Department of Meteorology

University of Reading

Expected water cycle responses to climate change

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How will the water cycle change?

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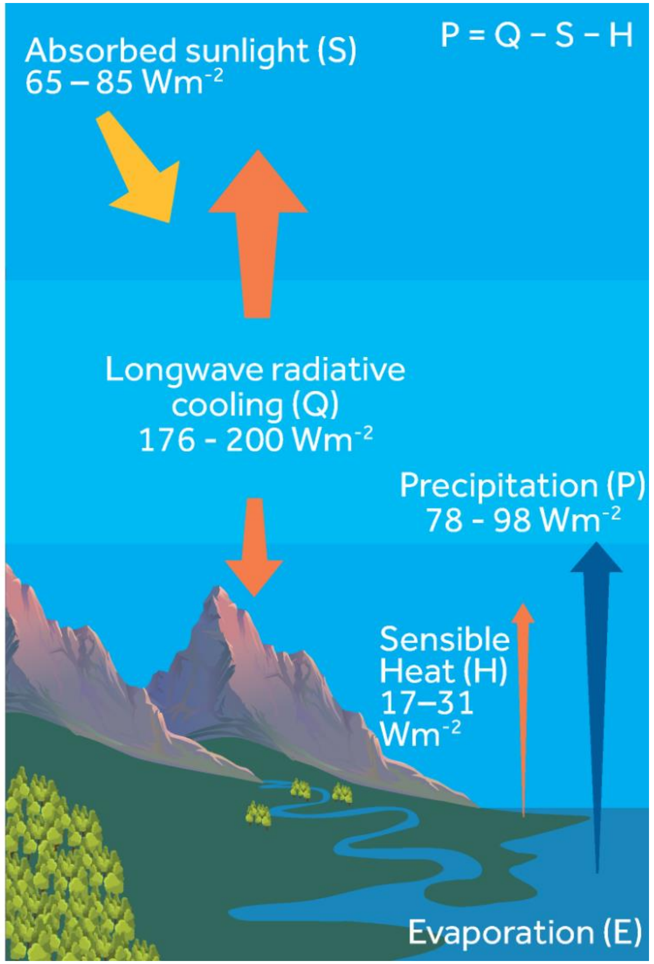
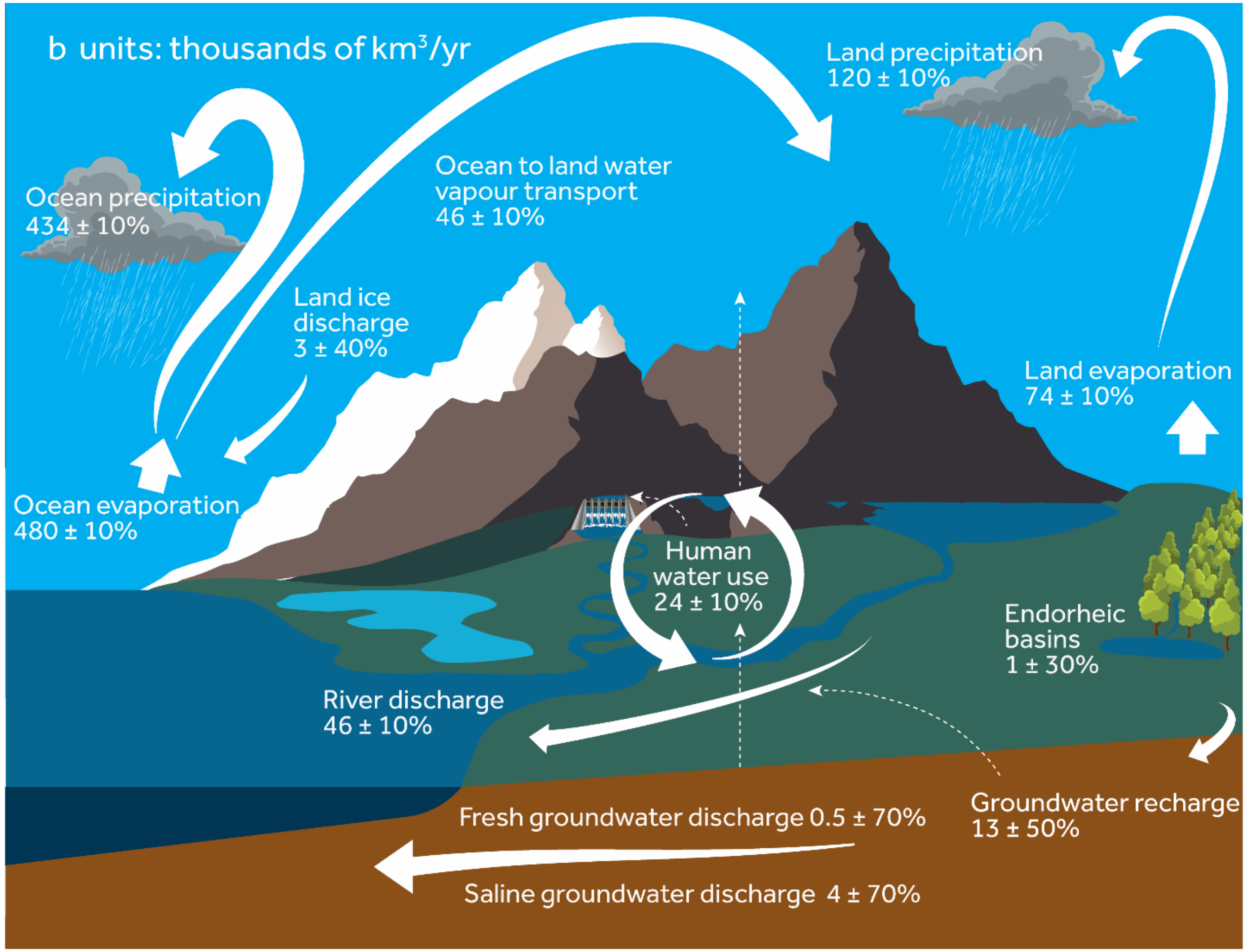
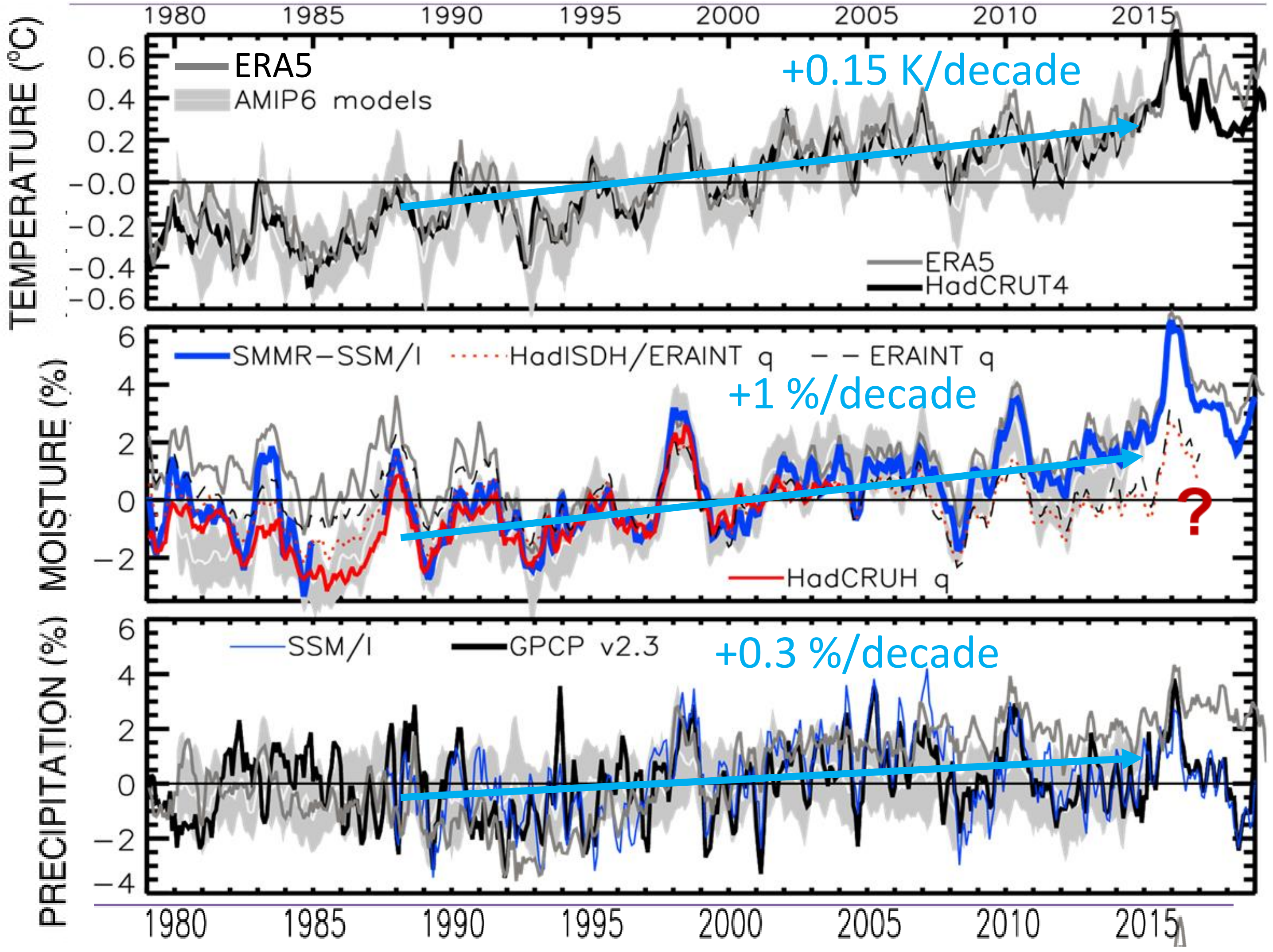




Allan et al. (2020) NYAS; see also Abbott et al. (2019) Nature Geosci.

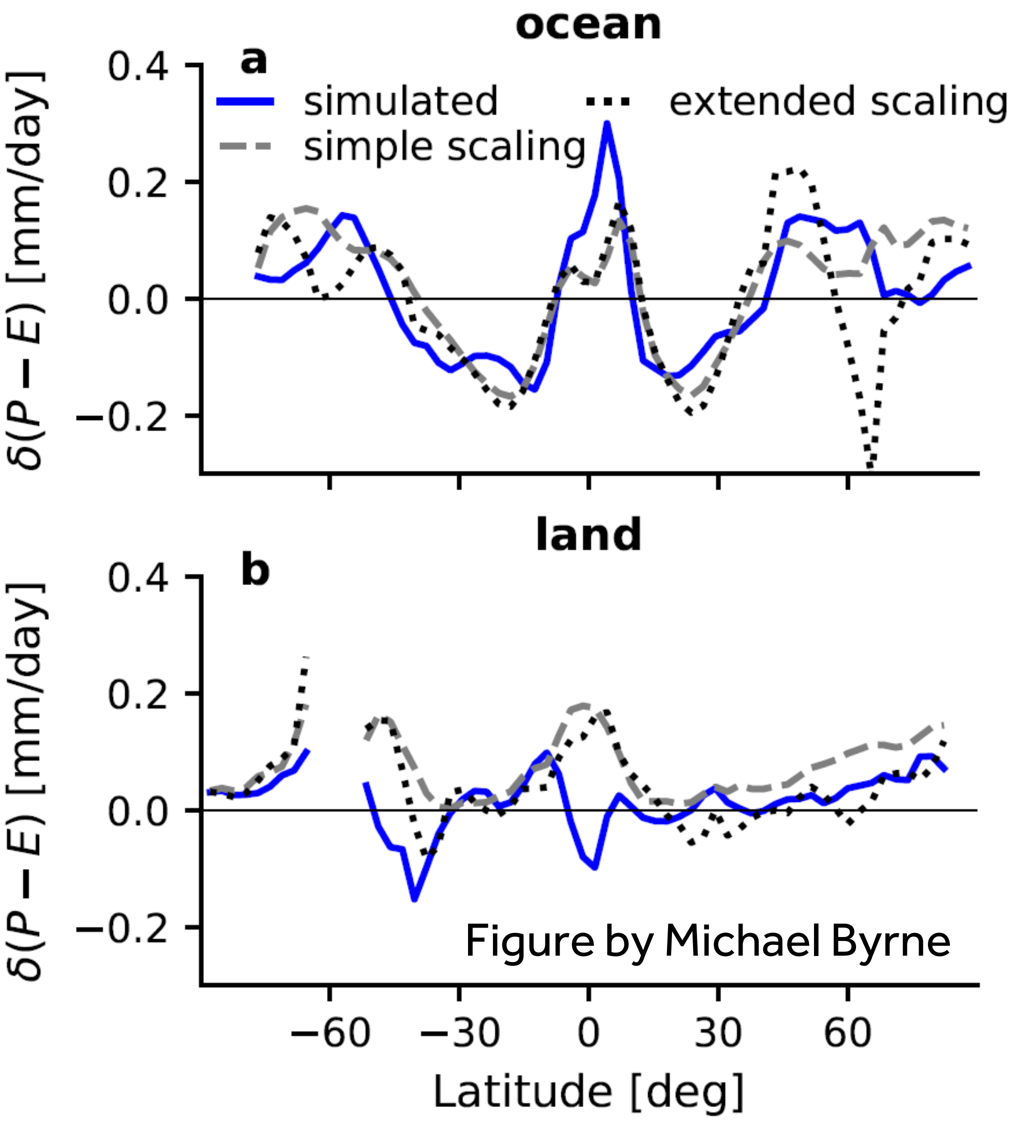
Observed changes in moisture & precipitation



Update from Allan et al. (2014) Surv. Geophys.

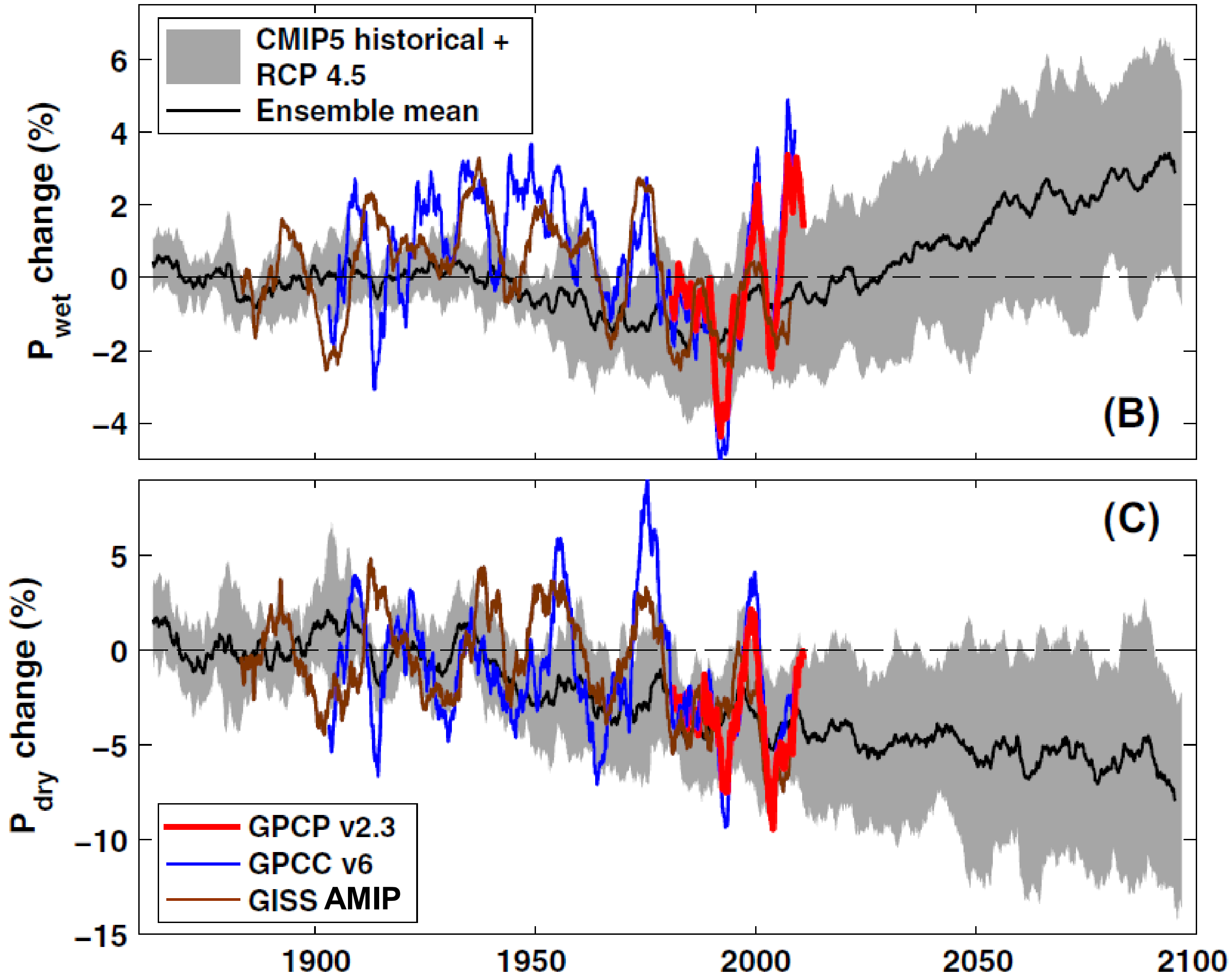
- Small global precipitation response expected (1-2.5 %/°C) on energetic grounds (aerosol cooling & fast adjustments to GHGs and absorbing aerosol)
- ERA5 captures water vapour changes (~7%/°C) since mid-1990s but not precipitation
- Relative humidity decline over land (Willett et al. 2020 ESSD) expected from land-ocean warming contrast (O'Gorman & Byrne 2018); underestimated by models? (Dunn et al. 2017)

Amplification of P-E and salinity patterns



- Increased moisture transport (~7%/°C) from evaporative ocean into weather systems, monsoons & high latitudes
- Amplification of existing P-E and salinity patterns over ocean e.g. Durack 2015
- Over land, complex interaction between land-ocean warming contrast, vegetation responses to climate and CO_2 and circulation changes, Byrne & O'Gorman 2015
- Wetter wet seasons and weather events
- More intense dry seasons and droughts

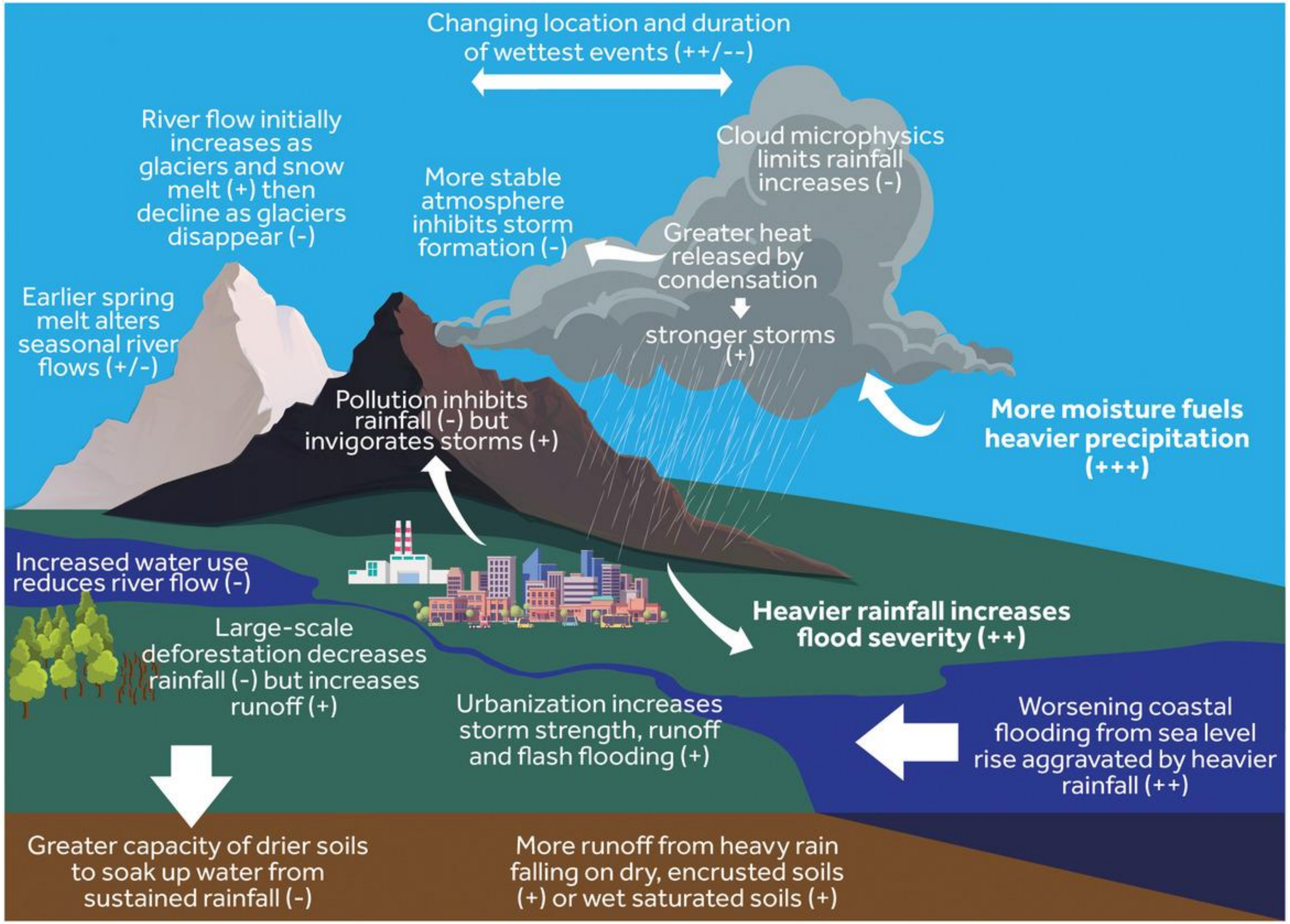
Larger seasonal & interannual contrasts in tropics



- Dynamically track wettest 30%, driest 70% regions each month
- Tropical land precipitation increases in wet regime, decreases in dry regime
- Observed decadal variability explained by internal variability
- See also **Schurer et al. (2020) ERL**; **Kumar et al. (2015) GRL**

Liu & Allan (2013) ERL update in *Tropical Extremes: Natural Variability & Trends*

Changes in heavy precipitation and flood hazard



- Intensification of extreme precipitation with increasing moisture (~7% per °C)
  - Latent heating strengthens storms but stabilised atmosphere
  - Flooding also modulated by catchment characteristics; glacier and snowmelt; sea level rise; direct human influence

Allan et al. (2020) NYAS; see also Fowler et al. (2021) Nature Rev.

Local-scale factors affecting water cycle change

- Increases in atmospheric evaporative demand intensify dry spells
  - Land-ocean warming contrast important in explaining declining continental relative humidity and change in regional precipitation patterns
  - Vegetation-soil-atmosphere feedbacks important in amplifying
- Direct CO_2 effect on plant growth and water use efficiency
  - how these combine regionally uncertain Peters et al. 2018; Lemordant et al. 2018
- Earlier but possibly slower spring snow melt Musselman et al. 2017
  - altitude/latitude/catchment dependent Pall et al., 2019; Musselman et al. 2018
  - Some rivers increase then decrease flow as glaciers melt then disappear (SROCC)
- Direct human effects: water extraction, irrigation and deforestation
  - Irrigation increases local precipitation, deforestation decreases local precipitation
  - Urbanisation can delay and intensify precipitation (heat island & aerosol effects)
- Many other factors but circulation change critical

Conclusions

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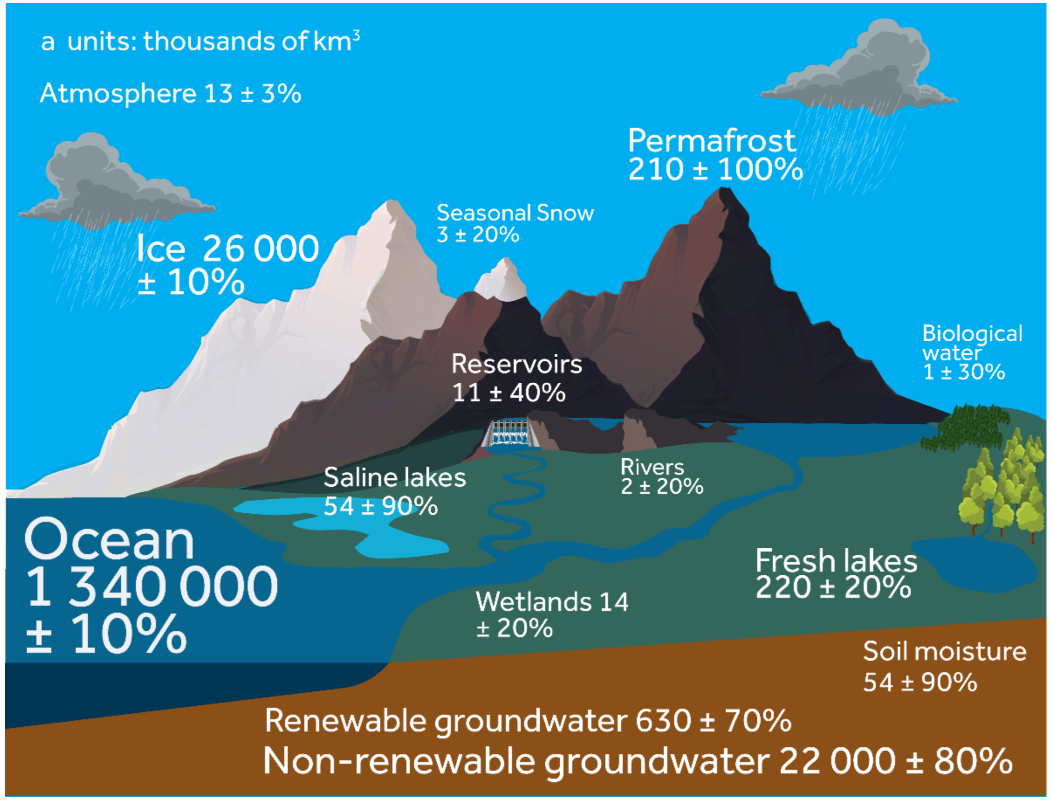
- **More stable/accurate global estimates of precipitation, evaporation and Earth's energy budget essential to confirm:**
  - Global energy and water budgets and coupling
  - Water cycle responses to radiative forcing and subsequent warming
- **Improved assessment of moisture and energy transports**
  - Essential in capturing regional water cycle changes
  - Require combination of satellite data & simulations
  - Intensification of wet and dry weather events
- **Local scale monitoring of water cycle components**
  - Cryosphere; surface water; subsurface moisture; vegetation; direct human influence
  - Synergistic use of observations, reanalyses and models
- **Shifts in atmospheric circulation dominate regionally**
  - least certain but potentially most impactful
  - Combine observing systems with physical understanding



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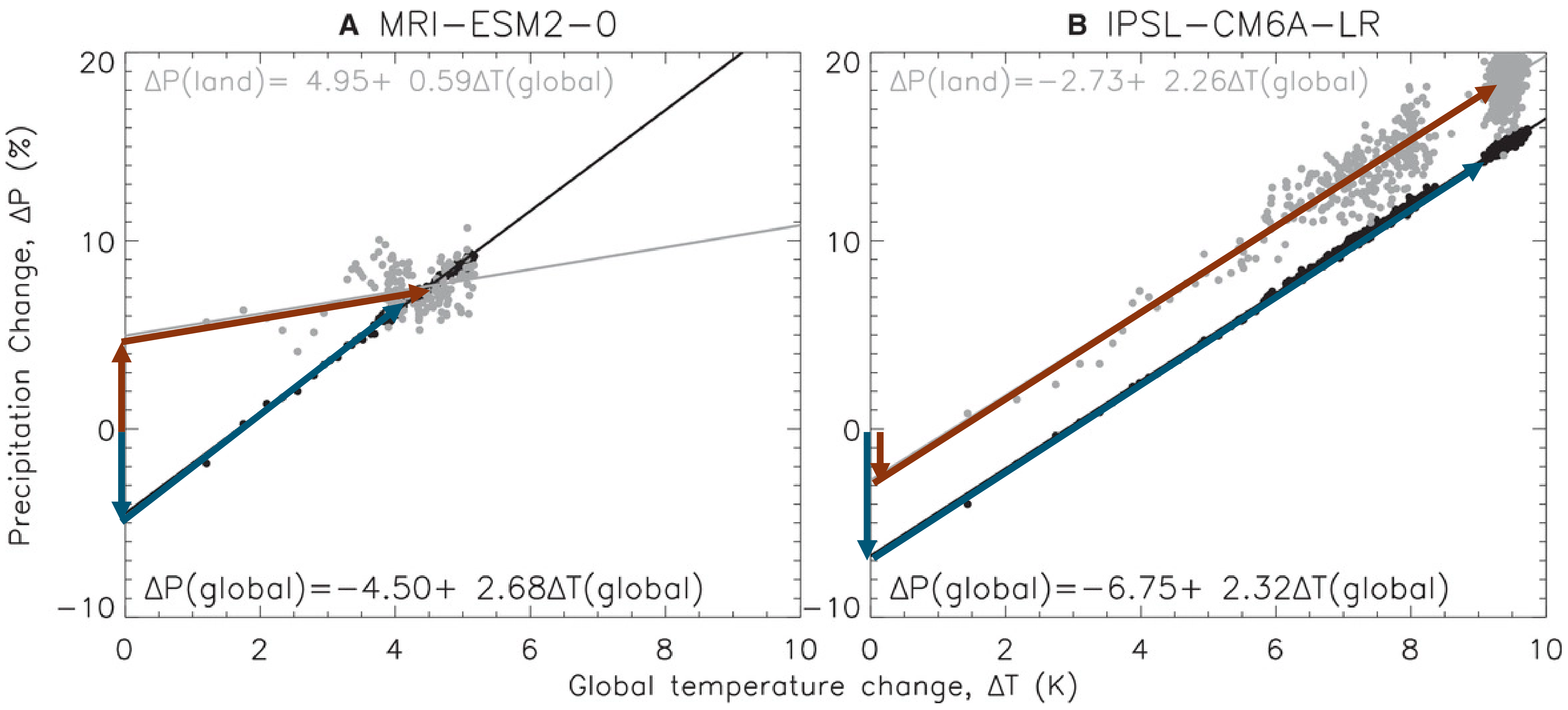
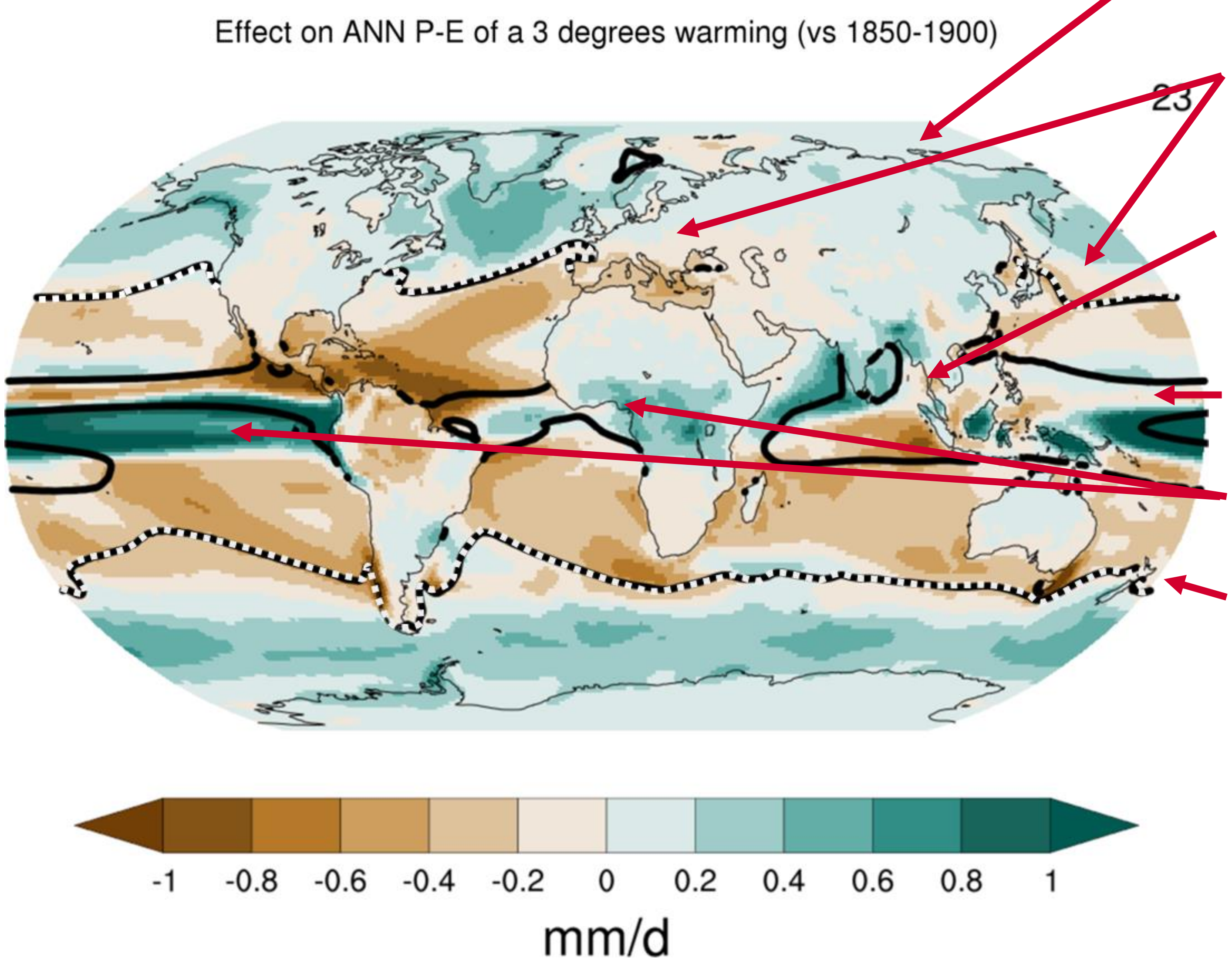
Fast & slow global precipitation responses to 4xCO_2



Allan et al. (2020) NYAS

Global: rapid decline, consistent slow increase with warming (2-3%/^{o}C)
Land: model-dependent rapid response & suppressed increase with warming

Circulation-related changes

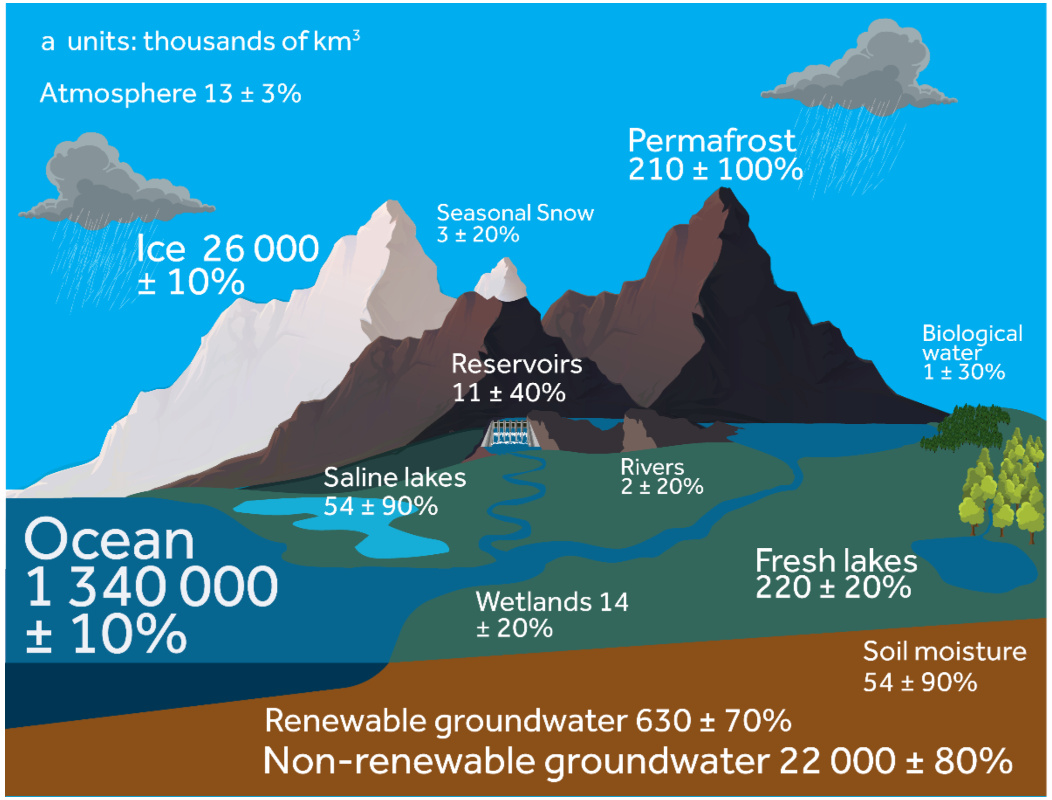


Thanks to Stéphane Sénési for P-E@3K figure

- Uncertain role of Arctic amplification on high latitude weather systems e.g. Henderson et al. 2018; Tang et al. 2014
- Poleward migration of subtropical belt over ocean, complex effects over land Grise & Davis 2020; Byrne & O'Gorman 2015
- Slowing tropical circulation supresses thermodynamic intensification of monsoons e.g. IPCC AR5
- Contraction and intensification of ITCZ e.g. Byrne & Schneider, 2016; Su et al., 2020
- Region dependent shifts in ITCZ e.g. Dong & Sutton 2015; Dunning et al. 2018
- Poleward, complex migration of storm tracks/contrasting hemispheric forcing Watt-Meyer et al., 2019; Zhao et al., 2020

Conclusions

- Advances in understanding global scale water vapour & precipitation responses to radiative forcings & subsequent warming
- Regionally, thermodynamic increases in moisture drives an intensification of extreme wet and dry events
- Locally, vegetation, cryosphere, micro-physical and human factors important
- Shifts in atmospheric circulation least certain but potentially most impactful



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