Advances in understanding large-scale responses of the water cycle to climate change

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Abstract

Globally, thermodynamics explains an increase in atmospheric water vapor with warming of around 7%/°C near to the surface. In contrast, global precipitation and evaporation are constrained by the Earth's energy balance to increase at 2–3%/degC. However, this rate of increase is suppressed by rapid atmospheric adjustments in response to greenhouse gases and absorbing aerosols that directly alter the atmospheric energy budget. Rapid adjustments to forcings, cooling effects from scattering aerosol, and observational uncertainty can explain why observed global precipitation responses are currently difficult to detect but are expected to emerge and accelerate as warming increases and aerosol forcing diminishes. Precipitation increases with warming are expected to be smaller over land than ocean due to limitations on moisture convergence, exacerbated by feedbacks and affected by rapid adjustments. However, these temperature-dependent changes offset rapid atmospheric adjustments to radiative forcings which tend to increase precipitation over land relative to the oceans. These factors therefore drive complex changes in the regional water cycle in time and space, some examples of which will be discussed. Thermodynamic increases in atmospheric moisture fluxes amplify wet and dry events, driving an intensification of precipitation extremes. The rate of intensification can deviate from a simple thermodynamic response due to in-storm and larger-scale feedback processes, while changes in large-scale dynamics and catchment characteristics further modulate the frequency of flooding in response to precipitation increases. Changes in atmospheric circulation in response to radiative forcing and evolving surface temperature patterns are capable of dominating water cycle changes in some regions. Moreover, the direct impact of human activities on the water cycle through water abstraction, irrigation, and land use change is already a significant component of regional water cycle change and is expected to further increase in importance as water demand grows with global population. This talk will summarize recent advances in understanding past and future large-scale responses in the water cycle.

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How will the water cycle change?

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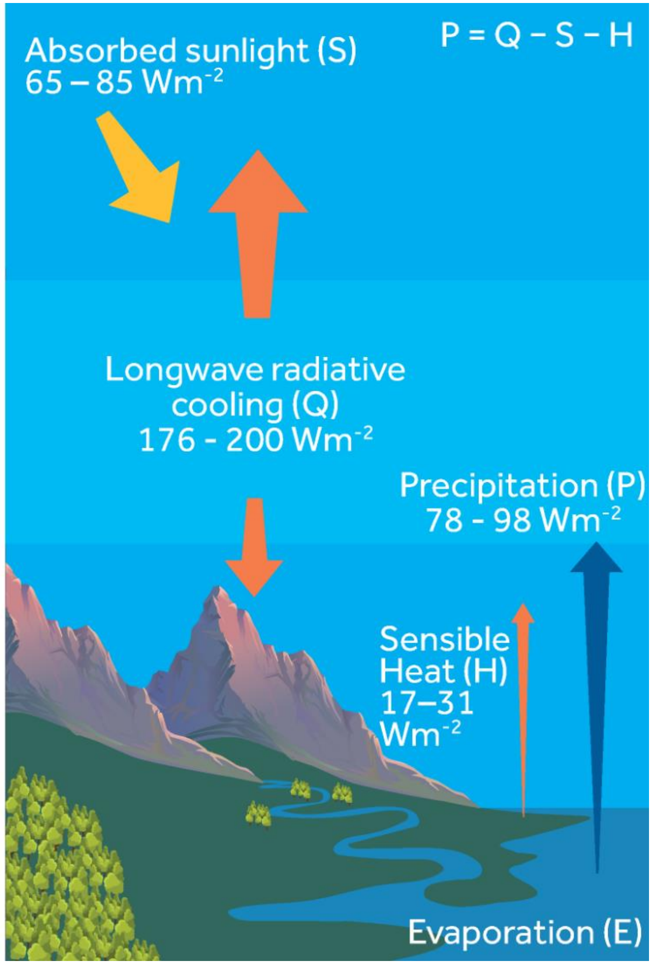
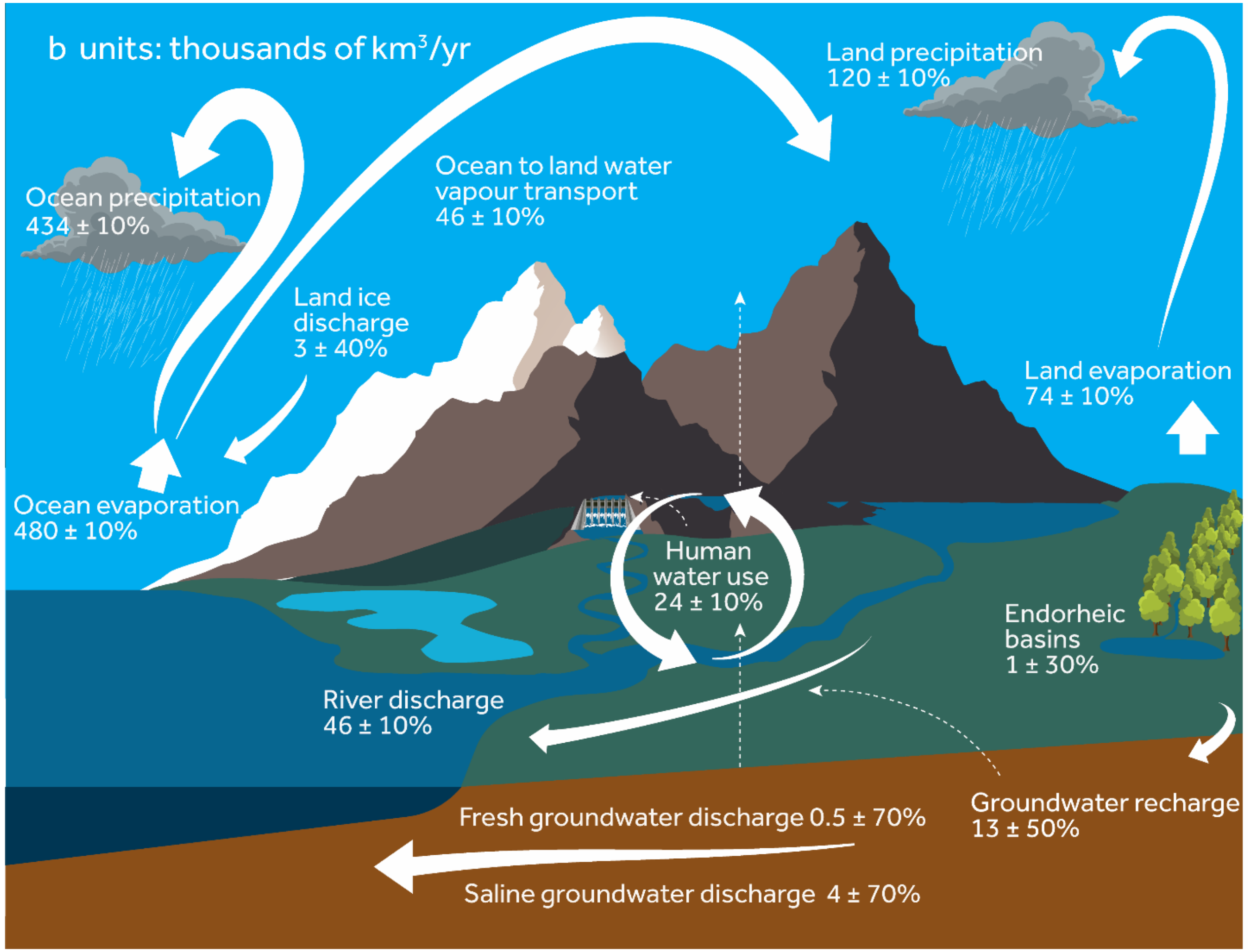
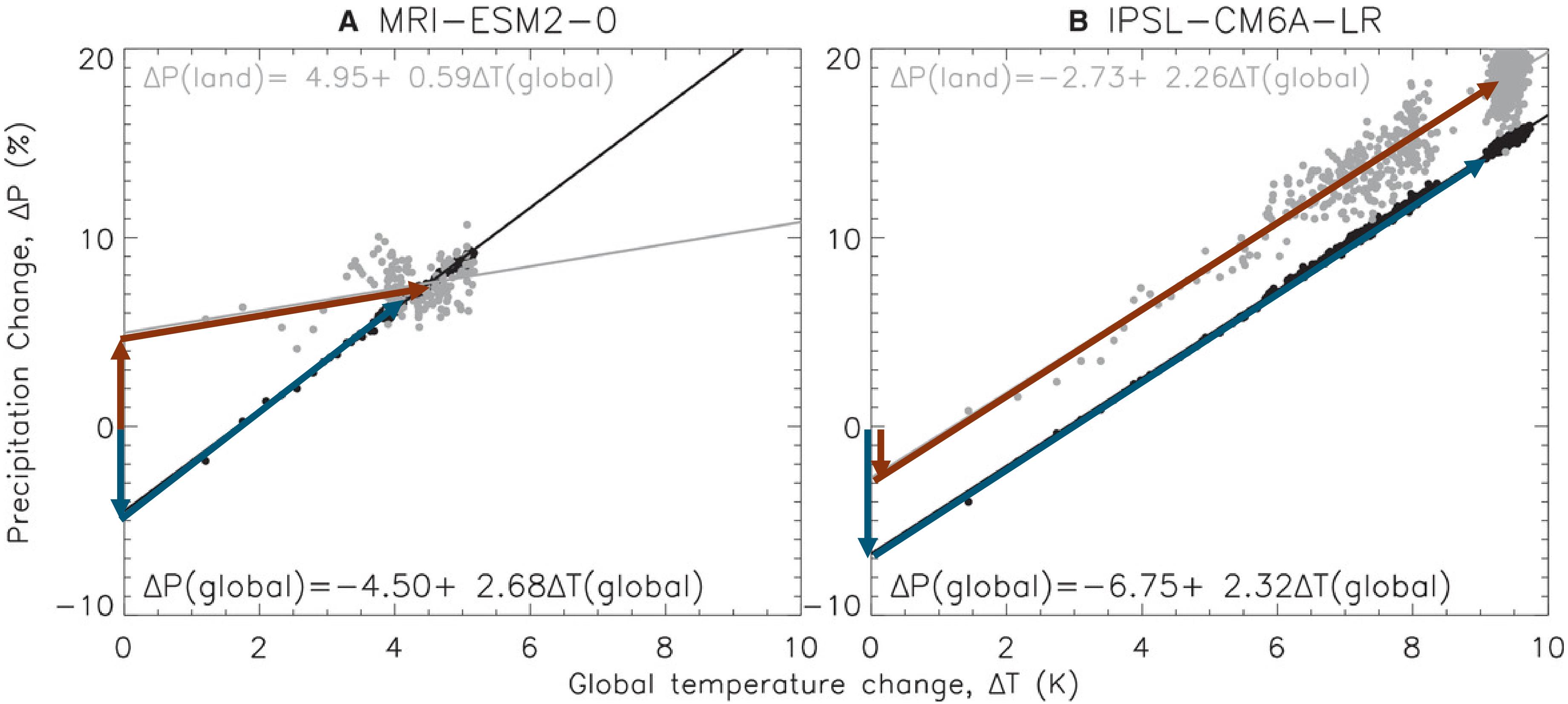




Allan et al. (2020) NYAS; see also Abbott et al. (2019) Nature Geosci.

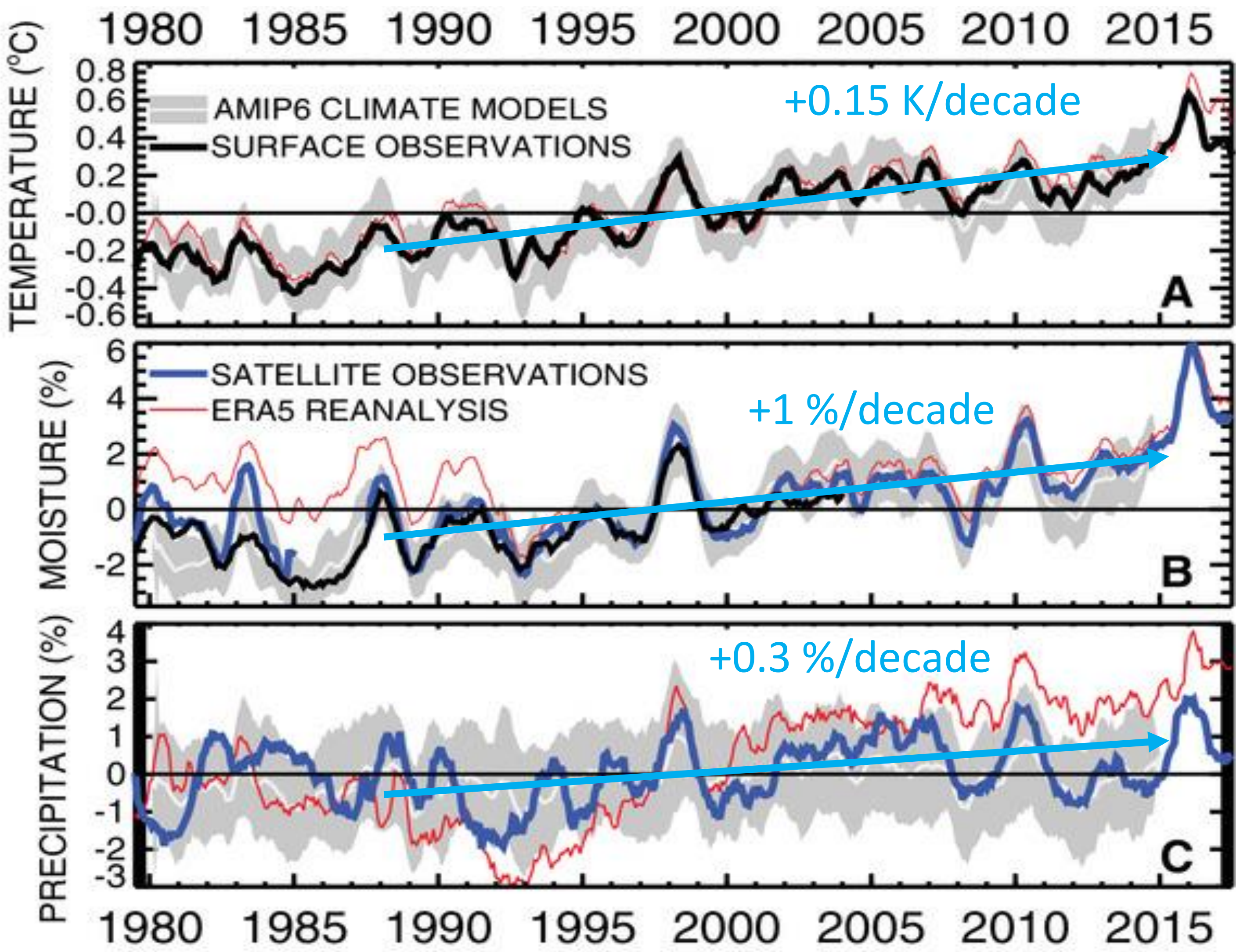
Fast & slow global precipitation responses to $4xCO_2$



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

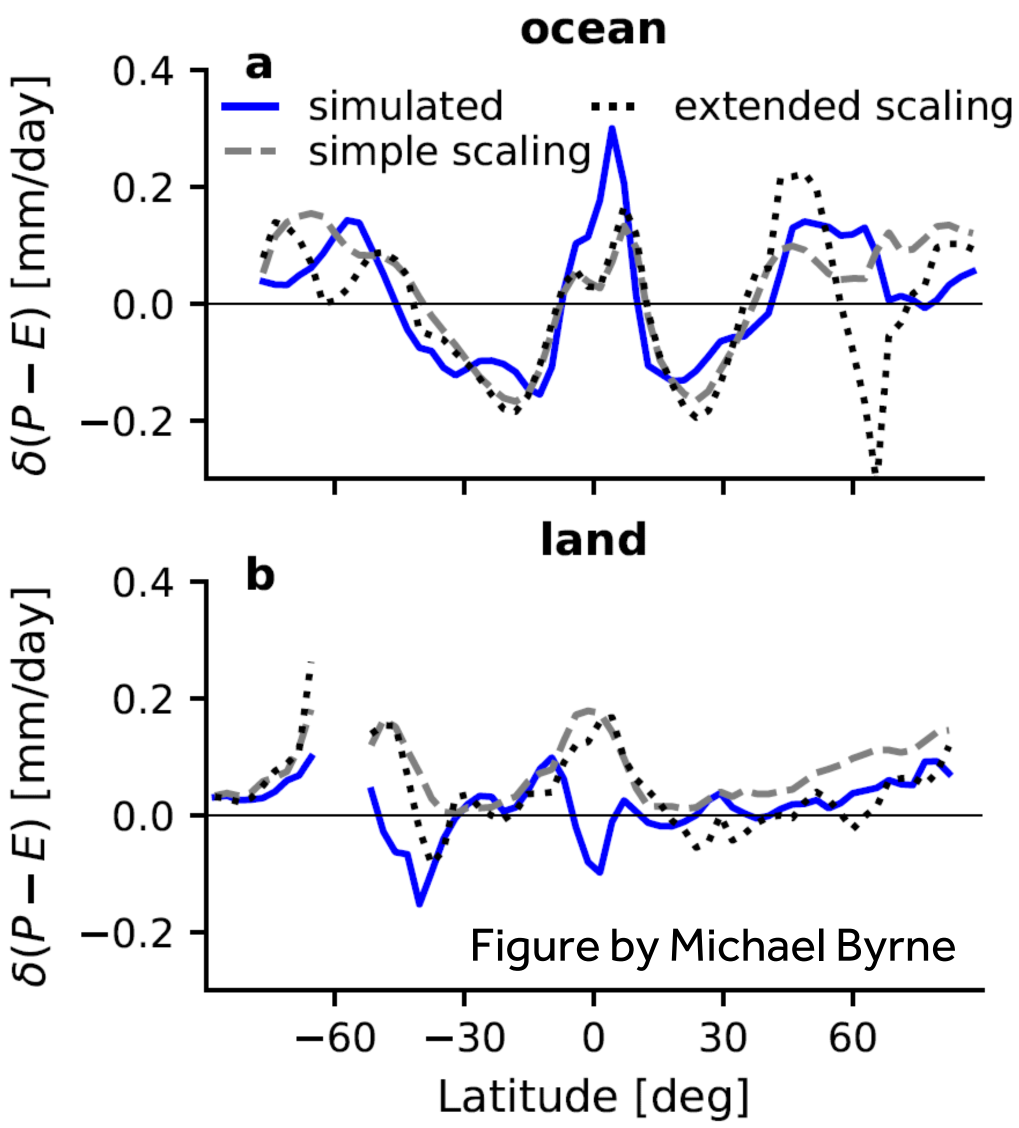
Observed changes in moisture & precipitation



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

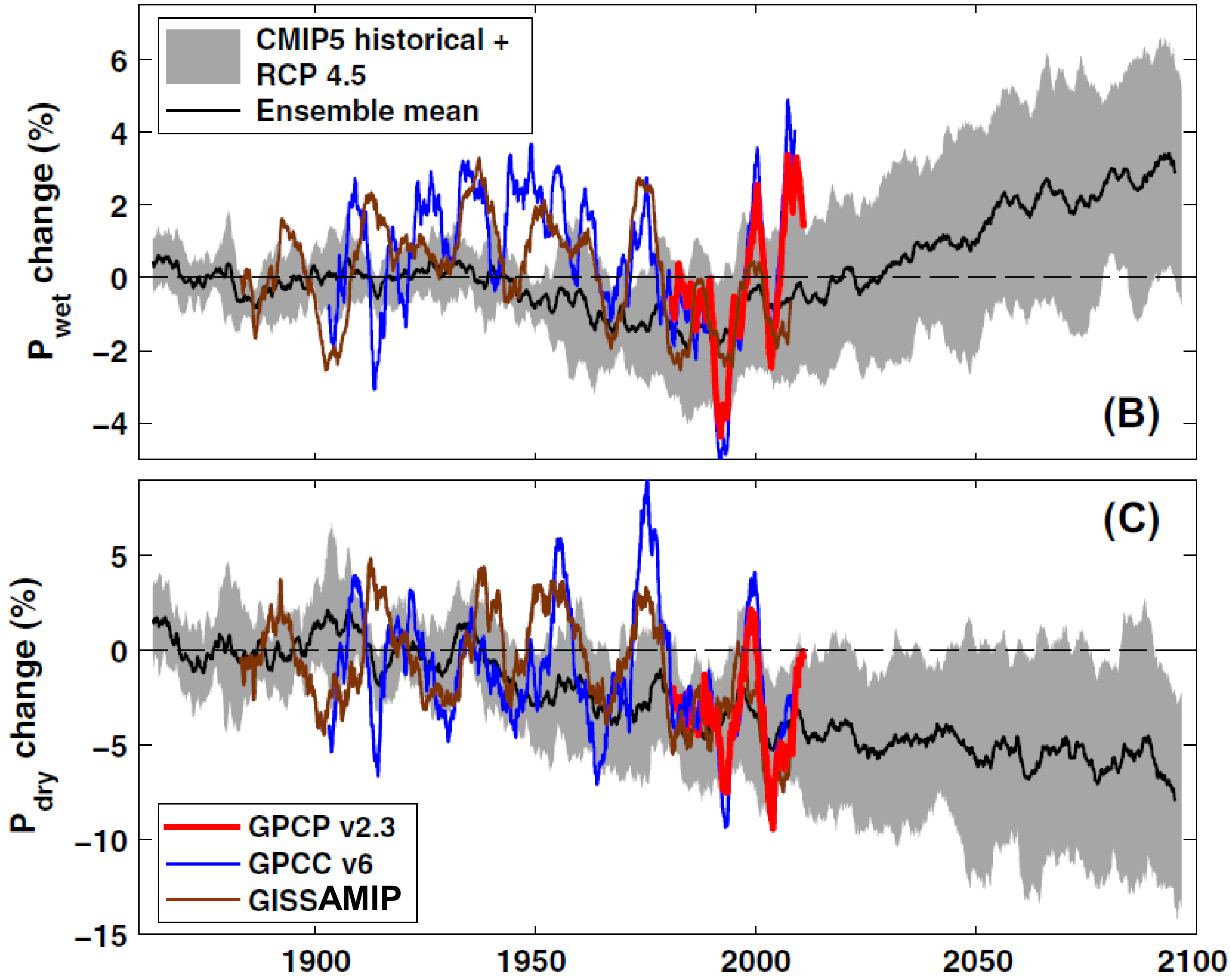
- Small precipitation response expected on energetic grounds (aerosol cooling & fast adjustments to GHGs and absorbing aerosol)
- ERA5 captures water vapour changes since mid-1990s but not precipitation
- Relative humidity decline over land expected from land-ocean warming contrast (O'Gorman & Byrne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

Amplification of P-E and salinity patterns



- Increased moisture transport 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

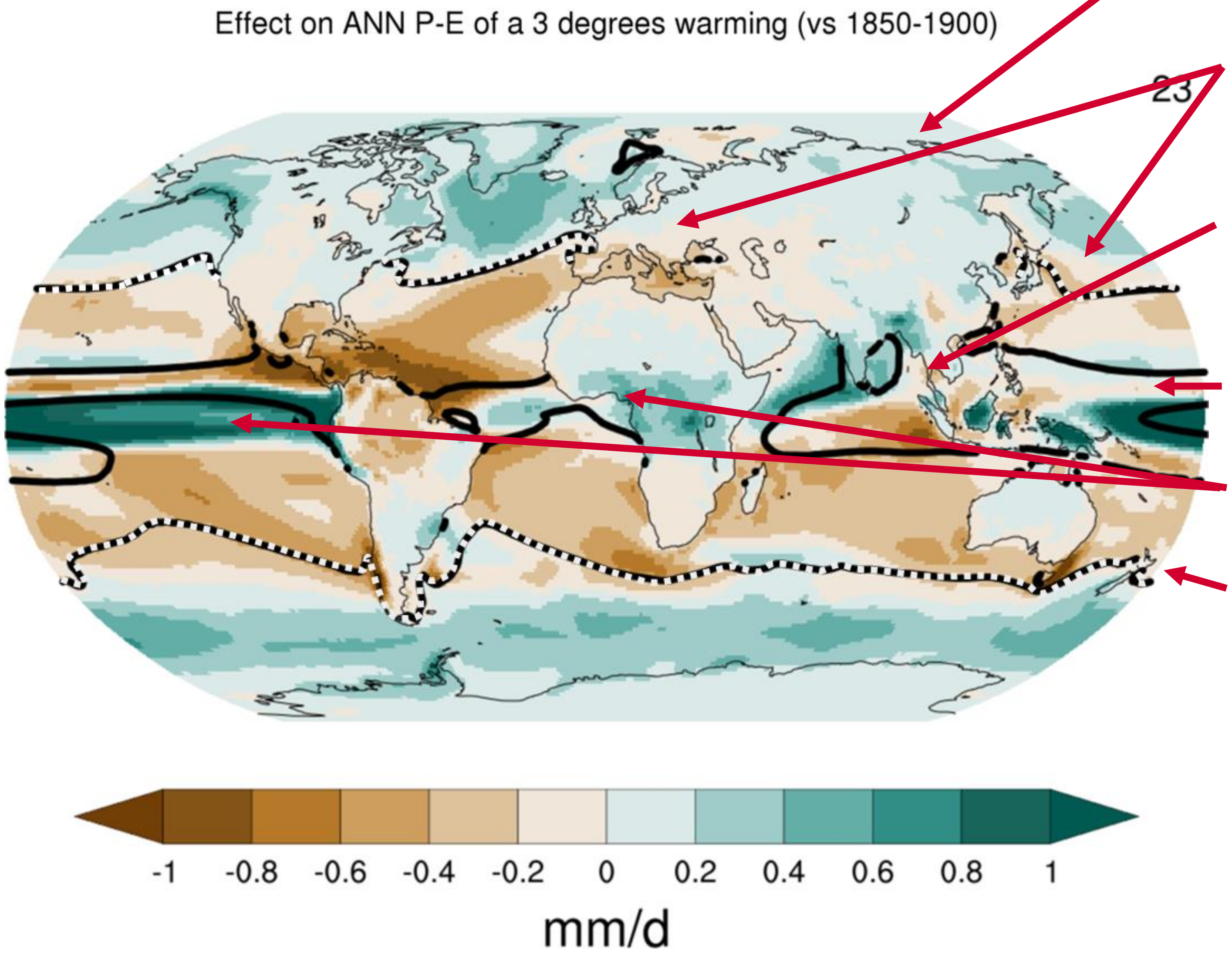
Larger seasonal & interannual contrasts in tropics



- 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**
- Also GC011-06 by Caroline Wainwright on wet/dry season characteristics in this session

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

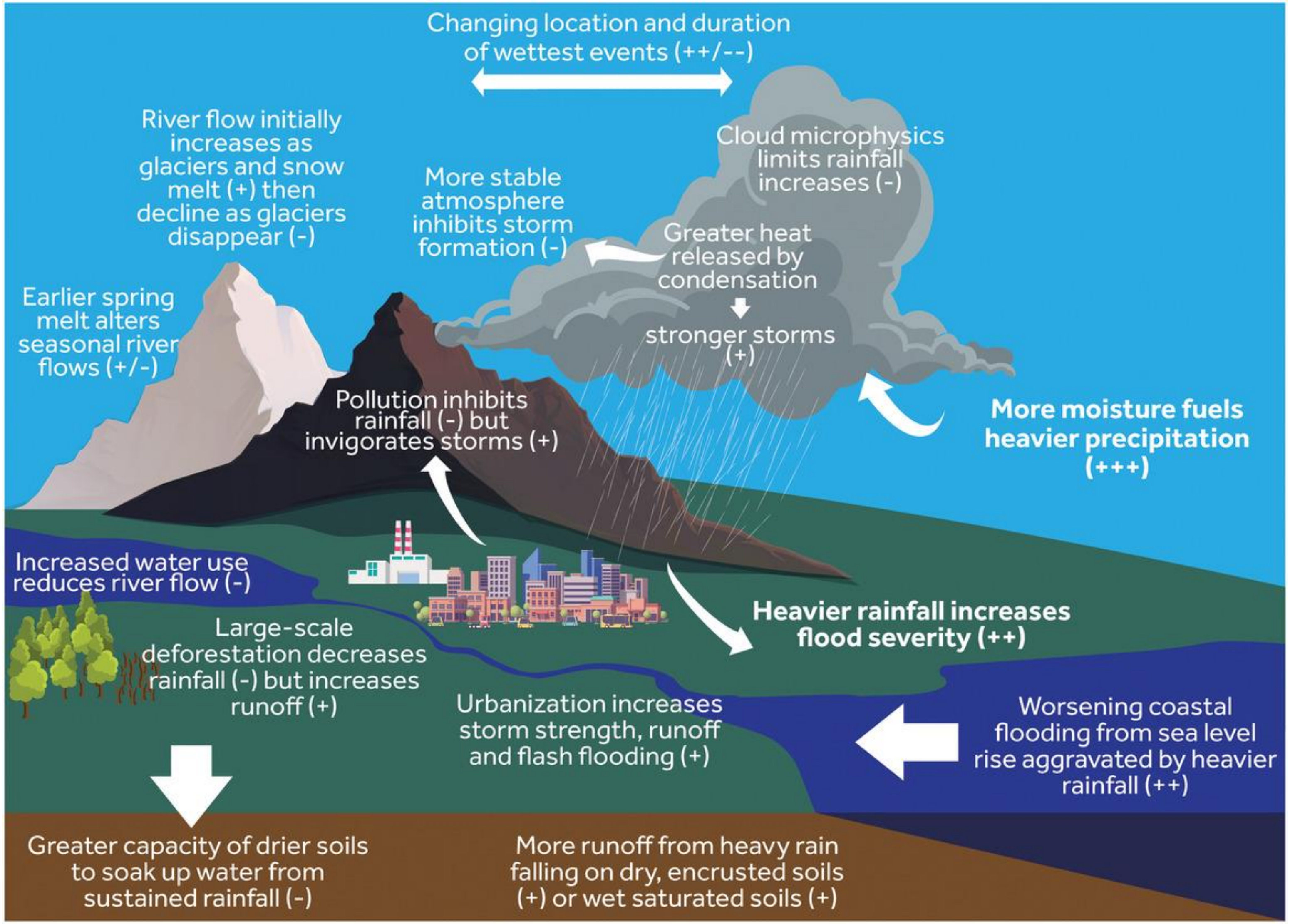
Circulation-related changes



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

Changes in heavy precipitation and flood hazard



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

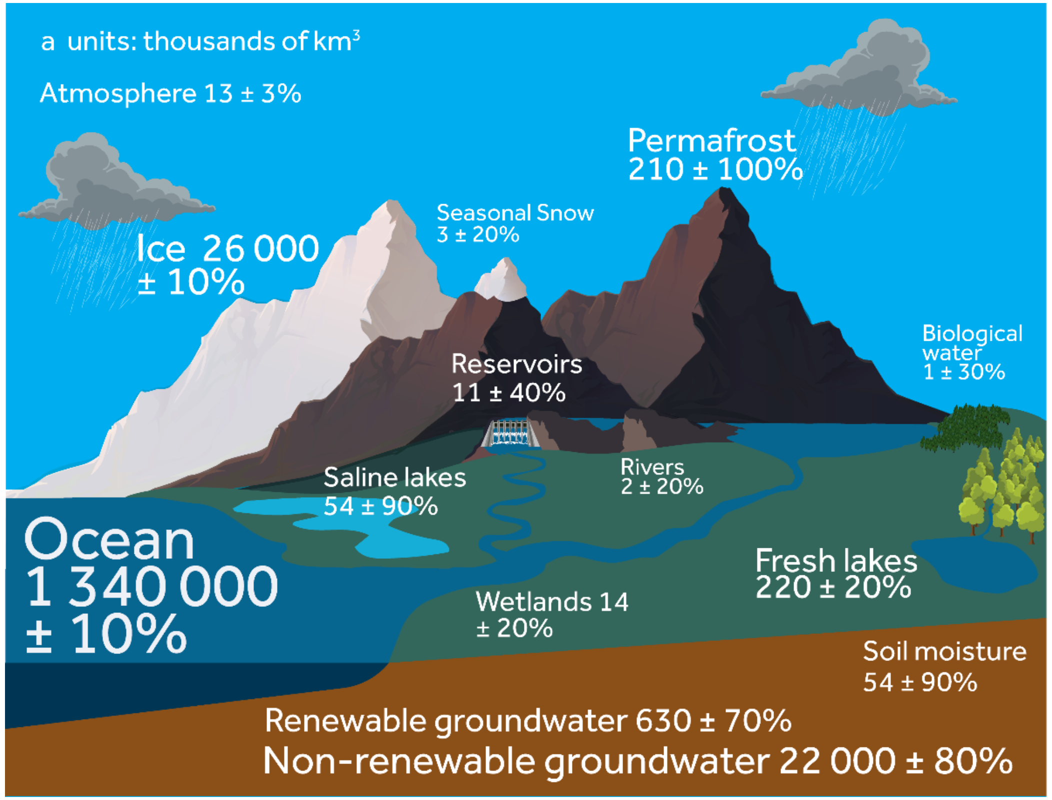
Allan et al. (2020) NYAS; see also Fowler et al. (2021) Nature Rev.

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
  - ➢ low confidence in how these combine regionally Peters et al. 2018; Lemordant et al. 2018
- Earlier but possibly slower spring snow melt e.g. Musselman et al. 2017
  - ➢ altitude/latitude/catchment dependent e.g. Pall et al., 2019; Musselman et al. 2018
  - ➢ Some rivers increase then decrease flow as glaciers melt then disappear (SROCC)
- Direct human effects on 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

- 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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