ClimKern: a new Python package and kernel repository for calculating radiative feedbacks

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Introduction

Radiative feedbacks are fundamental in understanding polar amplification and its causes. One of the most common methods of calculating feedbacks is the radiative kernel technique. Radiative kernels are pre-calculated radiative sensitivities to changes in fields such as atmospheric temperature, humidity, and surface albedo[1]. The radiative kernel technique has several advantages, namely that kernels from one model can be used to calculate feedbacks in the same or a different model with the required output. Using radiative kernels is less time-consuming and computationally cheaper than other methods of calculating feedbacks[2].

Despite the method's widespread use in the climate sensitivity community, **there are issues regarding the availability and use of radiative kernels that impact feedback study reproducibility**:

- Kernels are scattered among research groups and inconsistently defined
- Interkernel spread is not regularly quantified
- There is not a standard set of assumptions for computing feedbacks with kernels.

To address these issues, we developed ClimKern, an easy-to-use Python package and radiative kernel repository.

Methods

We collected **11 sets of radiative kernels** calculated using a variety of data: climate model output, reanalysis output, or satellite observation from the period 2006 – present. All kernels contain the top-of-atmosphere (TOA) radiative perturbations from changes in atmospheric temperature, surface skin temperature, specific humidity, and surface albedo, stored as netCDF files. Kernel variables were renamed to standard nomenclature and, if necessary, had their sign changed for consistency.

After quantifying zonal-average differences between the kernels, we used ClimKern to calculate feedbacks in a single 2×CO_2 experiment using the Community Earth System Model v1. The response for calculating feedbacks is defined as the difference between the monthly climatology of the last 30 years of the 2×CO_2 simulation and the 1×CO_2 control simulation.

```
[1]: import climkern as ck

     ctrl, pert = ck.tutorial_data('ctrl'),ck.tutorial_data('pert')
     LR,Planck = ck.calc_T_feedbacks(ctrl.T,ctrl.TS,ctrl.PS,
                                     pert.T,pert.TS,pert.PS)
```

Results

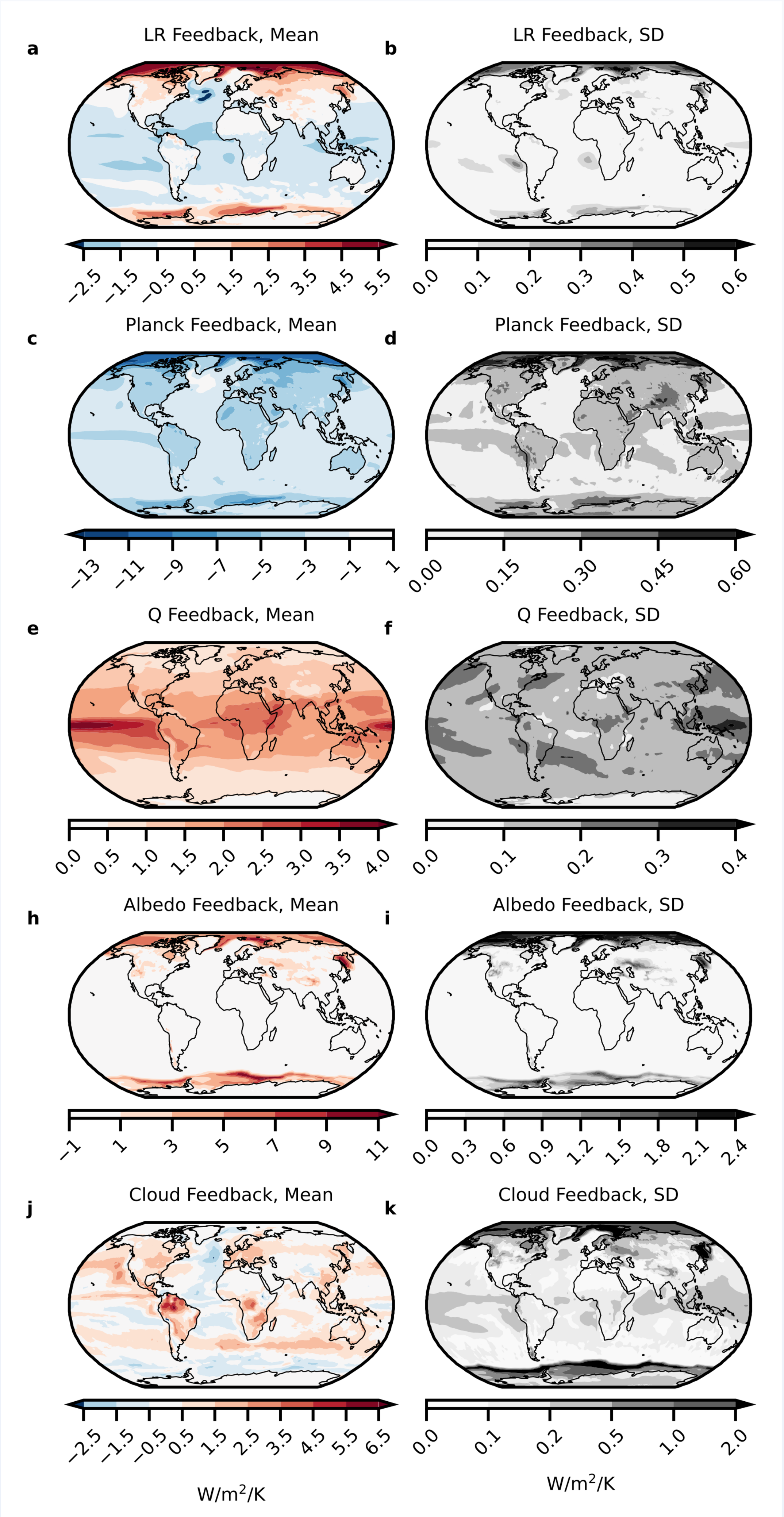

Figure 1. Kernel & annual average (a) lapse rate (c) Planck (e) water vapor (h) surface albedo and (j) cloud feedbacks (Wm⁻²K⁻¹). (b,d,f,I,k) as in (a,c,e,h,j), but the standard deviation among kernels. Note the different color bar scales between feedbacks.

Using ClimKern, we calculated the lapse rate, Planck, water vapor, surface albedo, and cloud feedbacks in the sample CESM 2×CO_2 simulation (Fig. 1). The kernel-mean feedbacks are physically reasonable, with spatial structures consistent with the results of past studies. The kernel-mean captures the strong latitudinal variation in the lapse rate feedback, the effect of the non-linearities in the Stefan-Boltzmann (Planck feedback) and Clausius-Clapeyron (WV feedback) relations, and the spatially variable cloud feedback. The global, annual average feedback values (Table 1) are also reasonable, except for ECHAM5, which has an unrealistically small (large) Planck (water vapor) feedback.

For the first time, we are also able to quantify interkernel spread with the largest kernel repository available. **Interkernel variability for all feedbacks except water vapor is greatest near the poles**, specifically over the Southern and Arctic Oceans. The sign of the cloud feedback in the Arctic changes based on the kernel used (Fig. 2).

The differences between kernels persist in the global average, with **the greatest interkernel spread** relative to the mean values **in the surface albedo and cloud feedbacks.**

Table 1. Arctic average annual feedback values in Wm⁻²K⁻¹ for each of the 11 ClimKern kernels. From left to right: lapse rate, local deviation of Planck feedback, total (LW+SW) water vapor, SW cloud, LW cloud, and total cloud feedbacks. The cloud feedbacks are calculated using the adjustment method from Soden et al. (2008)[3]. The last two rows show the kernel mean and SD of the feedbacks.

kernel	LR	P'	Q_{total}	Albedo	$Cloud_{SW,adj}$	$Cloud_{LW,adj}$	$Cloud_{total,adj}$
BMRC	1.02	0.54	0.23	1.69	-0.17	-0.00	-0.17
CAM3	1.14	0.55	0.28	0.85	0.55	-0.18	0.37
CAM5	0.98	0.60	0.27	1.67	-0.20	0.17	-0.03
CloudSat	0.86	1.08	0.19	1.02	0.06	-0.00	0.05
ECHAM5	1.08	0.50	0.36	nan	nan	0.14	nan
ECHAM6	1.08	0.58	0.26	1.13	0.25	-0.04	0.21
ECMWF-RRTM	1.15	0.56	0.30	1.27	0.12	-0.03	0.10
ERA5	1.15	0.52	0.31	1.38	0.03	-0.03	-0.01
GFDL	1.06	0.57	0.27	0.93	0.36	0.08	0.44
HadGEM2	1.03	0.68	0.28	1.27	-0.81	0.06	-0.75
HadGEM3-GA7.1	1.02	0.60	0.27	1.24	0.23	0.03	0.26
mean	**1.05**	**0.63**	**0.27**	**1.25**	**0.04**	**0.00**	**0.05**
std	**0.08**	**0.15**	**0.04**	**0.27**	**0.36**	**0.09**	**0.32**

Conclusions

1. **Kernel choice is an important consideration in polar amplification studies.** In our example, kernel choice determines which feedback is most important in the Arctic (Table 1, Fig. 2).
2. **Future studies can be more robust if they include discussion of the sensitivity to kernel choice or use multiple kernels from the ClimKern kernel repository.** One option to eliminate bias is to present the kernel mean feedbacks.
3. **ClimKern makes streamlines feedback calculations and makes results more reproducible.** By standardizing regridding and vertical integration techniques and making uniform assumptions about the input data, ClimKern removes a potential source of error.

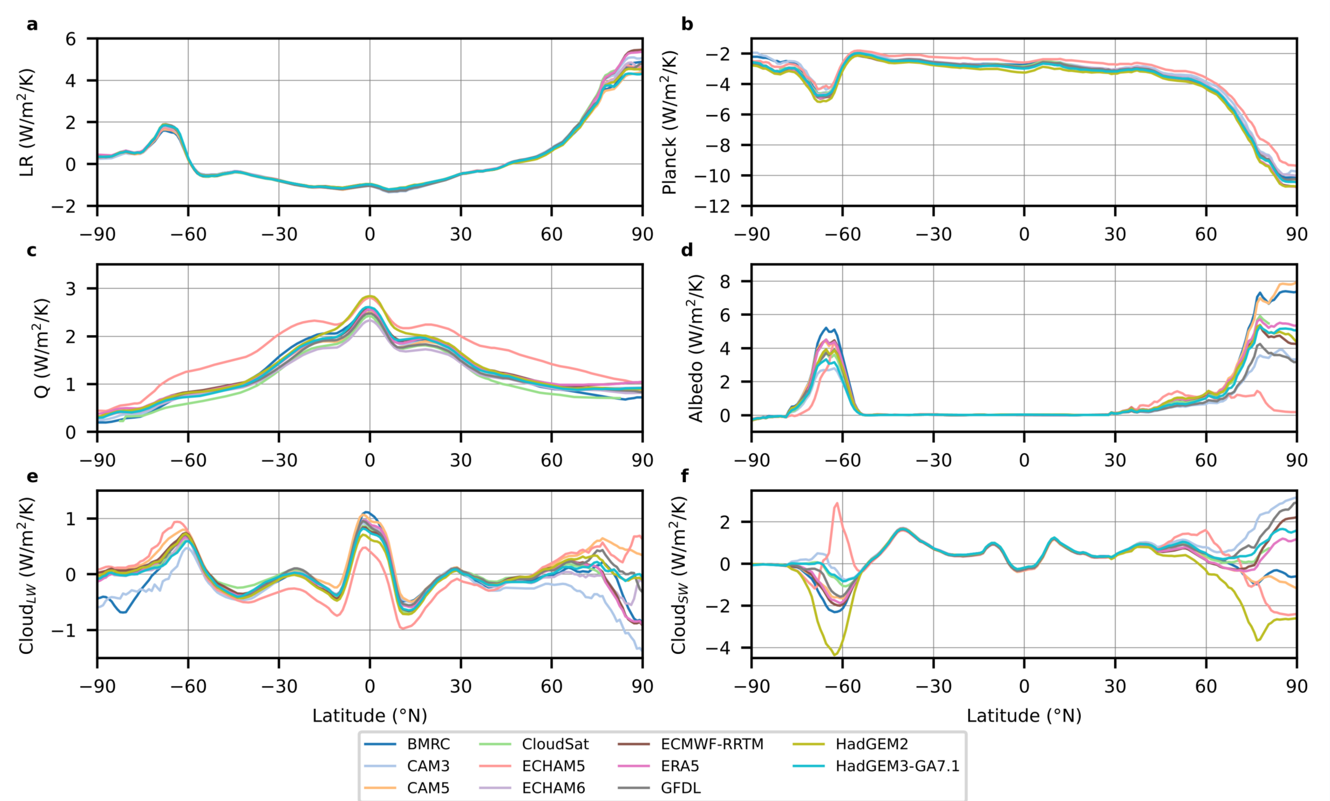

Figure 2. Zonal & annual average (a) lapse rate, (b) Planck, (c) water vapor, (d) surface albedo, (e) LW cloud, and (f) SW cloud feedbacks (Wm⁻²K⁻¹).

Try it yourself!

Want to recreate Table 1? Go to github.com/tyfolino/climkern or scan the QR code for a ClimKern installation and quickstart guide. Please consider contributing to the project on GitHub.

References

[1]Pendergrass, A. G. & National Center for Atmospheric Research Staff. (2022, September 9). The Climate Data Guide: Radiative kernels from climate models. Retrieved December 6, 2023, from https://climatedataguide.ucar.edu/climate-data/radiative-kernels-climate-models

[2]Smith, C. J., Kramer, R. J., & Sima, A. (2020). The HadGEM3-GA7.1 radiative kernel: the importance of a well-resolved stratosphere. Earth System Science Data, 12(3), 2157–2168. https://doi.org/10.5194/essd-12-2157-2020

[3]Soden, B. J., Held, I. M., Colman, R., Shell, K. M., Kiehl, J. T., & Shields, C. A. (2008). Quantifying Climate Feedbacks Using Radiative Kernels. Journal of Climate, 21(14), 3504–3520. https://doi.org/10.1175/2007JCLI2110.1

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