

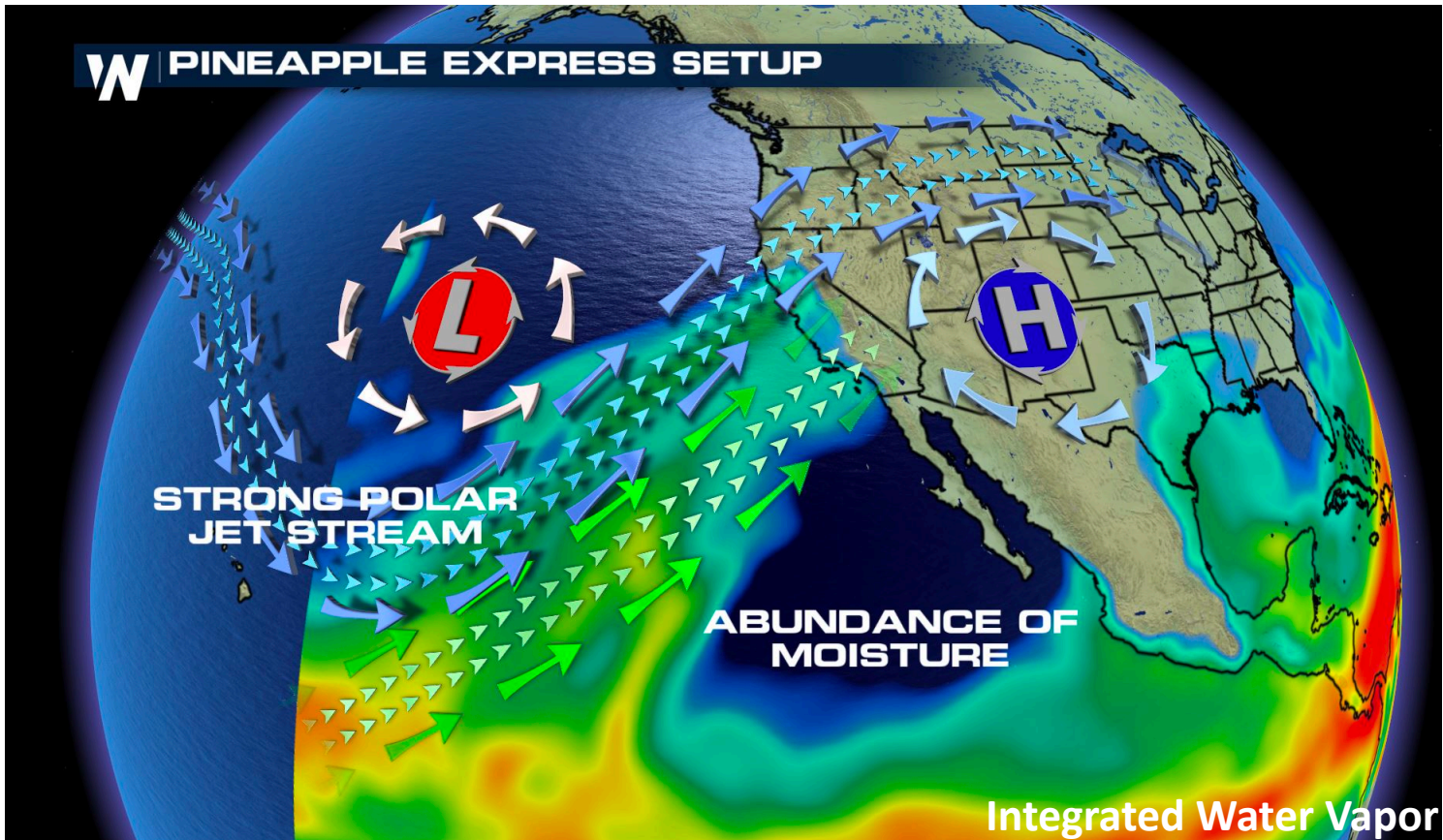
A satellite image of Earth showing a large, swirling storm system over the Pacific Ocean. The storm is characterized by a dense, white cloud core and a well-defined eye. The surrounding clouds are dark and textured, indicating intense weather. The landmasses of North and South America are visible on the right side of the frame, with the Gulf of Mexico and the Caribbean Sea to the south.

Atmospheric River Landfall- Latitude Changes in Future Climate Simulations

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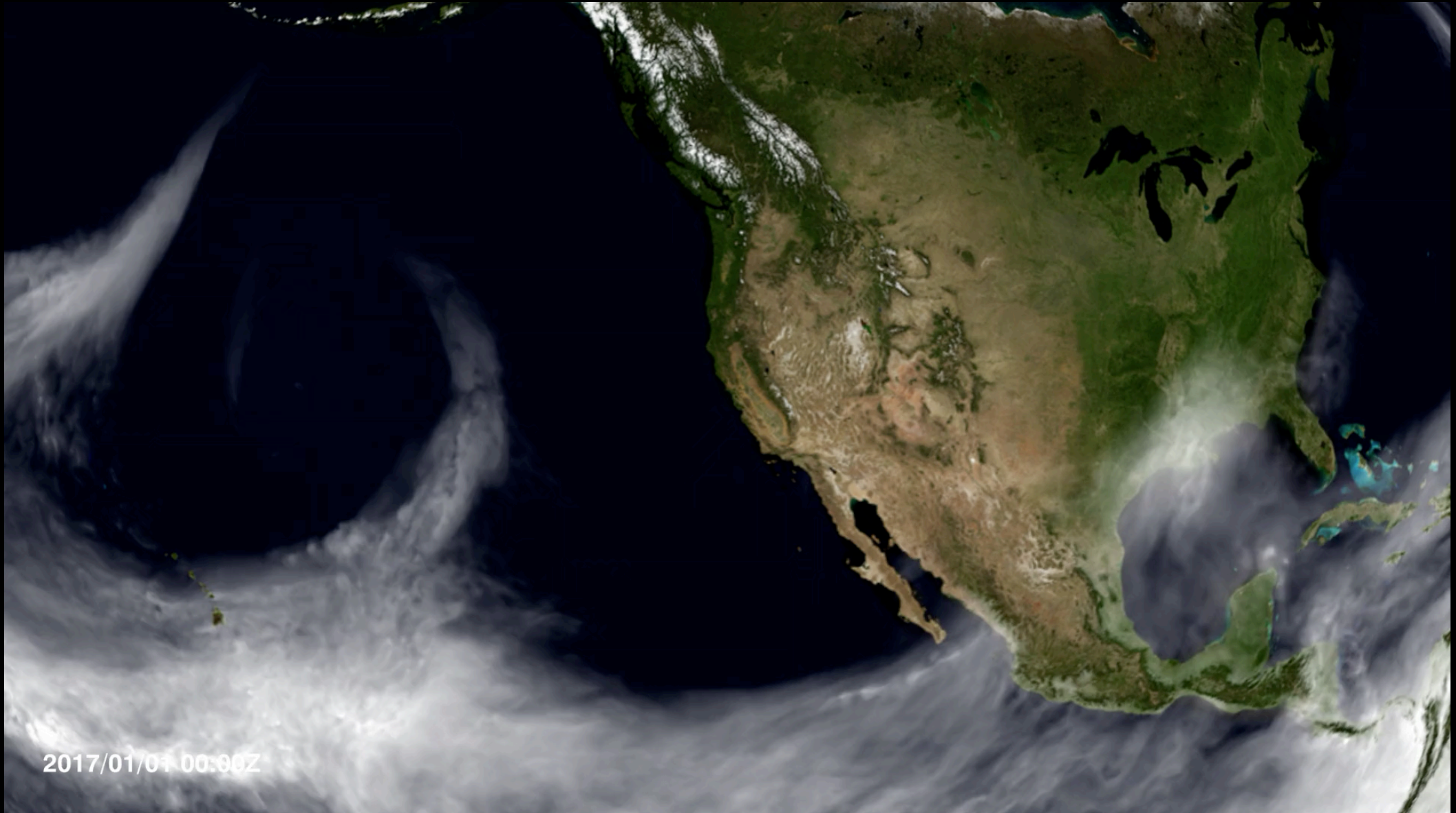
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What are Atmospheric Rivers (ARs)?

- Conveyor belts of high water vapor-content air moving from the subtropics towards the poles
- When ARs move inland and are forced over mountainous terrain, the water vapor rises, cools, and condenses, which can result in torrential rain and feet up on feet of snow.
- AR precipitation is often beneficial - they are vital to building the snowpack in the Sierra Nevada, upon which millions of Westerners rely. It can also be catastrophic.

What are Atmospheric Rivers?



NASA Scientific Visualization Studio

Atmospheric Rivers: Why They Matter

- **Atmospheric Rivers affect large population centers globally, and can have large positive (reservoir-filling) and negative (flooding) impacts**
- **30% to 50% of annual precipitation for the US West Coast can fall during just a few AR events**
- **Clearly a change in the distribution or strength of atmospheric rivers could have significant hydrological impacts on large population centers.**
- **Thus, this study set out to determine how the distribution of atmospheric rivers may vary latitudinally under global warming scenarios.**



Atmospheric Rivers & Climate Change

- Previous studies suggest:
 - **More ARs in the future** due to global warming, although the "severity of this increase is still an open question"
 - **A poleward shift** in the mean position of the jet streams with global warming
 - ARs track with the steering provided by atmospheric flow, i.e., jet streams, so the jet response to global warming must be studied

Atmospheric Rivers & Climate Change

- Additional studies suggest:
 - **Jet response depends on the geographic area in question** (Barnes and Polvani 2013)
 - **North Pacific AR frequency depends on a broadening of the subtropical jet position** (Payne and Magnusdottir 2015)
 - **Southern Hemisphere and North Atlantic jets vary in speed, or "pulse" with global warming** (Barnes and Polvani 2013)
 - **North Pacific jets show stronger variability in north-south "wobbling" with global warming** (Barnes and Polvani 2013)

Atmospheric Rivers & Climate Change

- “In [the Community Earth System Model] CESM, upon closer examination of feedbacks, it has been found that the lack of poleward shift in the winter months for the Northern Hemisphere is due to competing forcing responses from greenhouse gases and sea ice loss [Deser et al., 2014].”
- This paper endeavors to further research this finding

Definitions

- **Community Climate System Model, version 4 (CCSM4)**
 - Coupled climate model (atmosphere and ocean depend on one another). Atmosphere, ocean, land surface and sea-ice are integrated into the model.
- **CCSM4 Coupled Model Intercomparison Project phase 5 (CMIP5)**
 - Provides a standard framework for modeling climate and creating climate projections

Definitions

- **Ensemble Models**

- Multiple versions of the same model run using slightly perturbed initial conditions or different parameterization schemes. Then, the model runs are averaged to produce an ensemble forecast.

- **RCPs (and RCP 8.5)**

- Representative Concentration Pathways are greenhouse gas concentration scenarios developed by the IPCC. RCP 8.5 represents 8.5 Watts/m² of greenhouse gas forcing in the year 2100 and is considered the “business as usual” scenario.

Methods

- Used the fully coupled Community Climate System Model, version 4 (CCSM4) to **evaluate how changes in jet stream position affects ARs**
 - Moderately high horizontal resolution (used .5° version) for atmosphere and land components. Ocean & Sea Ice resolved at 1°.
 - Used 0.5° version because it does a better job than the 1° version at **representing extreme precipitation**
 - This higher resolution version also was shown to **better represent AR frequency** when compared to reanalysis data



Methods

- Modeled both historical (20th Century) and RCP 8.5 (21st Century) simulations for comparison purposes
- 5 ensemble members for each experiment
 - Due to resource constraints only 3 ensemble members contain the high-frequency (6-hour) output necessary for the AR detection/AR diagnostics algorithms



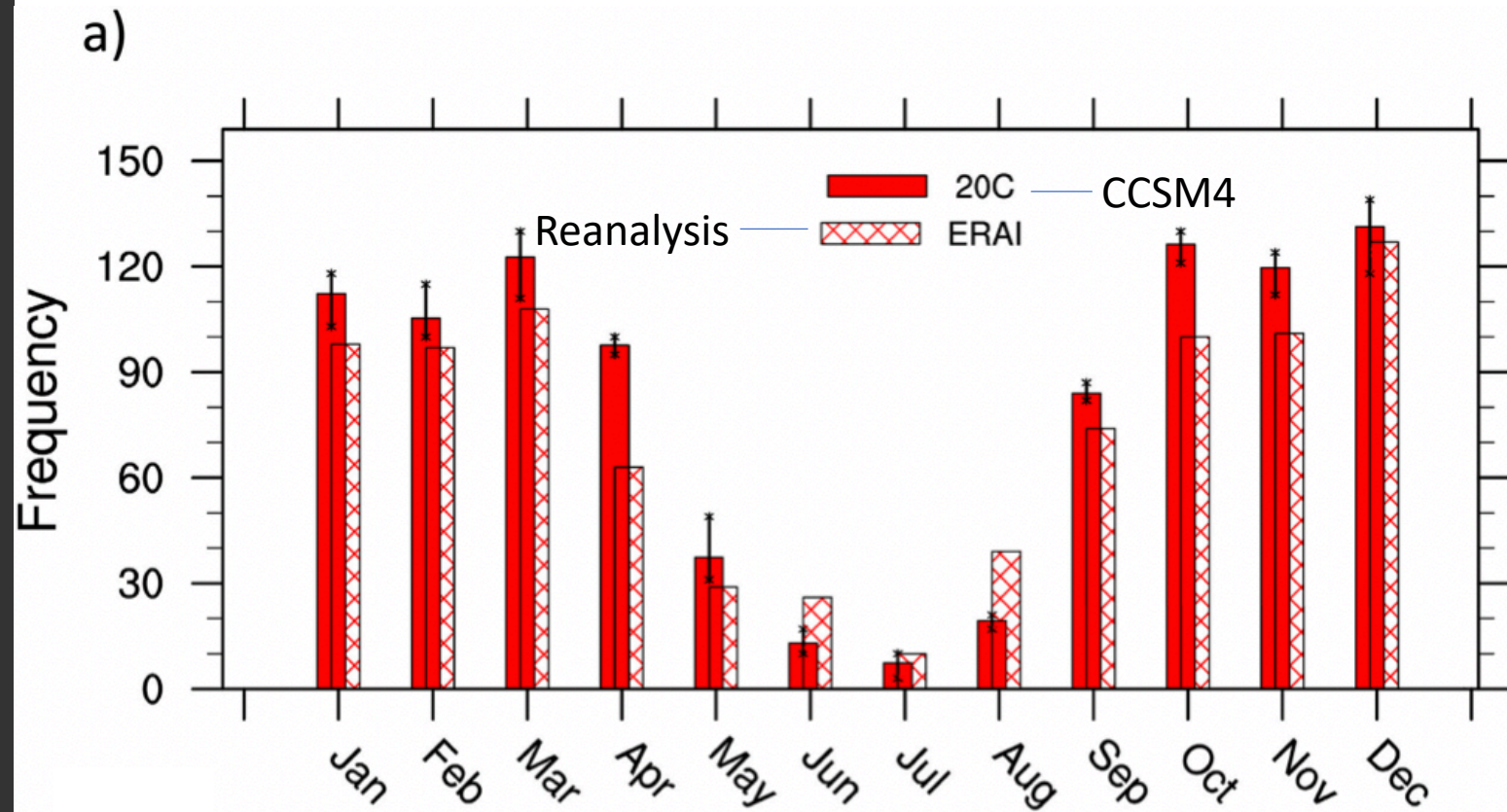
Methods

- AR Detection Method
 - Many types of AR detection exist: Integrated Water Vapor, Integrated Vapor Transport, Shape Identification, Statistical Clustering...
 - **This study used wind and shape thresholds, but also used:**
 - **A moisture threshold that's relative to the background state**
 - ARs are represented independent of the increase in moisture due to global warming and the Clausius-Clapeyron relationship
 - Computed a new AR moisture threshold every 6 hours based on mean and maximum moisture levels per latitude band (Zhu and Newell 1998, Newman et al. 2012)

Methods

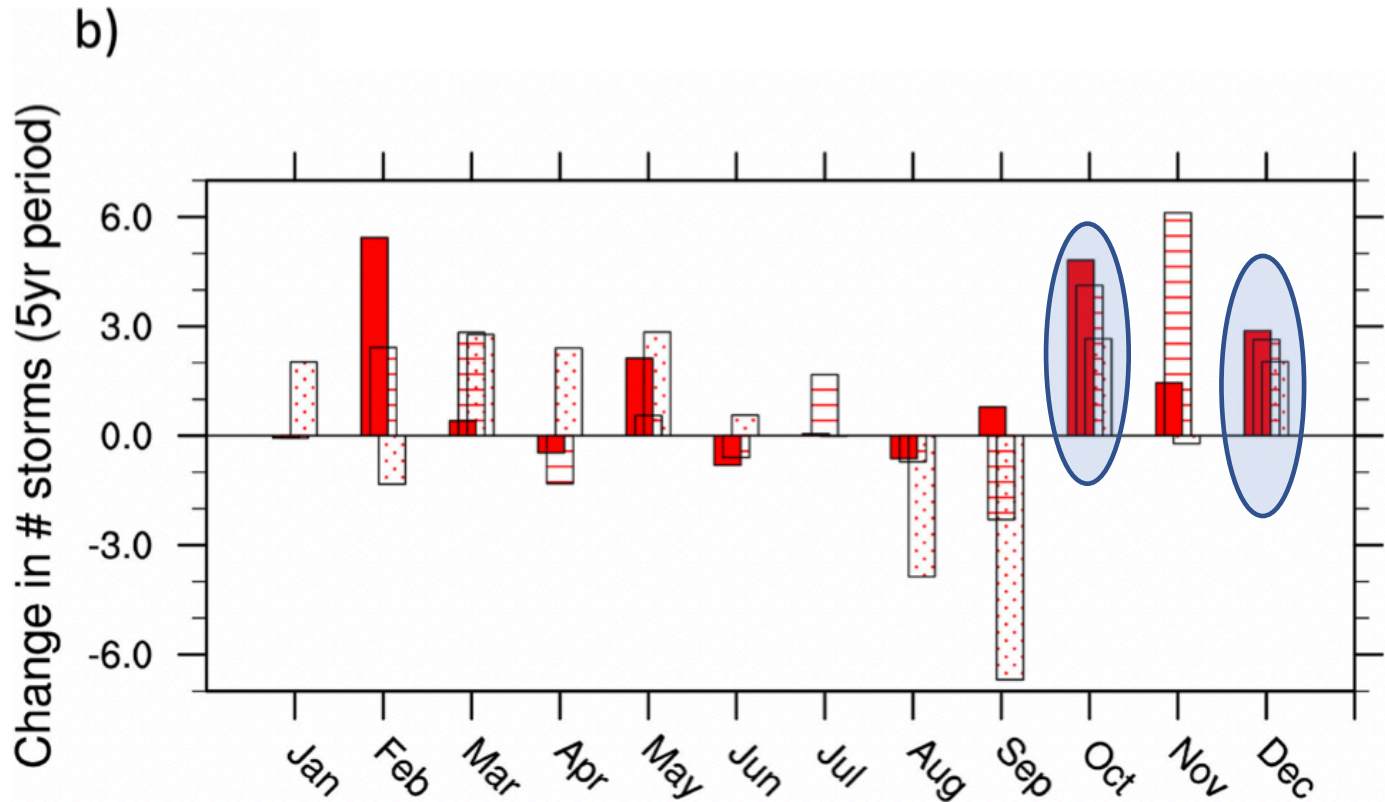
- Evaluated US West Coast Atmospheric Rivers (WEST) (32°N – 52°N)
 - ARs approaching from SW (180-270°) w/ 850mb wind speeds $>10\text{ms}^{-1}$
- And UK Atmospheric Rivers (UK) (49°N – 60°N)
 - ARs approaching from any direction so long as there is a component from the west and wind speeds $>25\text{ms}^{-1}$
- Shape
 - Length to width ratio >2 with a four-grid point length minimum (at least ~ 140 miles long)
- Wind thresholds filter out non-AR storms
 - These thresholds provide a good match between the CCSM4 model and the AR reanalysis climatology

Figure 1A: Climate Model and Reanalysis in Agreement



- CCSM ensemble members agree with ECMWF Reanalysis data on the frequency of atmospheric rivers for 1980-2005 for the United Kingdom
- **CCSM4 does a good job of modeling historic atmospheric rivers, so it may accurately model future ARs as well**

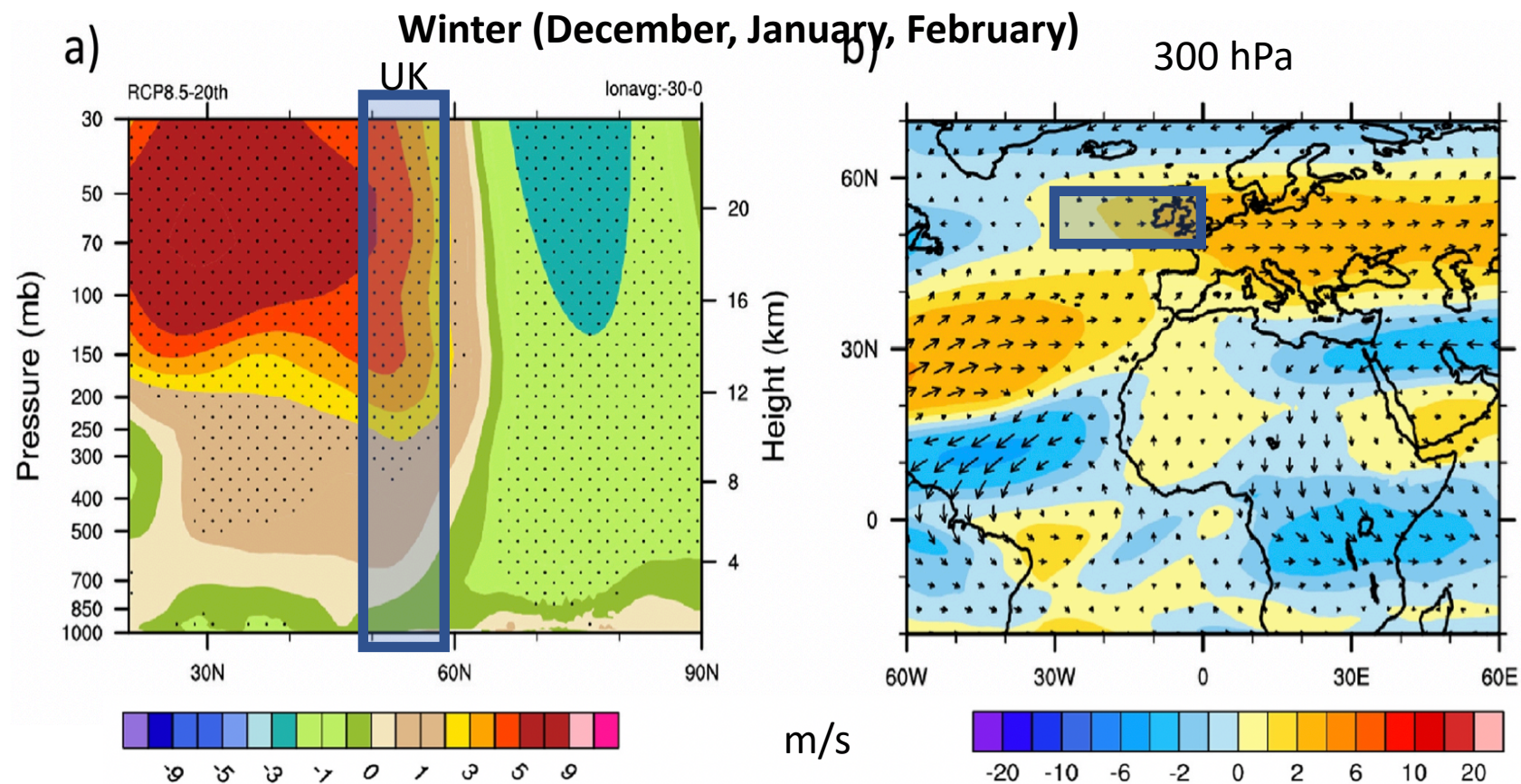
Figure 1B: Changes in AR Frequency Due to Climate Change



- Shows **projected change** in **AR frequency** (per 5-year period) in the 21st Century for the **UK domain**
- Each bar color represents a different model ensemble member
- Clearest climate change signal is the **increase in AR frequency** in **October** and **December** for the **UK domain**

Figure 2 A & B: Climate Change & Jet Response for UK

UK: Subtropical Jet shows variance in speed or “pulse” in response to global warming

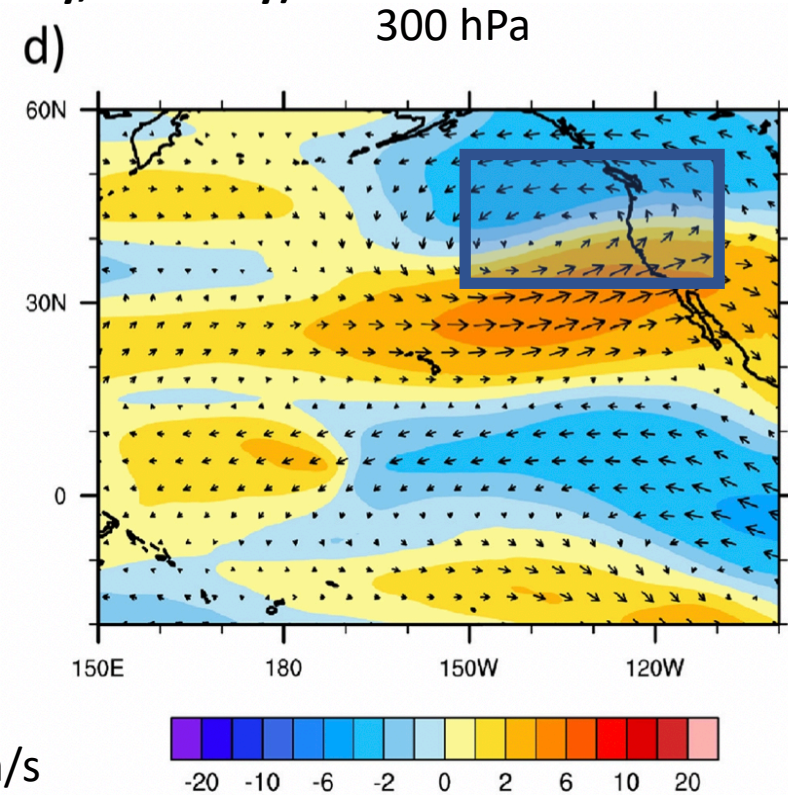
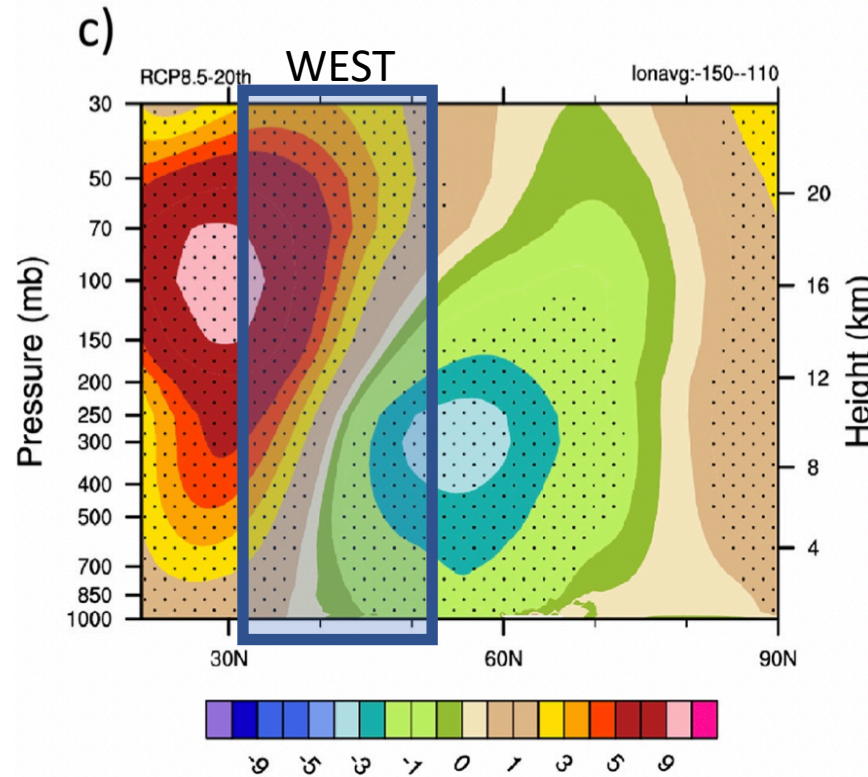


- **Upper-level weakening** in atmospheric flow **north of 60°N**. **Upper-level strengthening** south of 60°N.
- **Not a particularly significant signal for atmospheric river climate change** because AR flow is lower in the atmosphere than the statistically significant strengthening/weakening.
- **North Atlantic Jet, Subtropical Jet strengthen**, but no latitudinal change. Consistent with climate change research consensus.

Figure 2 C & D: Climate Change & Jet Response for US West Coast

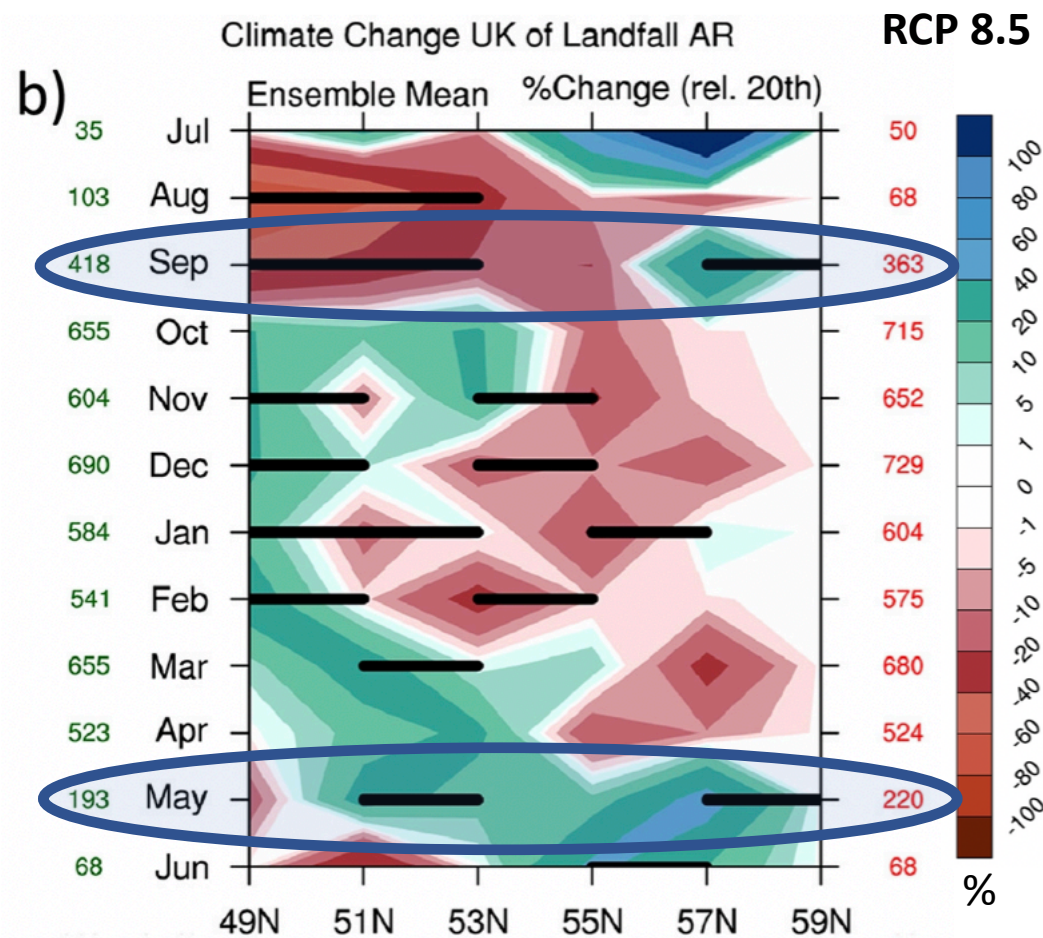
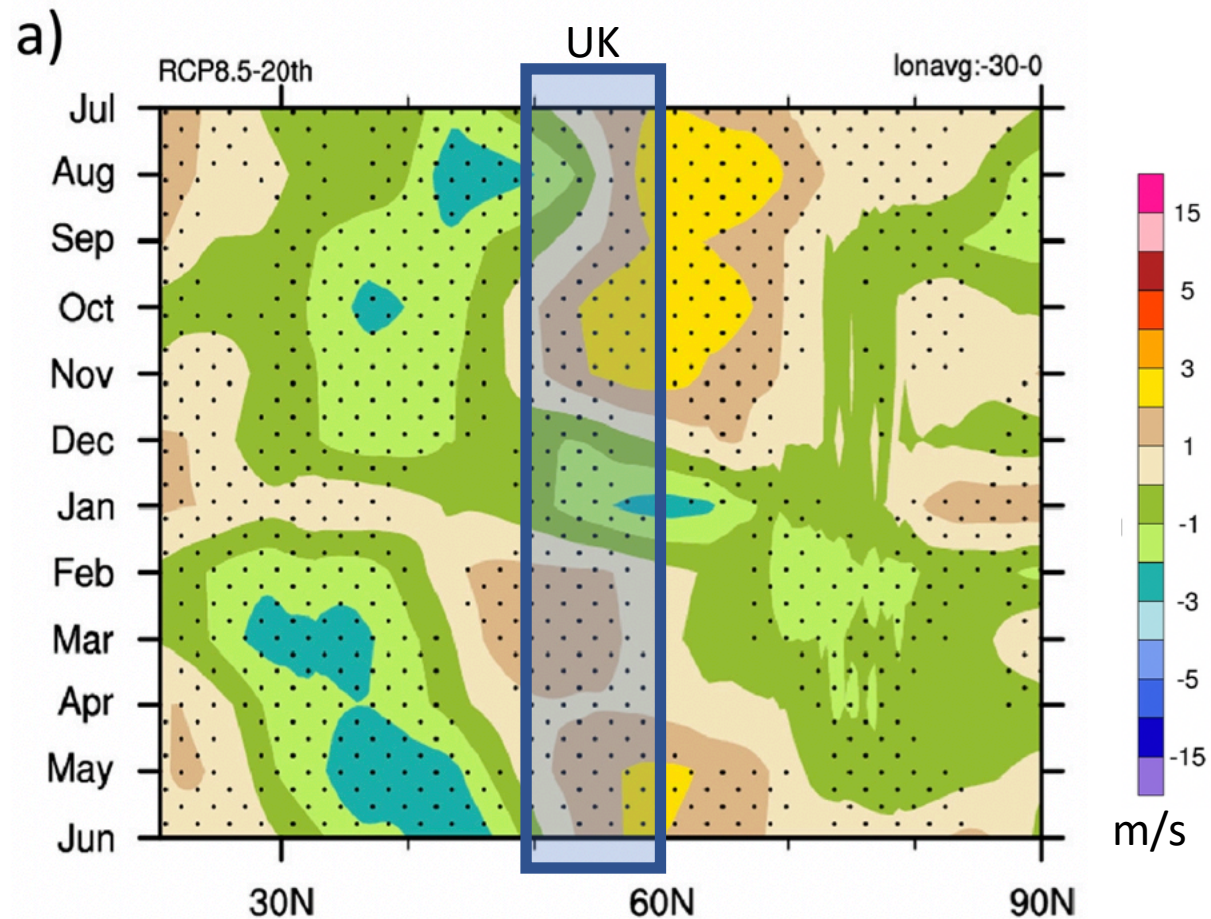
WEST: Subtropical Jet shows variance in speed and latitude in response to global warming

Winter (December, January, February)



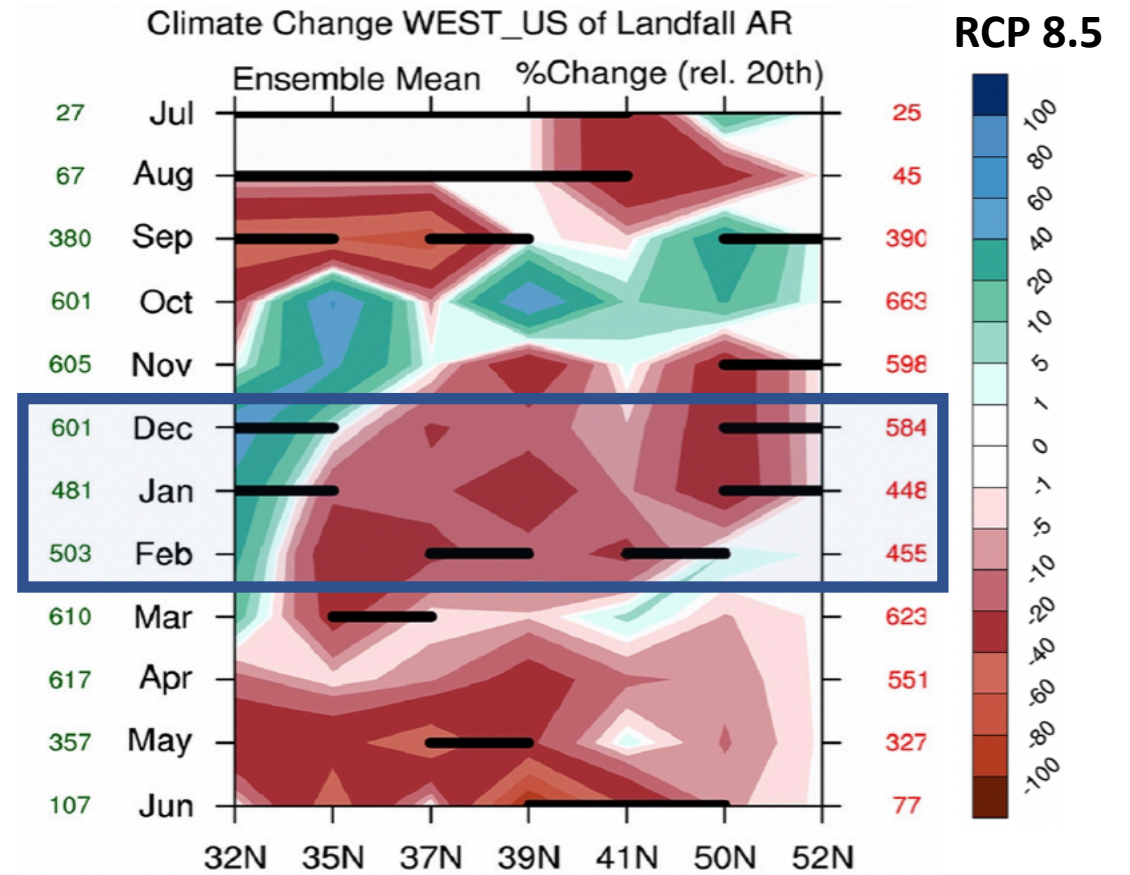
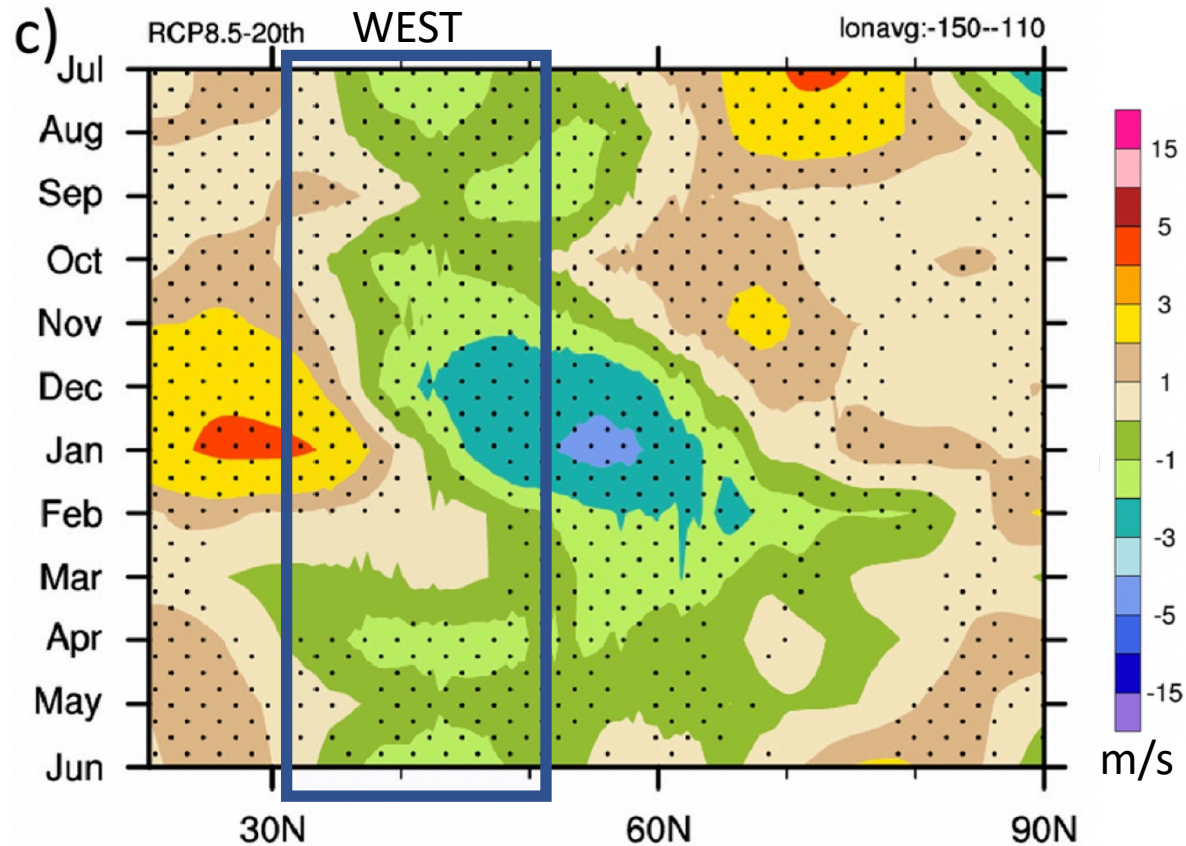
- Strengthening in atmospheric flow from the surface to aloft south of 40°N
- Weakening flow between ~40°N and 70°N from the surface to aloft
- Subtropical Jet increases in strength, particularly in Southern California, and the mean position of the jet moves equatorward.

Figure 3 A & B: UK 850 hPa Zonal Wind & AR Frequency



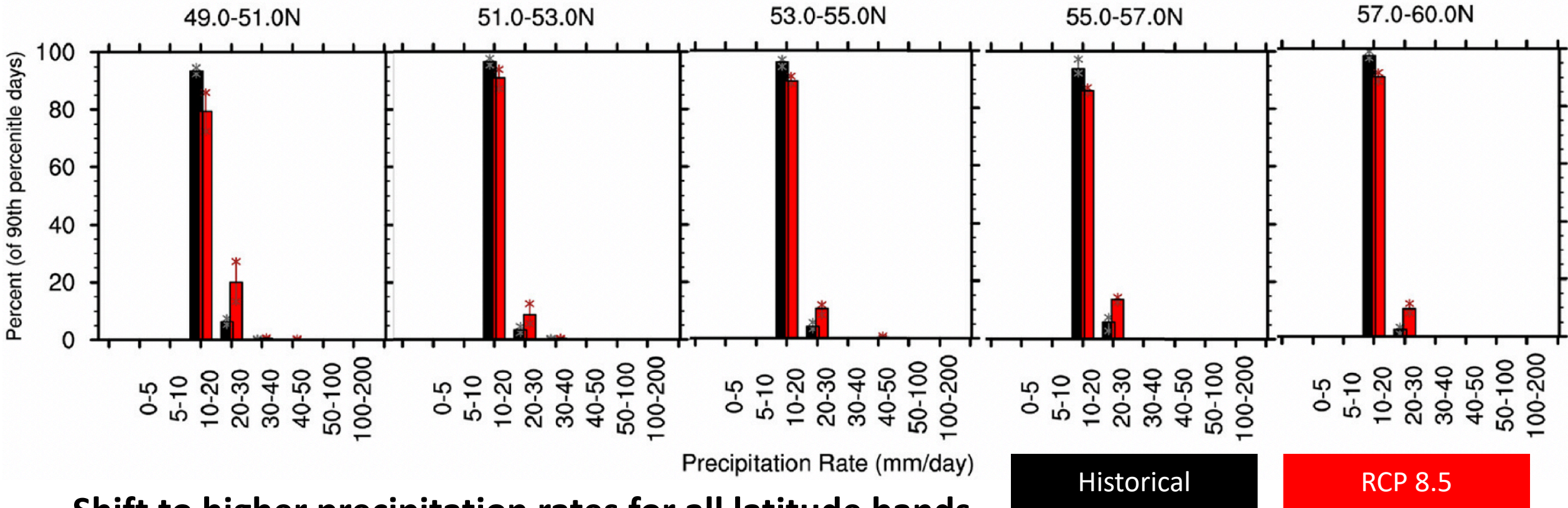
- Changes in 850 hPa Jet roughly approximate changes in AR frequency over the course of a year
- “Modest” changes in 850 hPa Jet in the winter months (DJF)
- Weak signal for poleward shift in AR frequency in September and May for UK domain
- Modest increase in wintertime ARs for southern portion of UK domain, but doesn’t match up with strongest jet changes

Figure 3 C & D: WEST 850 hPa Zonal Wind & AR Frequency



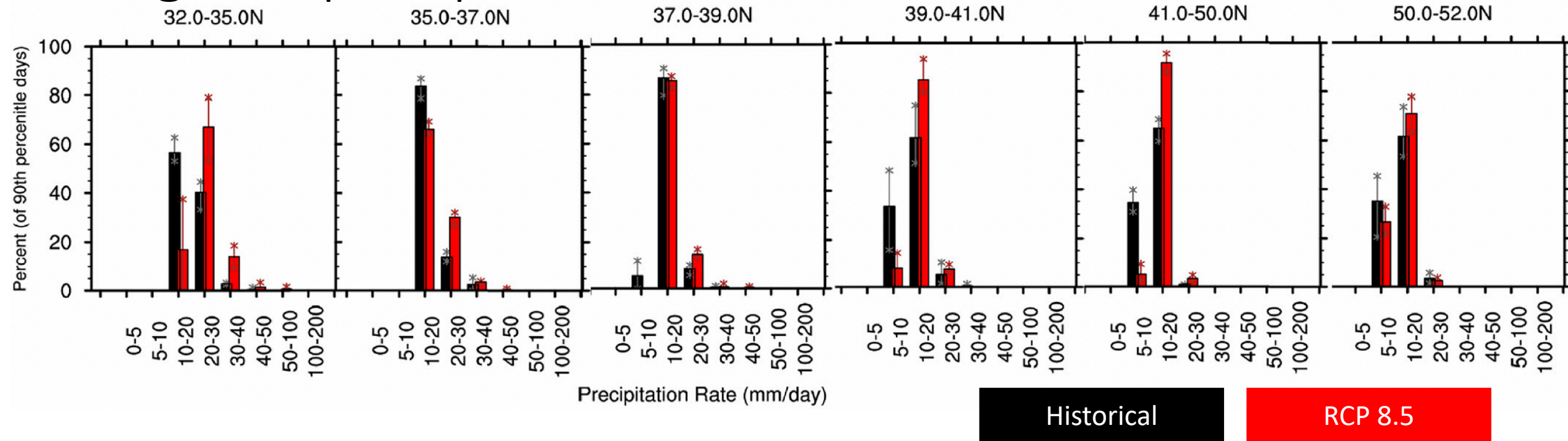
- “Significant and obvious” winter equatorward shift in ARs towards more southerly latitudes in conjunction with southerly shift in Subtropical Jet in response to global warming.
- What does this suggest for Reno? We’re located at $\sim 39.56^\circ\text{N}$ \rightarrow up to 20% fewer ARs during winter months
- Southern California could see more wintertime ARs
- Over the entire domain, October is the only month projected to see an increase in ARs, but this projection is not backed by statistical significance.

Figure 4 A: Probability Density Function for UK showing changes in precipitation rate distribution under RCP 8.5



- Shift to higher precipitation rates for all latitude bands
- Consistent with the prediction that precipitation rates will increase as the planet warms
- No change in the shape of the distribution – no change in the latitudinal distribution of precipitation in the UK

Figure 4 B: Probability Density Function for WEST showing changes in precipitation rate distribution under RCP 8.5



- **Shape of the precipitation distribution changes for the 32°N – 35°N latitude band**
 - **The simulations show that for this latitude band the top 90th percentile days now have the majority of precipitation falling within the 20-30 mm/day range rather than the 10-20 mm/day range.**
- **Confirms this study's finding of an equatorward shift in AR frequency along the US West Coast**
- **Other latitude bands also see an increase in precipitation intensity, but distribution shape does not change.**

Conclusions

- For the US West Coast:
- Equatorward shift in the landfall latitude of Atmospheric Rivers for the US West Coast
- This is intrinsically linked to the response of the Subtropical Jet to global warming
- Except for (possibly) October, locations other than Southern California are expected to receive fewer Atmospheric Rivers per year

Conclusions

- For the UK:
- Heavier precipitation overall, which is consistent with global warming consensus
- Modest change in AR frequency during winter months – however, this does not align with strongest jet response to global warming

Questions?

Mammoth Lakes, CA
January 2017
Paul Fremeau



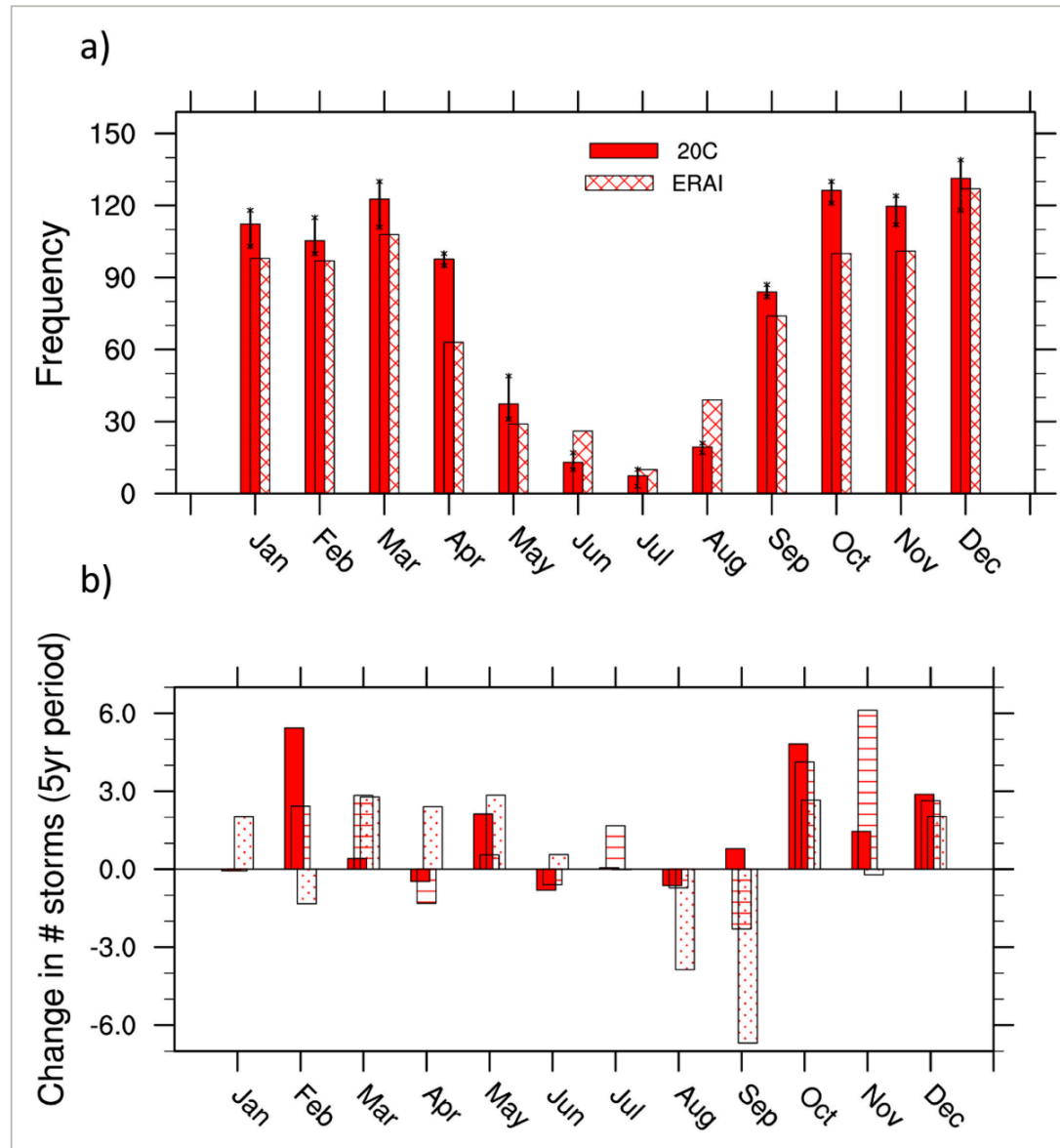


Figure 1

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(a) Seasonal cycle of the ensemble mean-simulated UK domain (solid) and ERAI reanalysis (hatched) 1980–2005 and (b) 21st century to 20th century changes to the seasonal cycle for simulated UK ARs for three ensemble members (number of storms/5 year period). Ensemble spread shown in black.

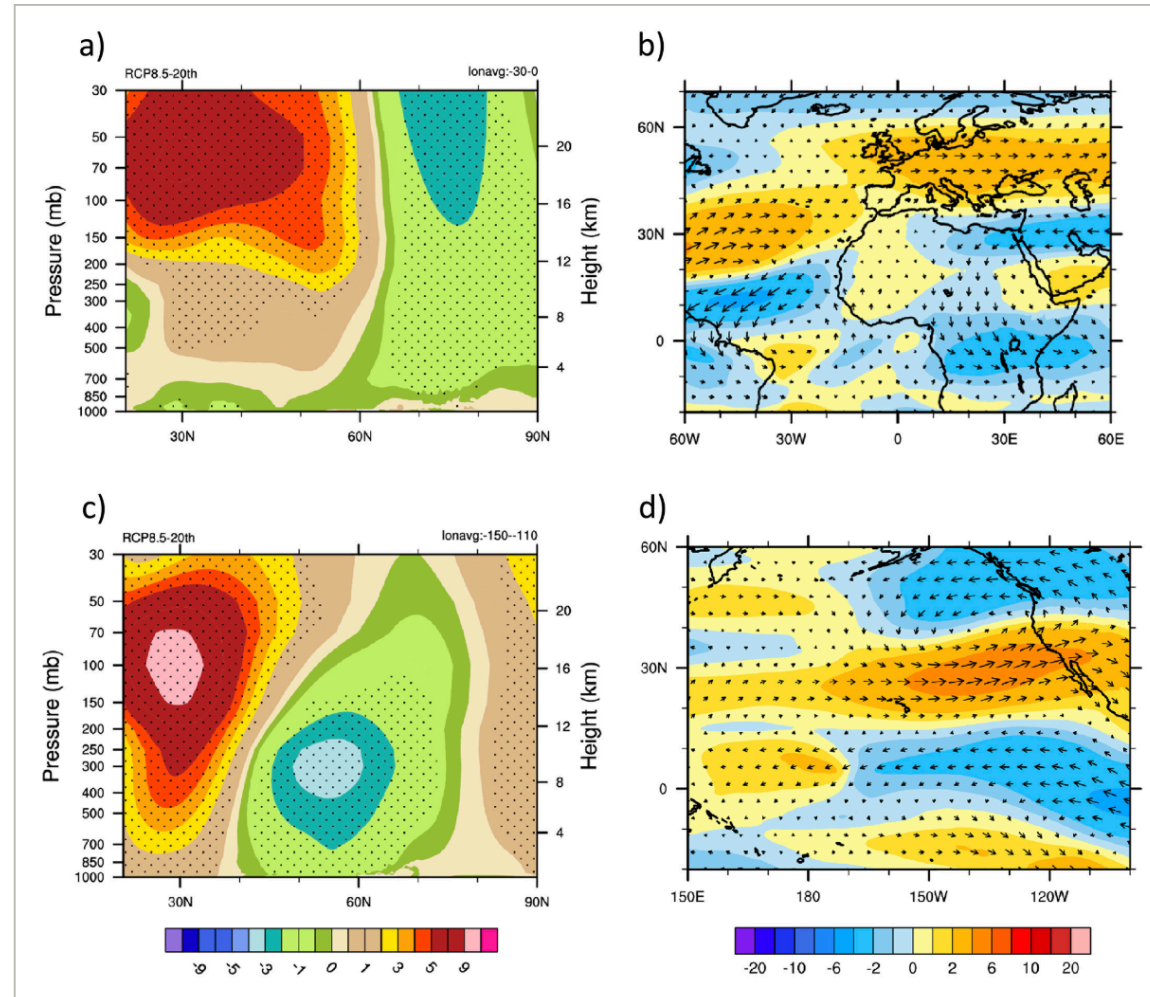


Figure 2

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Winter (December-January-February, DJF) climate change (RCP8.5-historical) for (a) zonal wind UK domain (0–30°W); (b) 300 mb total wind magnitude and direction over North Atlantic, Europe, and Africa; (c) same as Figure 2a except for WEST (110–150°W); (d) same as Figure 2b except over North Pacific and western North America. Wind is in m s^{-1} and is plotted with color contours ranging from -9 to $+9$ in Figures 2a and 2c and ranging from -20 to $+20$ with a reference vector of 10 m s^{-1} in Figures 2b and 2d. Entire ensemble suite (five members each) is used with statistical significance at 95% stippling for Figures 2a and 2c.

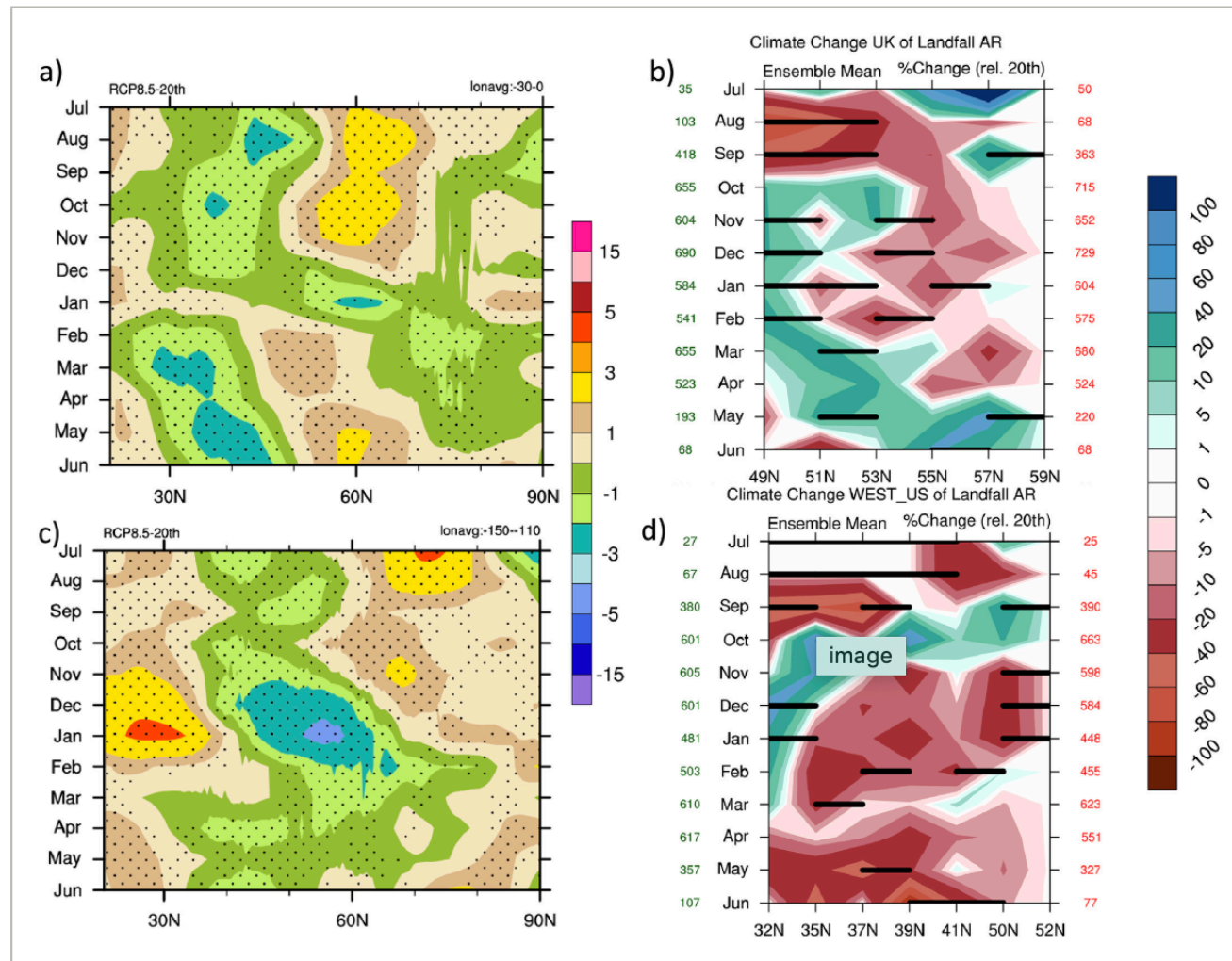


Figure 3

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(a) The 850 mb zonal wind climate change (RCP8.5-historical) seasonal cycle versus latitude for UK domain (0–30°W) with 95% significance stippling, (b) AR frequency climate change (RCP8.5-historical/historical) seasonal cycle versus latitude for UK domain, (c) same as Figure 3a except for WEST domain (110–150°W), and (d) same as Figure 3b except for WEST domain. Green (red) numbers in Figures 3b and 3d are ensemble-sum all-latitude storm counts for historical (RCP8.5) for 1960–2005 (2055–2100), and black bars denote significance.

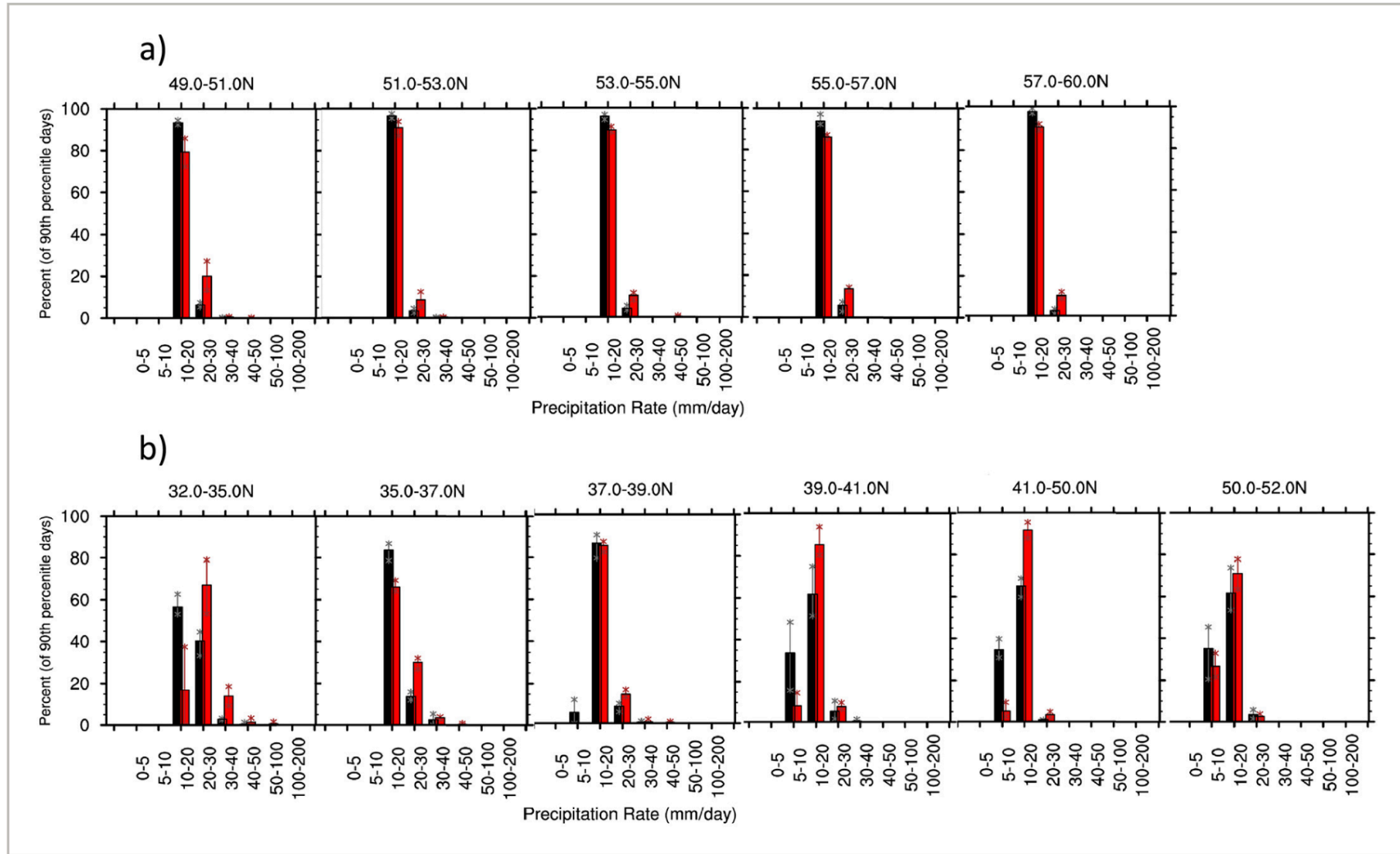


Figure 4

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AR precipitation probability density functions for (a) latitude bands spanning WEST domain and (b) latitude bands spanning UK domains. Binning is organized by precipitation rate in mm d^{-1} . Ensemble spread is shown.