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Contribution of forcings to Holocene climate evolution

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A suite of climate simulations incrementally adding forcings of the Holocene is performed. A widespread mid- to late-Holocene cooling only emerges with the inclusion of Holocene anthropogenic land-use by Kaplan et al (2011). This is mostly due to increased surface albedo following deforestation. This produces very good agreement with the pollen-based reconstructions over northern mid-latitudes (Marsicek et al 2018) and improves agreement with other global reconstructions. Our results support a widespread anthropogenic alteration of landscapes over millennia before Industrialisation and suggest an alternative resolution of the 'Holocene temperature conundrum'.

New transient Holocene climate model simulations

We performed a suite of Holocene simulations with HadCM3-M21 (Gordon et al 2000, Valdes et al 2017), recently updated so that it replicates the Sahara greening (Hopcroft et al 2021). We included a range of forcings incrementally:

1. **Orbit + ice-sheets + greenhouse gases.**
2. Orbit + ice-sheets + greenhouse gases + **solar.**
3. Orbit + ice-sheets + greenhouse gases + solar **+ volcanic eruptions.**
4. Orbit + ice-sheets + greenhouse gases + solar + volcanic eruptions + **land-use (Kaplan 2010)** ***(direct biophysical effects only).***
5. Orbit + ice-sheets + greenhouse gases + solar + volcanic eruptions + **land-use (Hyde 3.2)** – *still running* ***(direct biophysical effects only).***

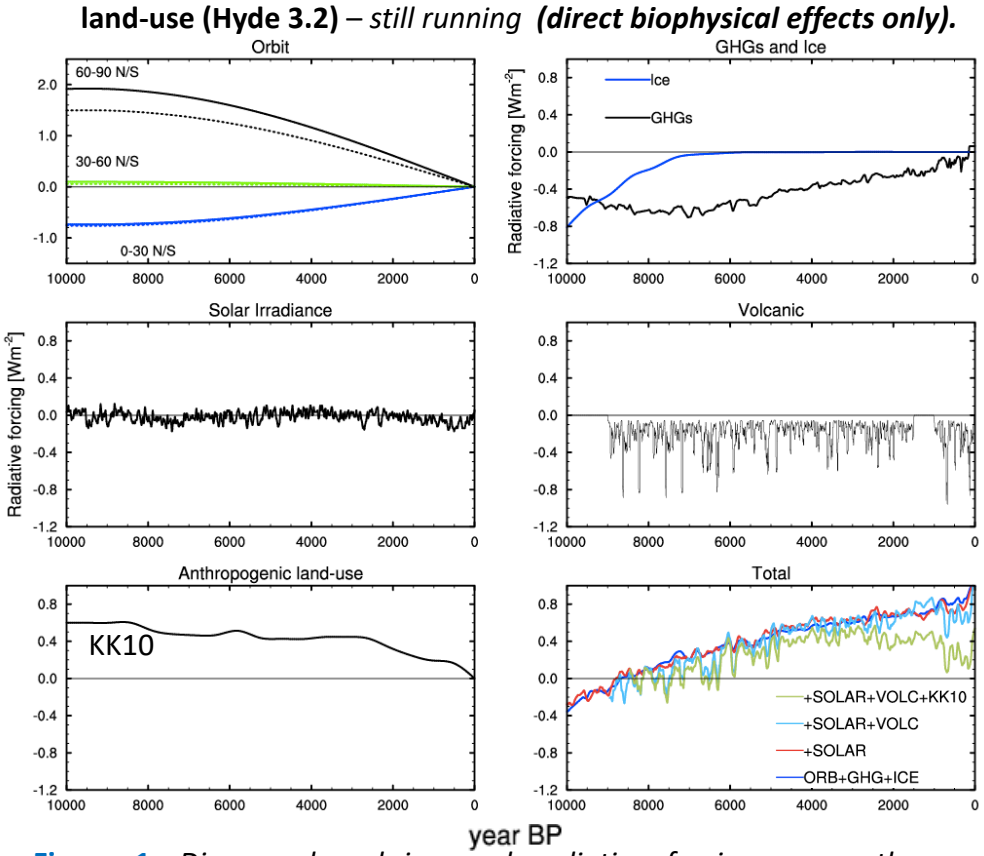

Figure 1: *Diagnosed and imposed radiative forcing across the Holocene. Greenhouse gases (GHG) and ice-sheets/sea-levl follow PMIP4 (Ivanovic et al., 2016), solar irradiance from Vieira et al. (2012) and volcanic aerosol from the EVA(GISP2) (Bader et al 2020). Land-use is from Kaplan et al 2011 (KK10).*

The radiative forcing due to greenhouse gases and ice-sheets/sea-level will produce a warming throughout the Holocene. At the global scale, the KK10 land-use is the only forcing with a significant cooling signal.

Comparison with reconstructions

We compare the modelled surface air or sea temperatures with recent reconstructions for northern mid-latitudes over land (Marsicek et al 2018), global land plus ocean (Kaufman et al 2020a,b) and tropical oceans (Bova et al 2021).

Including KK10 land-use produces excellent agreement with the Marsicek et al reconstruction (figure 2a) although it results in slightly too much cooling in the last 2000 years. Land-use also improves the comparison with the global (fig. 2b) and oceanic reconstructions (fig. 2c). The cooling is predominantly due to increased albedo following prescribed deforestation.

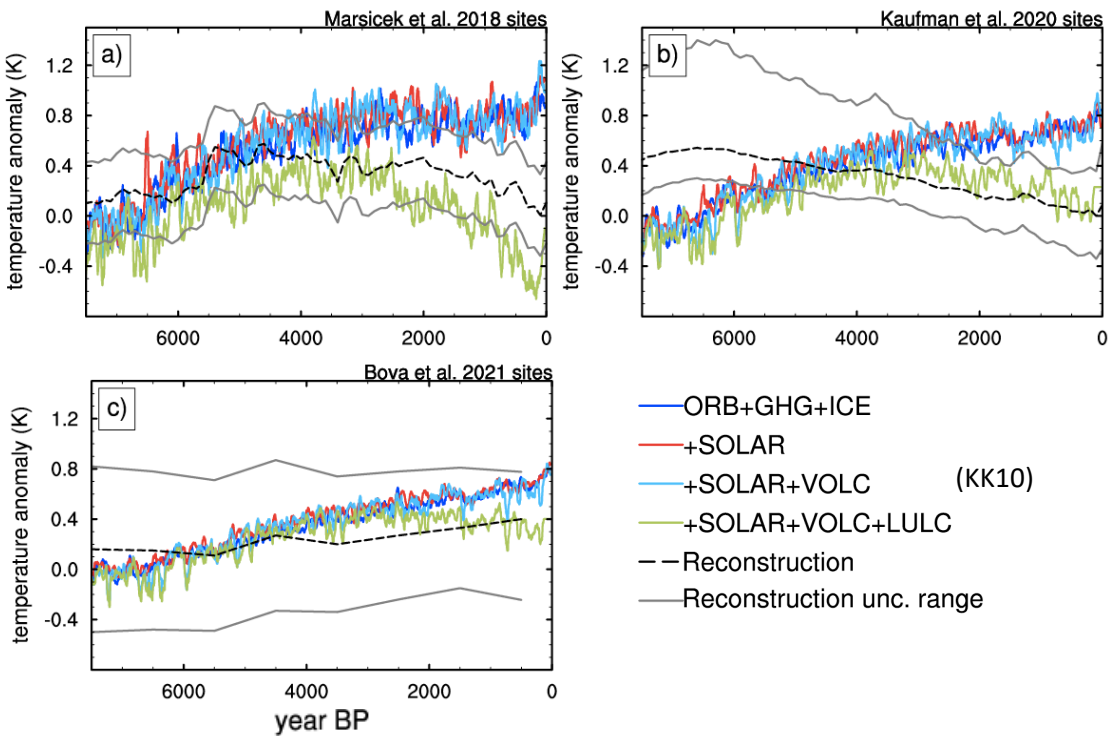

Figure 2: *Simulated and reconstruction surface air and sea temperatures. a) Northern mid-latitude terrestrial sites from Marsicek et al (2018), b) global stack from Kaufman et al (2020a,b) and c) tropical ocean sites from Bova et al (2021). Simulated time-series were extracted at the sites used in each respective reconstruction.*

Conclusions

Early- to mid-Holocene land-use provides a novel solution to Liu et al (2014)'s "Holocene temperature conundrum". Agreement among different model reconstructions is limited, and the potential biases arising from the seasonal cycle are still debated (e.g. Bova et al 2021). This hinders the model-data comparison and needs to be addressed in future work.

References

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