Atmospheric modelling of hot Jupiters with sophisticated radiation transport

David S. Amundsen[1,2,3], Nathan J. Mayne[1], Isabelle Baraffe[1,4], James Manners[1,5], Pascal Tremblin[1,6], Benjamin Drummond[1], Chris Smith[1,5], David M. Acreman[1] and Derek Homeier[7,4]

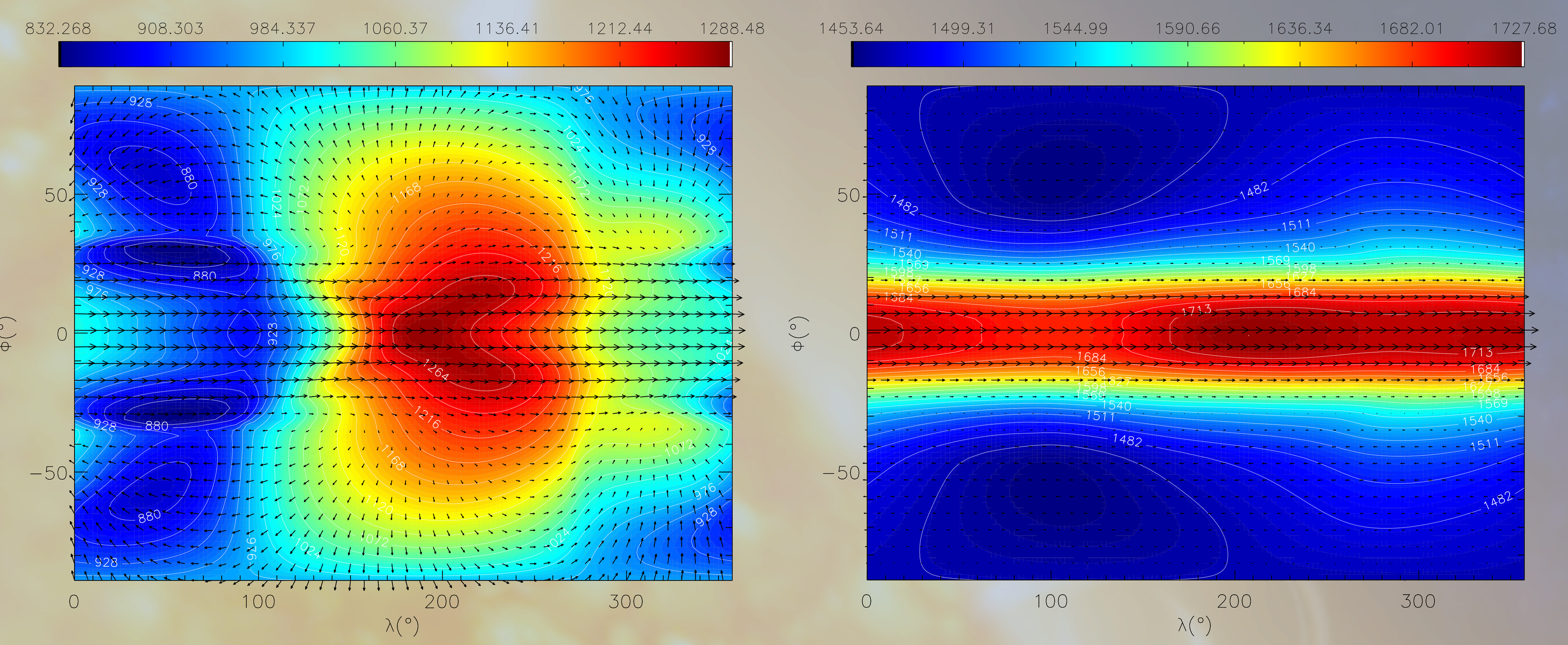
[1] Astrophysics Group, University of Exeter, UK, [2]APAM, Columbia University, NY, USA, [3]NASA GISS, NY, USA, [4]Univ Lyon, ENS de Lyon, France, [5] Met Office, UK, [6]Maison de la Simulation, CEA, Gif-Sur-Yvette, France, [7]Zentrum für Astronomie der Universität Heidelberg, Germany

Abstract: The UK Met Office GCM applied to HD 209458b

To study the complexity of hot Jupiter atmospheres revealed by observations of increasing quality, **we have adapted the UK Met Office Global Circulation Model (GCM)**, the Unified Model (UM), to these exoplanets. The UM solves the **full 3D Euler equations** with a **height-varying gravity**, avoiding the simplifications used in most GCMs currently applied to exoplanets. We present the coupling of the UM dynamical core to an accurate radiation scheme based on the **two-stream approximation and correlated-*k* method** with **state-of-the-art opacities from ExoMol**. Our first application of this model is devoted to the extensively studied hot Jupiter HD 209458b. We derive synthetic emission spectra and phase curves, and compare them to both previous models also based on state-of-the-art radiative transfer, and to observations. We find a **reasonable agreement between our day side emission, hotspot offset and observations**, while our **night side emission is too large**. Overall our **results are qualitatively similar to those found by Showman et al., ApJ, 2009** with the SPARC/MITgcm, however, our simulations show significant variation in the position of the hottest part of the atmosphere with pressure, as expected from simple timescale arguments, in contrast to previous works demonstrating "vertical coherency" (Showman et al., ApJ, 2009). **Our comparisons strengthen the need for detailed intercomparisons** of dynamical cores, radiation schemes and post-processing tools to understand these differences. This effort is necessary in order to make robust conclusions about these atmospheres based on GCM results.

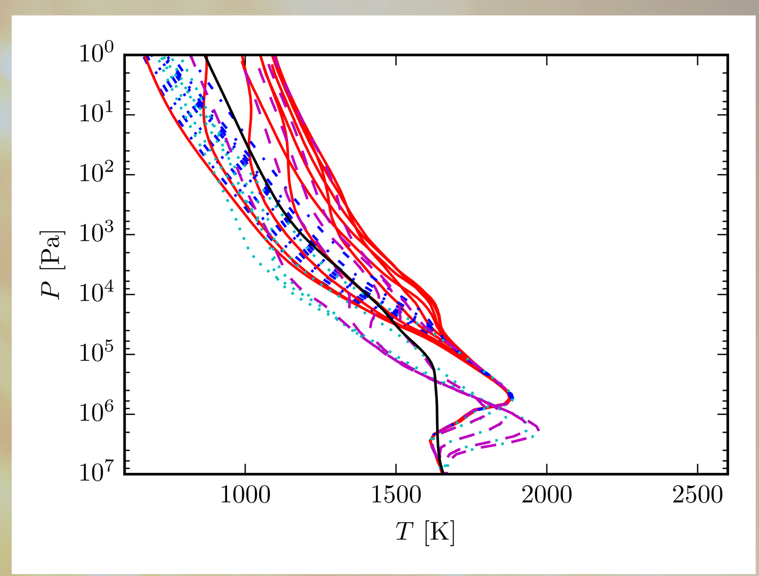
Paper: D.S. Amundsen, N.J. Mayne, I. Baraffe et al.: The UK Met Office GCM with a sophisticated radiation scheme applied to the hot Jupiter HD209458b, A&A 2016, submitted

Horizontal temperature and wind fields

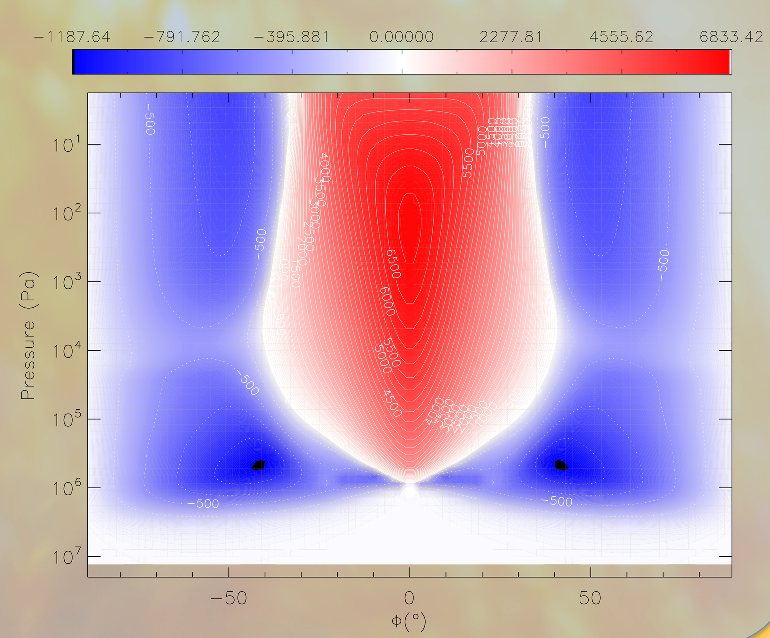


Wind as arrows and temperature as colours [K] from our simulation of HD 209458b at 10^2 Pa (left) and 10^5 Pa (right) after 1600 Earth days. The flow is diverging from the substellar point, although with a pronounced eastward equatorial jet. The hotspot is shifted eastward of the substellar point as seen in other models (e.g. Showman et al. ApJ 2009) and suggested by Spitzer phase curve observations (see e.g. Zellem et al. ApJ 2014).

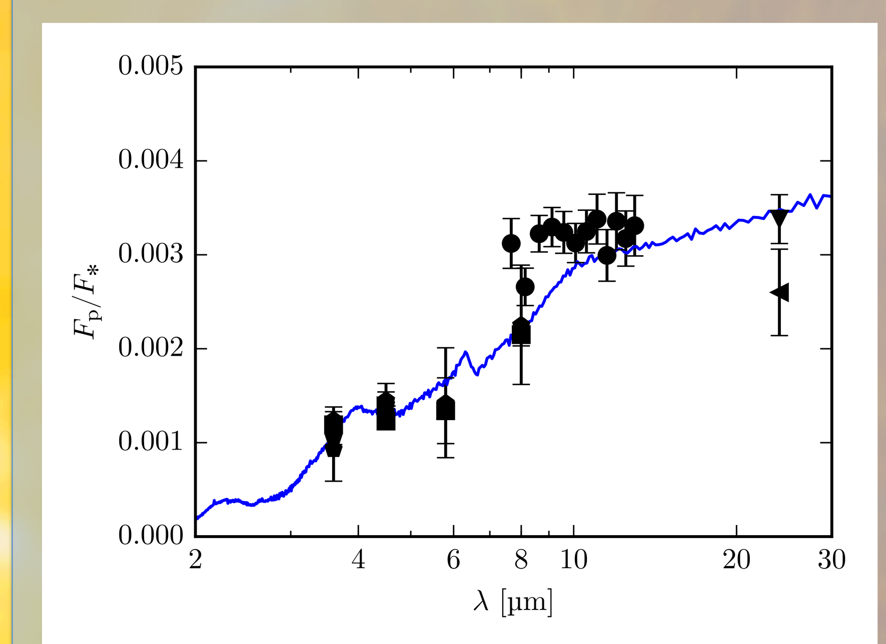
One characteristic of the SPARC/MITgcm that is present in both hot Jupiter models presented in Showman et al. (2009) is what the authors term a "vertical coherency" of temperatures. This term is used to describe the fact that the position of the hottest and coldest part of the atmosphere vary only modestly between 10^2 Pa and 10^5 Pa. Even at 10^5 Pa = 1 bar their models have temperature difference of about 500 K between the hottest and coldest points of the atmosphere, with the hottest point being offset significantly, about 80° longitude, from the substellar point. Interestingly, we do not see this vertical coherence in our models. The reason for this discrepancy is unclear, but we have run our model significantly longer, giving the system time to equilibrate at higher pressures, and we do not assume the atmosphere to be shallow. This may help explain these differences, but more in-depth comparisons are needed to understand these differences in more detail.

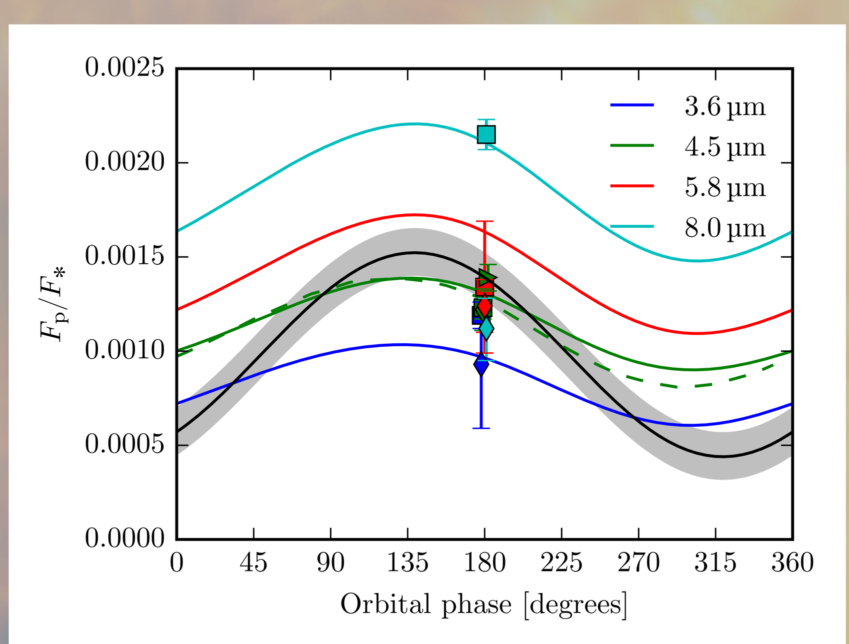


We show on the right the zonal mean of the zonal wind [m/s] as a function of pressure and latitude. The zonal jet in the eastward direction mentioned above is clearly seen, and it reaches its maximum strength at about 10^3 Pa with a velocity of about 7 km/s. At higher latitudes the mean flow is in the opposite (westward) direction, and much weaker in amplitude, with a maximum of about 1.2 km/s.



Comparison to observations





Dayside emission spectrum (left) and 4.5 μm phase curve (right) calculated from our 3D GCM results using our 1D atmosphere code ATMO. We are able to match the dayside emission quite well, including the offset of the peak flux, while our night side emission is too large. This is also the case for Showman et al.'s models from Zellem et al. (2014), particularly for the model with a setup close to ours (no TiO/VO).

Conclusions

- We obtain a good qualitative agreement with Showman et al. (2009): both global circulation patterns and synthetic observations are similar.
- We do not see a "vertical coherency".
- Further intercomparison is needed.
- We obtain a reasonable fit to the dayside emission.
- Like other models we overestimate the night side flux.

Abstract: Treatment of overlapping gaseous absorption with the correlated-*k* method in atmosphere models

The correlated-*k* method is frequently used to speed up radiation calculations in both one-dimensional and three-dimensional atmosphere models. **An inherent difficulty with this method is how to treat overlapping absorption**, i.e. absorption by more than one gas in a given spectral region. We have evaluated the applicability of three different methods in hot Jupiter and brown dwarf atmosphere models, all of which have been previously applied within models in the literature: **(i) Random overlap**, both with and without resorting and rebinning (Lacis & Oinas, JGR, 1991), **(ii) equivalent extinction** (Edwards, JAS, 1996) and **(iii) pre-mixing of opacities**, where **(i) and (ii) combine *k*-coefficients for different gases** to obtain *k*-coefficients for a mixture of gases, while (iii) calculates *k*-coefficients for a given mixture from the corresponding mixed line-by-line opacities. We find that **the random overlap method is the most accurate and flexible** of these treatments, and is fast enough to be used in one-dimensional models with resorting and rebinning. In three-dimensional models such as GCMs it is too slow, however, and **equivalent extinction can provide a speed-up of at least a factor of three with only a minor loss of accuracy** while at the same time retaining the flexibility gained by combining *k*-coefficients computed for each gas individually. **Pre-mixed opacities are significantly less flexible**, and we also find that **particular care must be taken** when using this method in order to properly resolve rapid changes in the total opacity caused by changing mixing ratios. Our *k*-tables have sufficient resolution to resolve opacity changes of individual gases, but not to resolve rapid changes in gas mixing ratios caused by e.g. condensation. We use the random overlap method with resorting and rebinning in our one-dimensional atmosphere model and equivalent extinction in our GCM, which allows us to e.g. consistently treat the feedback of non-equilibrium mixing ratios on the opacity and therefore the calculated *P-T* profiles in our models.

Paper: D.S. Amundsen, P. Tremblin, J. Manners et al.: Treatment of overlapping gaseous absorption with the correlated-*k* method in hot Jupiter and brown dwarf atmosphere models, A&A 2016, submitted

Treatments of overlapping gaseous absorption

i. Random overlap (Lacis & Oinas, JGR, 1991): *k*-coefficients are computed for each gas and combined assuming their absorption cross-sections are uncorrelated:

$$\mathcal{T}(u_x,u_y)=\mathcal{T}(u_x)\times\mathcal{T}(u_y).$$

$$\mathcal{T}(u_x,u_y)=\sum_{l=1}^{n_{k,x}}\sum_{m=1}^{n_{k,y}} w_{xy,lm}e^{-k_{xy,lm}u_{xy}},$$

$$k_{xy,lm}=\frac{k_{x,l}u_x+k_{y,m}u_y}{u_x+u_y}=\frac{k_{x,l}\zeta_x u+k_{y,m}\zeta_y u}{\zeta_x u+\zeta_y u}=\frac{k_{x,l}\zeta_x+k_{y,m}\zeta_y}{\zeta_x+\zeta_y},$$

$$w_{xy,lm}=w_{x,l}w_{y,m}.$$

Mixed *k*-coefficients can either be used as is (RO) or resorted and rebinned (RORR) into a smaller number of *k*-coefficients.

ii. Equivalent extinction (EE, AEE, Edwards, JAS, 1996): *k*-coefficients are computed for each gas and combined using an "equivalent grey absorption" for all minor absorbers and all *k*-coefficients for the major absorber in each band:

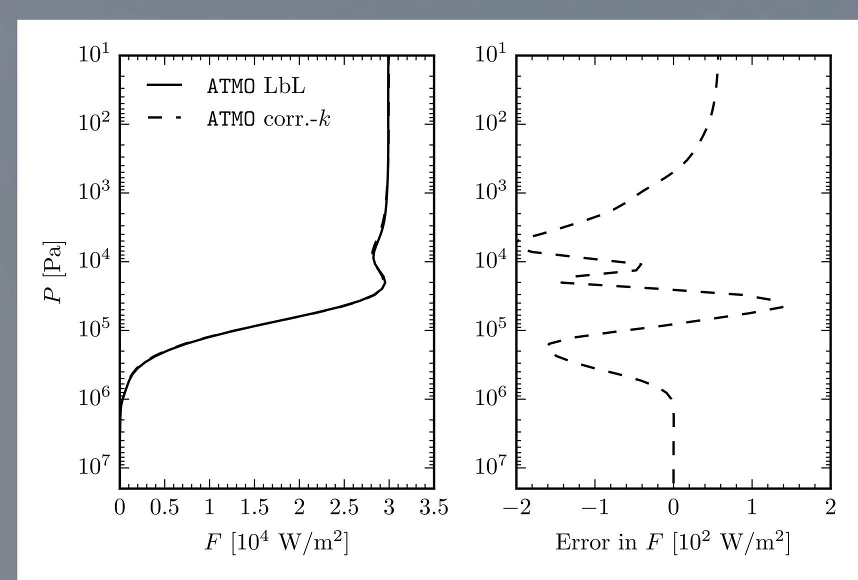
$$\bar{k}_x=\frac{\sum_{l=1}^{n_{k,x}} w_{x,l}k_{x,l}F_{\nu,l}}{\sum_{l=1}^{n_{k,x}} w_{x,l}F_{\nu,l}},\quad \text{(thermal component)}\qquad \bar{k}_x=\frac{\sum_{l=1}^{n_{k,x}} w_{x,l}k_{x,l}F_{s*,l}}{\sum_{l=1}^{n_{k,x}} w_{x,l}F_{s*,l}},\quad \text{(stellar component)}$$

iii. Pre-mixed opacities (PM, Goody et al., JGR, 1991): *k*-coefficients for the mixture are computed directly from the total line-by-line gas opacity:

$$k^{\rm tot}(\tilde{\nu},P,T)=\sum_{i=1}^{N_s}k_i(\tilde{\nu},P,T)\zeta_i(P,T),$$

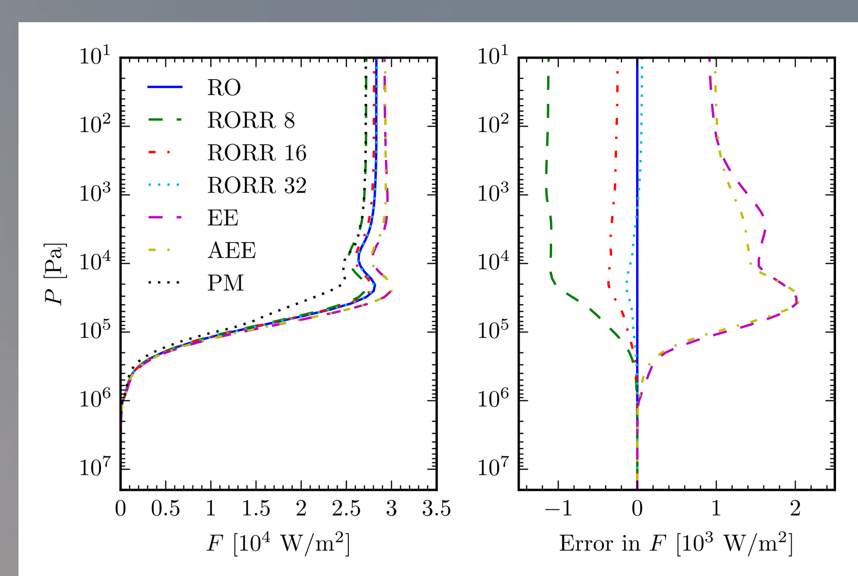
Verification of the random overlap assumption

This plots shows the thermal night side flux obtained using the random overlap method, with corresponding errors calculated by comparing to line-by-line fluxes. Fluxes obtained when using the correlated-*k* method with the random overlap method match the line-by-line result very well, with errors of a few percent. We note that these errors are both due to the use of the correlated-*k* method and the random overlap assumption, and in agreement with the errors found in Amundsen et al., A&A, 2014. Results for a day side *P-T* profile are similar.



Comparison of overlap treatments

This plot shows the thermal night side flux for the various overlap treatments with corresponding errors calculated by comparing to the random overlap method without resorting and rebinning (RO). It is clear that using the random overlap method with resorting and rebinning (RORR) with an increasing number of *k*-terms significantly decreases errors. Equivalent extinction (EE, AEE) is somewhat less accurate than RORR with only 8 *k*-terms.



Pre-mixed (PM) opacities are significantly less accurate than all other overlap treatments, this stems from errors introduced by the interpolation in the pre-mixed opacity table. Changes in mixing ratios with temperature and pressure can cause large changes in the pre-mixed opacities which are not properly resolved by our opacity table. We use an opacity table logarithmically spaced in temperature and pressure, with 20 temperature points between 70 K and 3000 K and 30 pressure points between 10^{-1} and 10^8 Pa, with the opacity interpolation performed linearly in temperature. This is similar to the resolution used in previous works (e.g. Showman et al., A&A, 2009). Results for a day side *P-T* profile are similar.

	CPU time [10^{-2} s]	Relative CPU time
RO	1.1×10^3	1.7×10^3
RORR 32	12.2	18.5
RORR 16	5.0	7.6
RORR 8	2.8	4.2
(A)EE	1.0	1.5
PM	0.66	1.0

Conclusions

- The random overlap method without resorting and rebining is accurate and flexible, but slow.
- The random overlap method with resorting and rebinning is accurate and flexible, and is fast enough to be used in 1D models.
- Equivalent extinction is faster than RORR, although slightly less accurate, but still flexible. Can be used in GCMs.
- Pre-mixed opacities are not flexible and can lead to significant errors if mixing ratios change rapidly.