Mechanisms affecting equilibrium climate sensitivity in the PlaSim Earth System Model with different ocean model configurations

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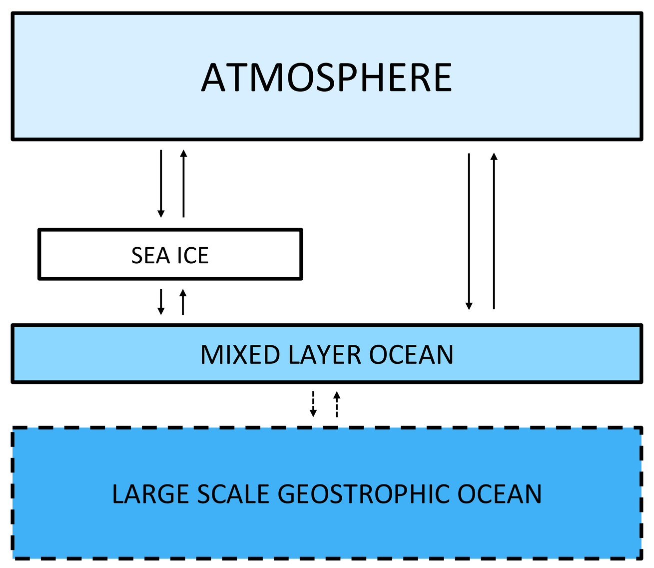
The equilibrium climate sensitivity (ECS) of a state-of-the-art Earth System Model of intermediate complexity, the **Planet Simulator (PlaSim)**, is determined under three tuned configurations, in which the model is coupled with a simple **Mixed Layer (ML)** or with the full 3D **Large Scale Geostrophic (LSG)** ocean model, at two horizontal resolutions, **T21 (600 km)** and **T42 (300 km)**. Equilibrium climate sensitivity experiments with doubled and quadrupled CO_2 were run, using either dynamic or prescribed sea ice. The resulting ECS using dynamic sea ice is **6.2 K** for PlaSim-ML T21, **5.5 K** for PlaSim-ML T42 and a much smaller **4.2 K** for PlaSim-LSG T21. A systematic comparison between simulations with dynamic and prescribed sea ice helps to identify a strong contribution of sea ice to the value of the feedback parameter and of the climate sensitivity. Additionally, Antarctic sea ice is underestimated in PlaSim-LSG leading to a further reduction of ECS when the LSG ocean is used. The ECS of ML experiments is generally large compared with current estimates of equilibrium climate sensitivity in CMIP5 models and other EMICs: a relevant observation is that the choice of the ML horizontal diffusion coefficient, and therefore of the parameterized meridional heat transport and in turn the resulting equator-poles temperature gradient, plays an important role in controlling the ECS of the PlaSim-ML configurations. This observation should be possibly taken into account when evaluating ECS estimates in models with a mixed layer ocean. The configuration of PlaSim with the LSG ocean shows very different **AMOC regimes**, including 250-year oscillations and a complete shutdown of meridional transport, which depend on the ocean vertical diffusion profile and the CO_2 forcing conditions.

(1) The Planet Simulator model

PlaSim is an Earth system Model of Intermediate Complexity developed at the University of Hamburg (*Fraedrich et al., 2005*).

- The dynamical core is a simplified General Circulation Model, the **Portable University Model of Atmosphere (PUMA)**
- The oceanic component can be prescribed by sea surface temperature climatology, introduced by a simple **Mixed Layer (ML) ocean model** or coupled as a dynamical model such as the **Large Scale Geostrophic (LSG) Ocean Circulation Model** (*Maier-Reimer et al., 1993*)
- Sea ice distribution can either be prescribed by climatology or simulated by a **thermodynamic sea ice model**

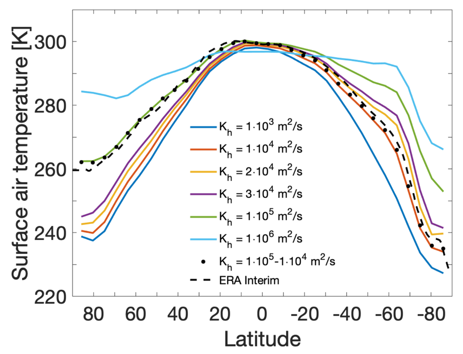


(2) Tuning

- ✓ perennial runs (CO_2 = 354 ppm)
- ✓ dynamic sea ice

T21 + ML

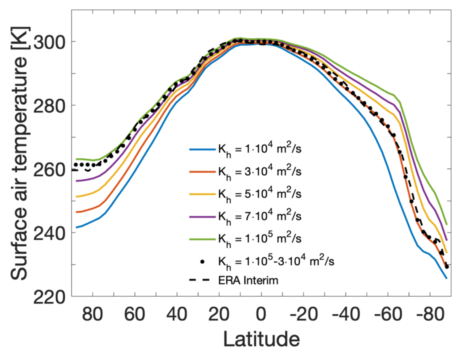
Mixed Layer ocean
T21 (~ 600 km) resolution
Tuned parameter:
horizontal oceanic diffusion coefficient K_h



$K_h = 1\cdot10^5$ m²/s (NH)
$K_h = 1\cdot10^4$ m²/s (SH)

T42 + ML

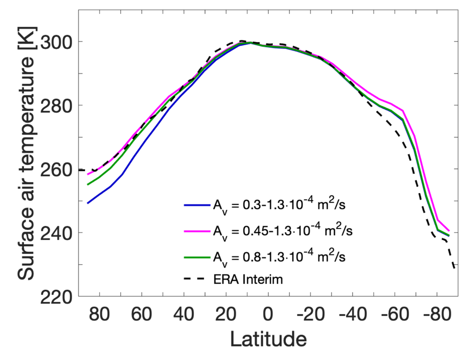
Mixed Layer ocean
T21 (~ 300 km) resolution
Tuned parameter:
horizontal oceanic diffusion coefficient K_h



$K_h = 1\cdot10^5$ m²/s (NH)
$K_h = 3\cdot10^4$ m²/s (SH)

T21 + LSG

Large Scale Geostrophic ocean
T21 (~ 600 km) resolution
Tuned parameter:
vertical oceanic diffusion coefficient A_v



A_v from $0.45\cdot10^{-4}$ m²/s (top) to $1.3\cdot10^{-4}$ m²/s (bottom)
to reduce the Sou. Ocean bias

(3) Simulated climate and energy balance

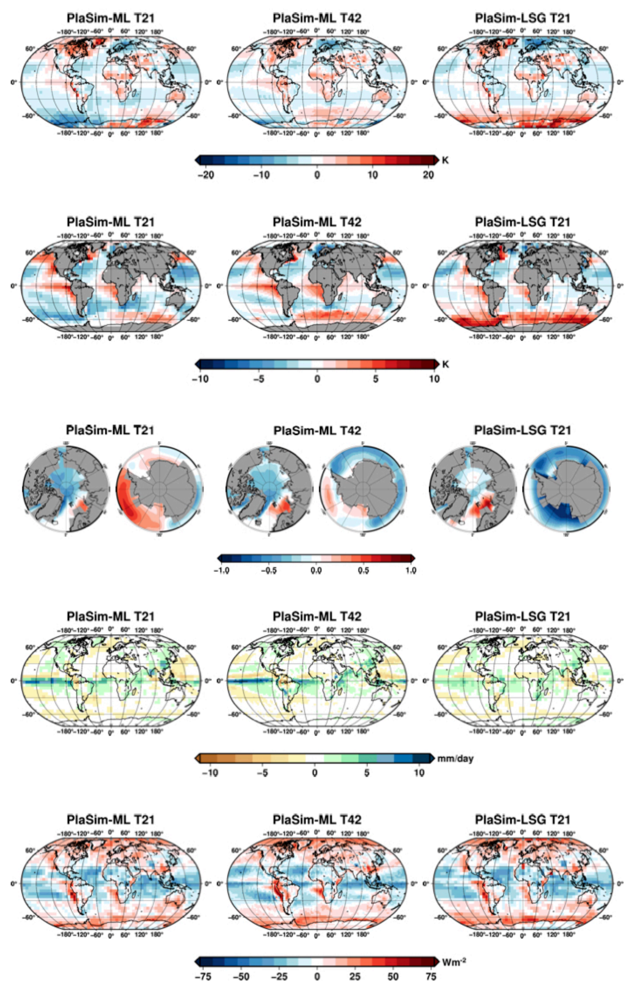
Surface air temperature anomaly [K] with respect to the ERA Interim reanalysis dataset (2005-2015 average) (*Dee et al., 2011*)

Sea surface temperature anomaly [K] with respect to the HadISST dataset (2005-2015 average) (*Titchner & Rayner, 2014*)

Sea ice cover anomaly with respect to the HadISST dataset (2005-2015 average) (*Titchner & Rayner, 2014*)

Precipitation anomaly [mm/day] with respect to the GPCP dataset (2005-2015 average) (*Adler et al., 2003*)

TOA energy budget anomaly [W/m²] with respect to the CERES-EBAF dataset (2005-2015 average) (*Loeb et al., 2018*)



Simulated and observed energy fluxes (Wm^{-2}) at the top of the atmosphere and at the surface

	PlaSim-ML T21	PlaSim-ML T42	PlaSim-LSG T21	Stephens et al. (2012)
TOA net shortwave	231.5	235.8	232.8	240.2
TOA net longwave	-232.3	-236.0	-232.9	-239.7
TOA energy budget	-0.8	-0.1	-0.1	0.6
Surface net shortwave	163.2	169.4	164.1	165
Surface net longwave	-62.8	-62.4	-63.0	-52.4
Sensible heat flux	-18.9	-20.8	-18.3	-24
Latent heat flux	-82.0	-86.5	-82.7	-88
Surface energy budget	-0.5	-0.2	0.1	0.6
TOA-surface net	**-0.2**	**0.1**	**-0.2**	**0**

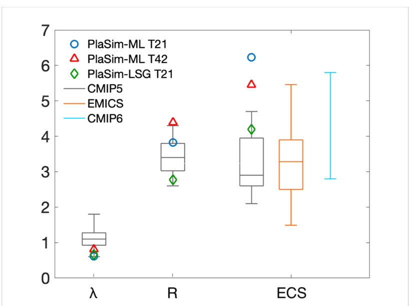
Please notice that the estimates from *Stephens et al. (2012)* are only reported for reference, since we are comparing **equilibrium model results** with the **current observed transient**.

(4) Equilibrium climate sensitivity and feedback parameter

- ✓ CO_2 doubling experiments (285 ppm → 570 ppm)
- ✓ CO_2 quadrupling experiments (285 ppm → 1140 ppm)
- ✓ dynamic or prescribed sea ice

EQUILIBRIUM CLIMATE SENSITIVITY (ECS)

Equilibrium (steady state) change in the annual global mean surface temperature following a **doubling** of the atmospheric equivalent carbon dioxide (CO_2) concentration (*IPCC*)

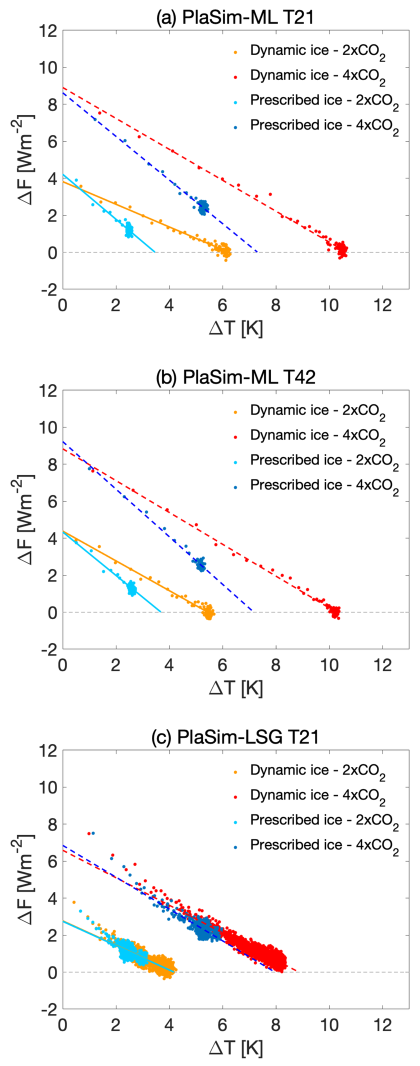


Feedback parameter λ

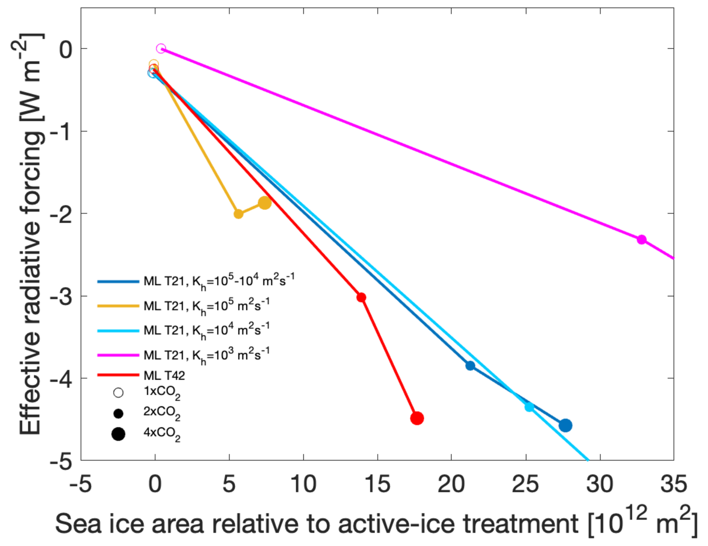
$$\Delta F = R - \lambda\,\Delta T$$

ΔF = net TOA radiative flux change
R = radiative forcing
ΔT = surface air temperature change

ECS and λ calculated as in *Gregory et al. (2004)*



Approach of *Caldeira & Cvijanovic (2014)*

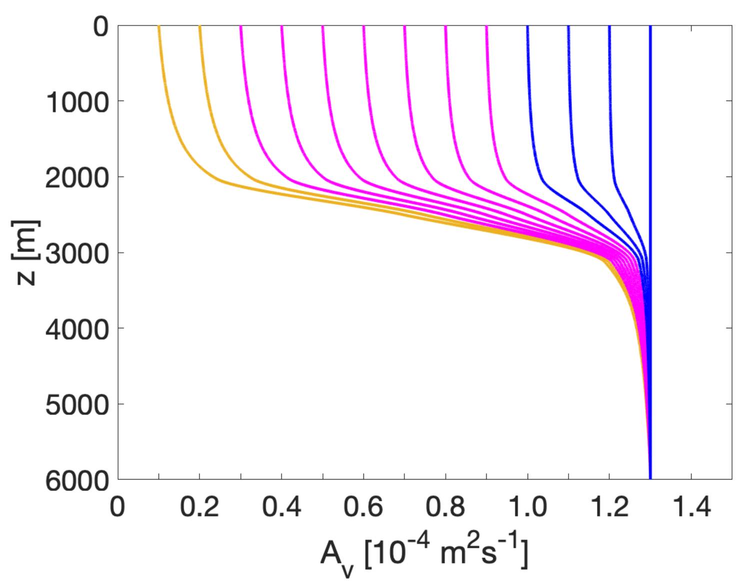


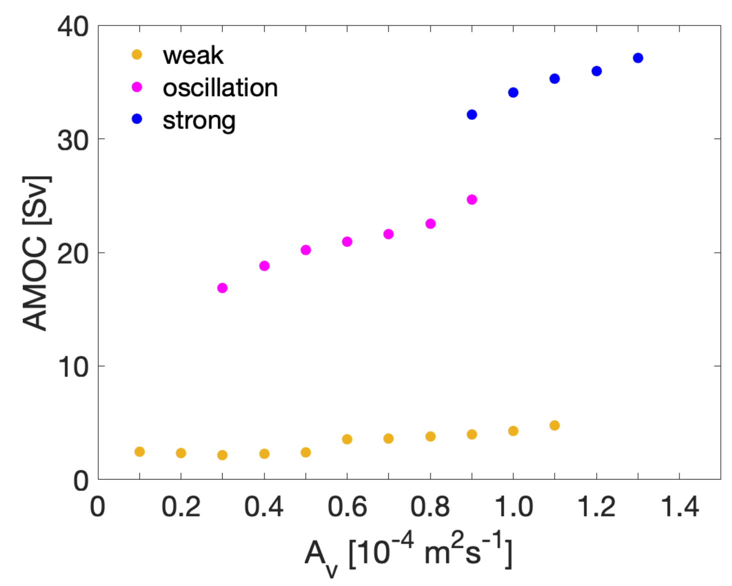
Increasing the horizontal diffusion coefficient of the Mixed Layer (K_h) the oceanic temperatures become globally more homogeneous. As a consequence the average outgoing longwave radiation (proportional to T^4) strongly decreases and the model tends to increase global average temperature in order to keep the energy balance. The high PlaSim-ML ECS depends on the choice of K_h during the model tuning.

(5) Atlantic Meridional Overturning Circulation regimes

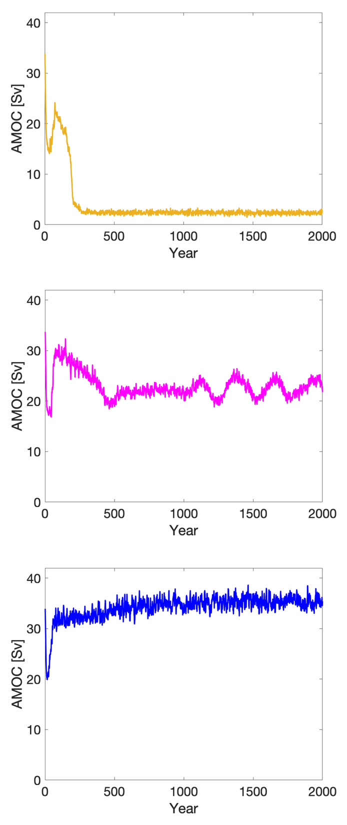
- ✓ perennial runs (CO_2 = 285 ppm)
- ✓ dynamic sea ice
- ✓ **T21 + LSG**

Tuned parameter:
vertical oceanic diffusion coefficient A_v from **$0.1\cdot10^{-4}$ m²/s** to **$1.3\cdot10^{-4}$ m²/s** (top) **$1.3\cdot10^{-4}$ m²/s** (bottom)





Example of weak, oscillating and strong regimes



(6) Conclusions

The tuning of PlaSim with the ML ocean suggests the use of **two different values** for the oceanic horizontal diffusion coefficient. The tuning of the coupled PlaSim-LSG model recommends an oceanic vertical diffusion ranging from **$0.45\cdot10^{-4}$ m²/s** to **$1.3\cdot10^{-4}$ m²/s**. The climatic variables are well simulated but there is a warm bias in the Southern Ocean using PlaSim-LSG. The **ECS** is estimated from CO_2 doubling and quadrupling experiments. The large ECS of PlaSim-ML depends on the choice of the horizontal diffusion coefficient, that is on the intensity of the meridional heat transport. The PlaSim-LSG configuration shows different AMOC regimes as a function of the vertical diffusion coefficient: in addition to two steady states, characterized by **weak** and **strong** AMOC, an intermediate regime with **oscillations** is also possible.

(7) Bibliography

- *Adler et al. (2003)*, J. Hydrometeor., 4, 1147-1167, https://doi.org/10.3390/atmos9040138
- *Caldeira & Cvijanovic (2014)*, J. Climate, 27, 8597-8607, https://doi.org/10.1175/JCLI-D-14-00042.1
- *Dee et al. (2011)*, Q. J. R. Meteorol. Soc., 137, 553-597, https://doi.org/10.1002/qj.828
- *Fraedrich et al. (2005)*, Meteorol. Z., 14 (3), 299-304, https://doi.org/10.1127/0941-2948/2005/0043
- *Gregory et al. (2004)*, Geophys. Res. Lett., 31, L03205, https://doi.org/10.1029/2003GL018747
- *Loeb et al. (2018)*, J. Climate, 31, 895-918, https://doi.org/10.1175/JCLI- D-17-0208.1
- *Maier-Reimer et al. (1993)*, J. Phys. Oceanogr., 23, 731-757, https://doi.org/10.1175/1520-0485(1993)023<0731:MCOTHL>2.0.CO;2
- *Stephens et al. (2012)*, Nature Geoscience, 5, 691-696, https://doi.org/10.1038/ngeo1580
- *Titchner & Rayner (2014)*, J. Geophys. Res., 119, 2864-2889, https://doi.org/10.1002/2013JD020316