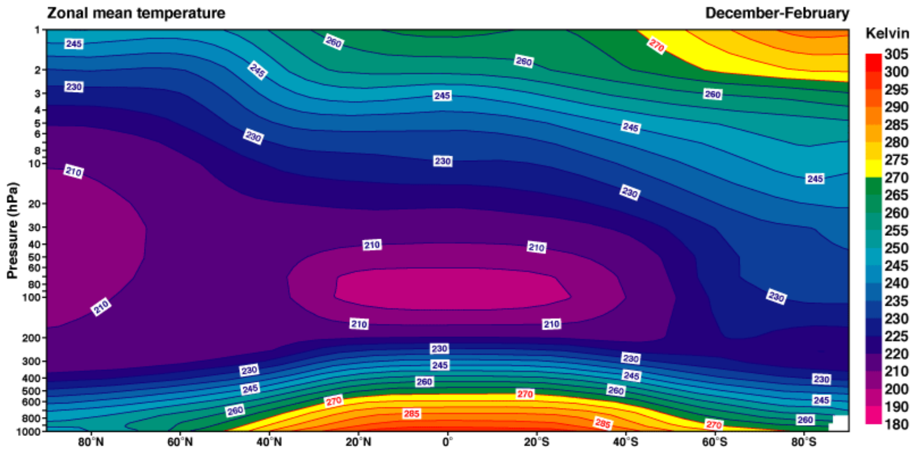
Climate change of sudden stratospheric warmings

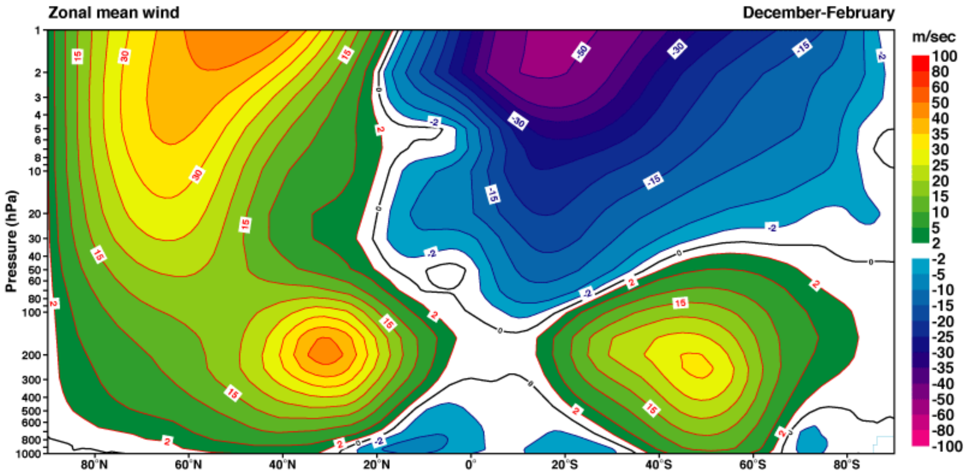
Structure

The stratospheric Polar Vortex

Temperatures in the lower stratosphere:

- Minimum at equator
- Maximum at pole in the summer hemisphere
- Maximum at 45° in the winter hemisphere, colder on the pole
- Thermal wind balance: easterly winds in summer
  strong westerly winds in winter

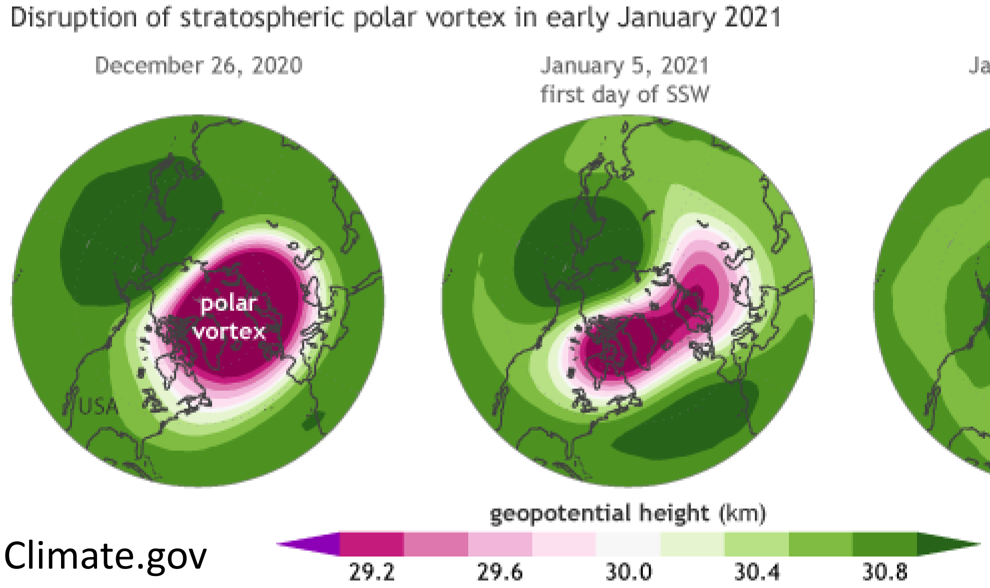




Sudden Stratospheric Warmings

Forming:

- Planetary wave propagates from troposphere upward
- Wave dissipates and easterly momentum is released
- Winds weaken, abrupt warming due to thermal wind balance
- Consequence: polar vortex displacement (moving away from pole to lower latitudes), polar vortex split (polar vortex is split into two separate vortices)
- Mainly in Northern Hemisphere due to orography and land-sea distribution
- About 6 SSWs/decade in NH and only 1 recorded SSW in SH in about 60 years of observations



Sudden Stratospheric Warmings

Classification:

Major Warming:

Reversal of zonal mean zonal wind in 10hPa at 60°(N)

WMO criterion:

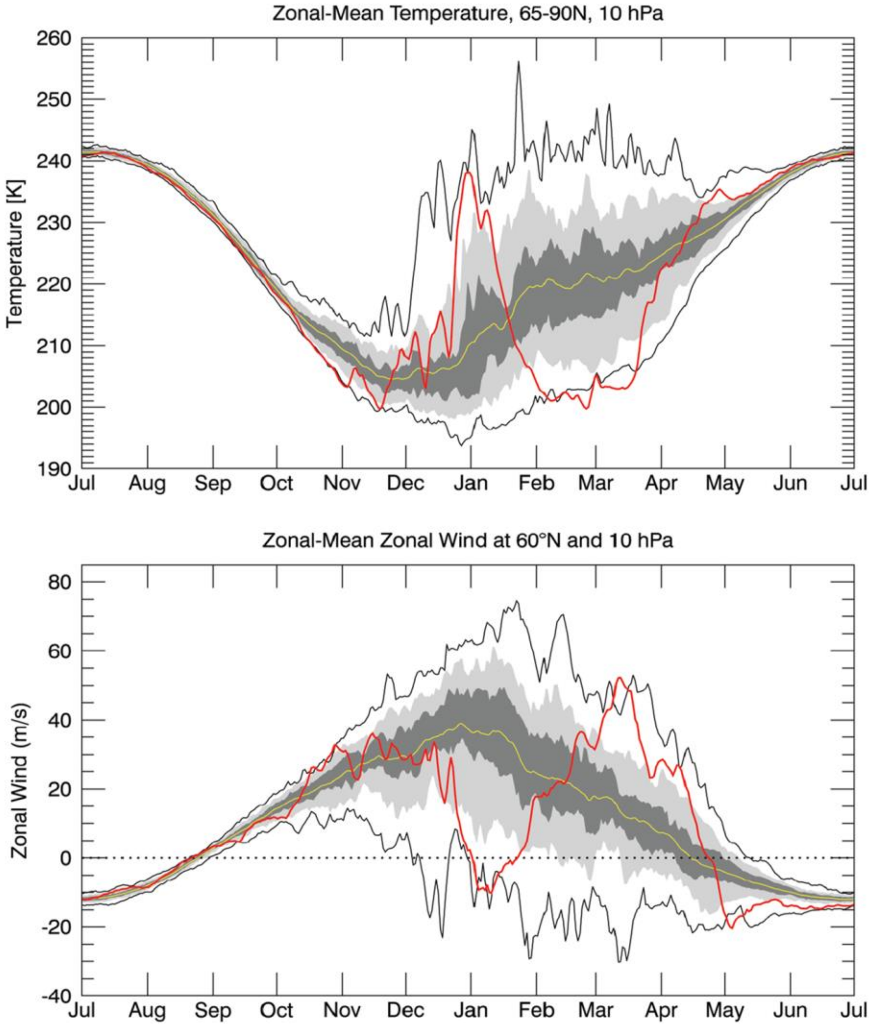
additional reversal of temperature gradient between 60°N and pole

Minor warming:

Significant warming and weakening of wind without wind reversal

Final warming:

Polar vortex winds returning to easterly winds for the entire summer

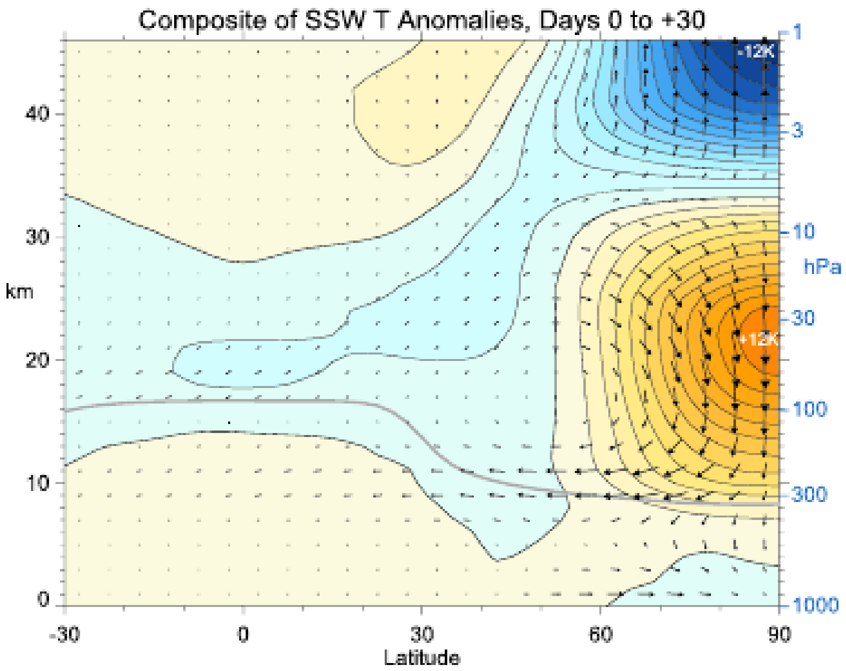


Impacts on Stratosphere

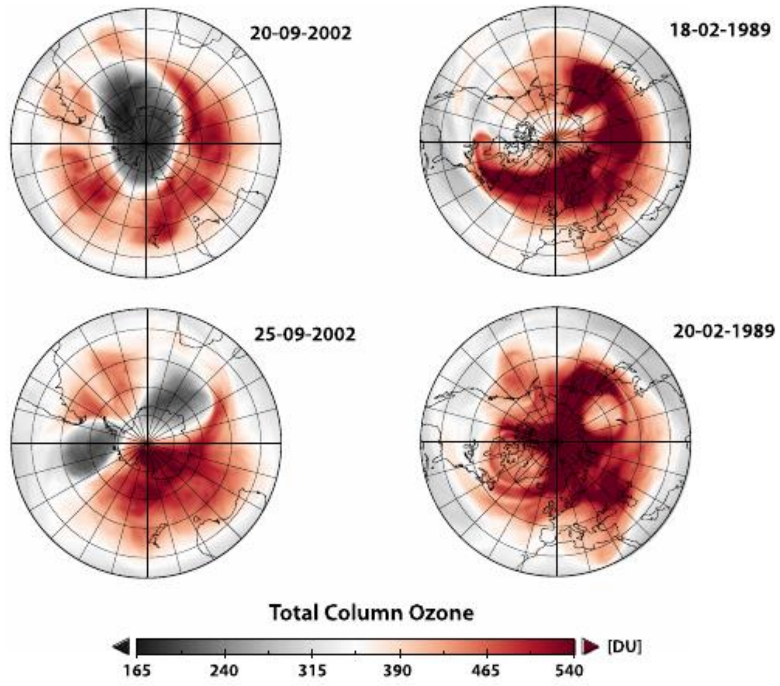
– Colder upper stratosphere due to reversed meridional circulation and resulting upward movement

– Opposite anomalies in midlatitude and tropical stratosphere (not so pronounced)

– Changed circulation patterns lead to increased total ozone column over the poles, especially well visible during southern hemisphere SSW in 2002



Shading shows zonal mean temperature anomalies 0-30 days after SSW, arrows indicate meridional circulation



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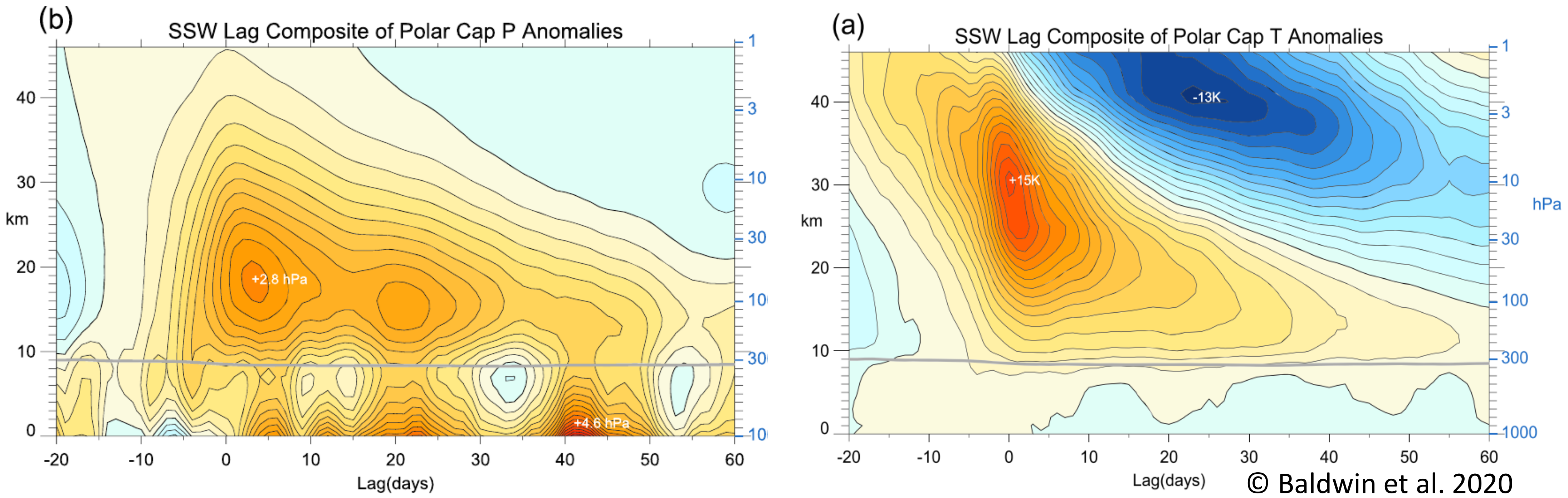
Stratosphere-Troposphere Coupling



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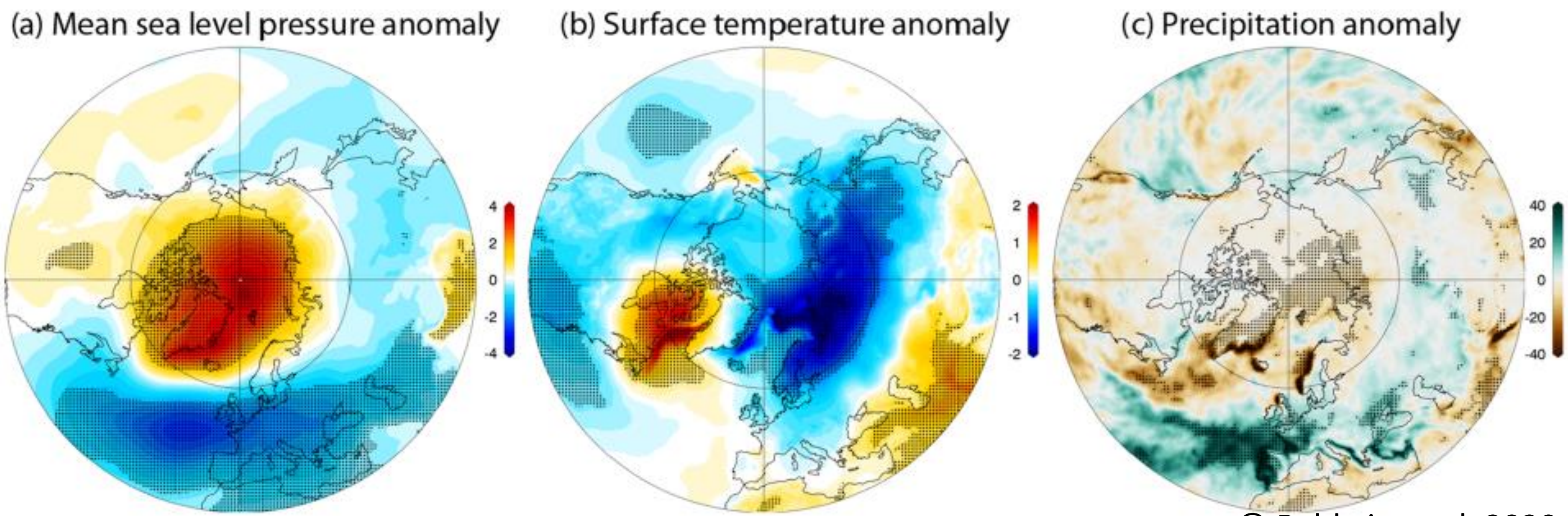
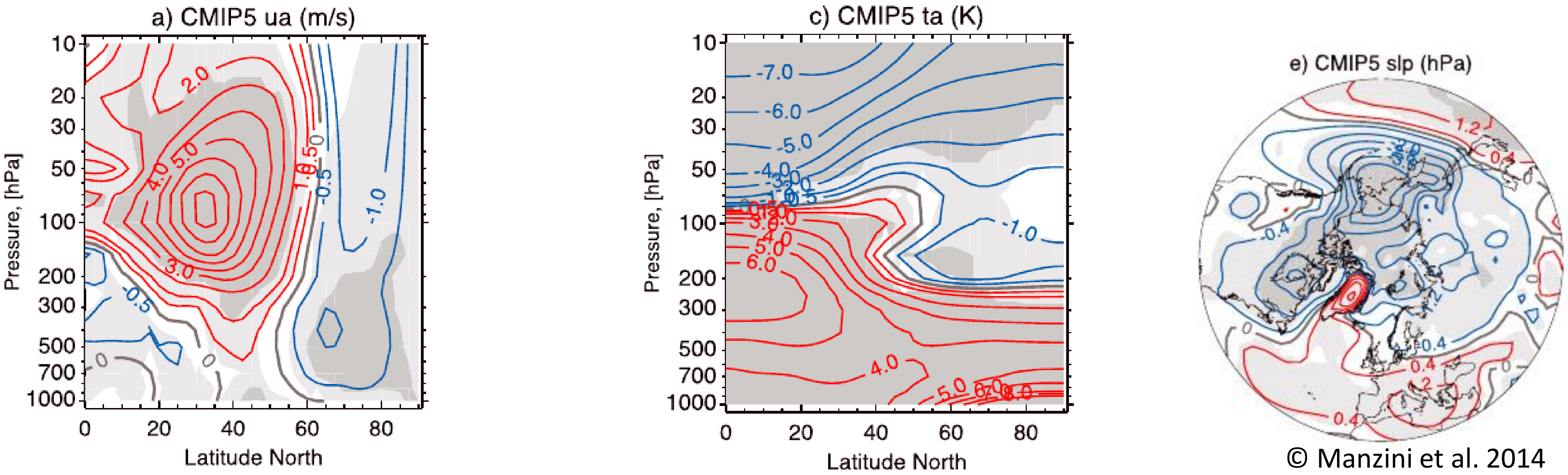
- Impact on the troposphere can last for up to 2 months
- Anomalies propagate downward
- About 2/3 of SSW have measurable impact on the troposphere

Impacts on Surface



- Higher sea level pressure over North Pole
- Lower pressure over mid-latitudes, especially Europe
- Results in a negative Northern Annular Mode and North Atlantic Oscillation
- Colder over Northern Eurasia, warmer over Eastern Canada and Greenland
- More precipitation over Southern and Western Europe, less over Northern Atlantic, polar regions, Northern Europe

Predicted changes in climate models



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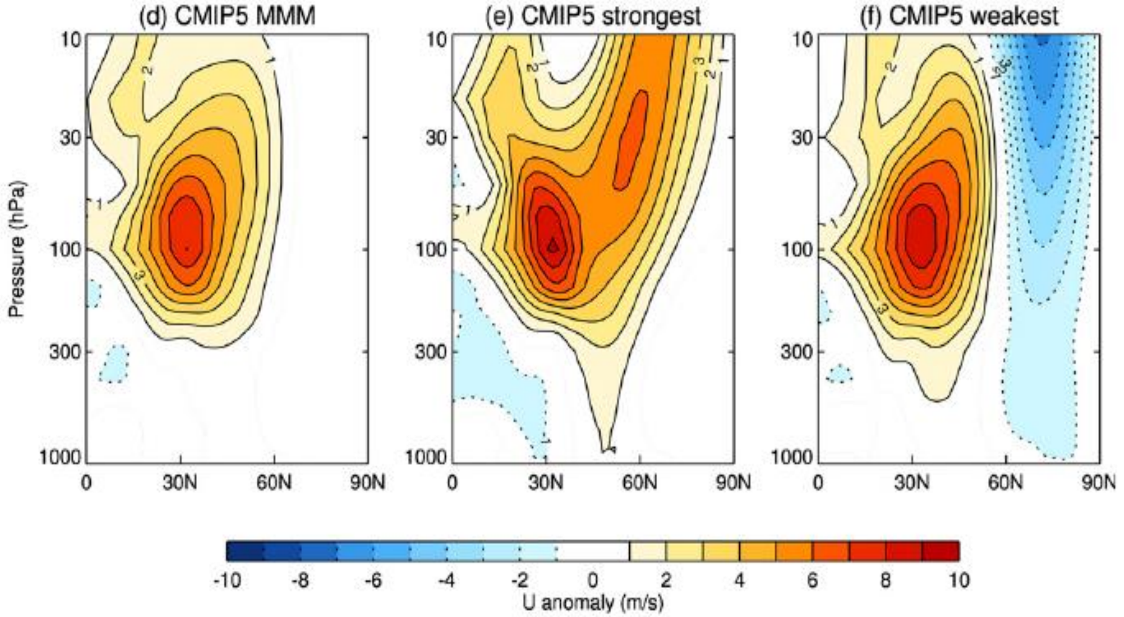
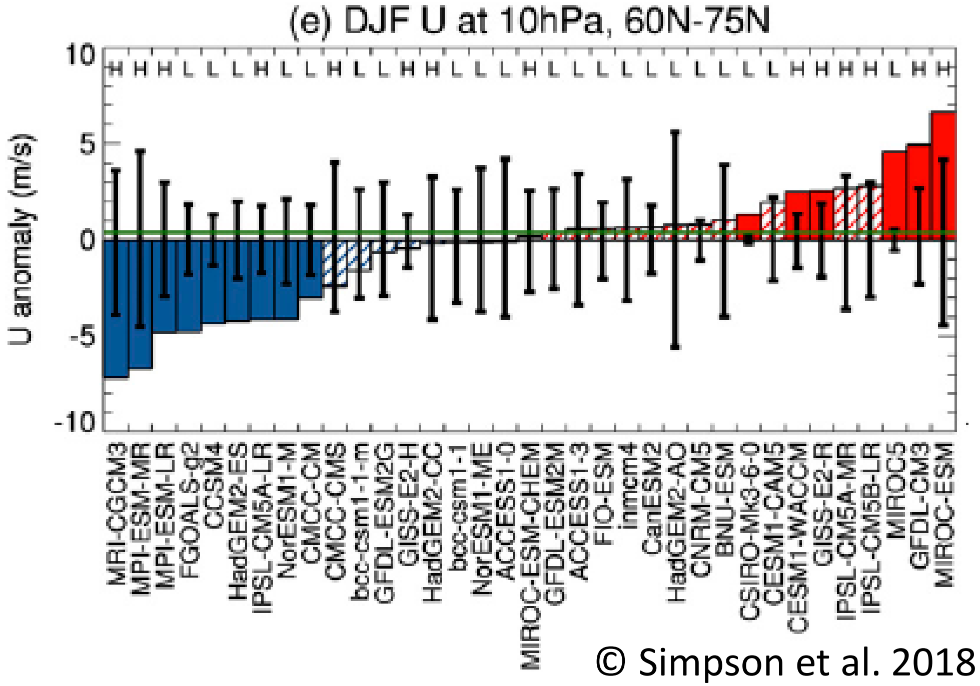
General changes (NH winter, CMIP5, RCP 8.5):

- Strengthening of lower to midlatitude zonal winds
- No clear sign for change of wind speed in higher latitude stratosphere
- Temperature increase in the troposphere, at the surface especially in the Arctic, at the equator especially in upper troposphere
- Temperature decrease in stratosphere
- Lower sea level pressure over Arctic, higher pressure over midlatitudes

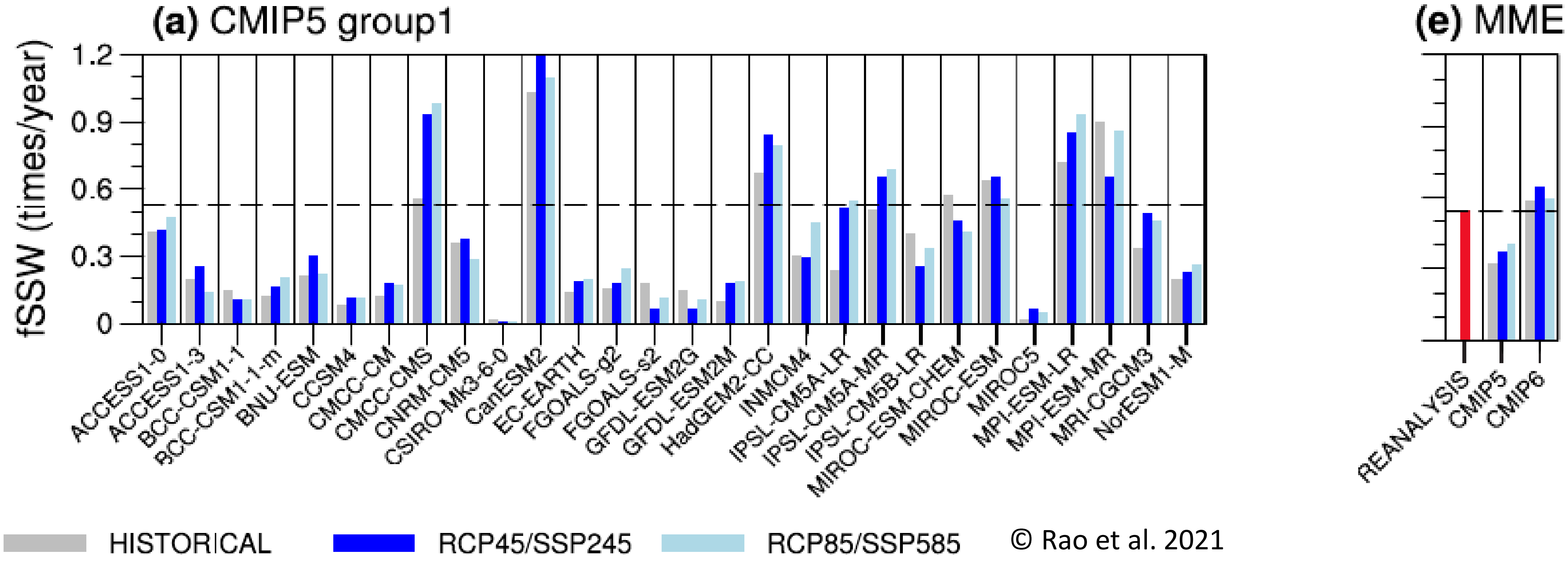
Changes in polar vortex wind speed





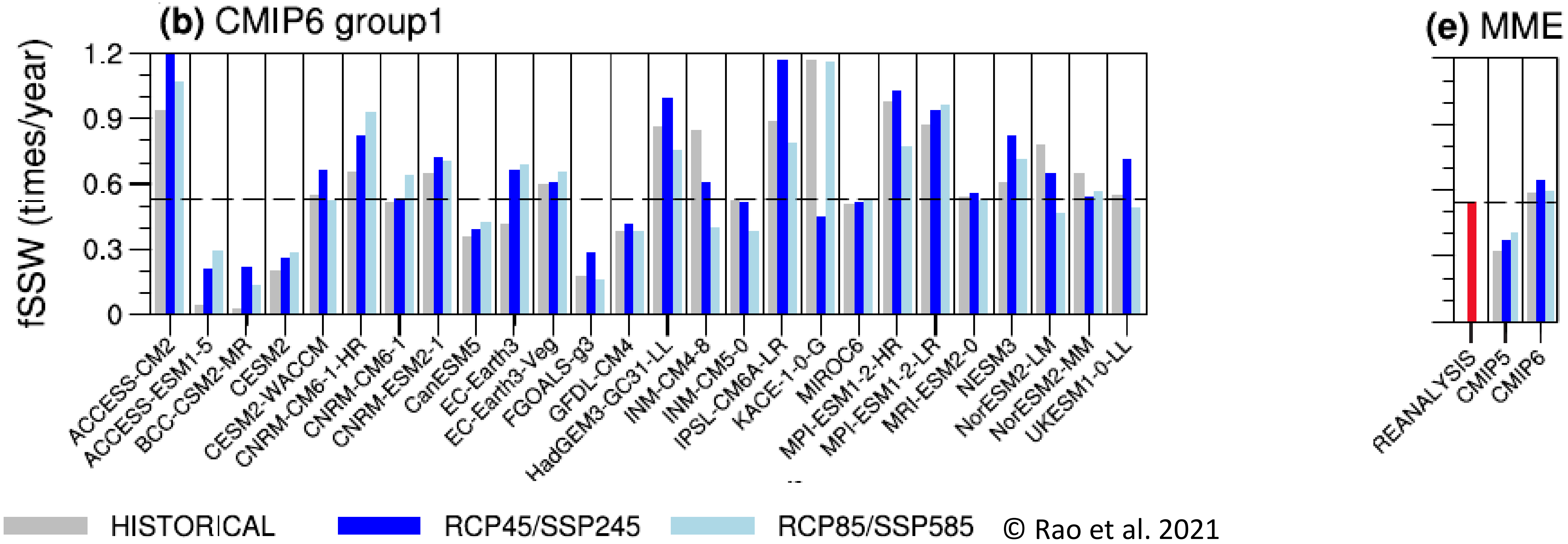
- Large spread in climate models(CMIP5, RCP8.5)
- models with significant strengthening and weakening of polar vortex winds in CMIP5 ensemble, but majority of models show no significant change

Changes in SSW frequency



- CMIP5: Large inter-model spread from almost no SSW to 1 per year
- Majority of models show less SSW than observed
- No clear signal for future changes: most models predict slight increase in frequency, but some also show a decrease

Changes in SSW frequency



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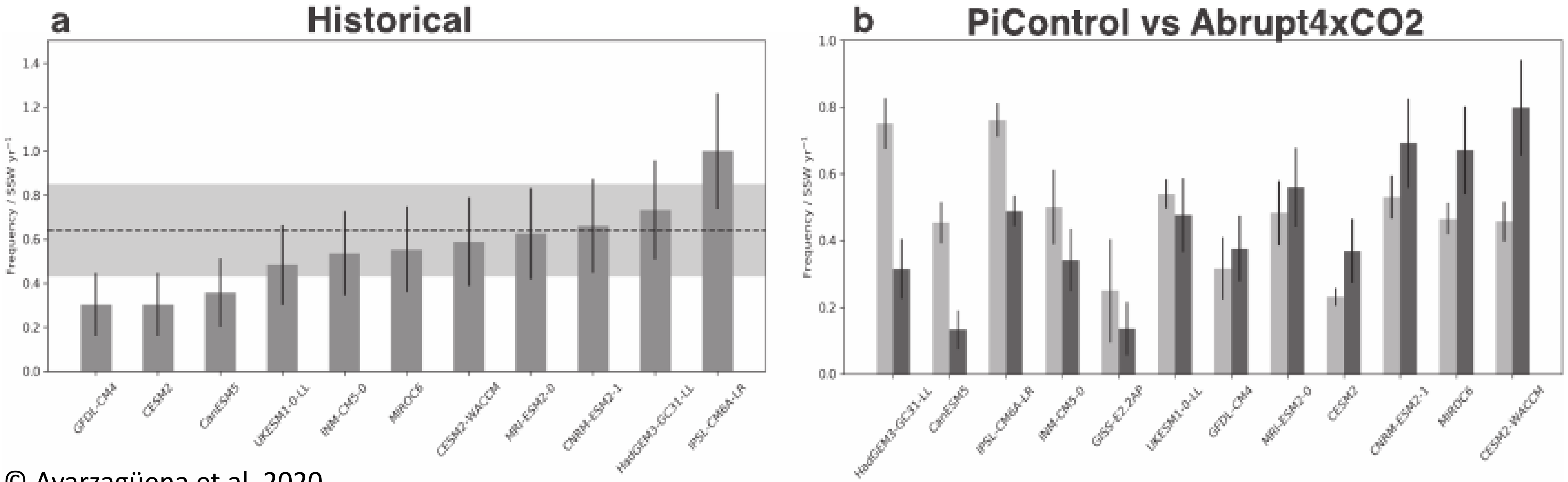
- CMIP6: large inter-model spread remains, generally closer to reanalysis
- Sign and magnitude of change (ensemble mean) similar compared to CMIP5 for RCP 4.5
- In RCP8.5 (SSP585) CMIP6 frequency decreases compared to RCP4.5, and no change compared to historical simulation

Changes in SSW frequency



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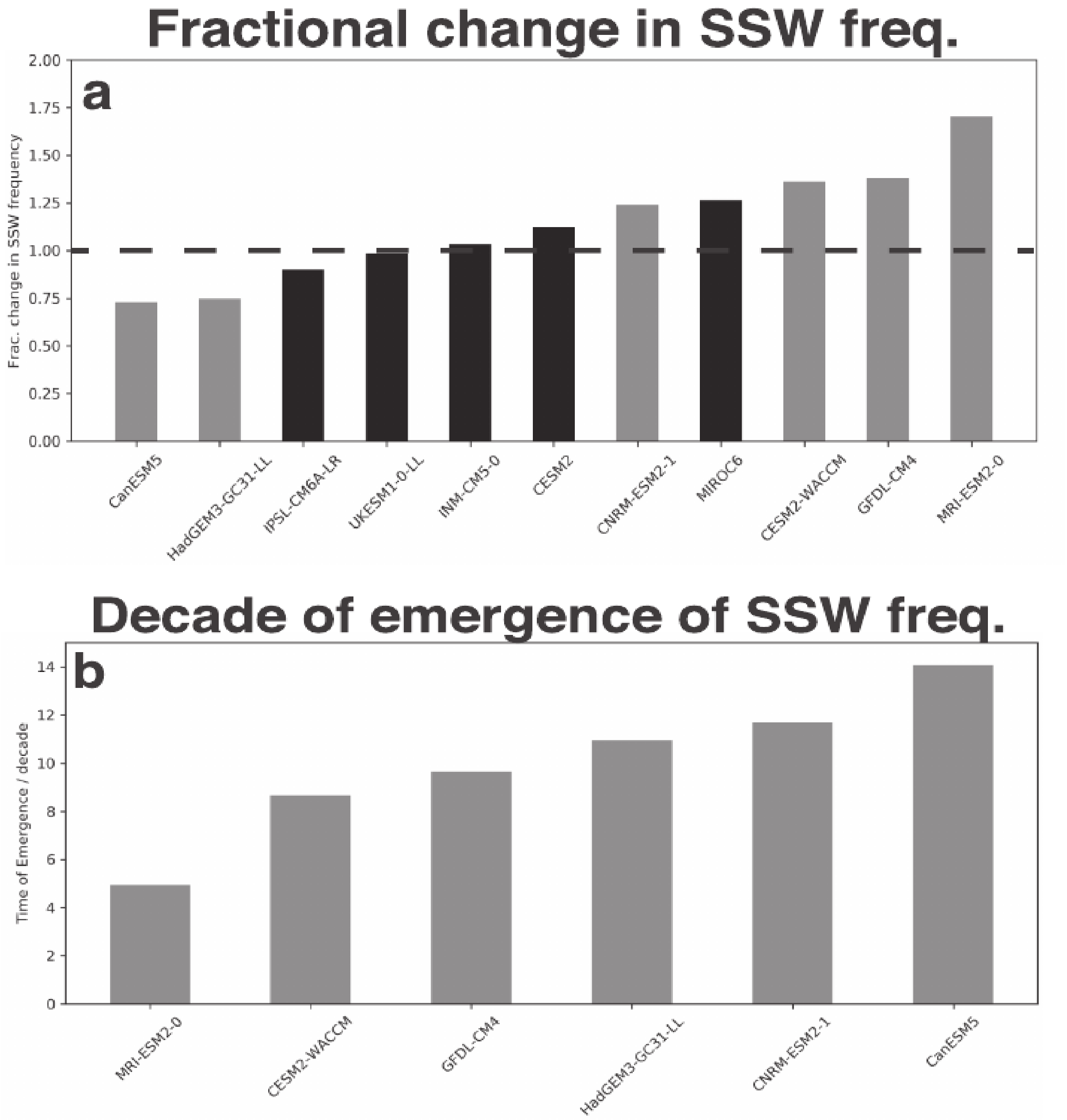
- CMIP 6, quadrupling of CO_2, simulation using 12 models
- 4models significant decrease, 4models significant increase, 4models no significant change → majority of models predict significant change but no consensus on direction

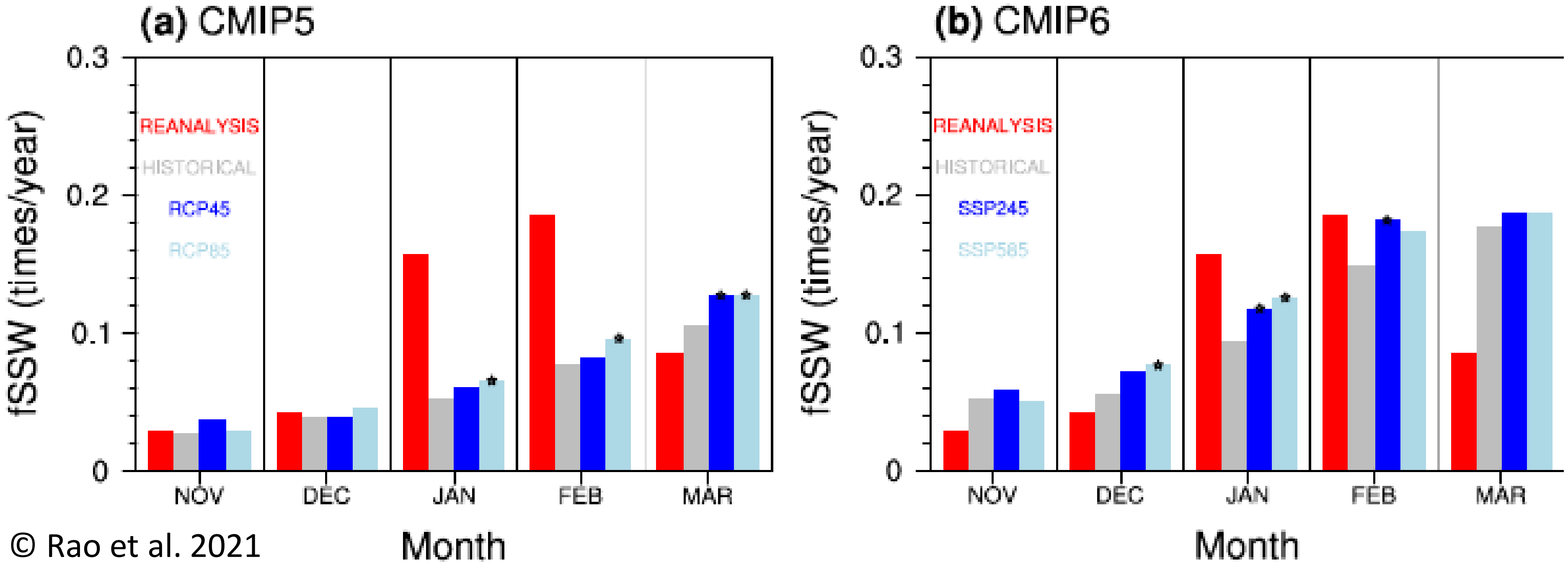
Changes in SSW frequency

- CMIP6, 1% CO_2 increase per year
- 6/11 models show significant change in SSW frequency
- Doubling of CO_2 between decade 6-7 (2060-2070 in RCP 8.5)

→ change in SSW frequency unlikely before that



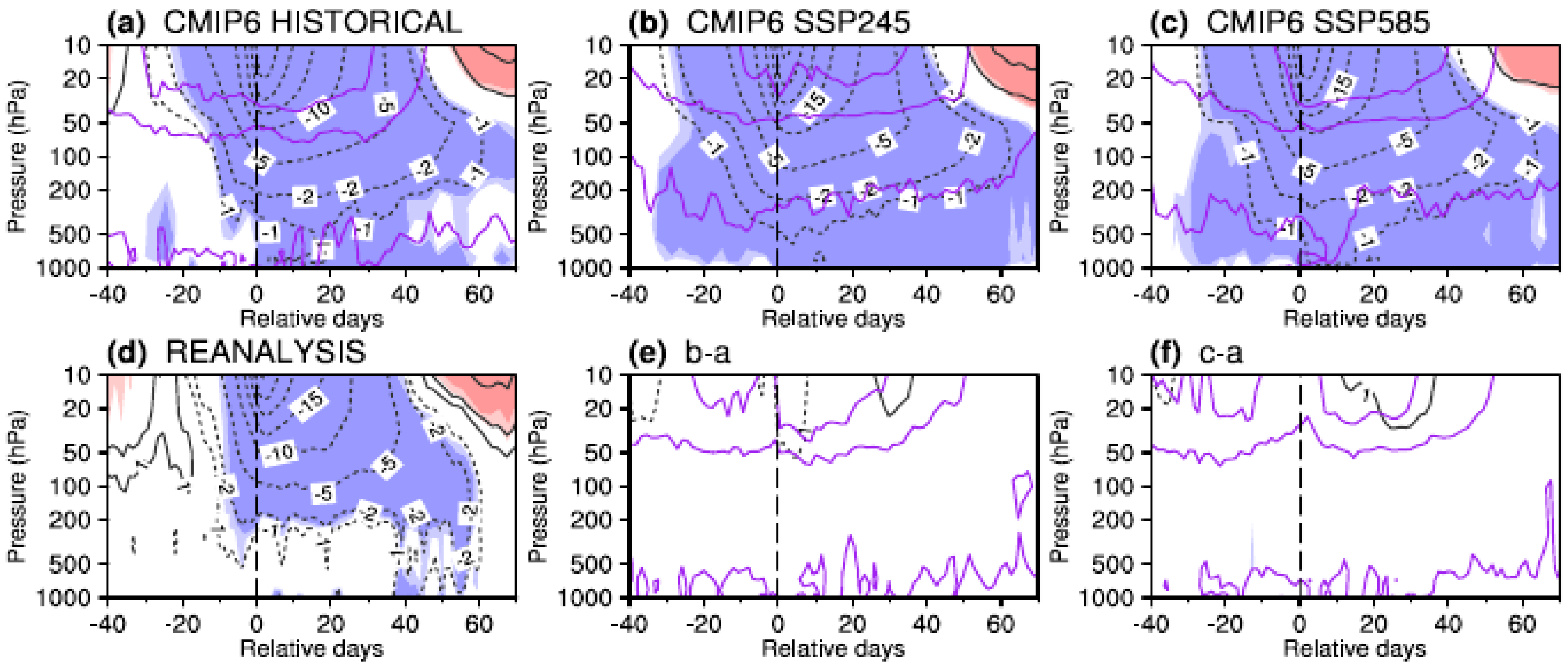
Changes in seasonality of SSW



- Reanalysis: most SSW in mid-winter(Jan+Feb)
- Both CMIP5&6 simulate most SSW in March
- Significant increase shifts from Jan-Mar in CMIP5 to Dec-Feb in CMIP6
- No clear conclusion possible because of differences between models and differences compared to reanalysis

Changes in tropospheric response

- CMIP5&6 simulate tropospheric response close to reanalysis
- No significant changes predicted in RCP4.5 or RCP8.5



Evolution of zonal mean zonal wind anomalies after SSW; contours show values and shading shows statistical significance (light:90%, dark:95%)

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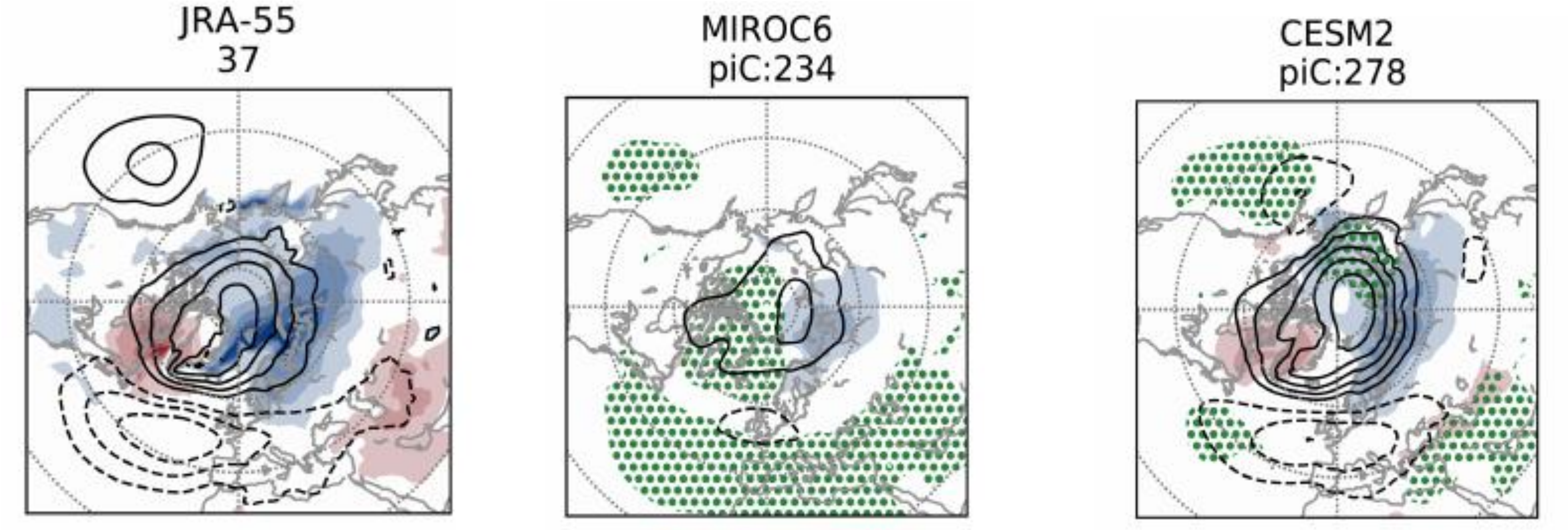
Changes in surface pressure response

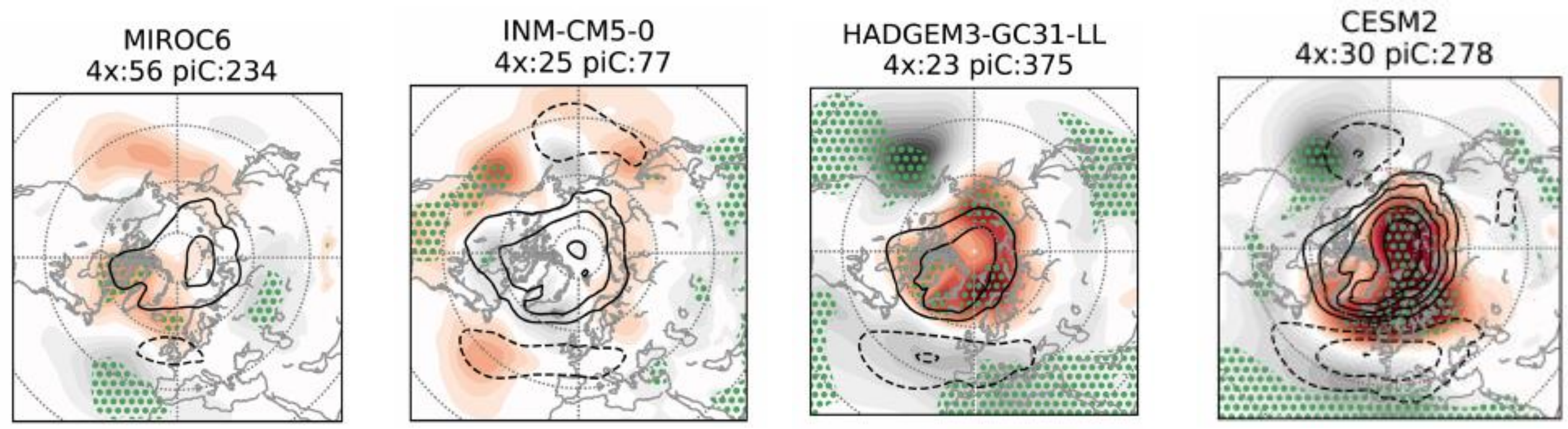
- CMIP6: almost all models show the same pattern of pressure anomalies as in the reanalysis
- Magnitude of change varies between models
- High pressure anomalies in Northern Pacific are not represented in any model



Sea level pressure anomalies as contours and temperature anomalies as shading 15-60 after a SSW, green stipling shows significant differences of pressure to reanalysis

Changes in surface pressure response

- Most models show no significant changes
- Some show stronger negative Northern Annular Mode (higher pressure over pole, lower over midlatitudes)
- Some show significant negative pressure anomalies over the Northern Pacific



Sea level pressure anomalies in preindustrial control simulations as contours and changes in $4xCO_2$-scenario as shading
green stipling shows significant differences to preindustrial control simulation (95%)
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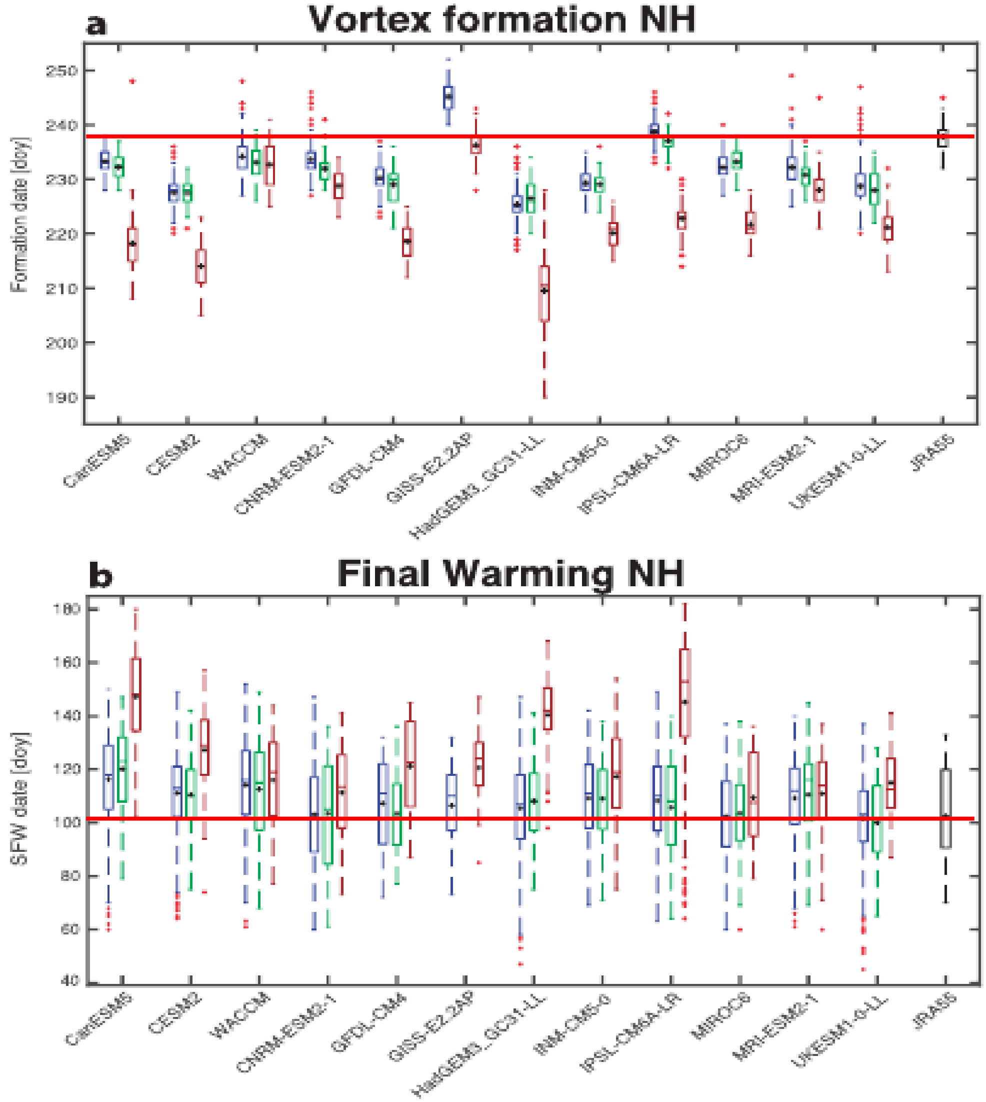
Changes in seasonal cycle of the polar vortex

- Historical models(green) simulate earlier vortex formation than in reanalysis
- All models show a longer persisting polar vortex with 4xCO_2 (brown)



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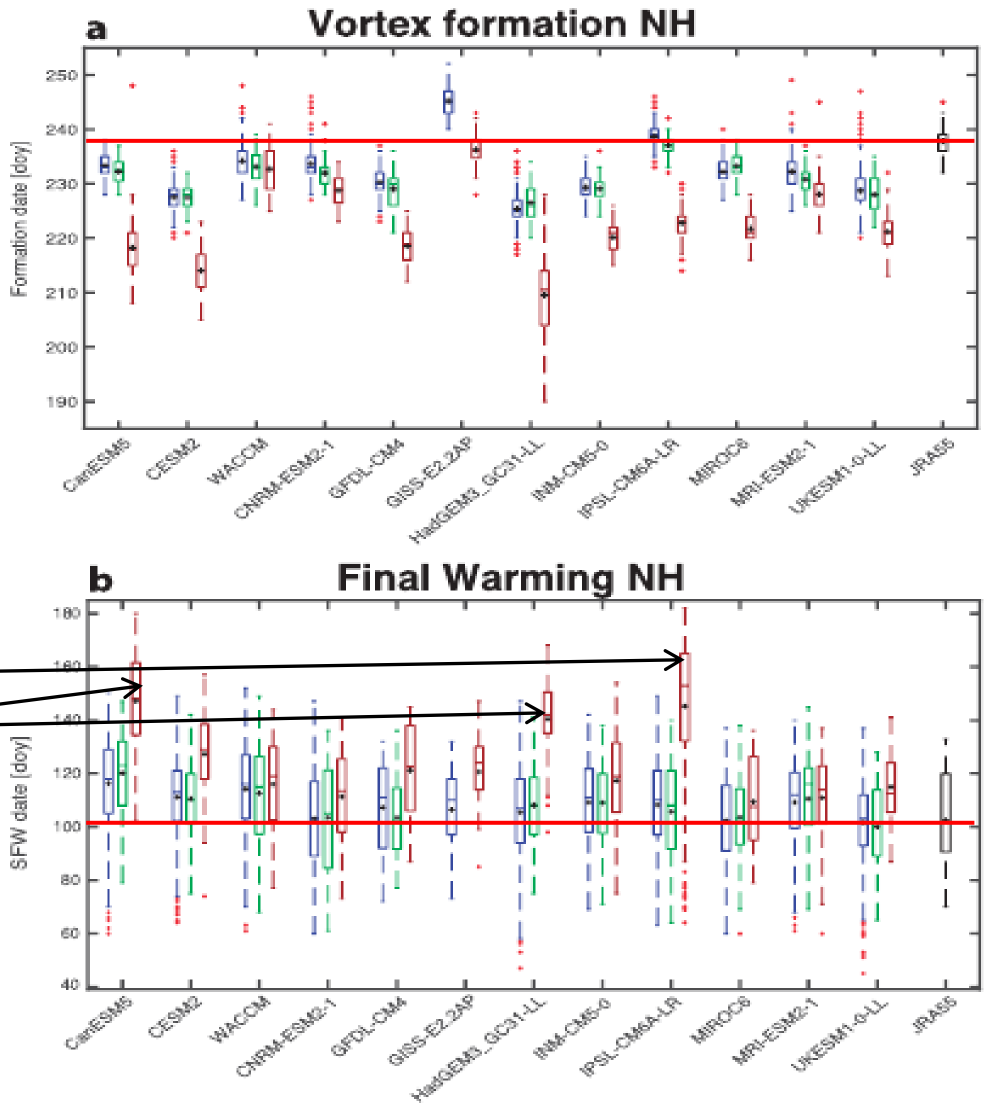
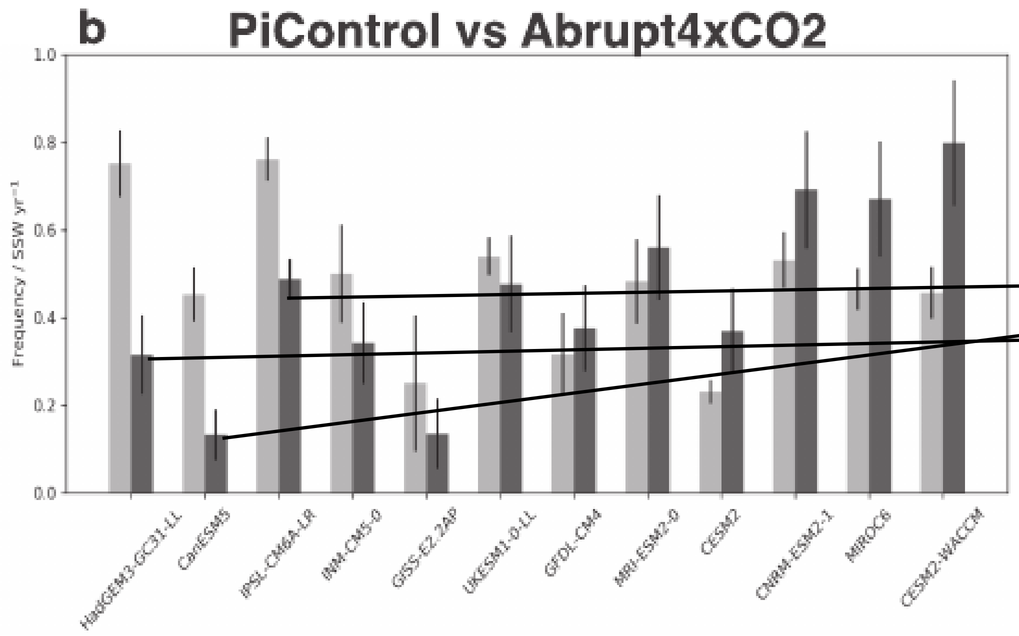
Changes in seasonal cycle of the polar vortex

Models with longest persisting vortex simulate less SSW in future





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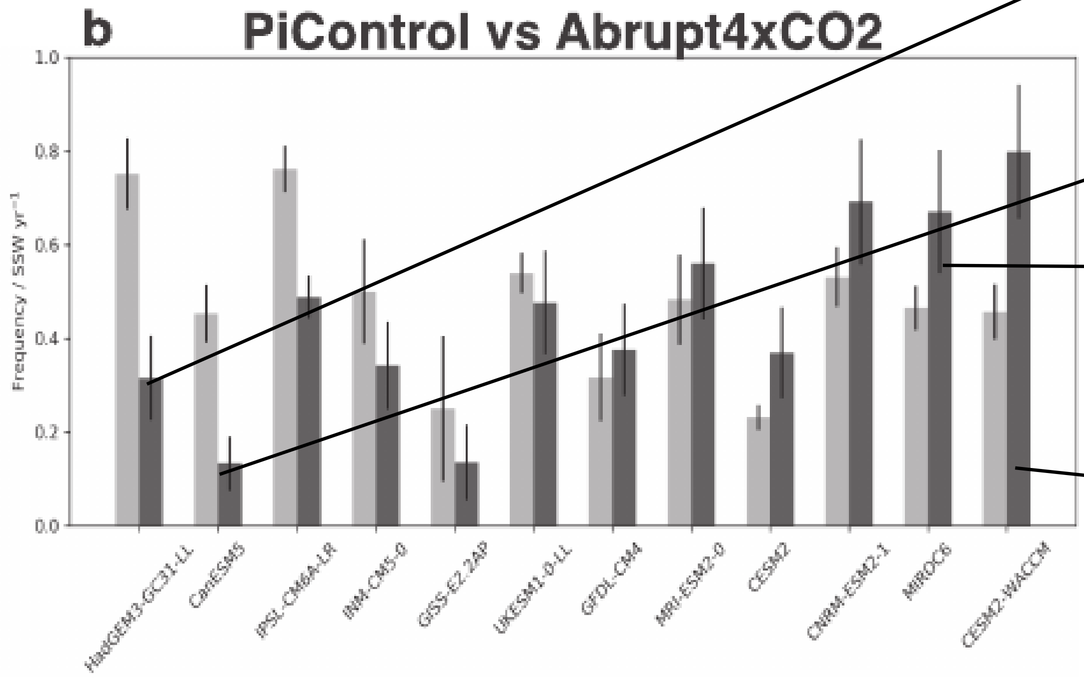
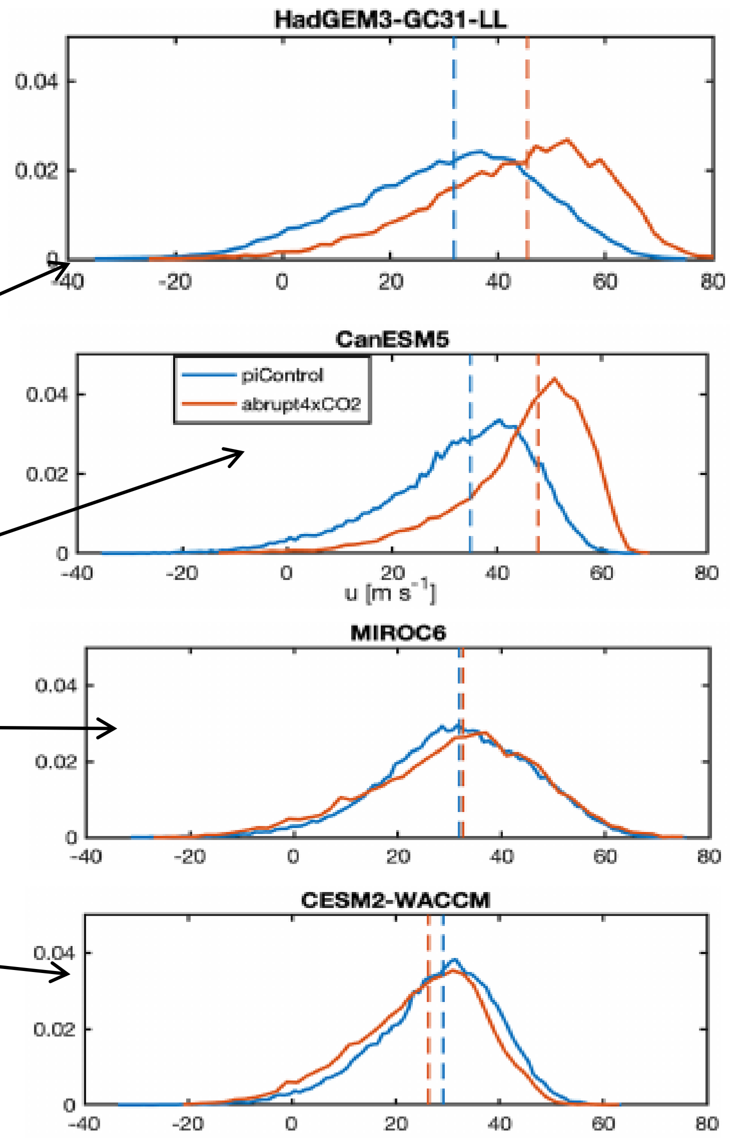
Influence of polar vortex wind speed

- Models that simulate significantly less SSW show much stronger polar vortex winds in the future
- Change in SSW frequency not necessarily tied to mean wind speed: see models with increased SSW frequency





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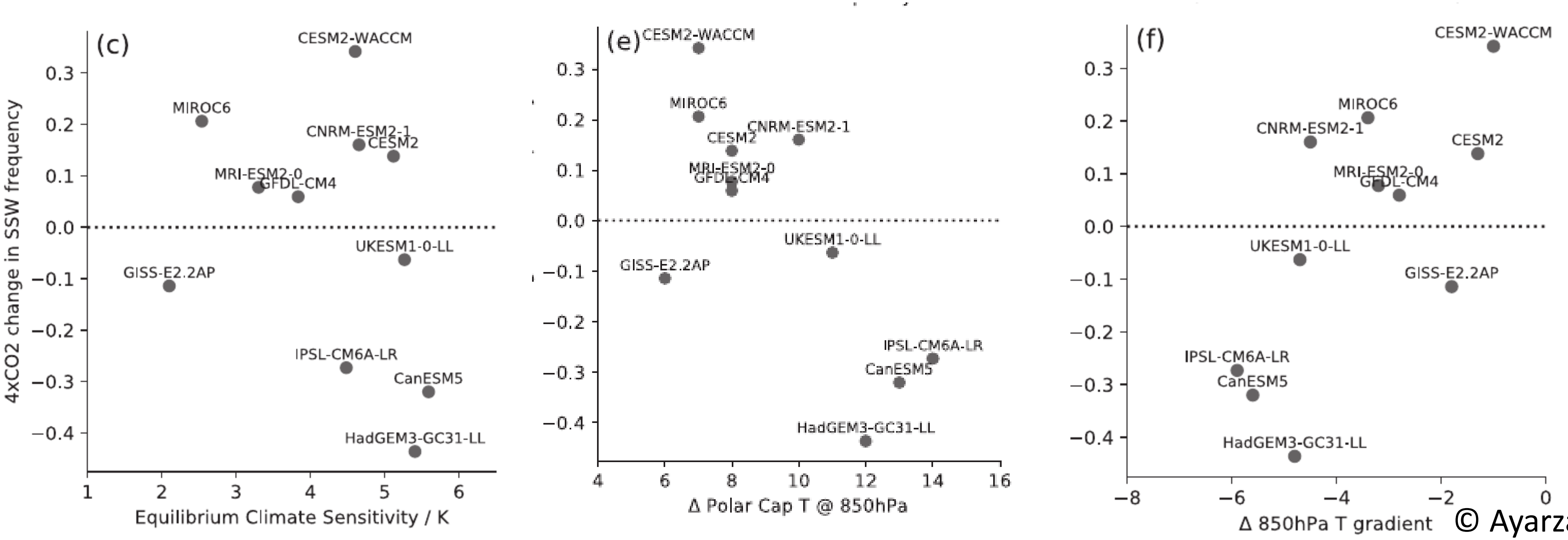
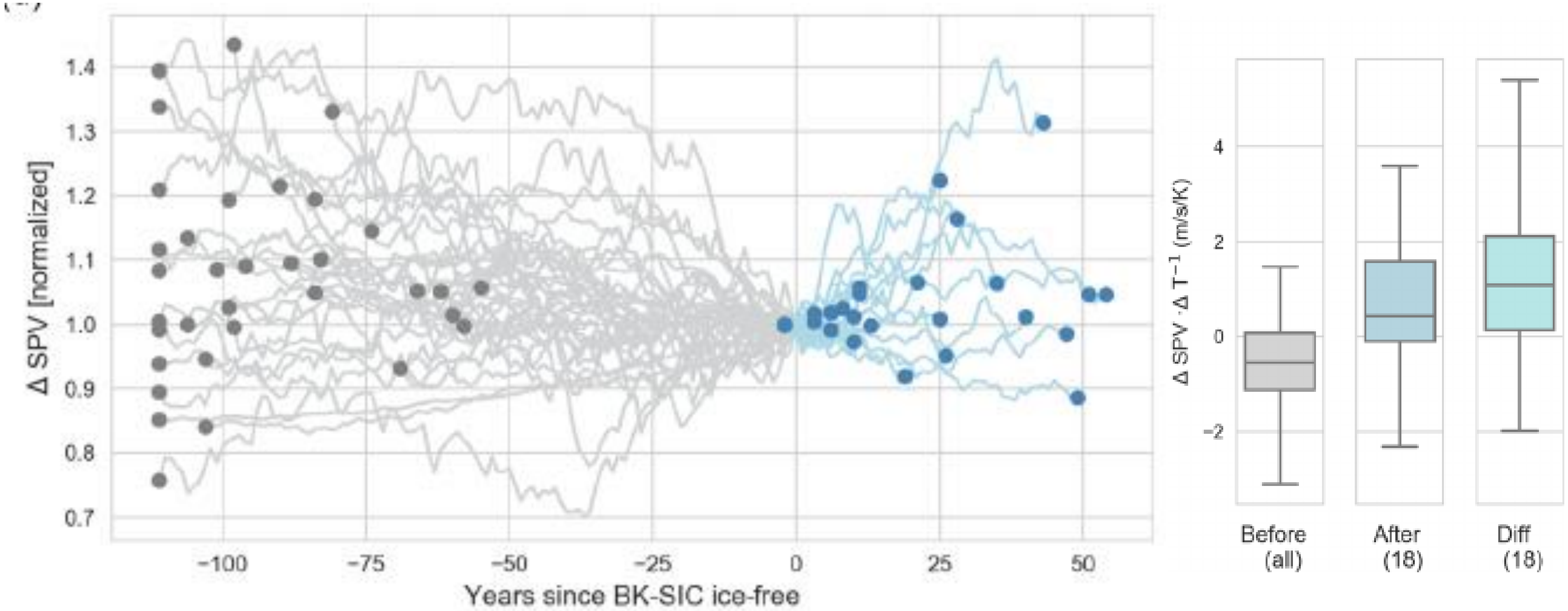
Reasons for uncertanties in the models

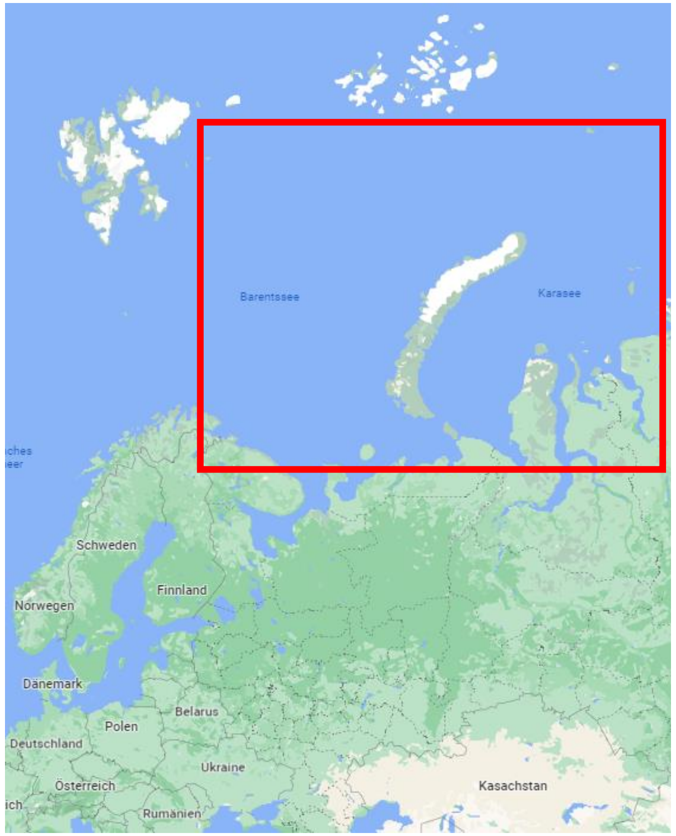
- Negative correlation between SSW frequency and climate sensitivity of models (-0.33, not significant)
- Significant negative correlation between SSW frequency and change in lower tropospheric temperature (850hPa) over North pole
- Significant positive correlation between SSW frequency and change in temperature gradient in 850hPa
- Probably due to effects on wave propagation but still not well understood



Role of sea ice in Barents and Kara-Sea

- Changes in sea ice concentration could alter meridional heat flux and with that wave propagation
- Non-linear response of polar vortex wind speeds to increasing temperatures depending on sea ice concentration
- With decreasing ice concentration wind speeds decrease
- Once Barents and Kara-Sea are ice free wind speed is increasing again





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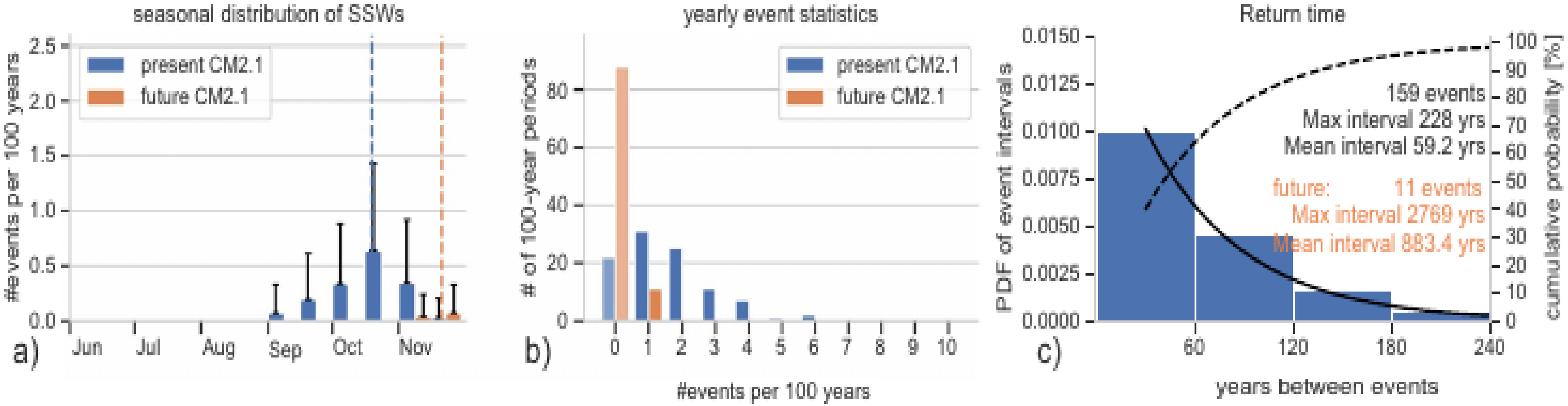
SSWs in the Southern hemisphere

- Especially interesting for ozone hole projection and surface pressure response (could lead to more wildfires in Southern hemisphere)
- Historical simulation: 1SSW every 59 years (recorded: 1 in 63 years of observations)
- With increased CO_2 forcing (1120ppm): 1SSW every 883 years and significant strengthening of polar vortex

SSW-
reversal



Conclusion

- No consensus in models on change in SSW frequency in Northern hemisphere, most likely a slight increase considering multimodel mean
- Large spread in models probably due to multiple factors (non-linear response to sea ice loss, arctic amplification, climate sensitivity)
- No significant changes in stratosphere-troposphere coupling and surface pressure response predicted
- No clear sign for changes in seasonality of SSWs: climate models biased to more SSWs in late winter
- Much clearer for Southern hemisphere: significant decrease in SSW frequency and strengthening of the stratospheric polar vortex that will probably lead to a longer persisting ozone hole

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