Effect of ocean tidal mixing on exoplanet climates and habitability

Maria Di Paolo[1] (m.di-paolo@uea.ac.uk), David P. Stevens[1], Manoj Joshi[2], Robert A. Hall[2]

[1] School of Mathematics, University of East Anglia, Norwich, United Kingdom
[2] School of Environmental Sciences, University of East Anglia, Norwich, United Kingdom

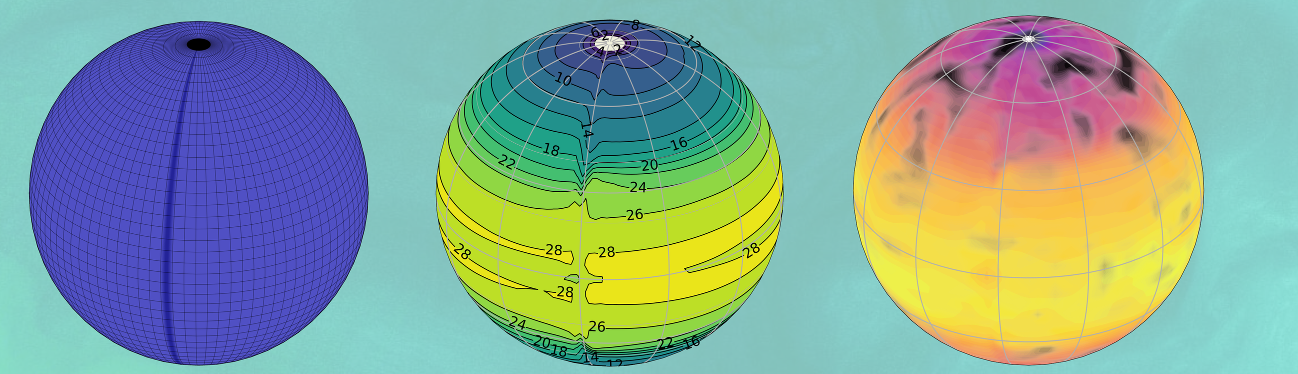
University of East Anglia

1 Introduction

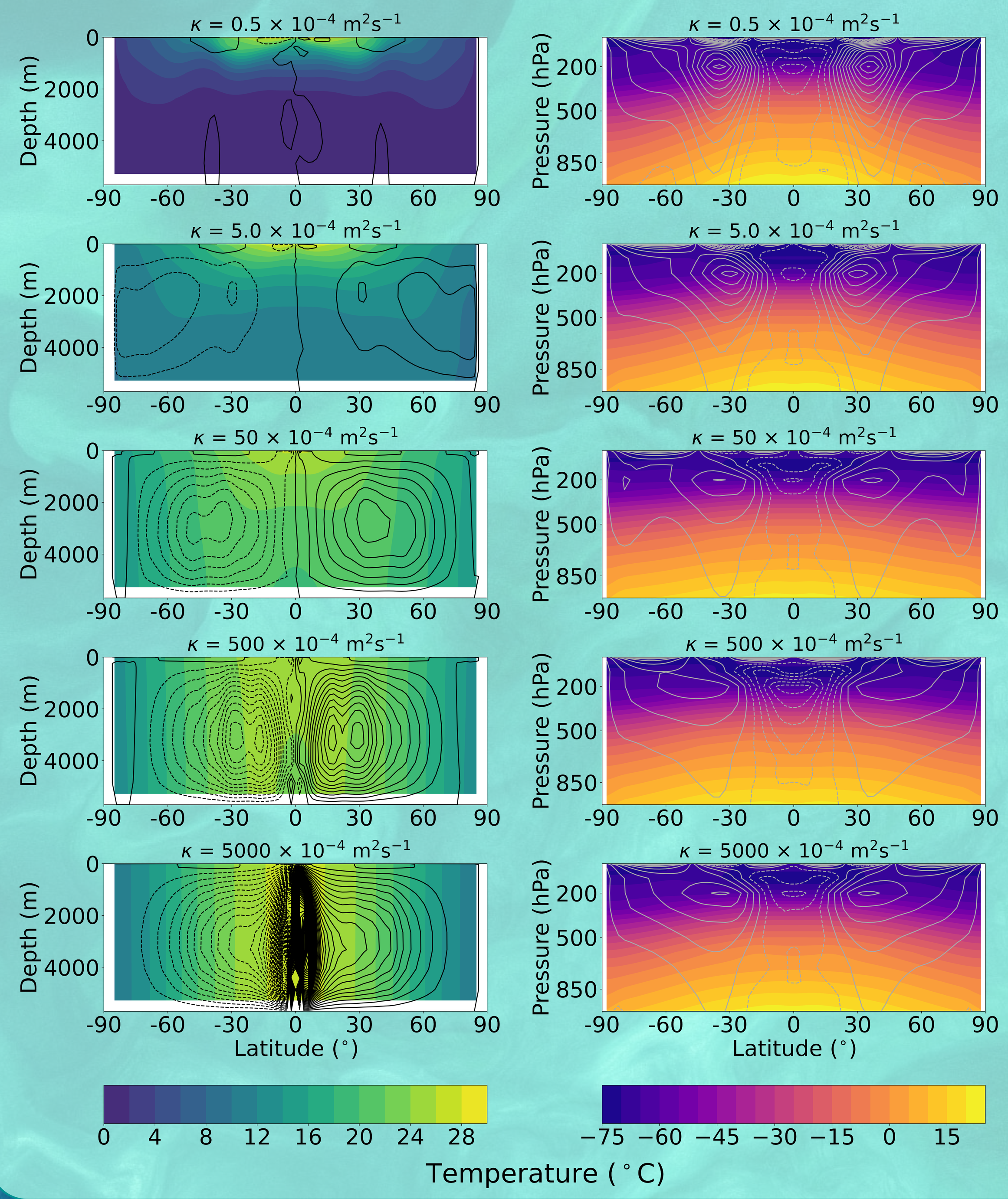
- Due to their abundance and their observational advantages, **M dwarfs** offer the best chance of finding **habitable planets** through sheer numbers. Therefore, in the race to detect signs of life beyond the Solar System, rocky M-dwarf planets offer exciting prospects.
- Oceans have a dominant impact on planetary climate, so understanding their effects is a necessary part of modelling terrestrial exoplanets.
- Planets in close orbits around their host star experience particularly strong **tidal interactions**. Potentially habitable planets orbiting M dwarfs are often tidally locked, but under some circumstances they may **not** be **synchronously rotating** [1].
- Planetary rotation rate and star-planet distance shape the non stationary tidal bulge. These quantities are strongly dependent on the host star. The **ocean diffusivity**, related to the non stationary tides, is therefore intrinsically linked to the host star type.
- We investigated the case of non synchronous terrestrial planets in close orbits in the habitable zone of their M host star, parameterising the effect of propagating tides and analysing their impact on climate. Taking into account the impact of ocean tides can lead to **significant effects on planetary climate**.

2 Model setup

- **FORTE2.0** [2], a coupled atmosphere-ocean general circulation model.
  Ocean: horizontal resolution of 2°×2°, 15 z-levels, whose thickness increases progressively with depth.
  Atmosphere: T42 spectral resolution, i.e. a grid spacing of ~ 2.8°, it extends to around 25 km in altitude and is subdivided in 20 σ levels.
- **Earth-like aquaplanet:** a 5500 m deep ocean world, with a meridional barrier of depth 145 m that connects two polar islands.
- Ocean diffusion: varying values of the **vertical diffusion coefficient**, κ = (0.5, 1.5, 5.0, 15, 50, 150, 500, 1500, 5000) × 10^{-4} m^2s^{-1} ($κ_{Earth}$ = 10^{-4} m^2s^{-1} [3]).



3a Effect of vertical diffusion: circulation and temperature structure



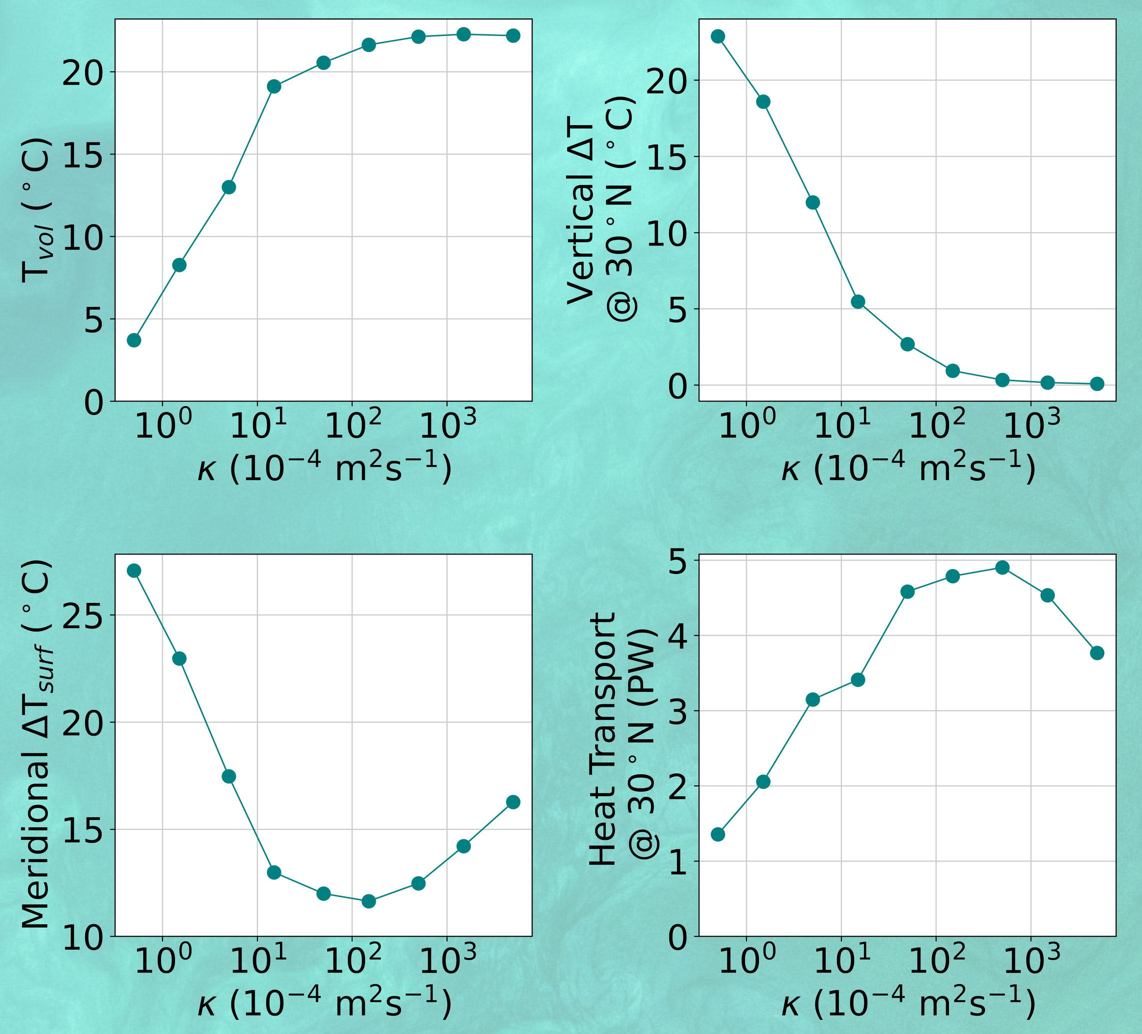
- **Ocean circulation is tightly linked to the value of κ.**
  Increasing values of κ result in an enhanced circulation [4] and thus in milder differences between equatorial and polar temperatures.
  As oceanic diffusion becomes more important, the thermocline deepens progressively. Deep water, especially at high latitudes, gets warmer and warmer with increased diffusion.
- **Zonal wind is more intense for lower values of κ,** associated with a larger meridional gradient in surface temperature.

Shading shows zonally averaged values of temperature for the atmosphere (left) and the ocean (right).

Black contours show the meridional overturning streamfunction. Contour interval is 50 Sv. Clockwise circulation is depicted by solid lines, anticlockwise circulation is depicted by dashed lines.

Grey contours show the zonal wind. Contour interval is 3 ms^{-1}. Westerlies are depicted by solid lines, easterlies are depicted by dashed lines.

3b Effect of vertical diffusion: ocean temperature and heat transport

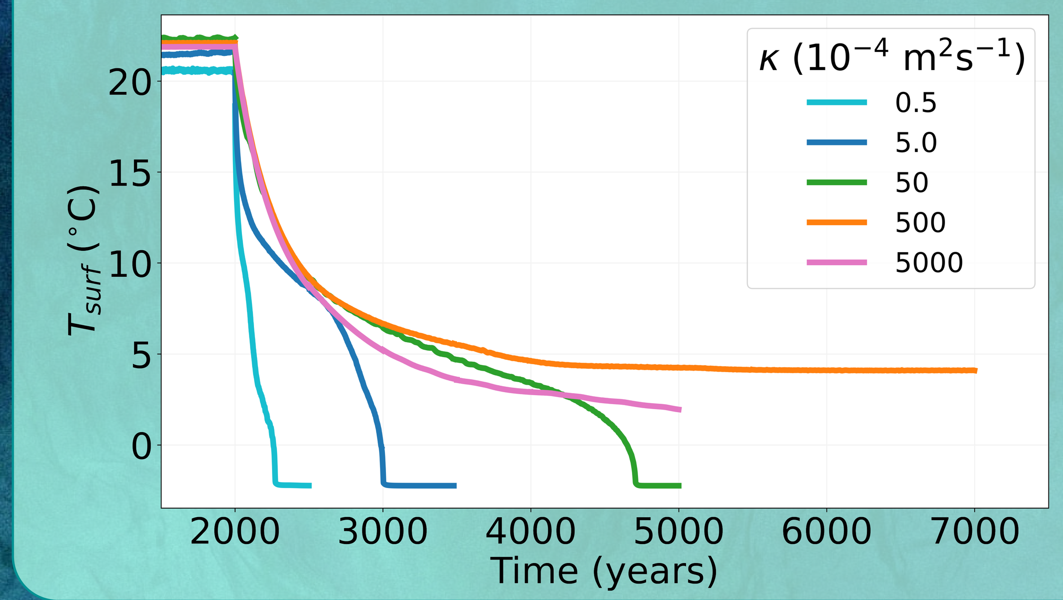


- **Higher values of κ correspond to a more efficient oceanic vertical mixing.**
  Volume averaged temperatures increase and top-to-bottom temperature gradients decrease.
- **Meridional gradients of surface temperature reach a minimum at κ~10^{-2} m^2s^{-1}, which corresponds to the peak in heat transport.**
  For even higher values of κ, the meridional overturning is mostly concentrated at low latitudes, and consequently the meridional heat transport is less efficient.

Volume averaged temperature, mean vertical and meridional temperature gradients, meridional heat transport as a function κ.

4 Effect of change in instellation

$S_\star$ ($S_\odot$)	κ (10^4 m^2s^{-1})	Mean annual climate state		
		T_{surf} (°C)	T_{vol} (°C)	ϕ_{ice} (° N or S)
1.0	0.5	20.6	3.7	88.0
	5.0	21.6	13.0	88.0
	50	22.3	20.5	88.0
	500	22.1	22.1	88.0
	5000	15.0	15.3	88.0
0.90	0.5	6.5	-0.0	39.0
	5.0	14.7	7.1	88.0
	50	15.2	13.7	88.0
	500	15.5	15.6	88.0
	5000	15.0	15.3	88.0
0.85	0.5	-2.2	-1.9	0.0
	5.0	-2.2	-1.9	0.0
	50	10.7	9.3	88.0
	500	11.0	11.2	88.0
	5000	10.4	10.7	88.0
0.80	0.5	-2.2	-1.8	0.0
	5.0	-2.2	-1.9	0.0
	50	-2.2	-1.9	0.0
	500	4.1	4.2	51.2
	5000	2.0	2.3	39.0



- **An enhanced oceanic circulation can prevent the planet from entering in a snowball state.**
  A reduced instellation ($S_\star$= 0.90, 0.85, 0.80 $S_\odot$) causes a drop in temperatures and, in some cases, the formation of sea ice. A more efficient oceanic heat transport mitigates these effects.
  In some scenarios, the aquaplanets characterized by higher values of κ are spared from completely freezing over.
- **Ocean diffusion effectively plays a role in determining the position of the outer edge of the habitable zone.**
  A 20% decrease in instellation corresponds roughly to a 12% increase of the orbital radius.

Mean sea surface temperature timeseries for the case $S_\star$= 0.80 $S_\odot$, starting from the steady states achieved after 2000 years of standard simulations.

5 Conclusions and future work

Ocean diffusion plays an important role in determining the **basic state of the planetary surface**, and therefore in determining surface temperatures. This has obvious repercussions in defining the **edges of the habitable zone**.

In the scenario of non-synchronous rotating, tidally locked planets orbiting in the habitable zone of their host M stars, there is an **ocean based potential habitability that depends on the stellar type**.

Apply this reasoning to the case of **TRAPPIST-1e, f and g**, that reside in their host star habitable zone. Despite being in close orbit to the M8 star, recent studies show that these planets may not be synchronous rotators [5].

Investigate the effects of ocean properties in the case of **synchronously rotating planets**.

References

[1] R. Barnes, *Celest. Mech. Dyn. Astron.*, **129**, 509-536, 2017.
[2] A. T. Blaker et al., *Geosci. Model Dev.*, **14**, 275-293, 2021.
[3] W. Munk & C. Wunsch, *Deep-Sea Res. I: Oceanogr. Res. Pap.*, **45** (12), 1977-2010, 1998.
[4] J. Cullum et al., *Astrobiology*, **14** (8), 645-650, 2014.
[5] A. M. Vinson et al., *Mon. Notices Royal Astron. Soc.*, **488** (4), 5739-5747, 2019.

Scan to download the poster!

Acknowledgements

This work was supported by the Engineering and Physical Sciences Research Council.

Engineering and Physical Sciences Research Council