Hot Jupiter Clouds in 3D: Spatial Heterogeneity Across Planetary Phase Space

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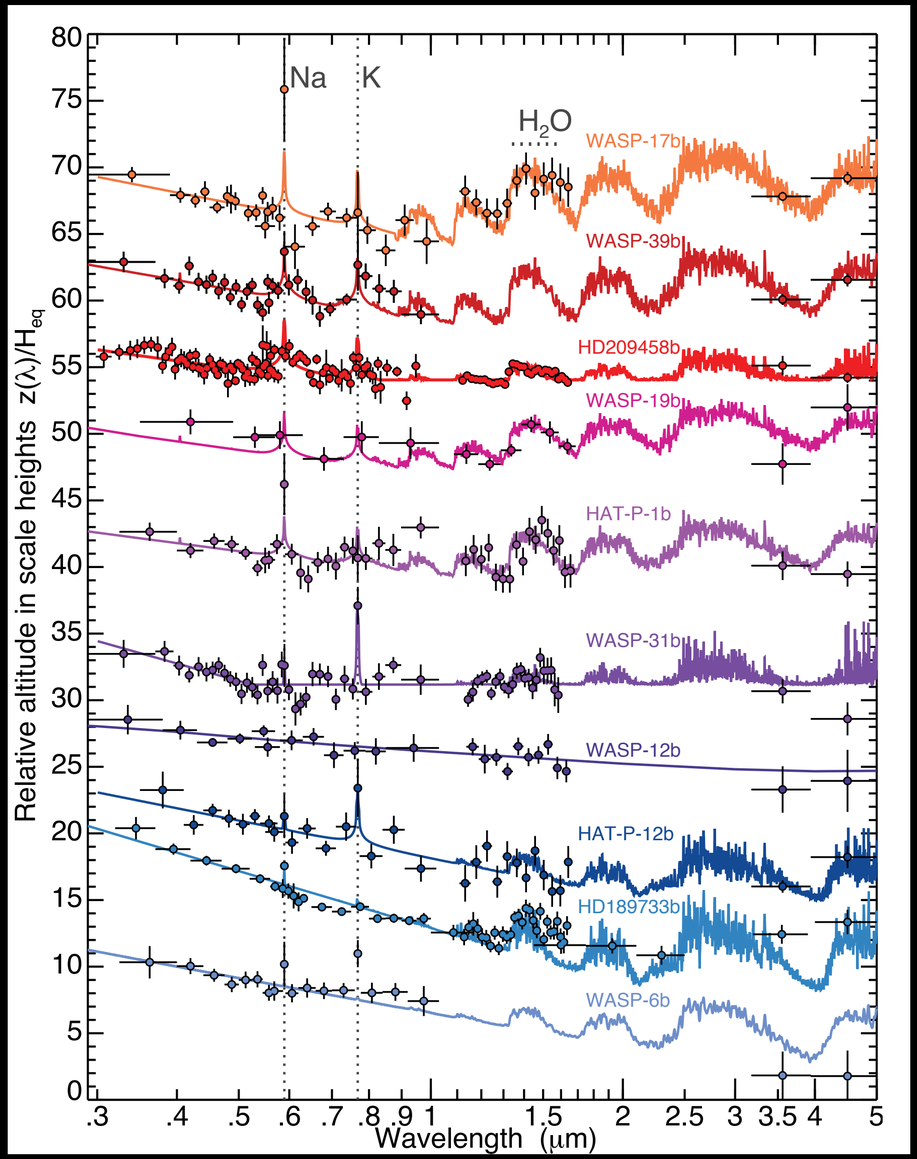
Observed diversity in the atmospheres of hot Jupiters

Clear

Cloudy/ hazy



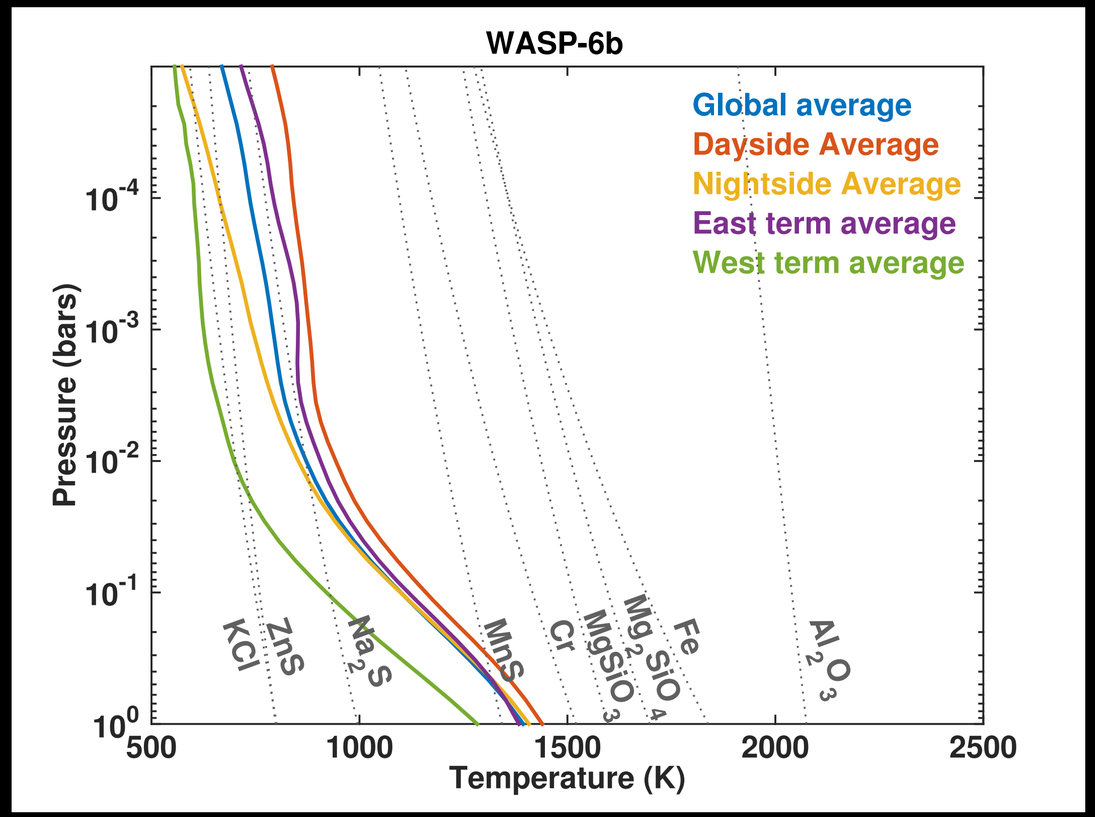
Observations suggest aerosols are ubiquitous in hot Jupiter atmospheres

Vary stochastically over a range of equilibrium temperatures, rotation rates, radii, and gravities

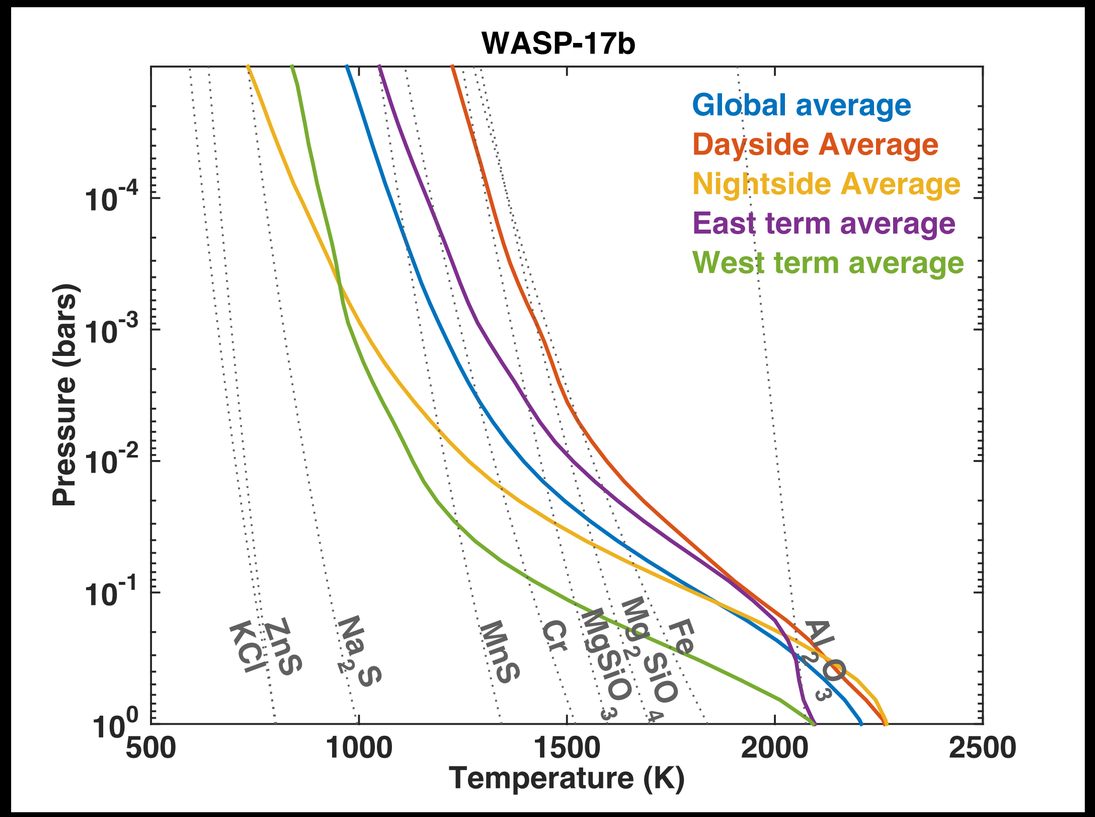
Sing et al. 2016, *Nature*

Localized clouds?

WASP-6b: cloudy



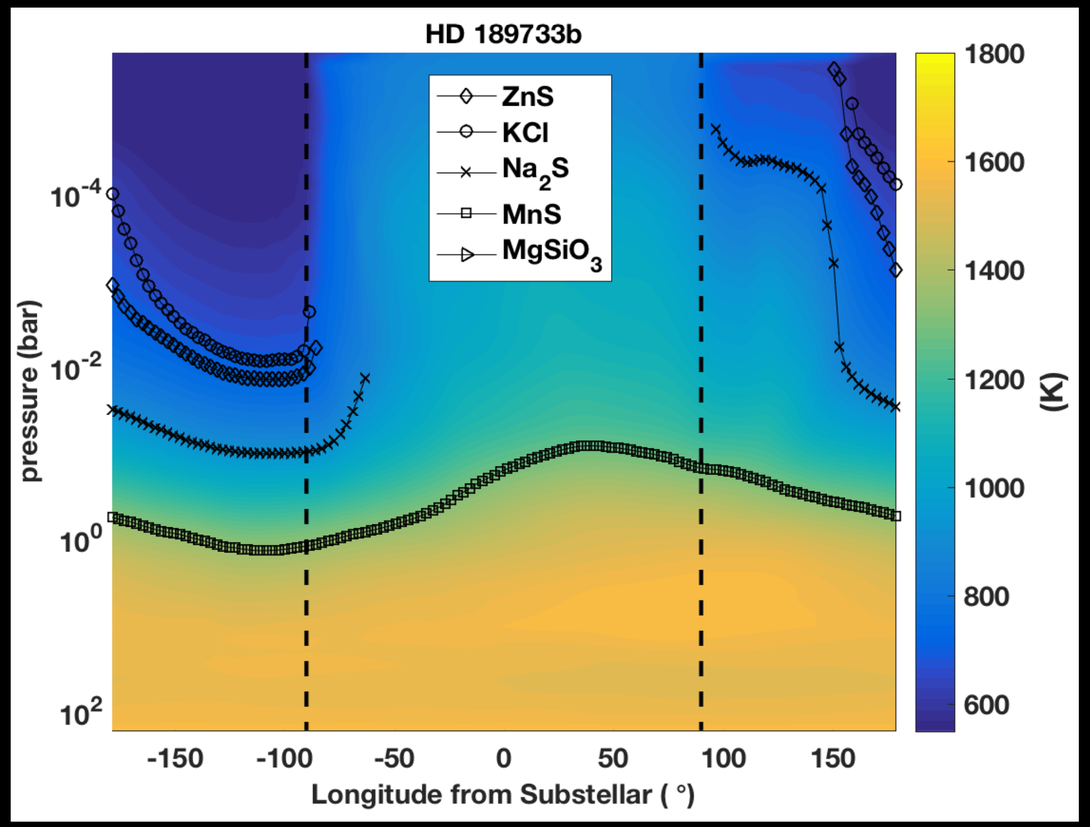
WASP-17b: clear



Kataria et al. 2016, *ApJ*

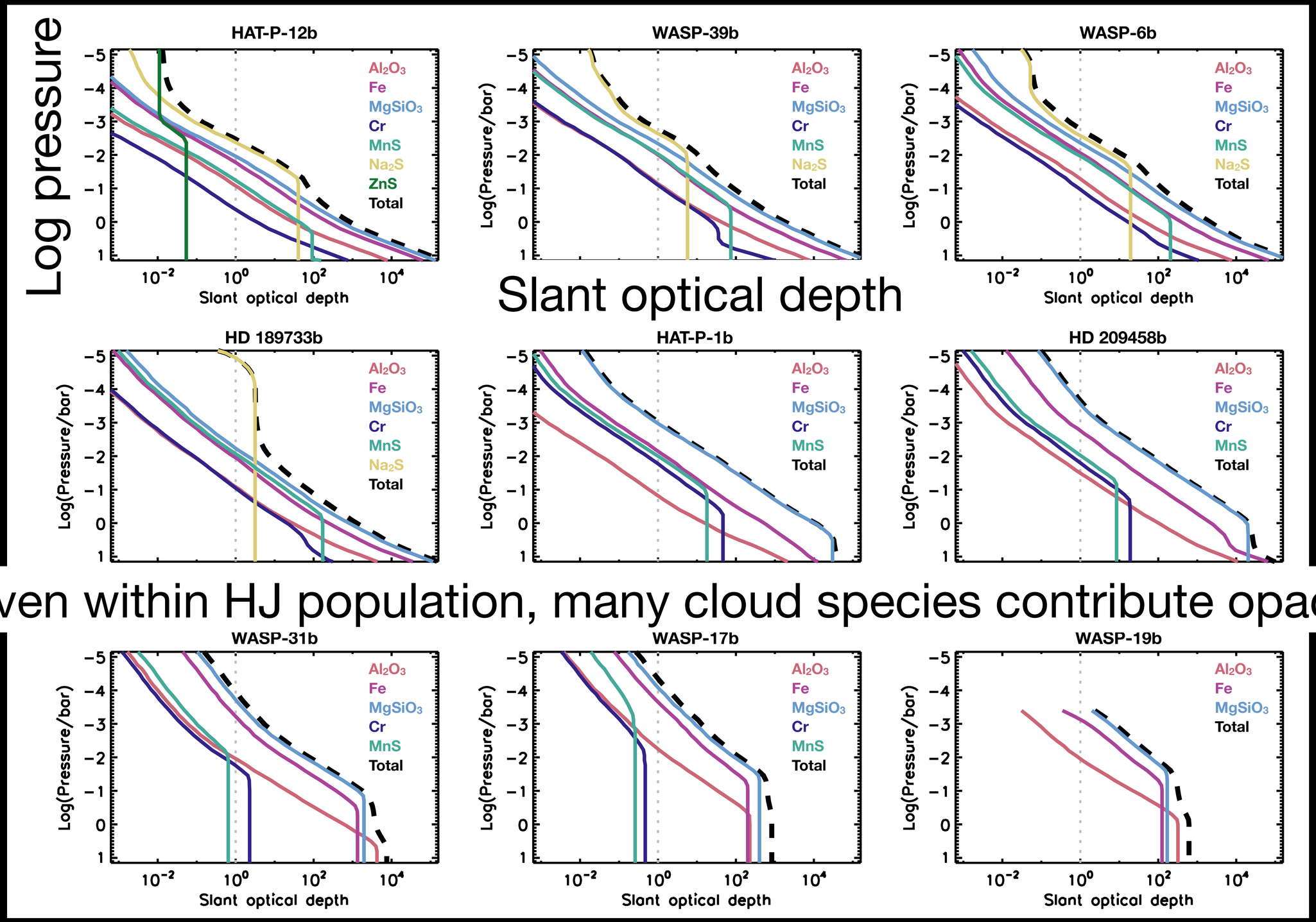
If we want to understand clouds in hot Jupiters, we must consider three-dimensional temperature structure

GCMs + post-processed clouds



Kataria et al., in prep

- Add cloud opacities to **GCM results from Kataria et al. (2016)**
- **Ackerman and Marley (2001) cloud code (aka eddysed)**
  - Evaluates geometric scattering optical depth by cloud particles following Mie theory
  - Additions by Morley et al. (2012, 2013) to include sulfide clouds
  - Eventually including ultra-high T clouds (Wakeford et al. 2017)
- **Transmission spectra computed in 1D** (Hubbard et al. 2001, Fortney et al. 2003) **and 3D** (Fortney et al. 2010, Shabram et al. 2011)

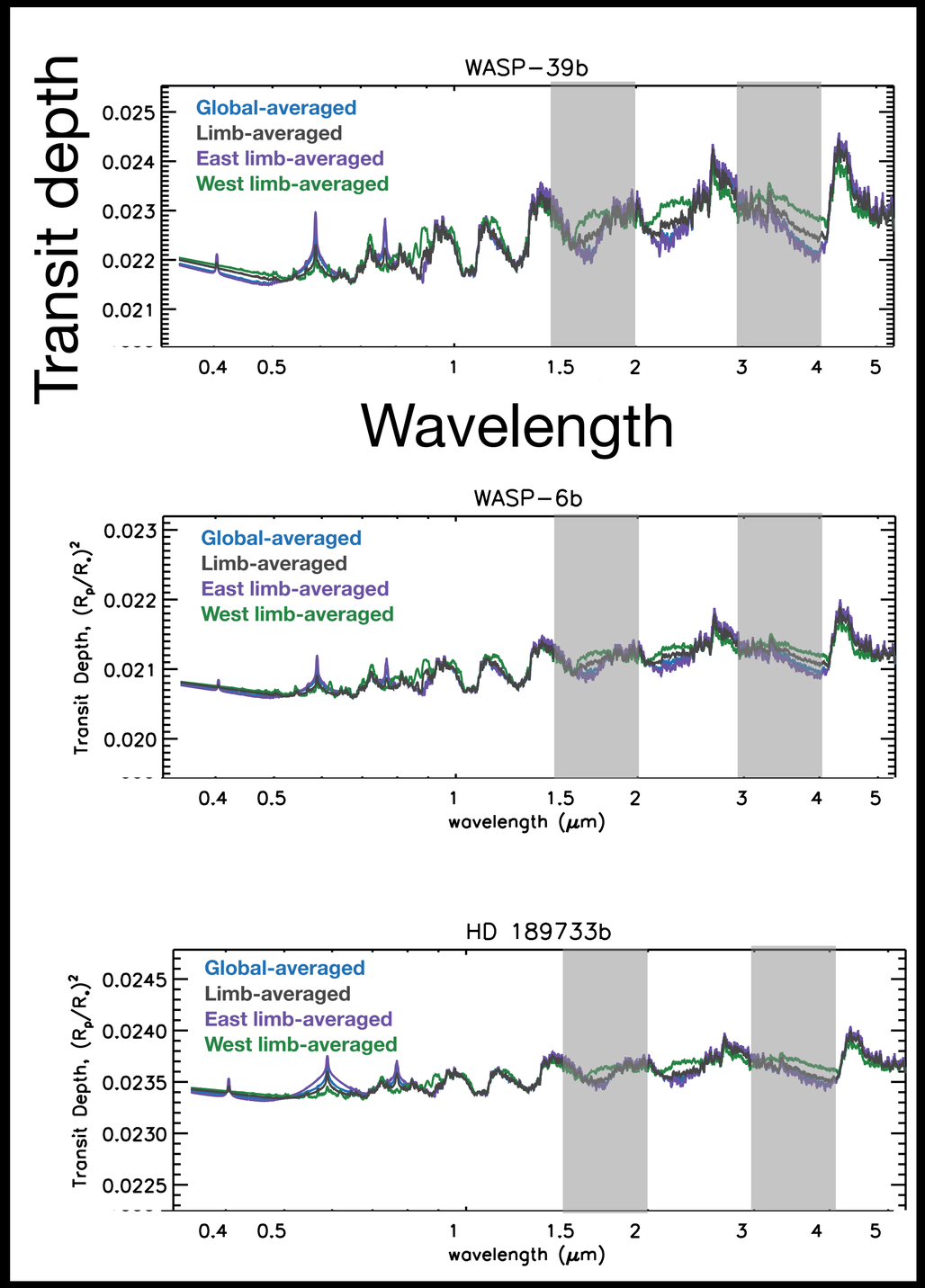


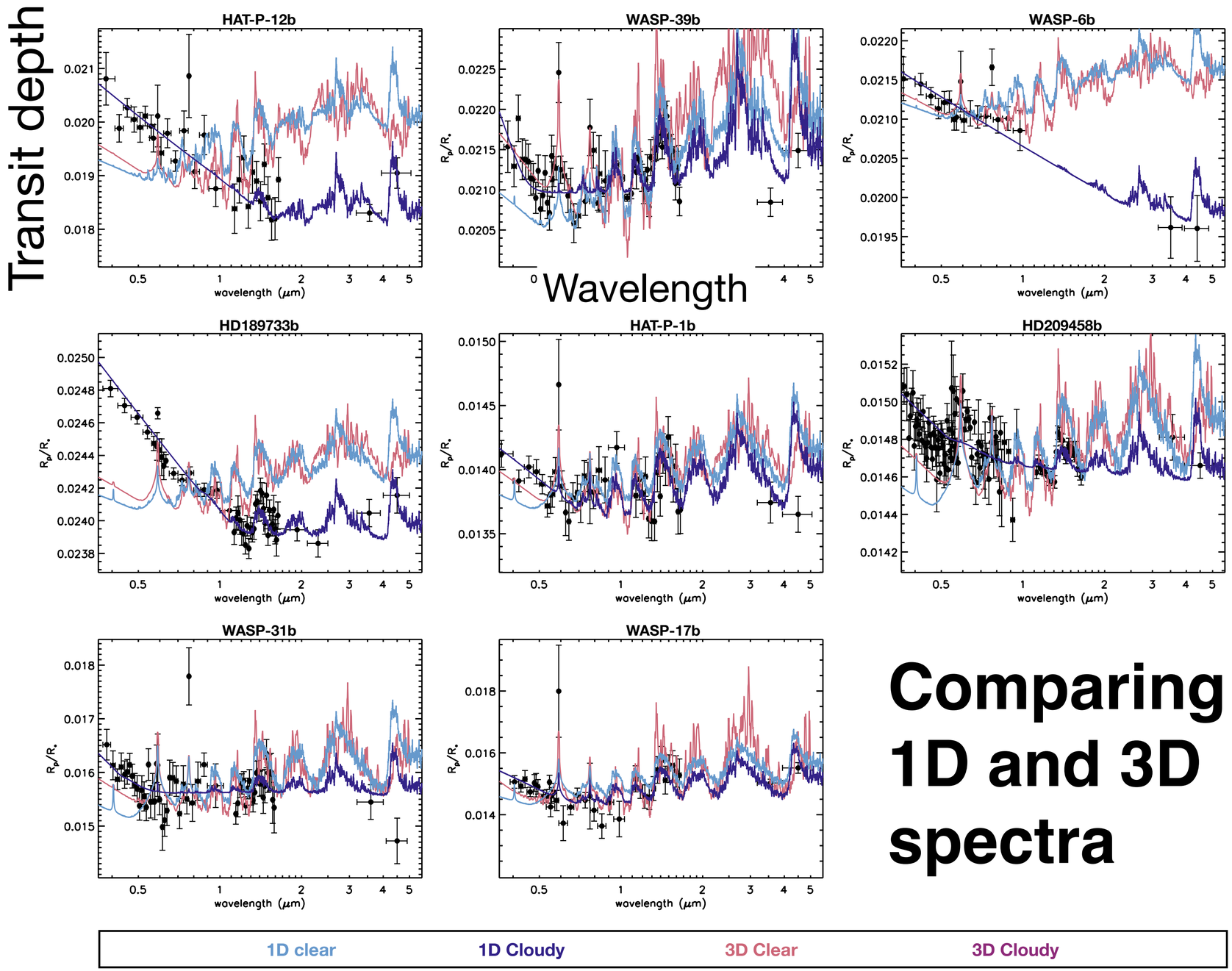
Kataria et al., in prep

Even within HJ population, many cloud species contribute opacity

Even without clouds, some marked differences between limb-averaged spectra

- Arise from differences in gas-phase opacity (Fortney et al. 2010)

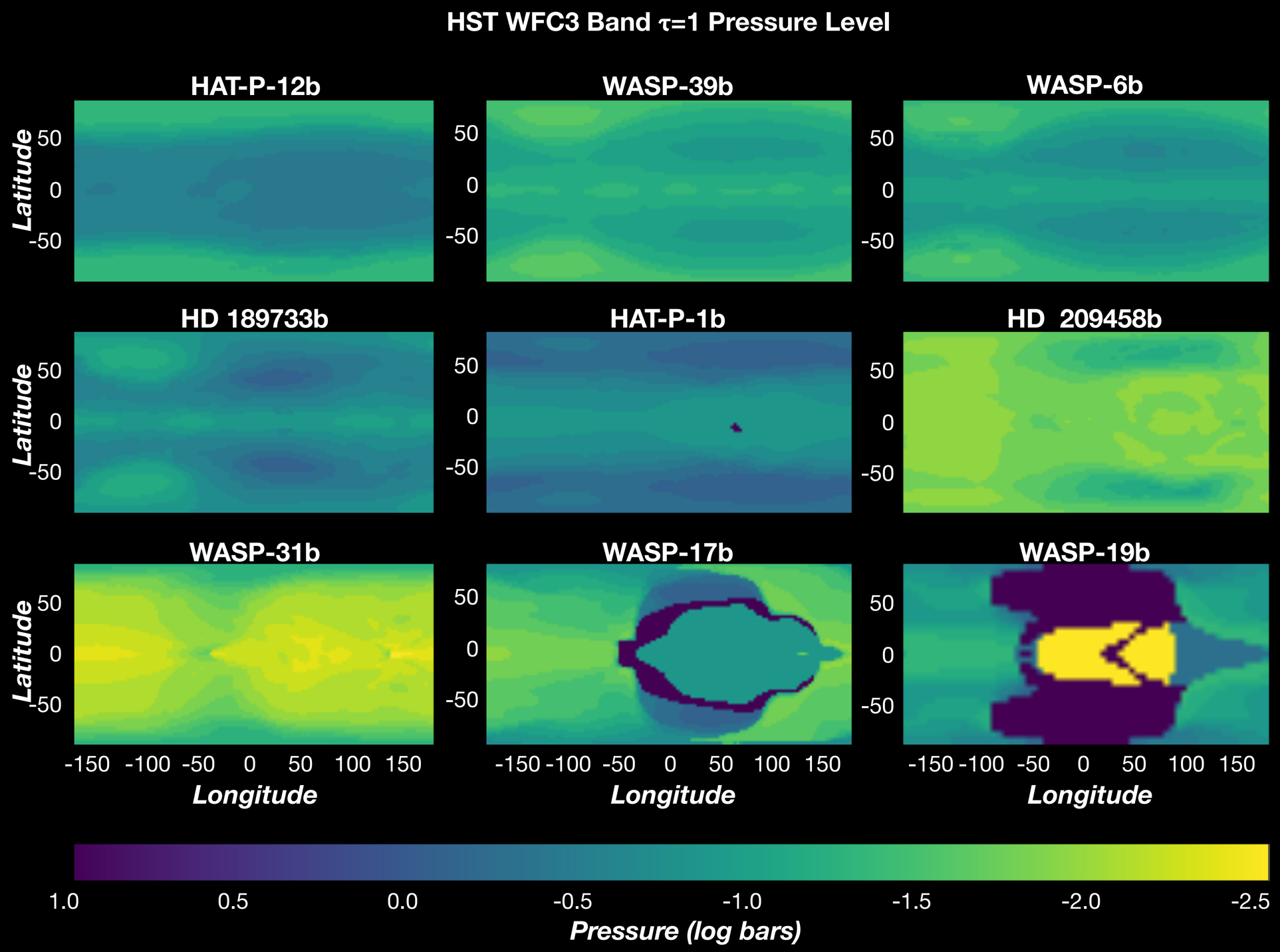




Comparing 1D and 3D spectra

Cloudy spectra provide better fits to data

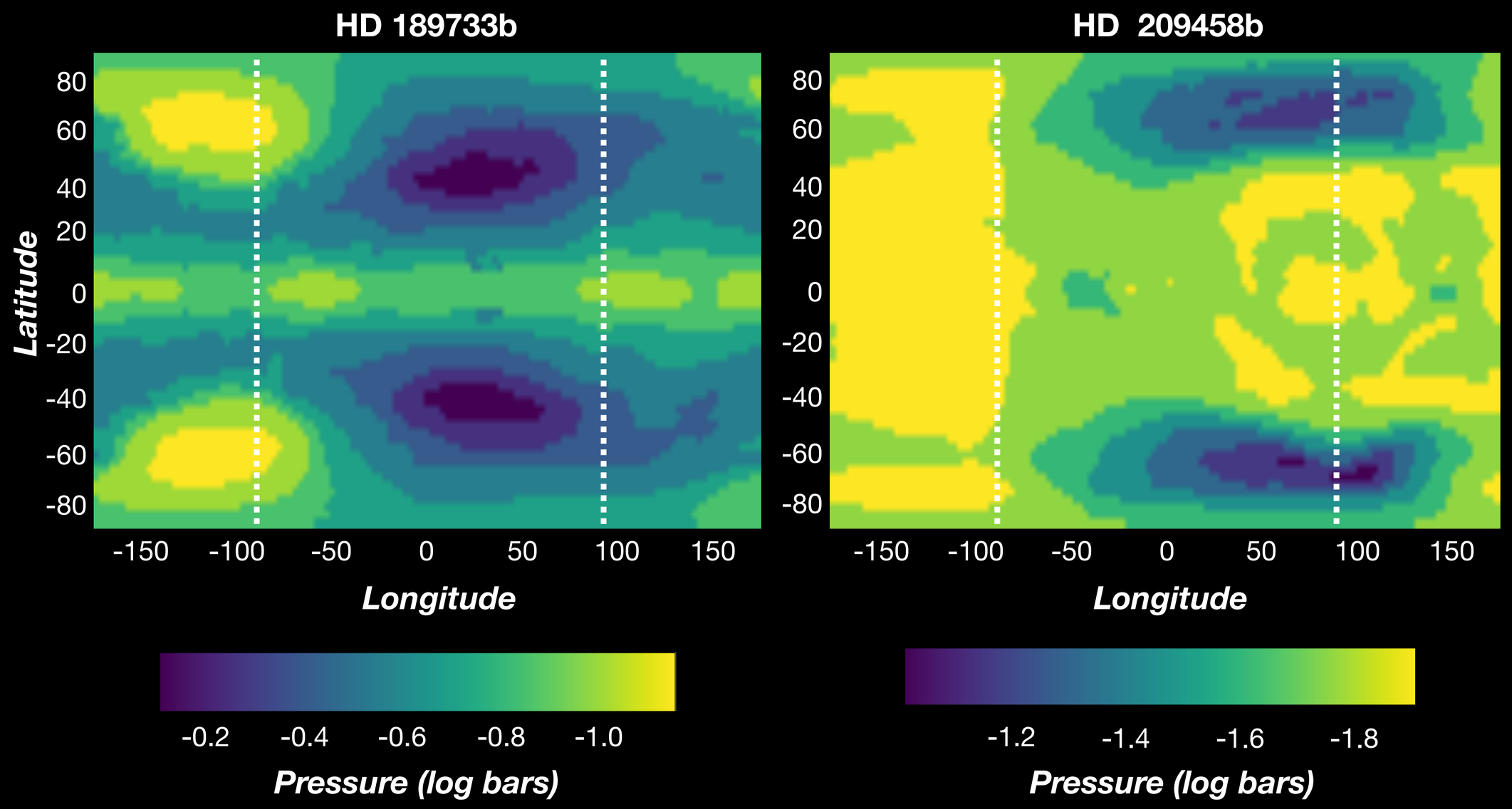
Kataria et al., in prep



Kataria et al., in prep

HST WFC3 Band τ=1 Pressure Level

Kataria et al., in prep



Conclusions

- Even within HJ population, many cloud species can contribute opacity
- Even for cloud-free spectra, spectral differences can emerge from gas-phase opacity
  - Likely tracks with limb-to-limb temperature differences —> dynamics
- Cloudy model spectra generally provide better fit to observations than clear model spectra in both 1D and 3D
- Multiple pressures can be accessed in a single observation
  - Spatial inhomogeneities will become especially important for future mapping efforts (e.g., eclipse mapping)

The SPARC Model

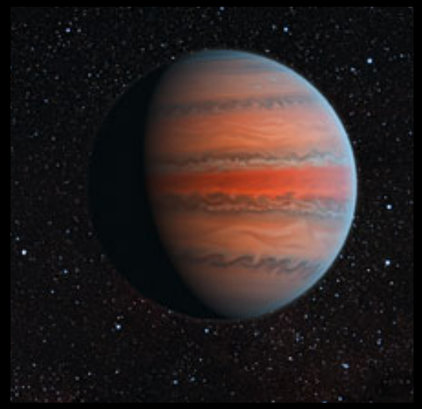
Substellar and Planetary Atmospheric Radiation and Circulation Model

Dynamics
Calculate wind speeds and temperatures given heating rates

Radiative Transfer
Solve for heating rates given pressure, temperature, and chemical abundances

Chemistry
Determine chemical abundances given chemical and dynamical timescales and overall atmospheric composition

The Three Musketeers

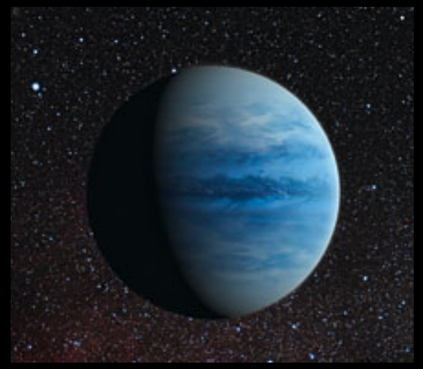


WASP-39b

$R_p = 1.27\ R_J$
$M_p = 0.28\ M_J$
$g = 4.07\ ms^{-2}$
$T_{orb} = 4.1$ d
$T_{eq} = 1110$ K
clear

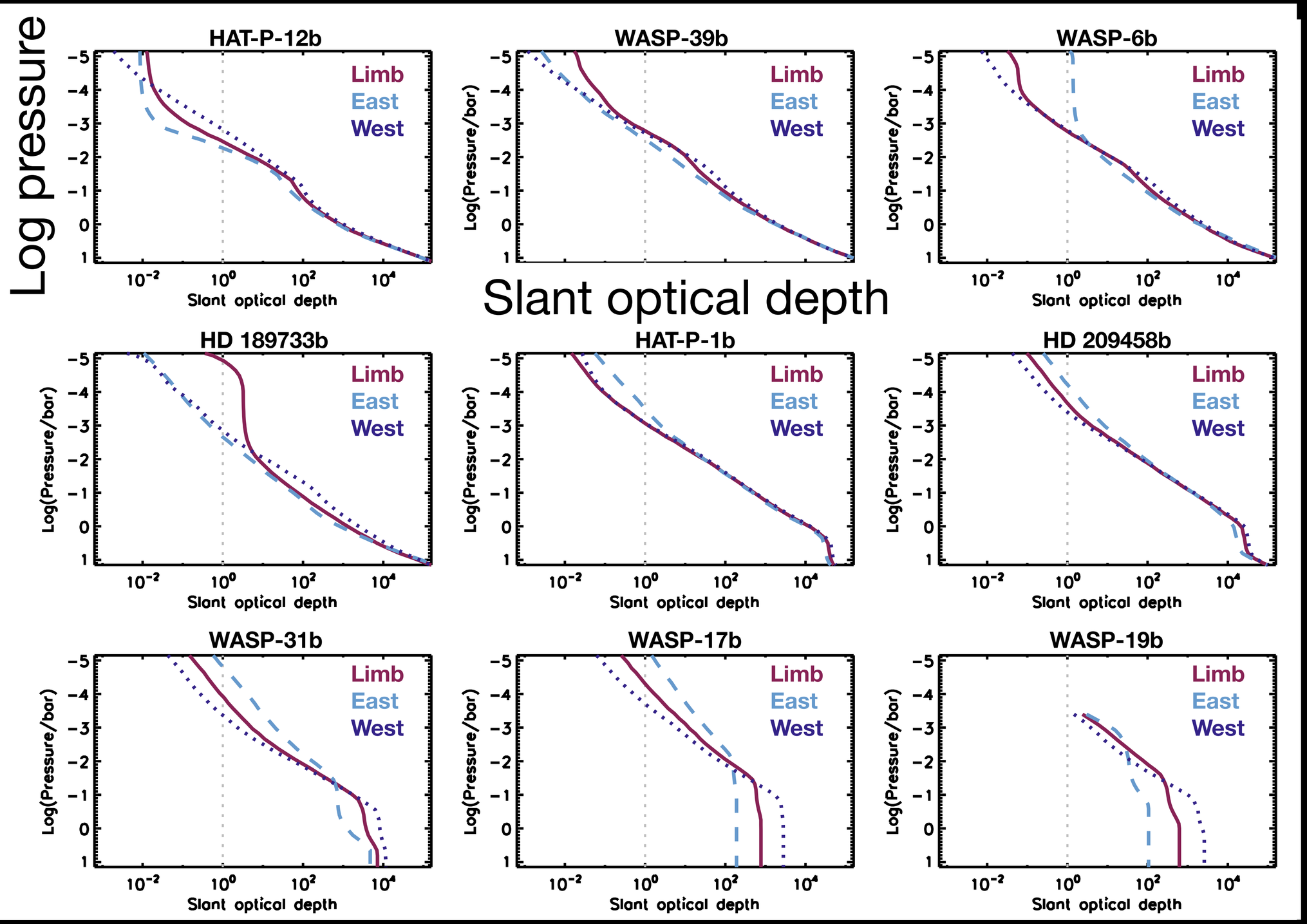
WASP-6b

$R_p = 1.22\ R_J$
$M_p = 0.50\ M_J$
$g = 8.71\ ms^{-2}$
$T_{orb} = 3.4$ d
$T_{eq} = 1145$ K
cloudy/hazy

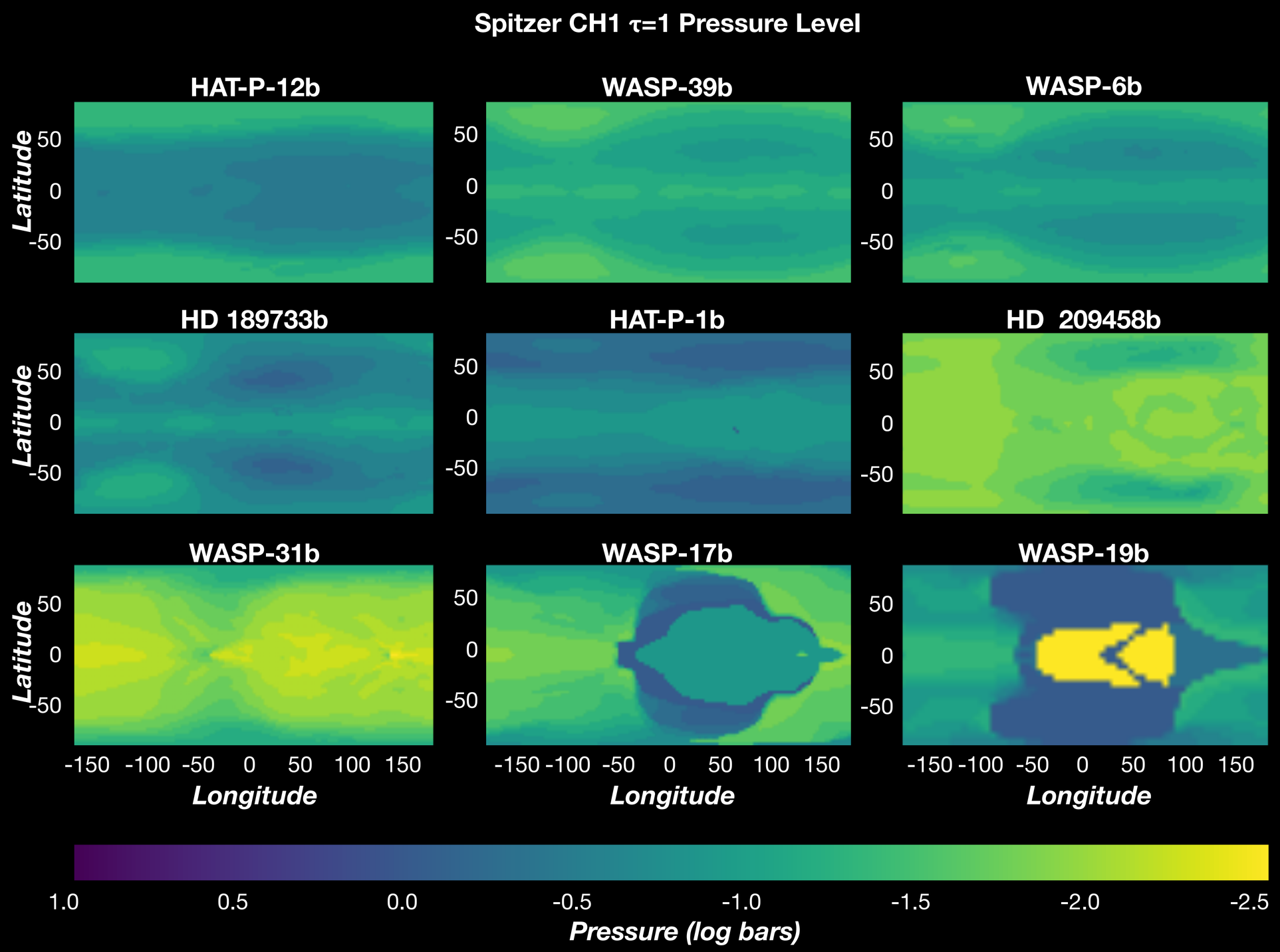


HD 189733b

$R_p = 1.14\ R_J$
$M_p = 1.14\ M_J$
$g = 21.4\ ms^{-2}$
$T_{orb} = 2.2$ d
$T_{eq} = 1201$ K
cloudy/hazy

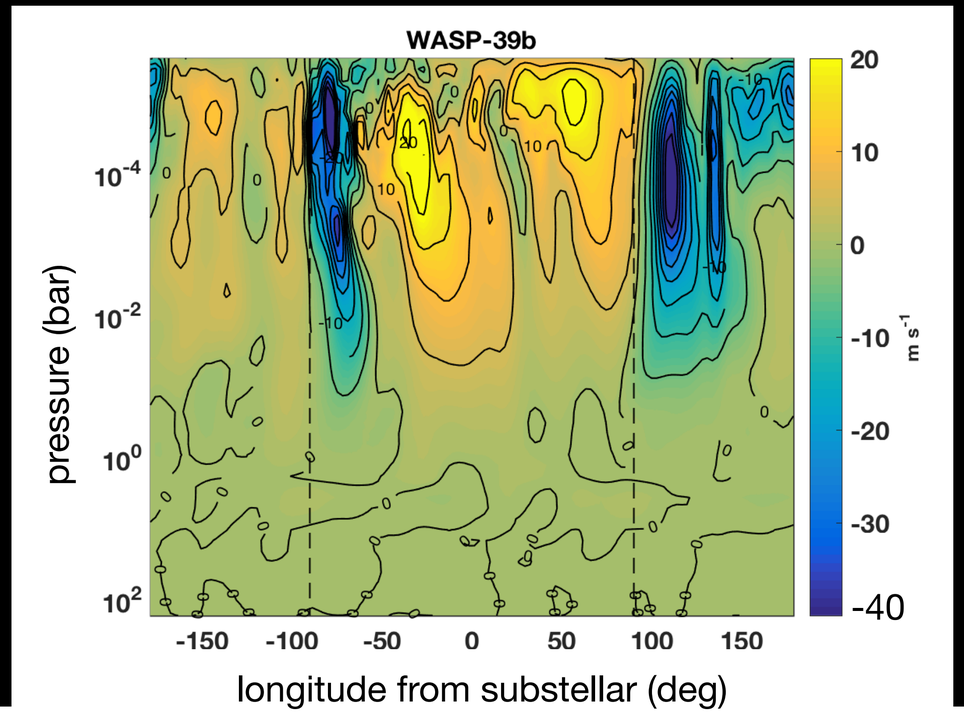


Kataria et al., in prep

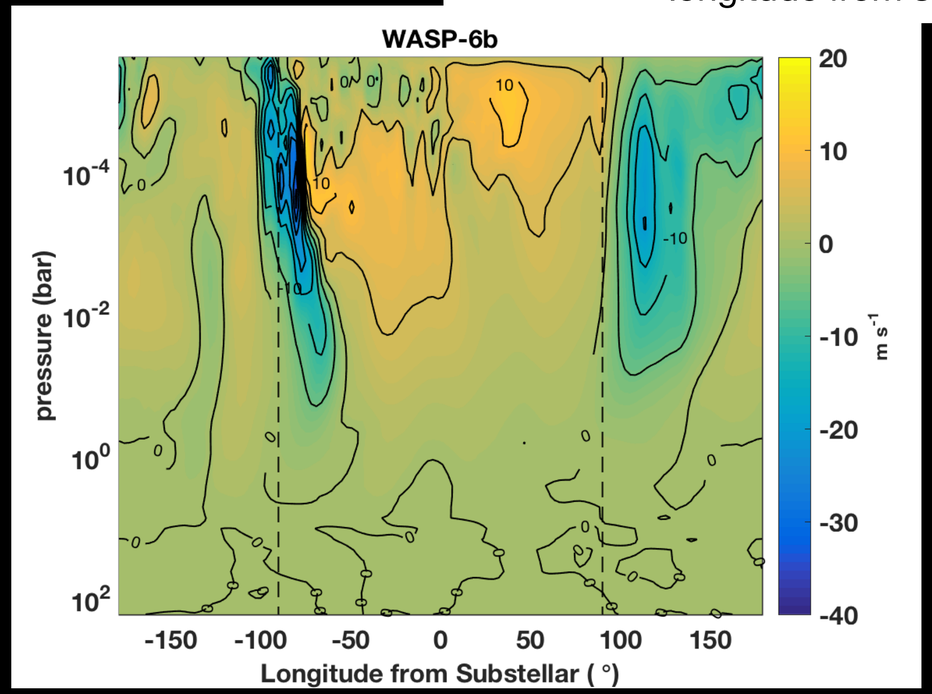


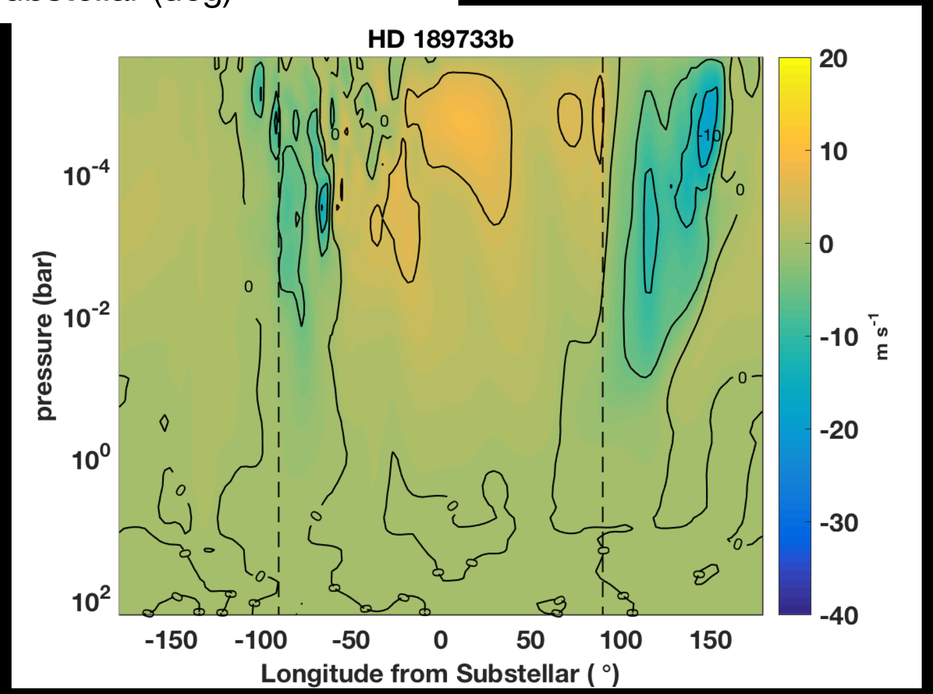
Kataria et al., in prep

Vertical velocity vs. longitude and pressure



positive = **upwelling**
negative = **downwelling**





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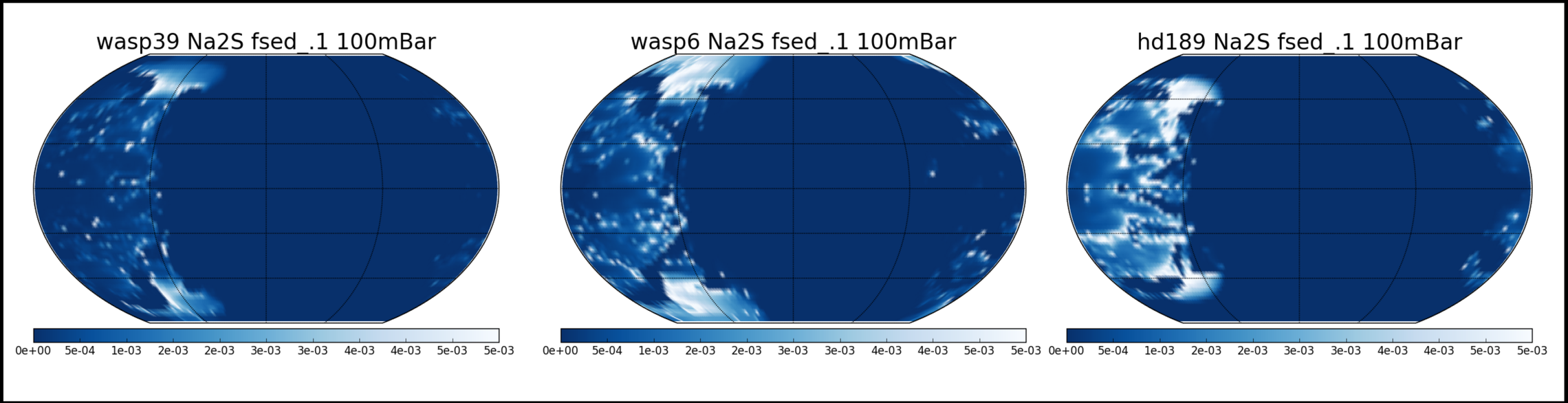
Mapping cloud optical depth

Na_2S clouds at 100 mbar, fsed = 0.1



Kataria, Wakeford, Batalha, Baldwin et al., in prep