Integrating soil moisture and groundwater into climate models

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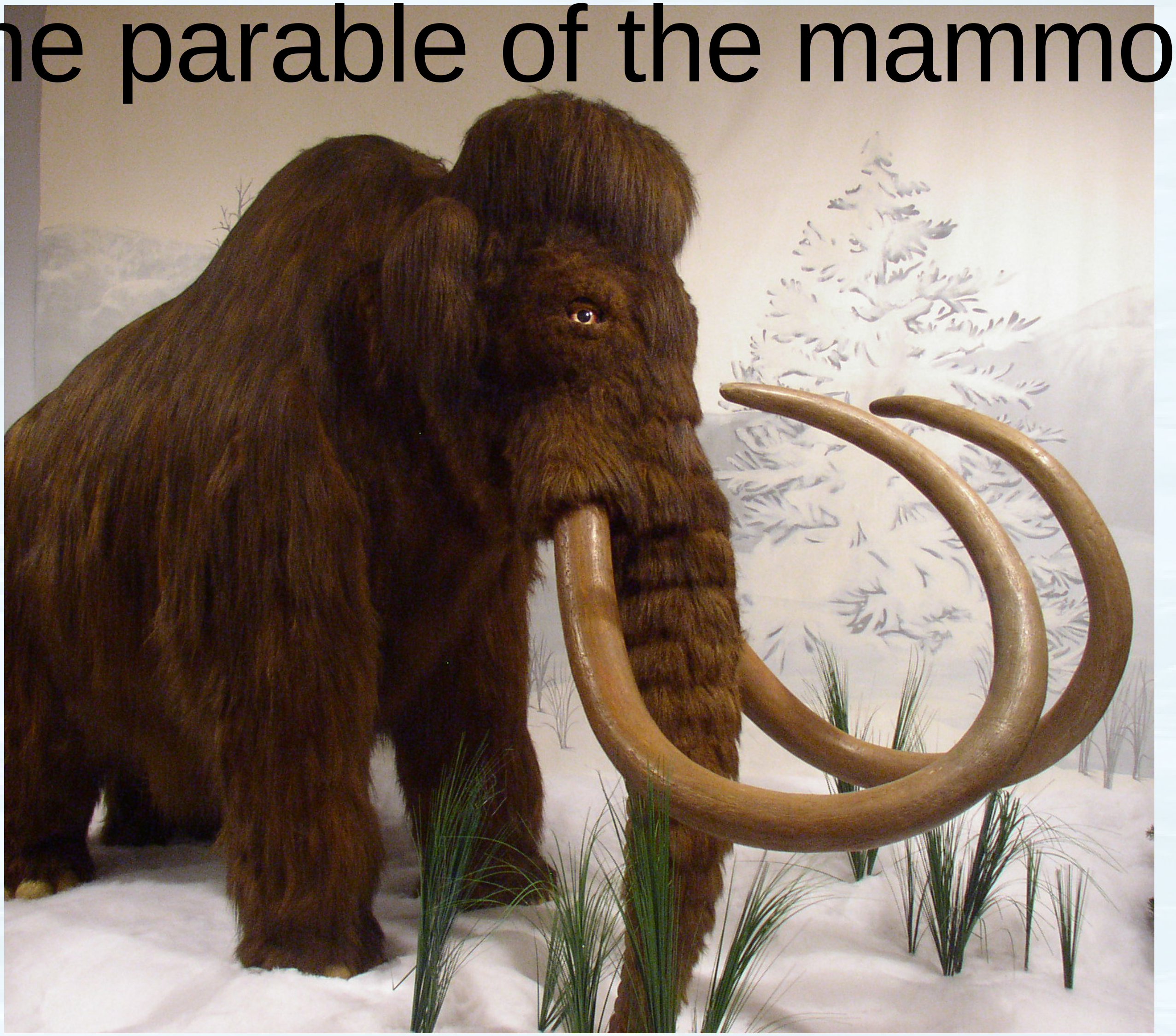
Talk outline

- Motivation
- Soil moisture and climate
- Irrigation and climate
- Groundwater and climate
- Planned directions

The parable of the mammoth

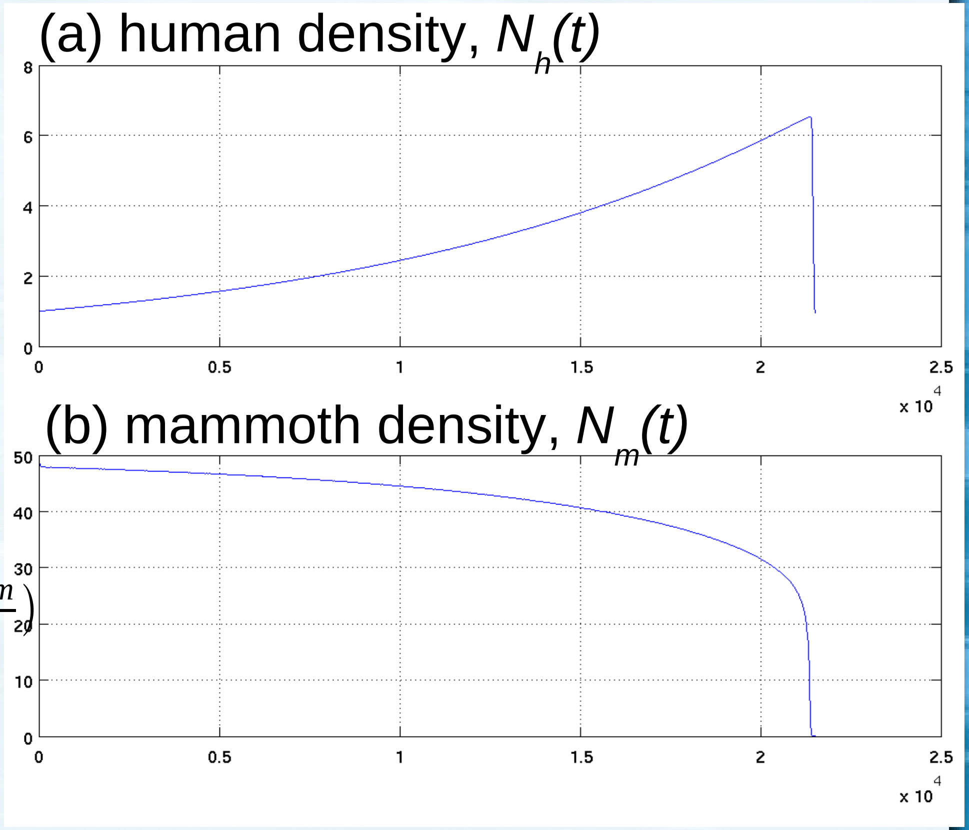


How did mammoths perish after coexisting with humans for millennia?

How mammoths could go extinct

$$\frac{dN_h}{dt} = \beta_h N_h (\Box - \frac{\gamma}{N_m})$$

$$\frac{dN_m}{dt} = \beta_m N_m (1 - \frac{N_m}{\alpha}) - h N_h \min(1, \frac{N_m}{\gamma})$$



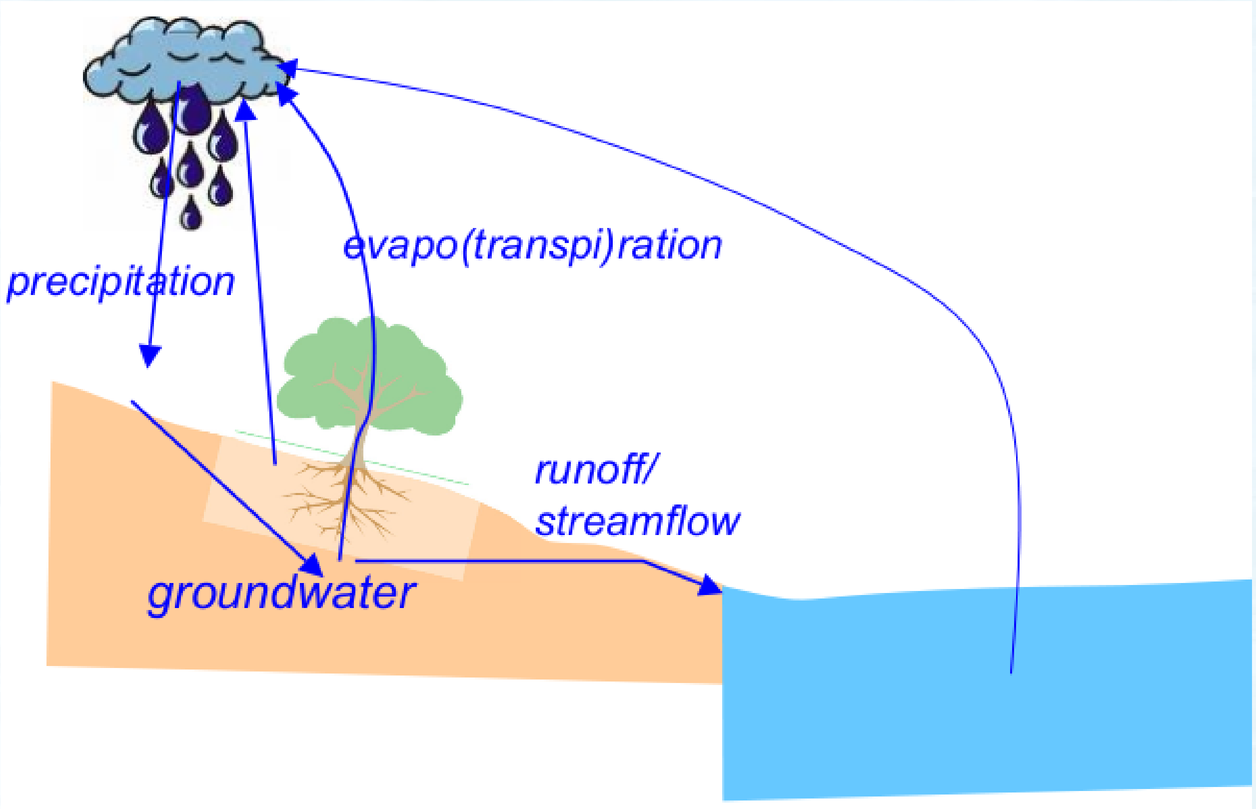
State transition to oscillatory solutions with efficient hunting ($\gamma \ll \alpha$): even slow human population growth ($\beta_h = 10^{-4}\ yr^{-1}$) dooms mammoths (Budyko, 1968)

Lesson: efficiency without (nonlinear!) foresight can be deadly

Not just mammoths...

- Freshwater and moderate climate – like other resources – are equally vulnerable to running out as people become more numerous and skillful
- This may not be obvious until heavy depletion has occurred
- To provide more advance warning for preemptive measures, need to model the interaction of water use and climate

Soil moisture -climate feedbacks



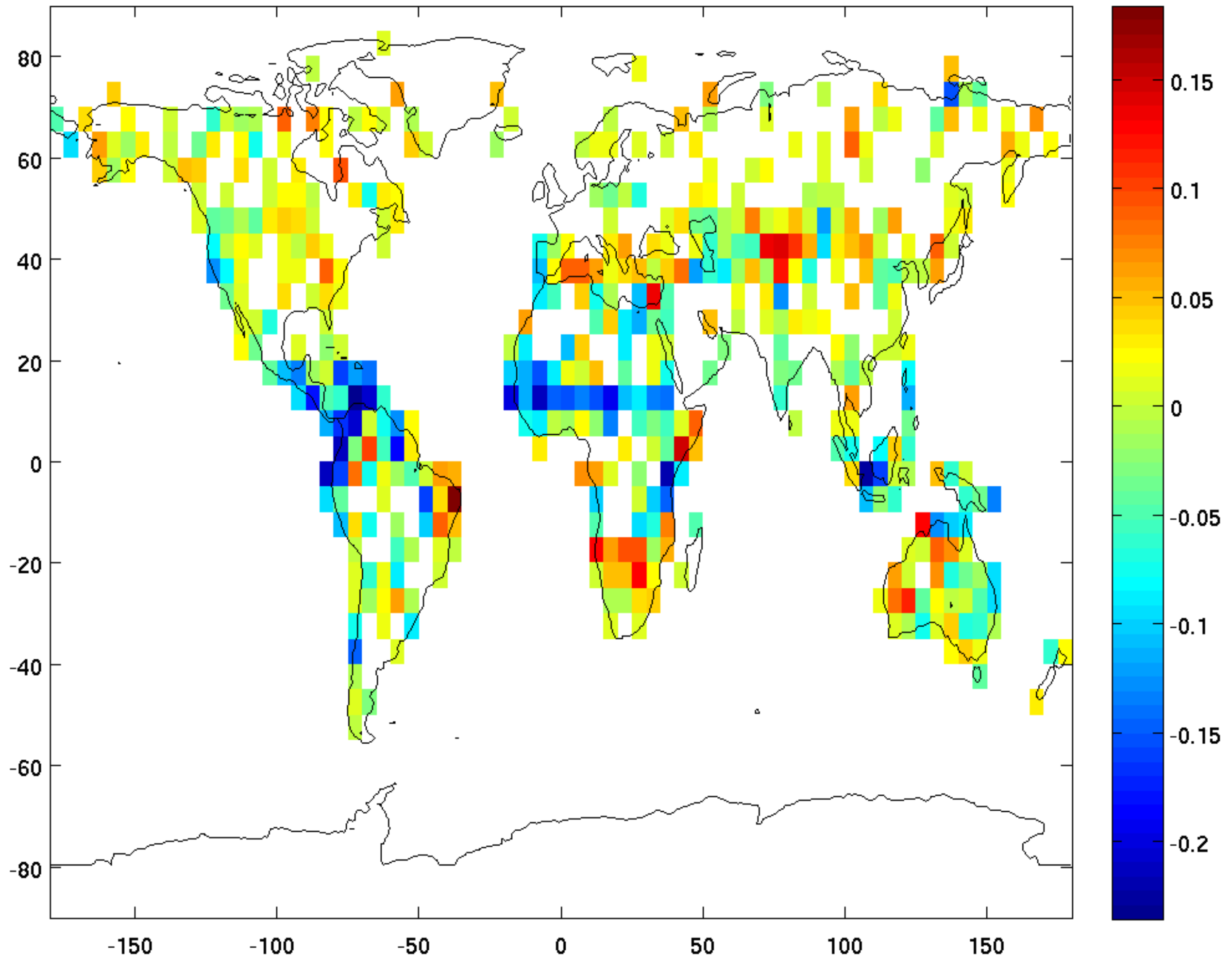
S → E → –T → (+/–)P → S (direct, local)

S → E → P → S (indirect, regional)

Soil moisture influence on climate: What do we know?

- Observational studies: more precipitation when soil is already moist (e.g. Findell & Eltahir, *WRR* 1997)
- Model studies of this correlation (e.g. GLACE, Koster et al., *Science* 2004)
- Combining the two: “correct” soil moisture model initialization leads to better forecasts (e.g. Dirmeyer, *J Climate* 2000)

Mapping feedback strength



Jul.-Sep. land-surface moisture index (P - PE)
Red: better predicted using Apr.-Jun. Land-surface moisture
Blue: better predicted using Apr.-Jun. SST

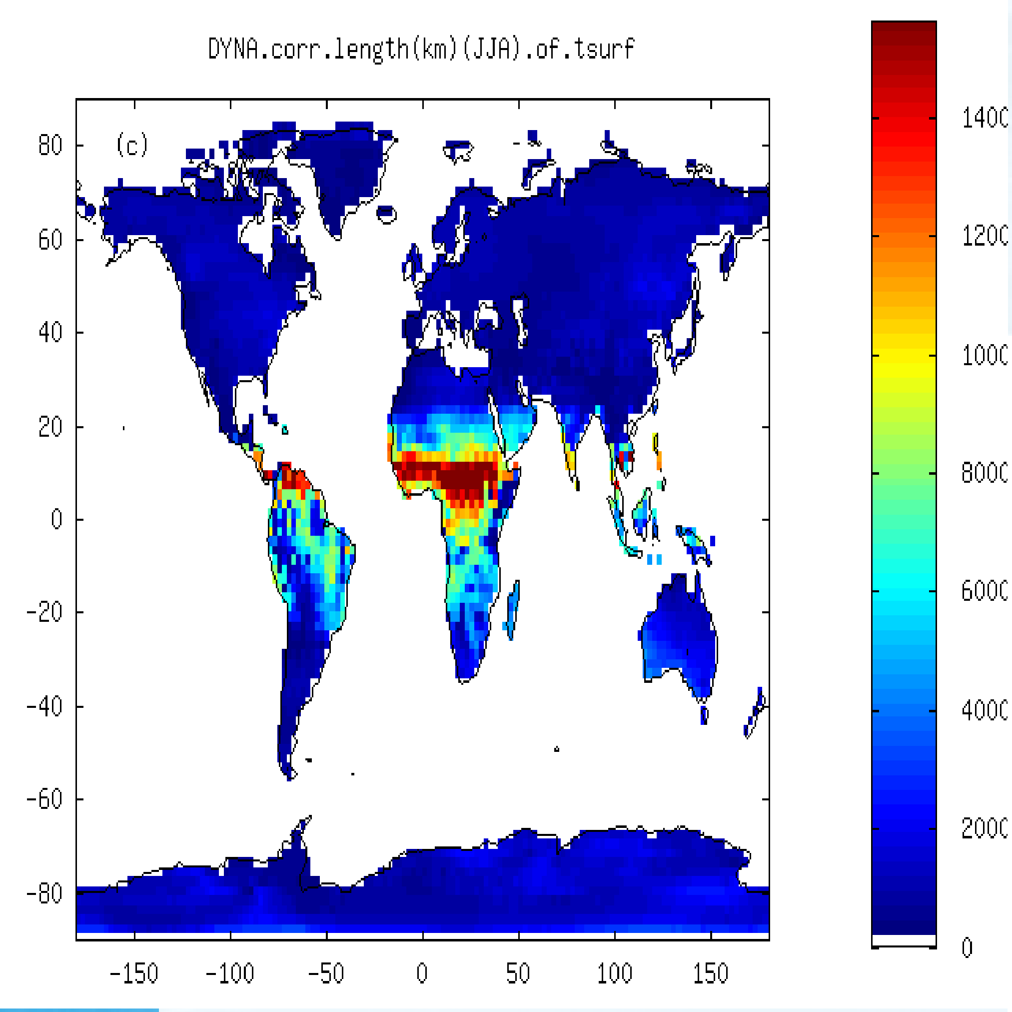
Initial questions: Soil moisture

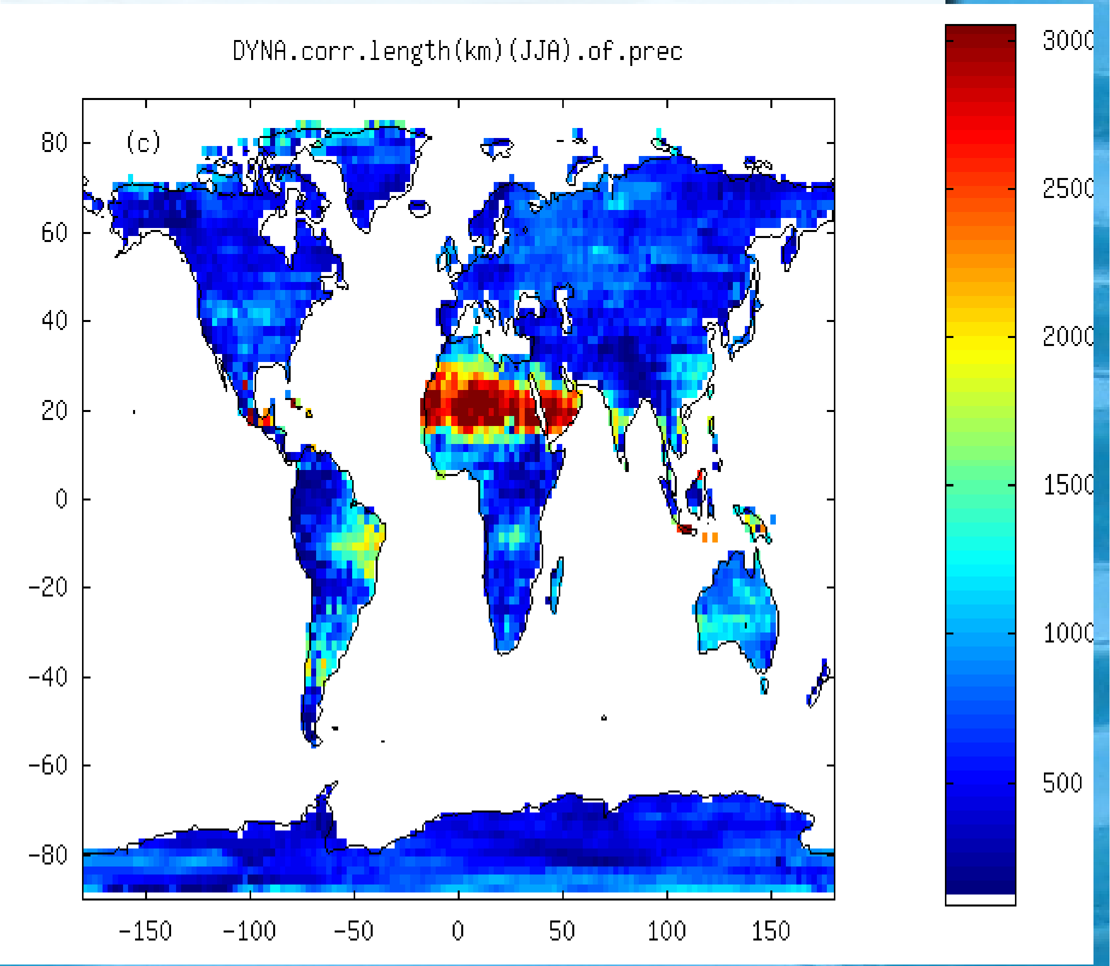
- Does soil moisture feedback make droughts longer or bigger, and where? More generally, what is the impact of soil moisture feedback on space and time correlation scales?
- Potential applications: seasonal drought prediction, impact of land/water management on climate.

Model experiments

- GISS ModelE GCM
- DYNA run: 1951-1980, prescribed SST
- CLIM run: same initial and boundary conditions, but soil moisture set to seasonal climatology from DYNA
- (Krakauer, Cook, and Puma, *HESS* 2010)

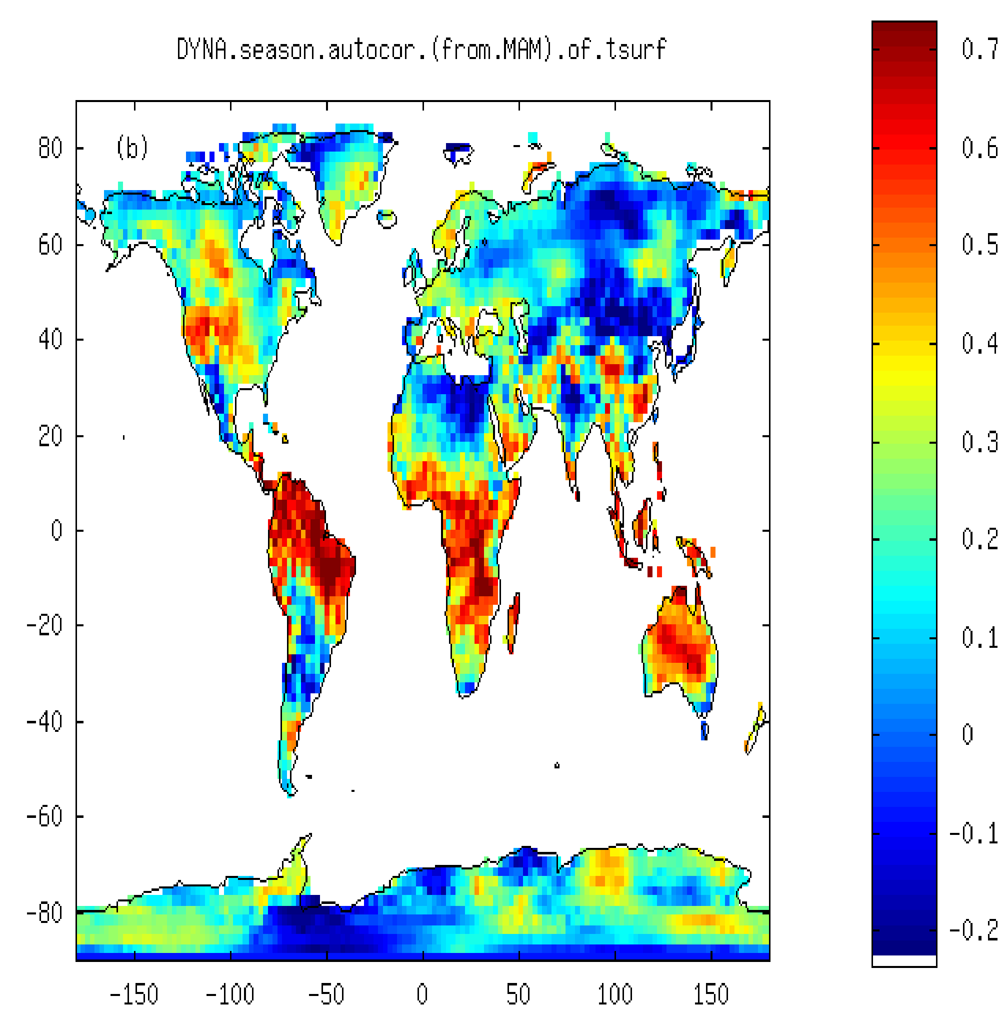
Correlation lengths

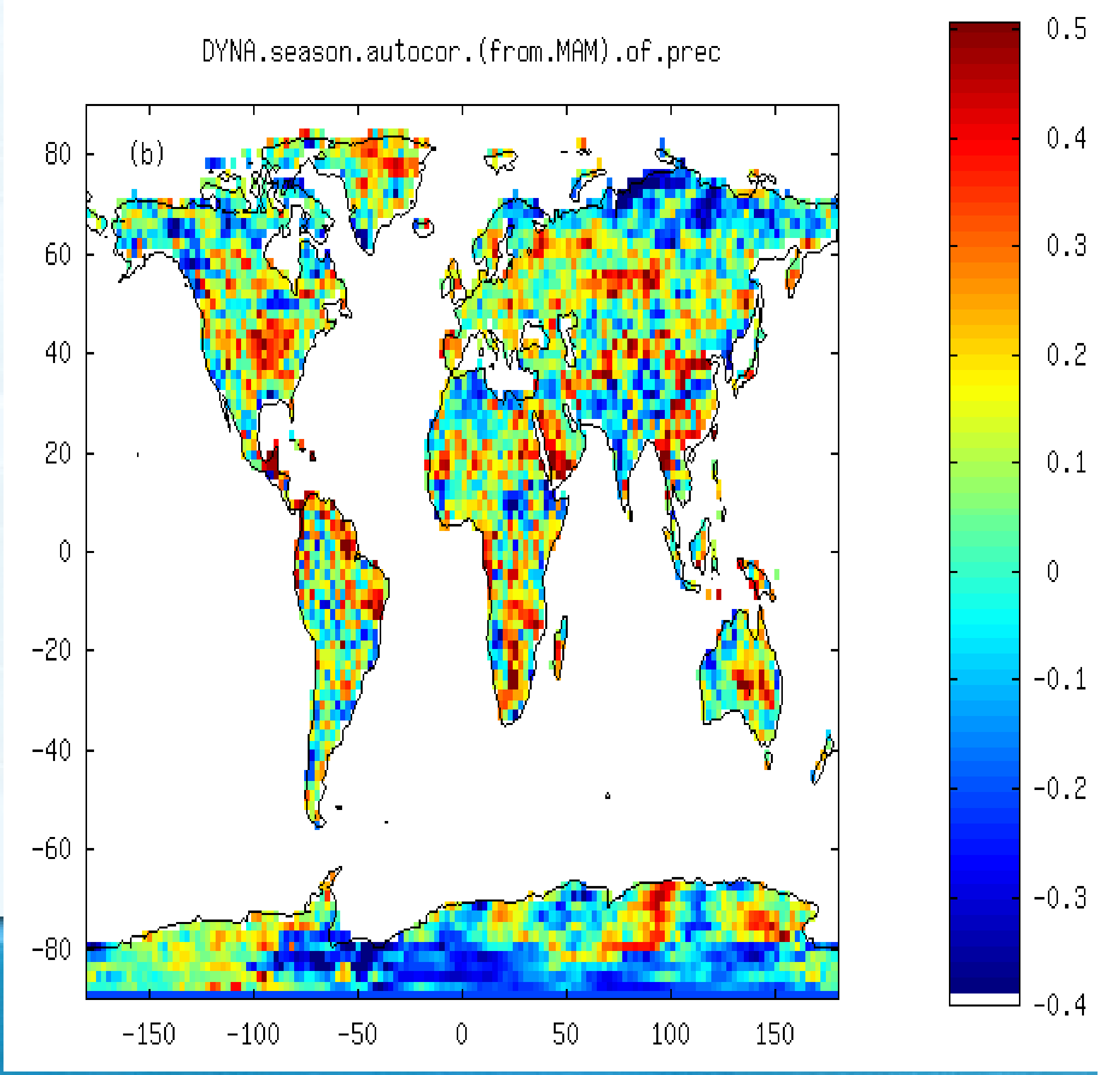




Decay length of correlation between seasonal climate anomalies in the E-W direction

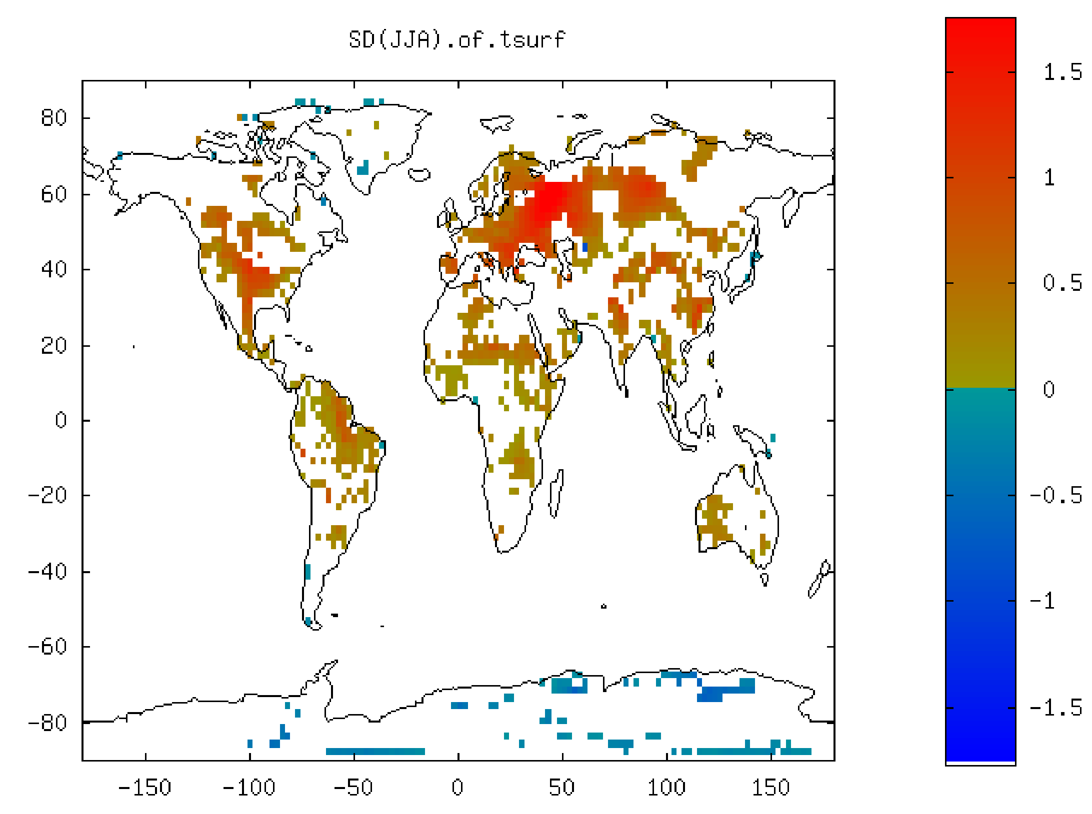
Correlation times

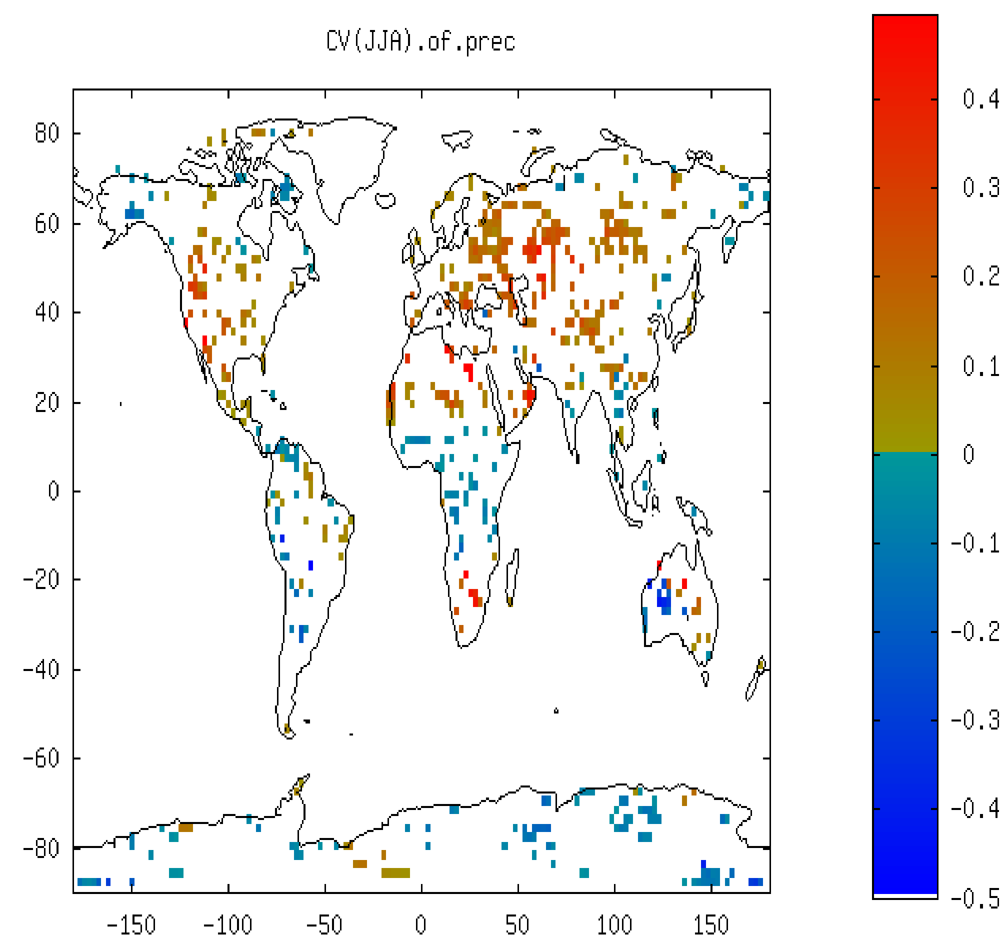




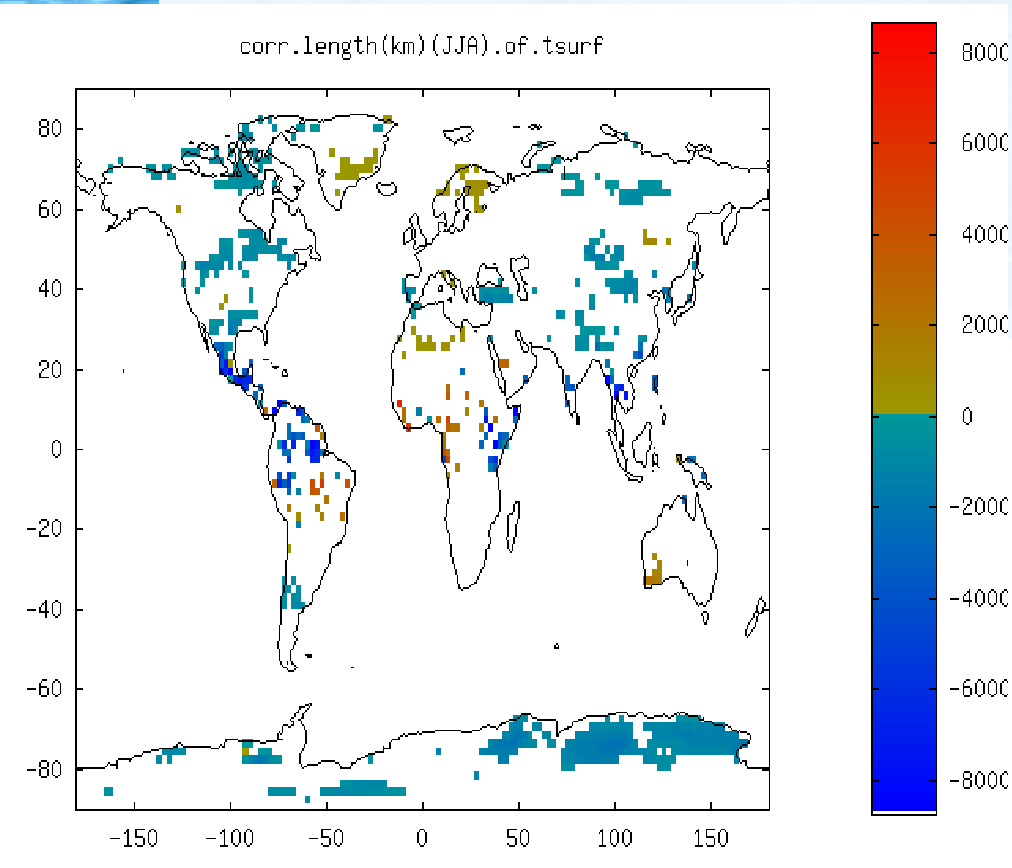
Correlation coefficient between MAM and JJA means

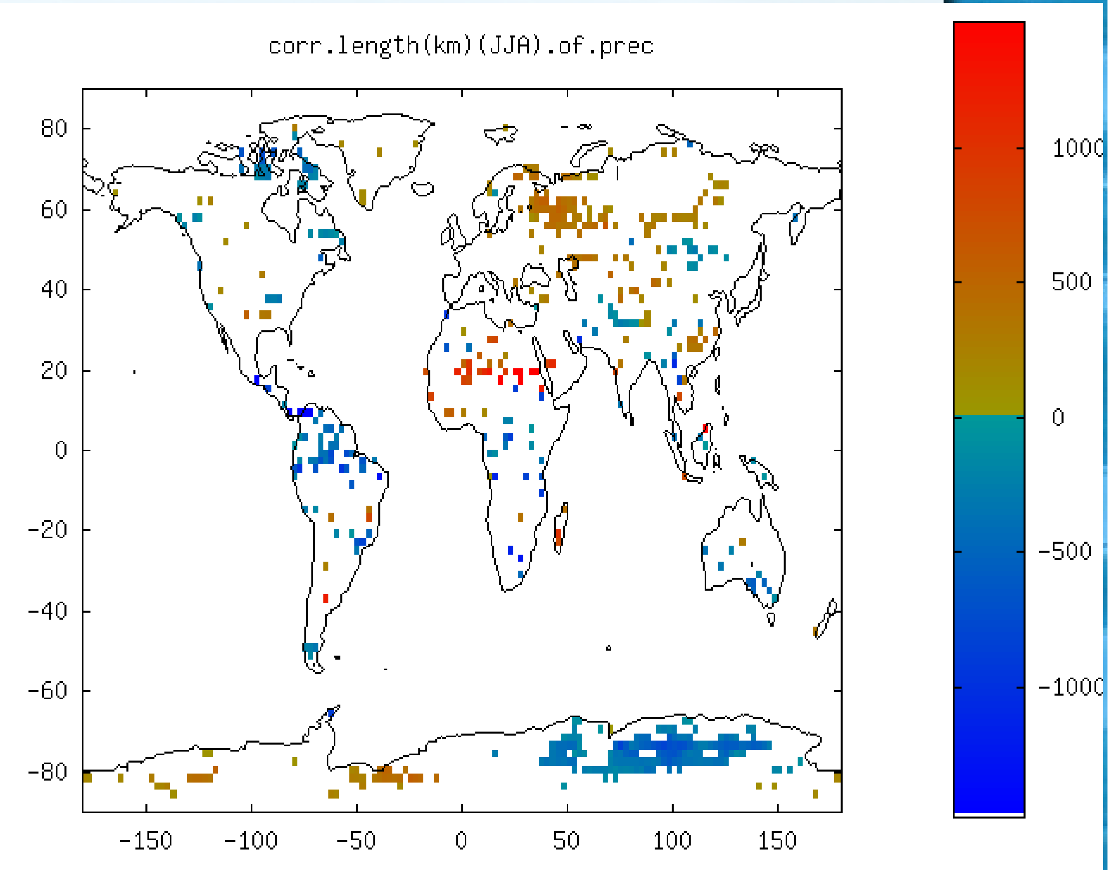
Impact of soil moisture feedback on interannual variability (DYNA – CLIM)



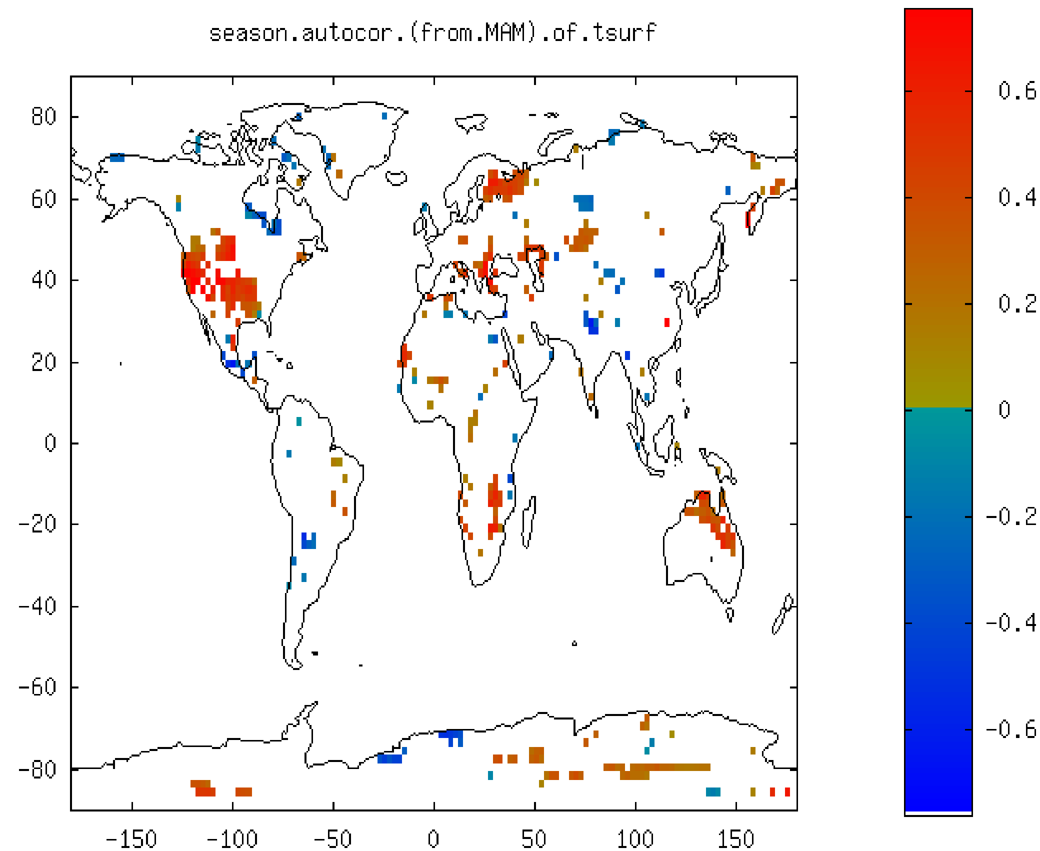


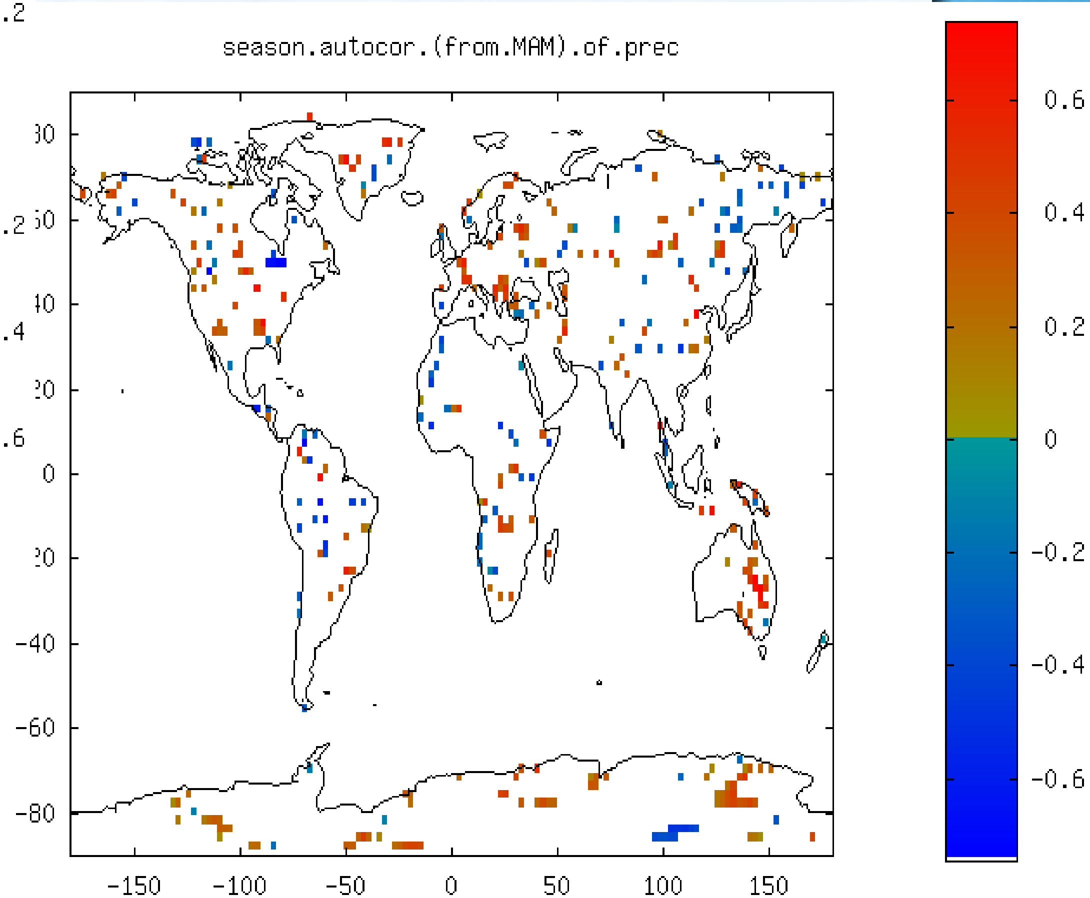
Impact on correlation lengths DYNA - CLIM



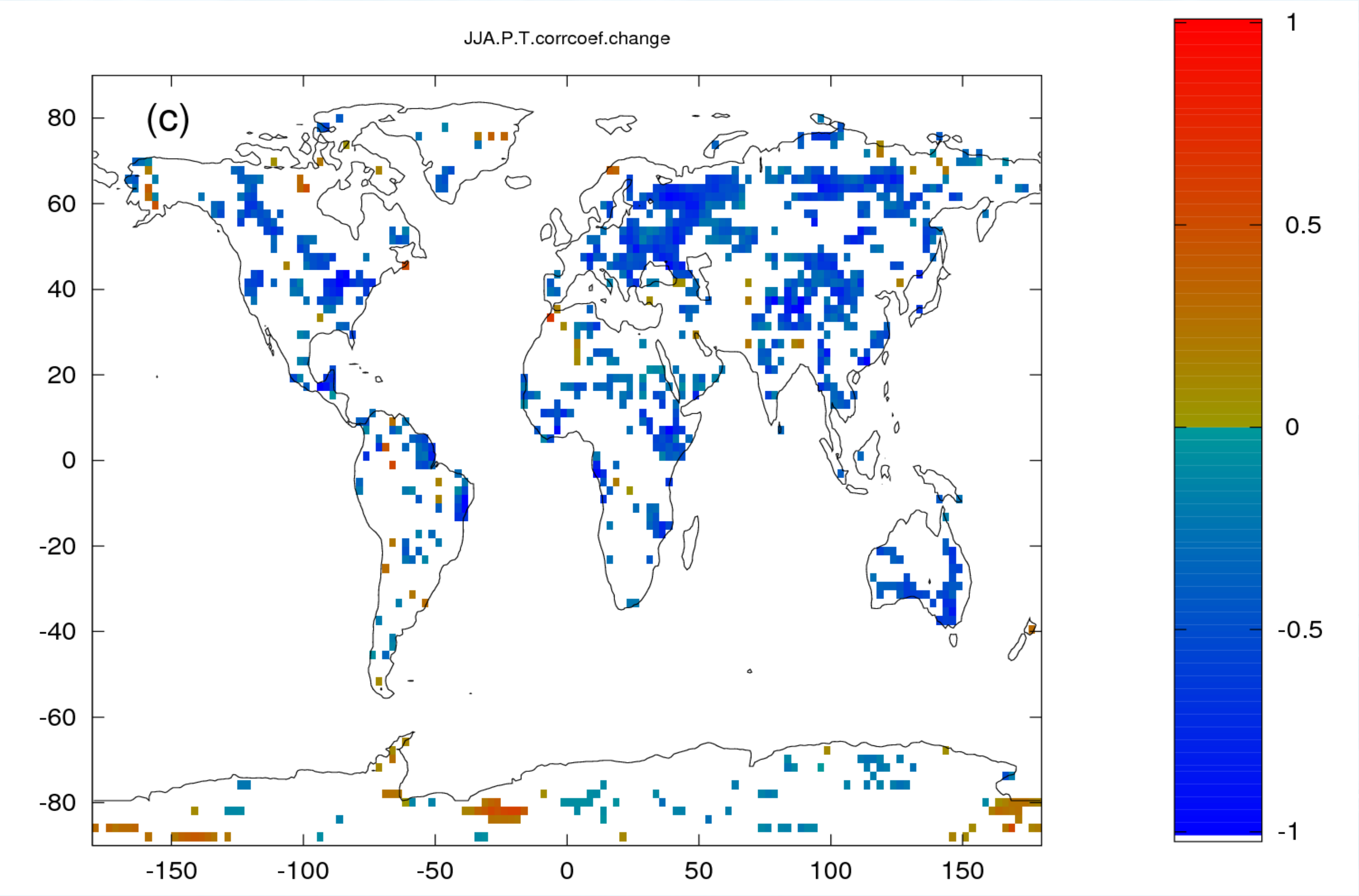


Impact on inter-season correlations





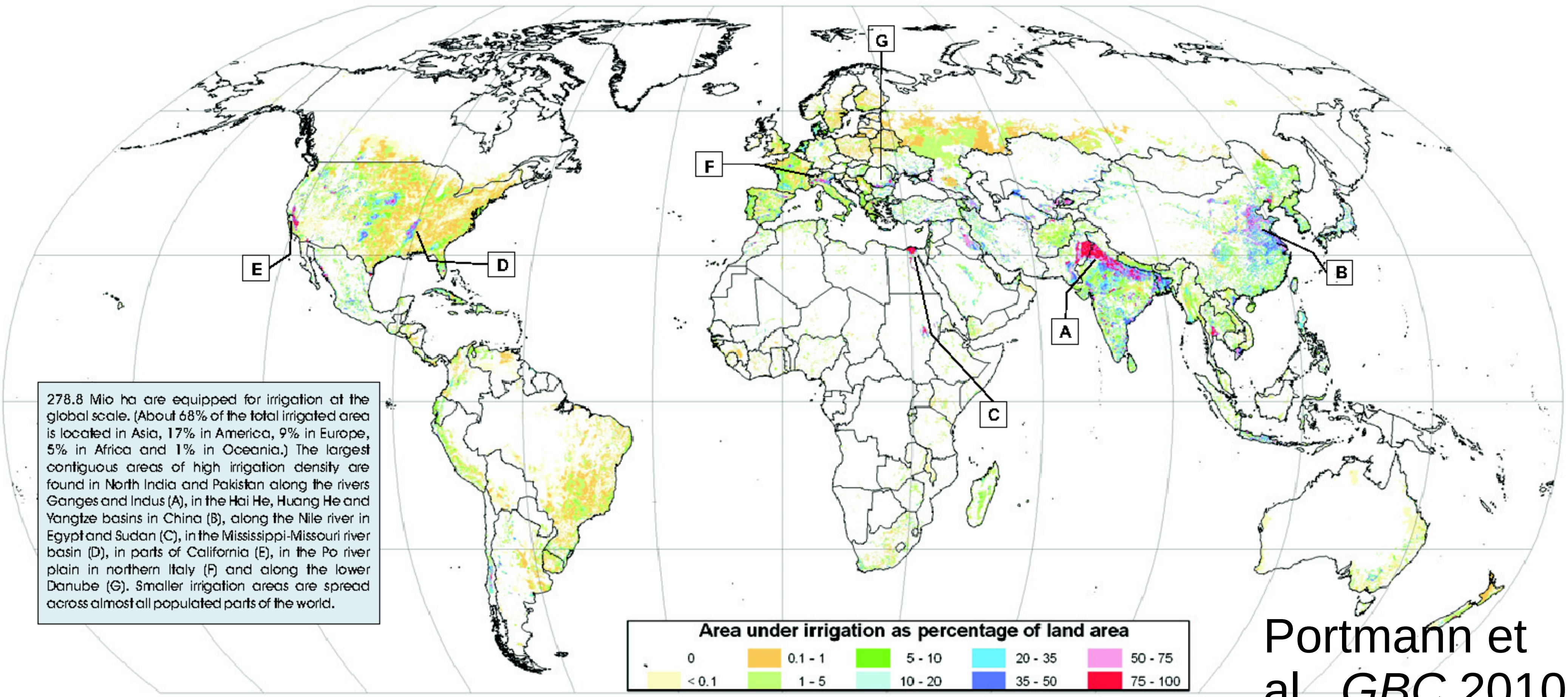
and on P-T correlation



Conclusions: soil moisture

- Soil moisture feedback couples anomalies in temperature and precipitation and increases seasonal persistence, potentially increasing predictability. Impact on the space and time scales of climate variability is quantifiable, which can be compared to observational datasets
- Role of deep roots, dynamic vegetation, and groundwater remains to be determined

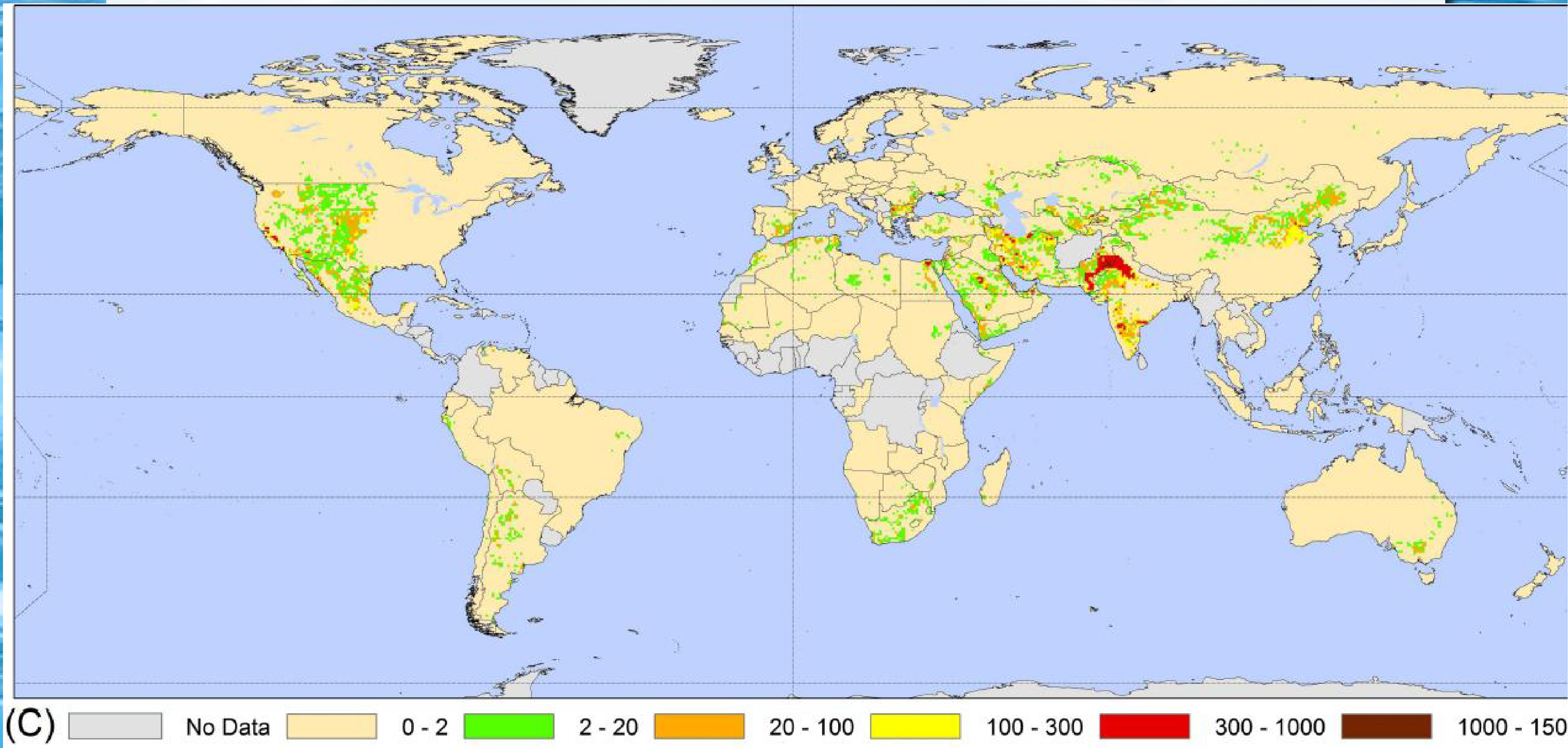
Irrigated land



Portmann et al., *GBC* 2010

- 17% of cultivated land, 40% of yield
- Largest consumptive water use: 1000 L water / person*day
- Combination of surface water and groundwater

Groundwater depletion



mm/year; Wada et al., *GRL* 2010

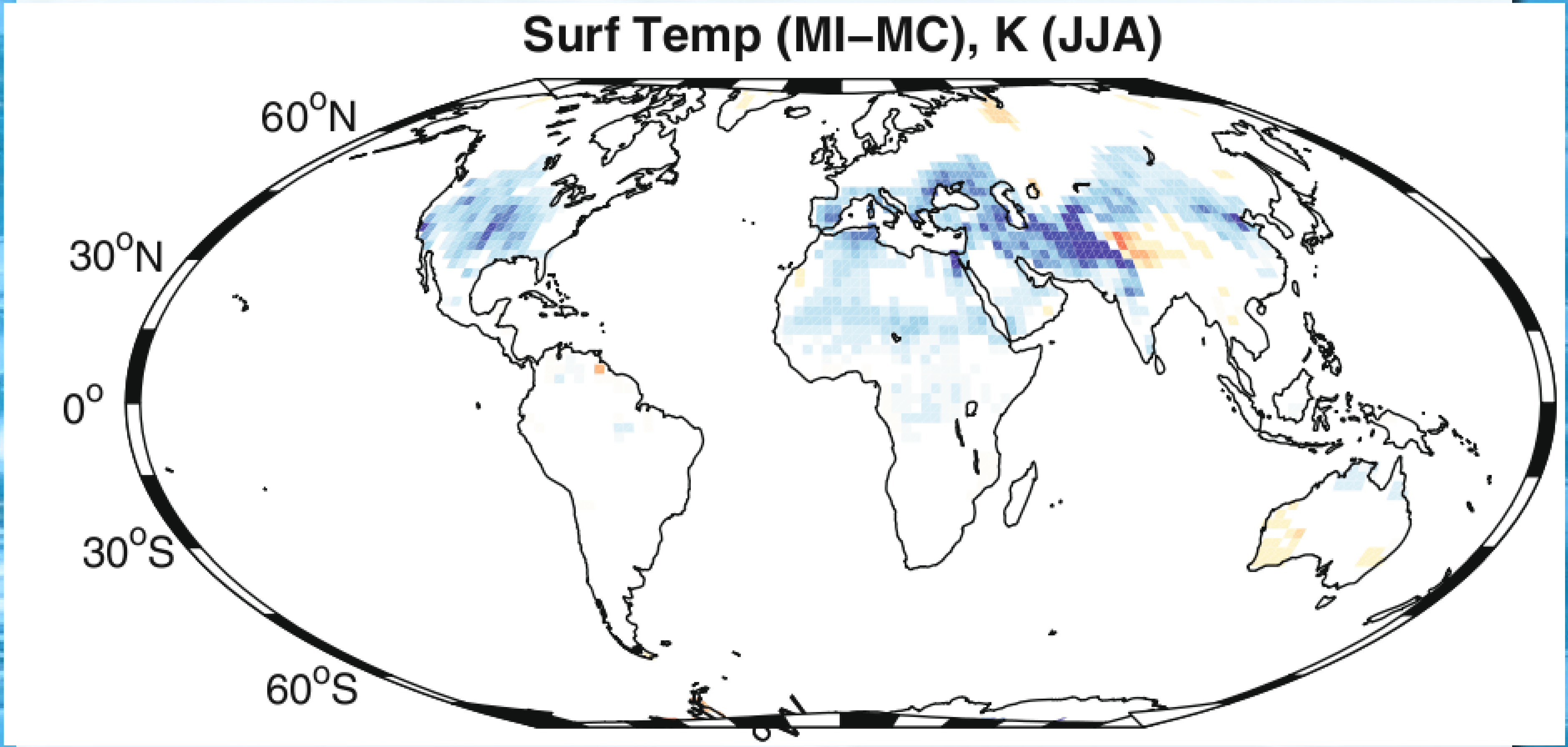
Irrigation impact on climate

- Local cooling large enough to offset global warming (e.g. in Central Valley)
- Unknown impacts on large-scale circulation
- Contributes ~30% of current sea-level rise
- Questions:
  - Impact of irrigation on global climate
  - How will irrigation and greenhouse gas forcings interact?

Model experiments: Irrigation

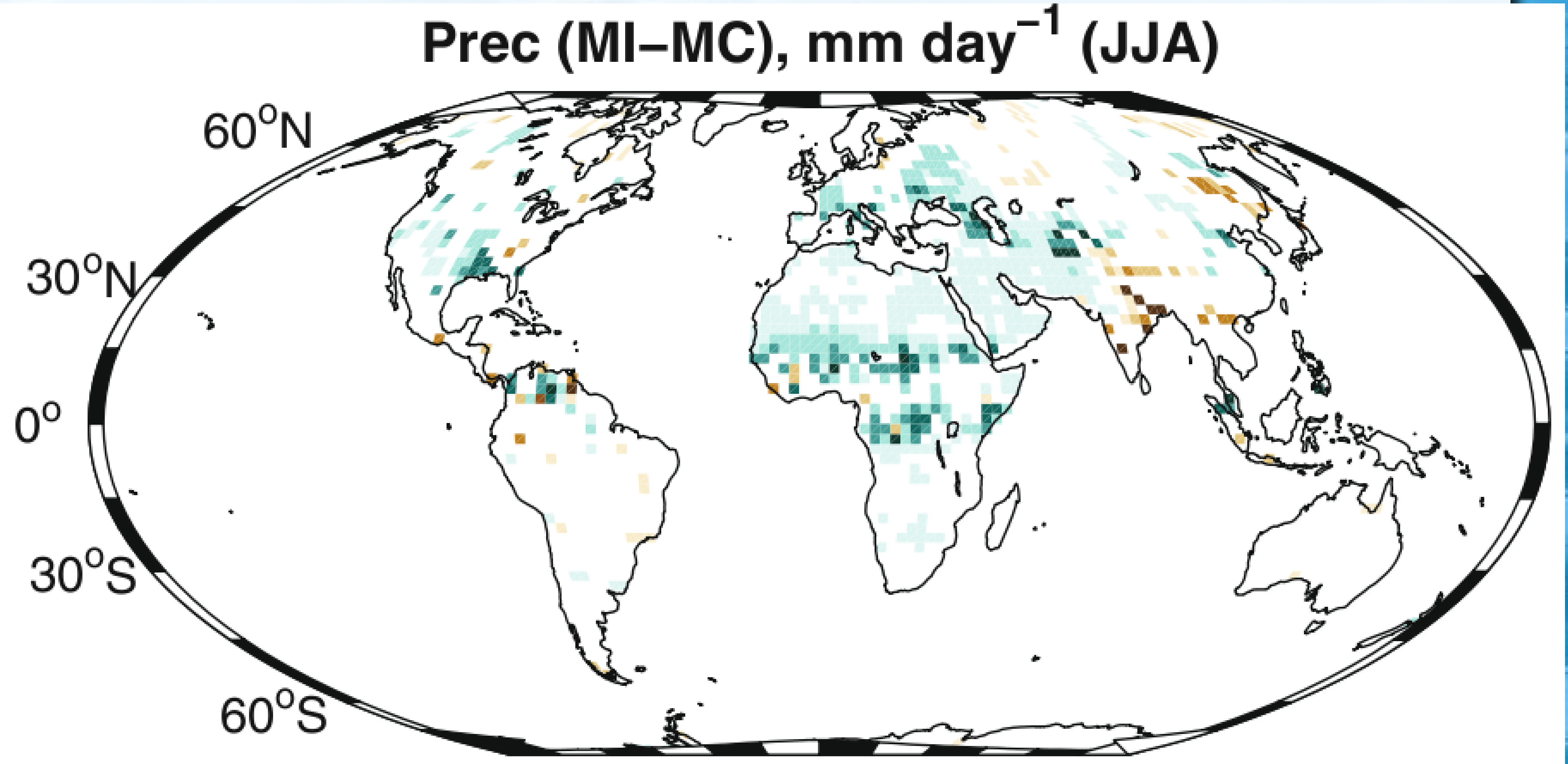
- Simulate equilibrium climate with a mixed-layer ocean, year-2000 or 2050 (A1B) greenhouse gas concentrations, and year-2000 or no irrigation
- Irrigation amount, applied to top soil layer, is based on a dataset; withdrawn from surface water if available, otherwise provided magically
- (Cook, Puma, and Krakauer, *Climate Dynamics* in press)

Impact of irrigation on temperature: present



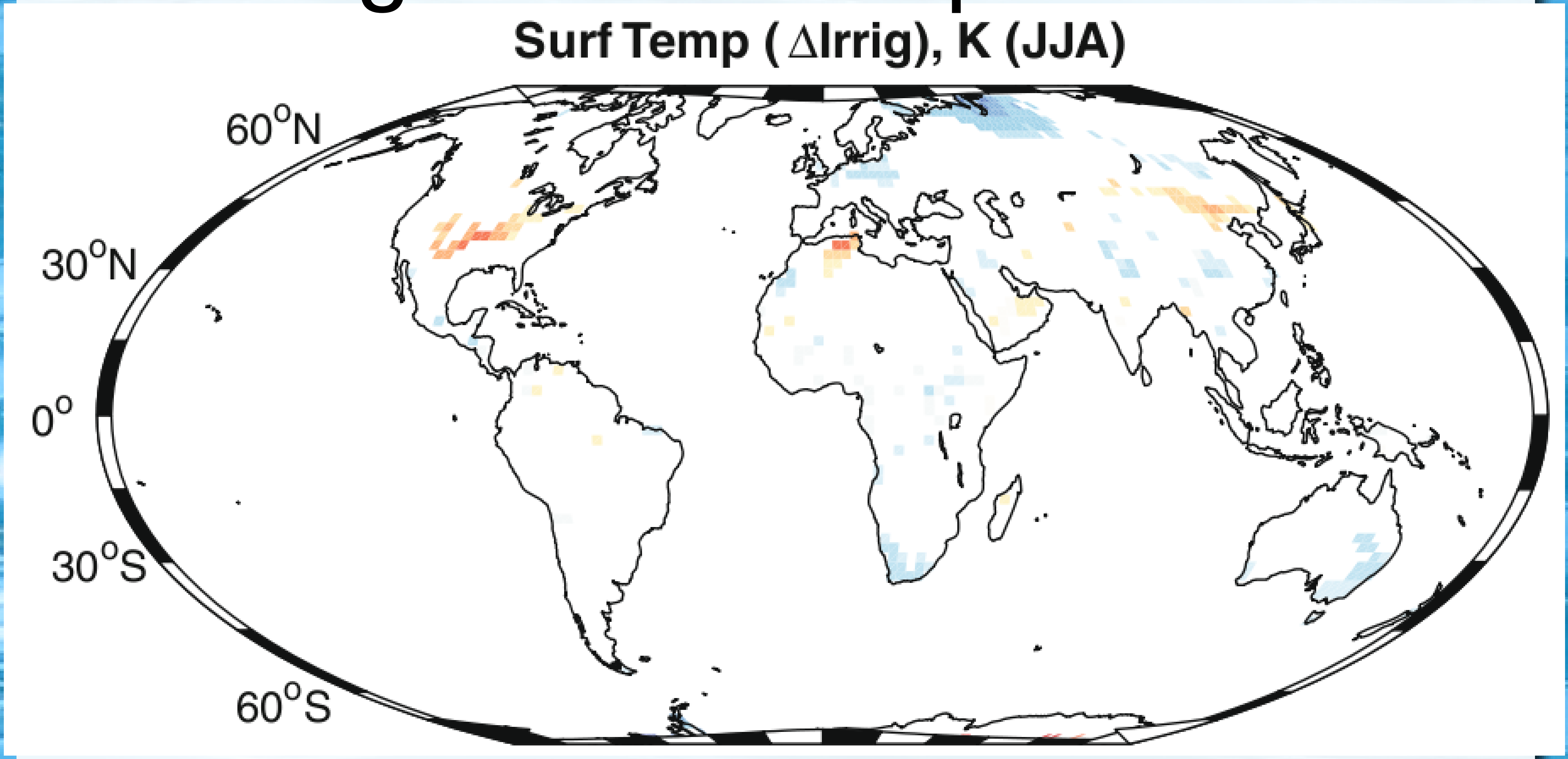
- Local 1-3 K cooling during warm season

Impact of irrigation on precipitation



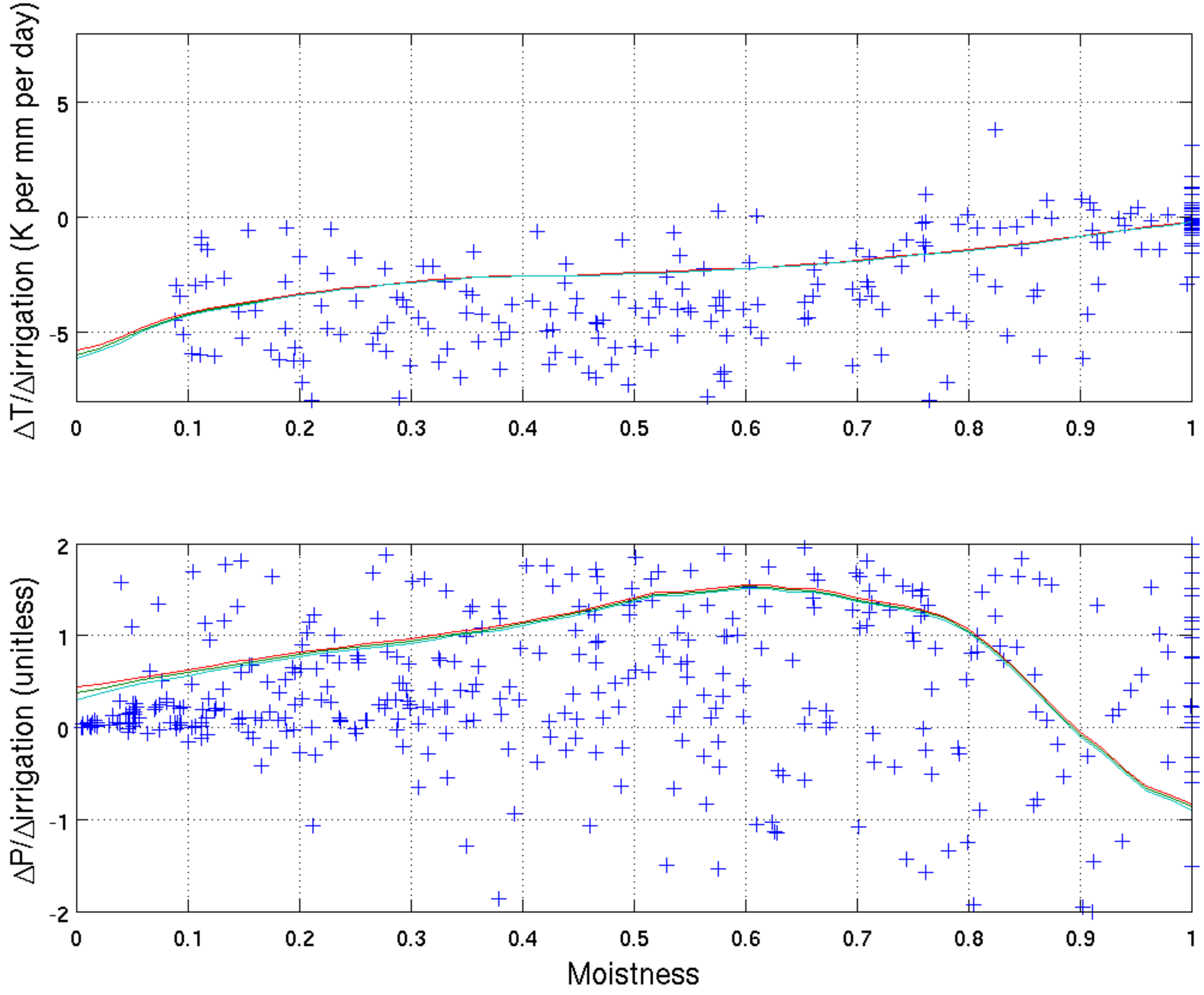
- Regional moistening (0.5-1 mm/day), except in monsoon India

Future vs. present impact of irrigation on temperature



- The same level of irrigation will result in less cooling (red) over the central US -- why?

Local-regional irrigation impacts depend on moistness (AET/PET)



- Because the central US will dry under global warming, irrigation will not be as effective at enhancing precipitation and hence indirect cooling

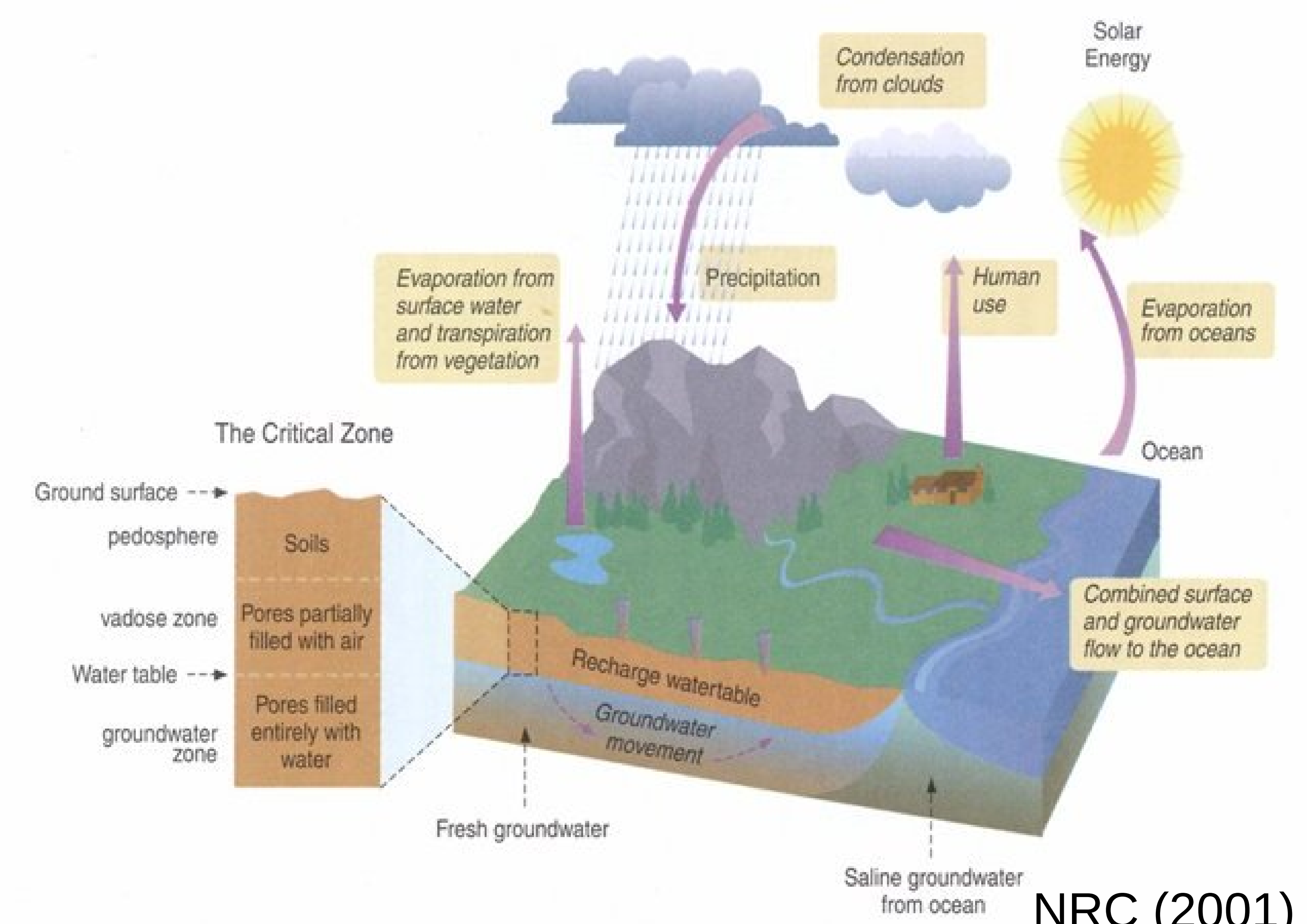
Conclusions: Irrigation

- Irrigation-induced cooling regionally offsets global warming through direct and indirect evaporation enhancement
- The magnitude of irrigation-induced cooling will remain similar under high greenhouse gas concentrations, provided current irrigation rates can be maintained
- *Can* they? To find out, we need to model groundwater as well as surface water.

Groundwater in the climate system

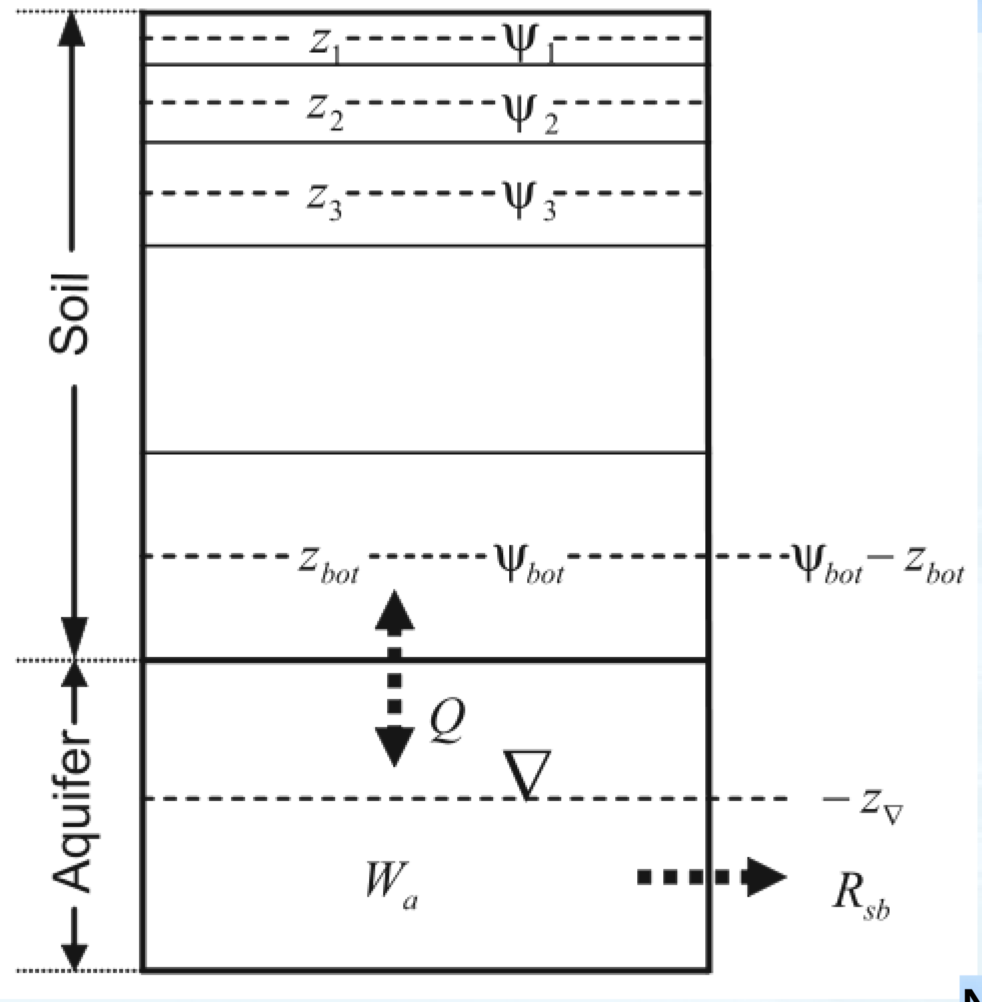
- Comparable in volume to the icecaps, groundwater interacts with the soil, and hence the atmosphere, over timescales ranging from days to millennia, depending on climate and topography
- Important resource, depleting in places
- Not included in climate models until recently; still no specific studies of role in global climate

Groundwater



NRC (2001)

A simple groundwater representation

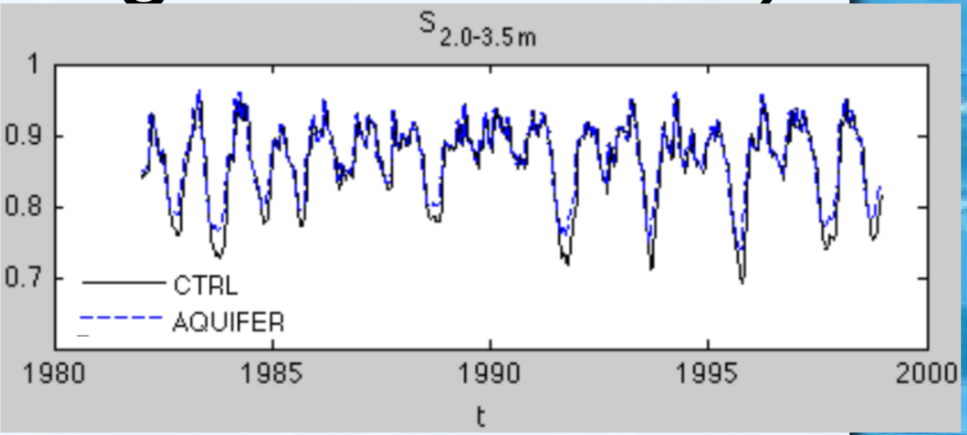


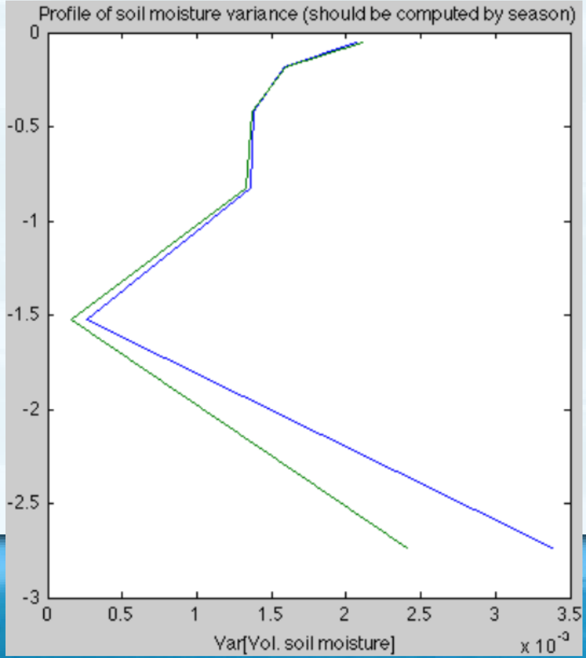
Niu et al., *JGR* 2007

- Assume equilibrium water and heat profiles below the soil layers

Impacts of groundwater on climate (LSM-only/regional studies)

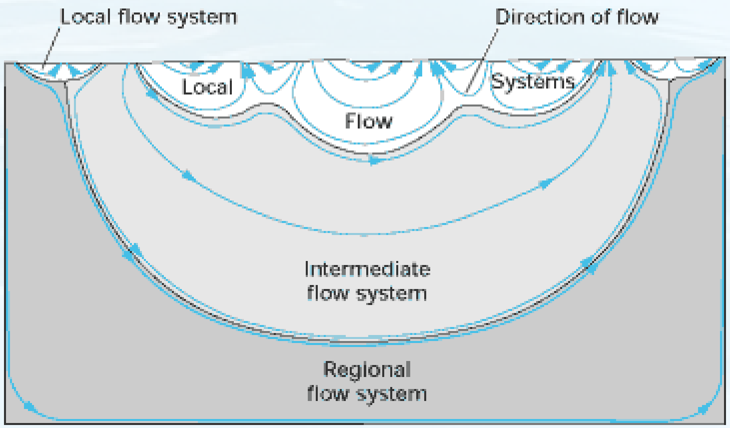
- Lo and Famiglietti, *JGR* 2010: can increase or decrease soil moisture memory
- Leung et al., *Climate Dynamics* 2011: increases evapotranspiration and precipitation





Plans: technical development

- Compare to reality (well levels, GRACE, climate) and data assimilation (GLDAS +groundwater)
- Include lateral flow
- Nested model for better regional coverage, parametrize subgrid variation



Plans: applications

- Initial goal: Determine impact of groundwater on seasonal correlation scales and predictability of climate variables
- Study interaction with dynamic vegetation, role in annual to decadal variability (megadroughts)
- Evolve with human water withdrawal for physically-based irrigation scenarios and water sustainability decision support

Thanks!

No mammoths were harmed in the preparation of this talk.