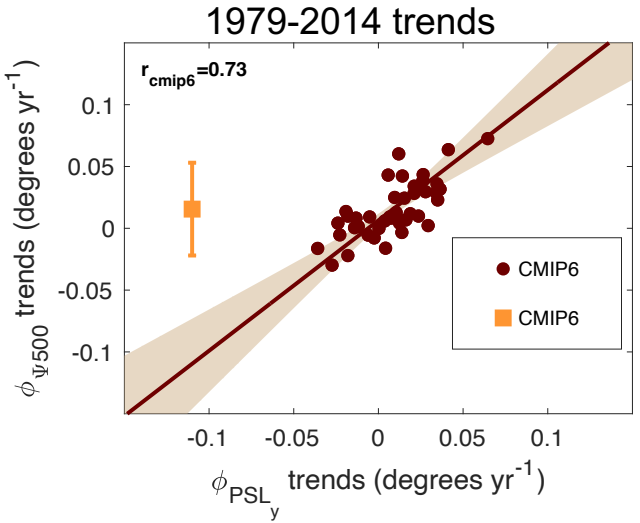
- The Hadley cell edge is projected to shift poleward by the end of this century



Constraining the Hadley cell edge

- The meridonal gradient of sea-level perssure in models adequatley captures the changes in the Hadley cell strength in recent and coming decades

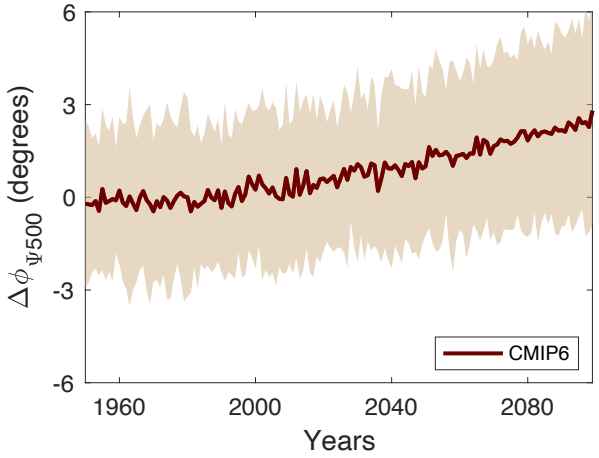


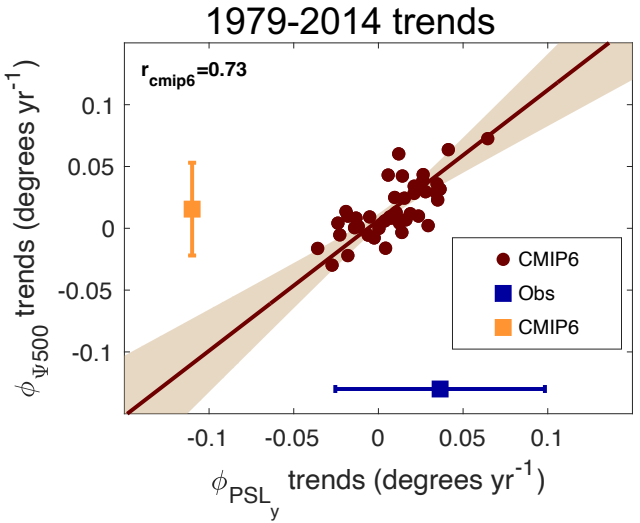


Constraining the Hadley cell edge

- Emergent constraint analysis

- Exploit the strong linear relation, which stems from the momentum equations, between the Hadley cell edge and sea level pressure gradient
- Use the observed trend to constrain the observed Hadley cell edge trend

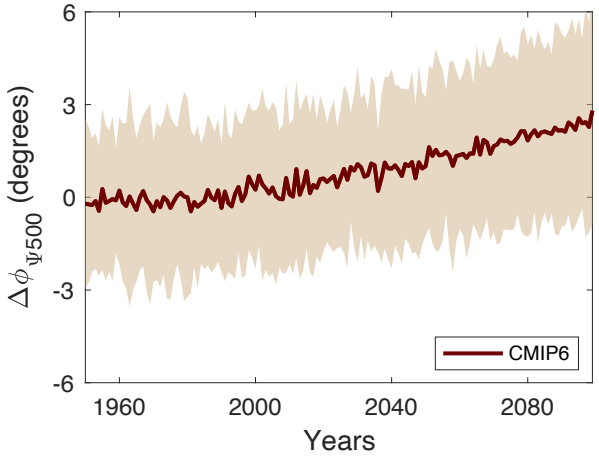


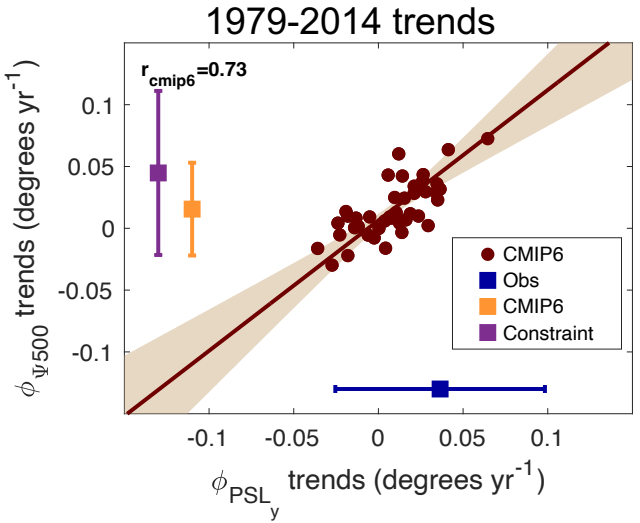


Constraining the Hadley cell edge

Emergent constraint analysis

- Based on sea level pressure measurements, the Hadley cell edge has been shifting poleward in recent decades

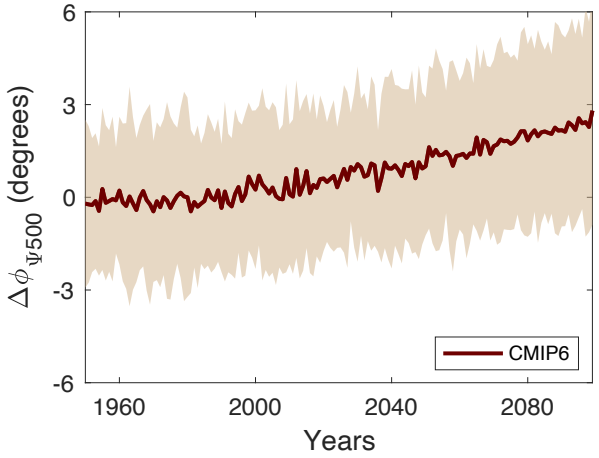


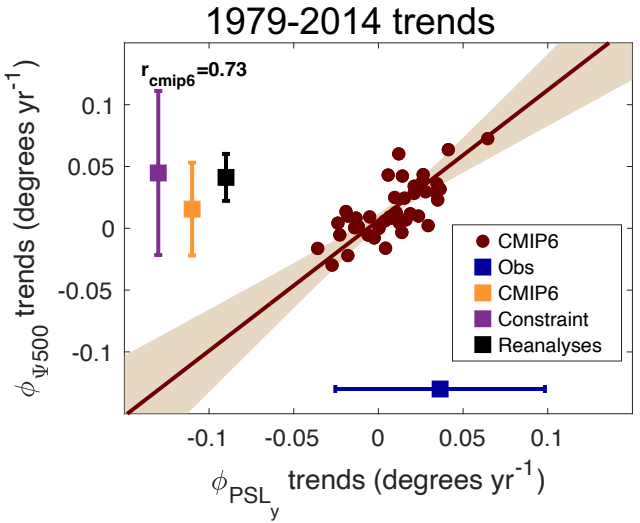


Constraining the Hadley cell edge

Emergent constraint analysis

- Based on sea level pressure measurements, the Hadley cell edge has been shifting poleward in recent decades
- The consistent shift of the circulation as inferred from observations, reanalyses, and climate models increases our confidence in the historical and model-projected shift of the flow





Could the recent poleward shift of the Hadley circulation be attributed to anthropogenic emissions?

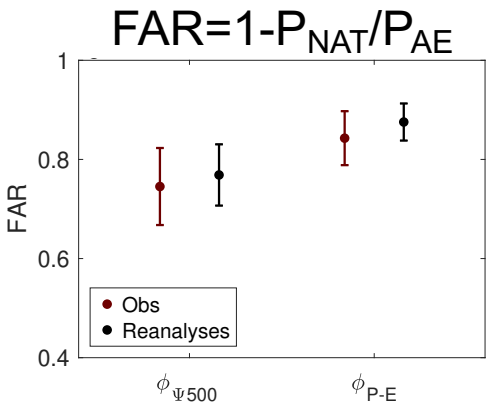
Fractional Attributional Risks (FAR) analysis

- Estimate the probability of having such a trend across CMIP6 simulations with (P_{AE}) and without (P_{NAT}) anthropogenic emissions

Could the recent poleward shift of the Hadley circulation be attributed to anthropogenic emissions?

Fractional Attributional Risks (FAR) analysis

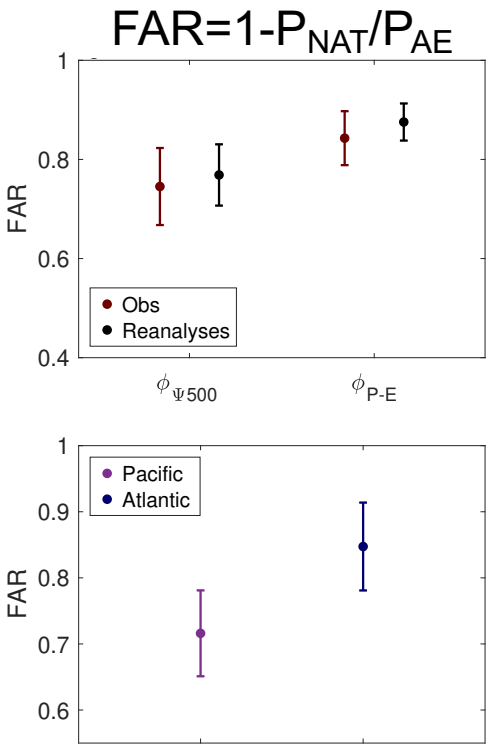
- By 2014, FAR has reached a value of 0.8
- There is an ~80% chance that the recent shift is attributed to anthropogenic emissions
- Human emissions have increased the probability of observing such a trend by a factor of ~5 over this period



Could the recent poleward shift of the Hadley circulation be attributed to anthropogenic emissions?

Fractional Attributional Risks (FAR) analysis

- By 2014, FAR has reached a value of 0.8
- There is an ~80% chance that the recent shift is attributed to anthropogenic emissions
- Human emissions have increased the probability of observing such a trend by a factor of ~5 over this period
- Regionally, the impact of anthropogenic emissions are evident over the Pacific and Atlantic basins



Main take-home messages

- Observation-based weakening of the circulation over recent decades
  - Attributed to anthropogenic emissions
  - Consistent with models but not with reanalyses
  - ❖ *Chemke and Yuval, Nature 2023*

Main take-home messages

- Observation-based weakening of the circulation over recent decades
  - Attributed to anthropogenic emissions
  - Consistent with models but not with reanalyses
  - ❖ *Chemke and Yuval, Nature 2023*

- Observation-based poleward shift of the Hadley cell edge over recent decades
  - Likely attributed to anthropogenic emissions
  - Consistent with models and reanalyses
  - ❖ *Chemke and Grise, 2025 (in revisions)*

Main take-home messages

- Observation-based weakening of the circulation over recent decades
  - Attributed to anthropogenic emissions
  - Consistent with models but not with reanalyses
  - ❖ *Chemke and Yuval, Nature 2023*

- Observation-based poleward shift of the Hadley cell edge over recent decades
  - Likely attributed to anthropogenic emissions
  - Consistent with models and reanalyses
  - ❖ *Chemke and Grise, 2025 (in revisions)*

Thank you