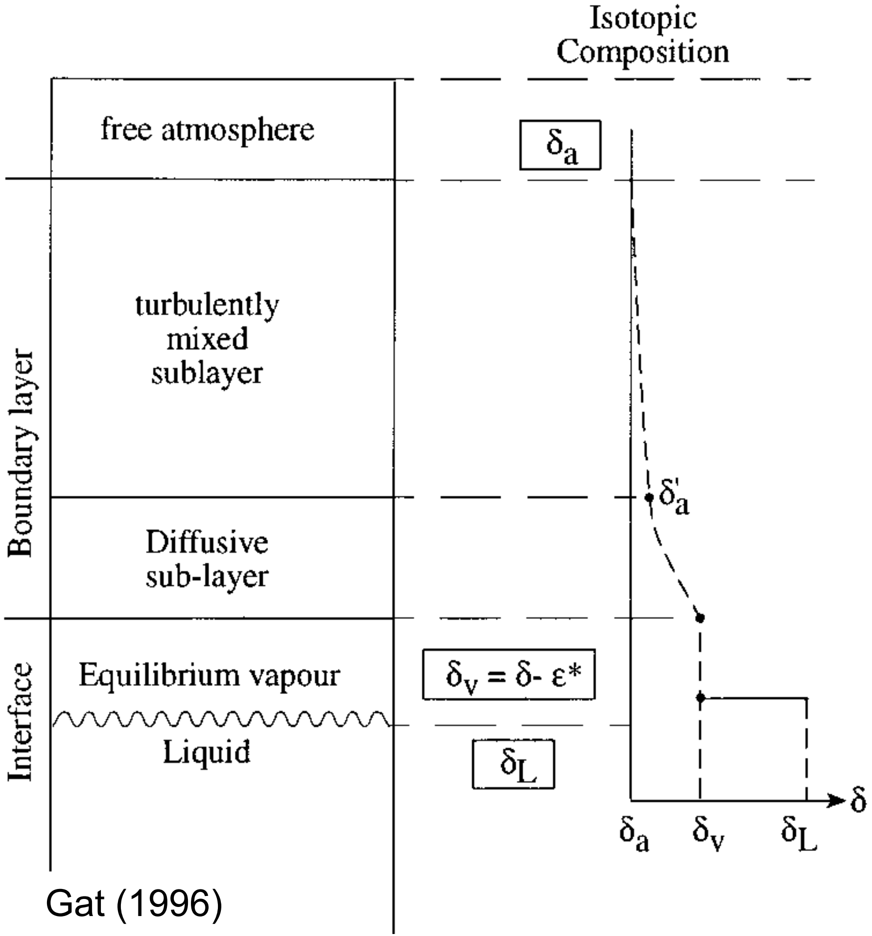
# A new theoretical framework for parameterizing nonequilibrium fractionation during evaporation from the ocean

Marina Dütsch[1], Christopher W. Fairall[2] , Peter N. Blossey[3]

[1]University of Vienna, Vienna, Austria
[2]National Oceanic and Atmospheric Administration, Boulder, CO, United States
[3]University of Washington, Seattle, WA, United States

# Isotopic fractionation during evaporation from the ocean



Gat (1996)

## Bulk formulas for evaporation flux

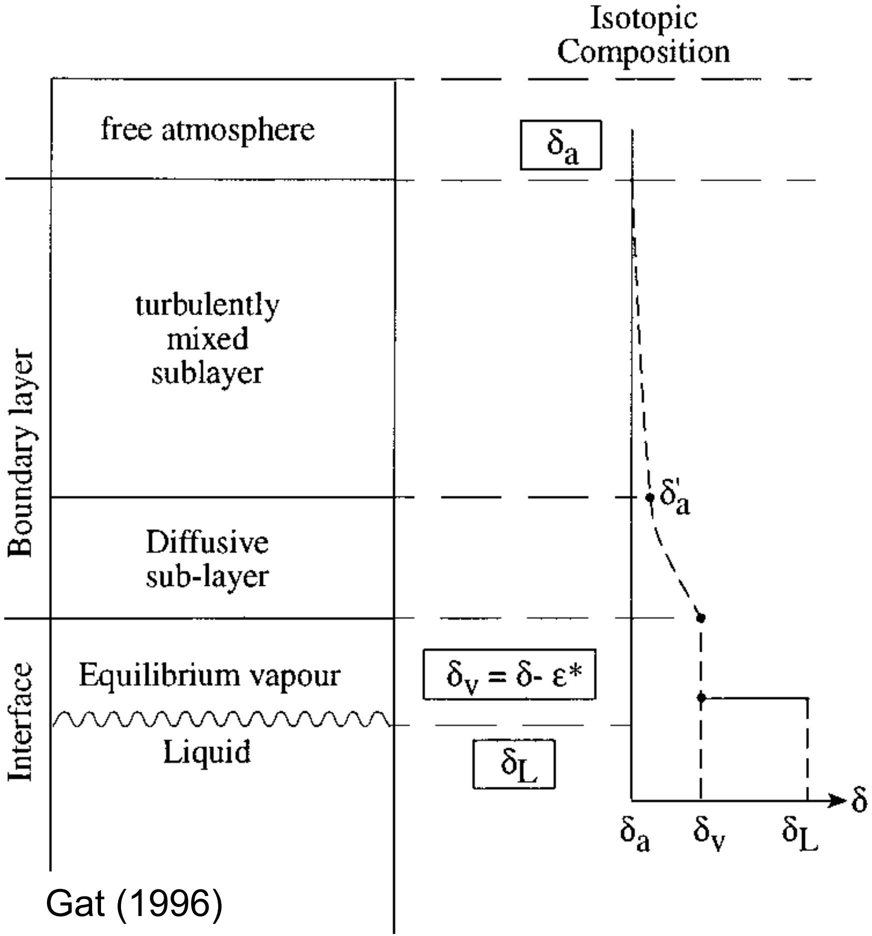
$$\overline{w'q'} = C_E U_{10}(q_s - q_{10}) \quad (1)$$

$$\overline{w'q'_{iso}} = C_{E,iso} U_{10}(\alpha_{eq} R_{oce} q_s - q_{10,iso}) \quad (2)$$

wind speed at 10m

moisture transfer coefficient

# Isotopic fractionation during evaporation from the ocean



Gat (1996)

## Bulk formulas for evaporation flux

$$\overline{w'q'} = C_E U_{10}(q_s - q_{10}) \quad (1)$$

$$\overline{w'q'_{iso}} = C_{E,iso} U_{10}(\alpha_{eq} R_{oce} q_s - q_{10,iso}) \quad (2)$$

wind speed at 10m

moisture transfer coefficient

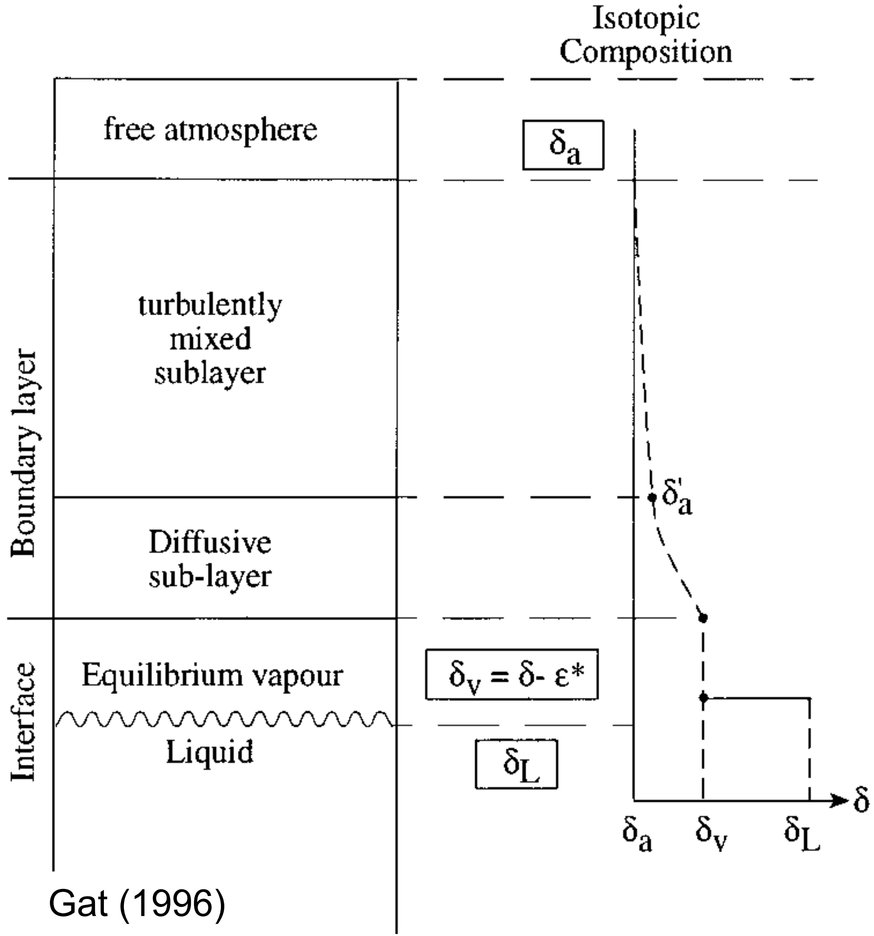
(2)/(1)

relative humidity with respect to saturation at the surface

$$R_e = \alpha_k \frac{\alpha_{eq} R_{oce} - h R_{atm}}{1 - h}$$

Craig & Gordon (1965)

# Isotopic fractionation during evaporation from the ocean



Gat (1996)

## Bulk formulas for evaporation flux

$$\overline{w'q'} = C_E U_{10}(q_s - q_{10}) \qquad (1)$$

$$\overline{w'q'_{iso}} = \underset{\uparrow}{C_{E,iso}}\,\underset{\uparrow}{U_{10}}(\alpha_{eq}R_{oce}q_s - q_{10,iso}) \qquad (2)$$

wind speed at 10m

moisture transfer coefficient

$$\Downarrow \; (2)/(1)$$

relative humidity with respect to saturation at the surface

$$R_e = \underset{\overset{\uparrow}{\frac{C_{E,iso}}{C_E}}}{\alpha_k}\frac{\alpha_{eq}R_{oce} - hR_{atm}}{1-h}$$

Craig & Gordon (1965)

# Wind-speed dependent parameterization of $k_{iso}$ (and especially the discontinuity) is not in line with observations

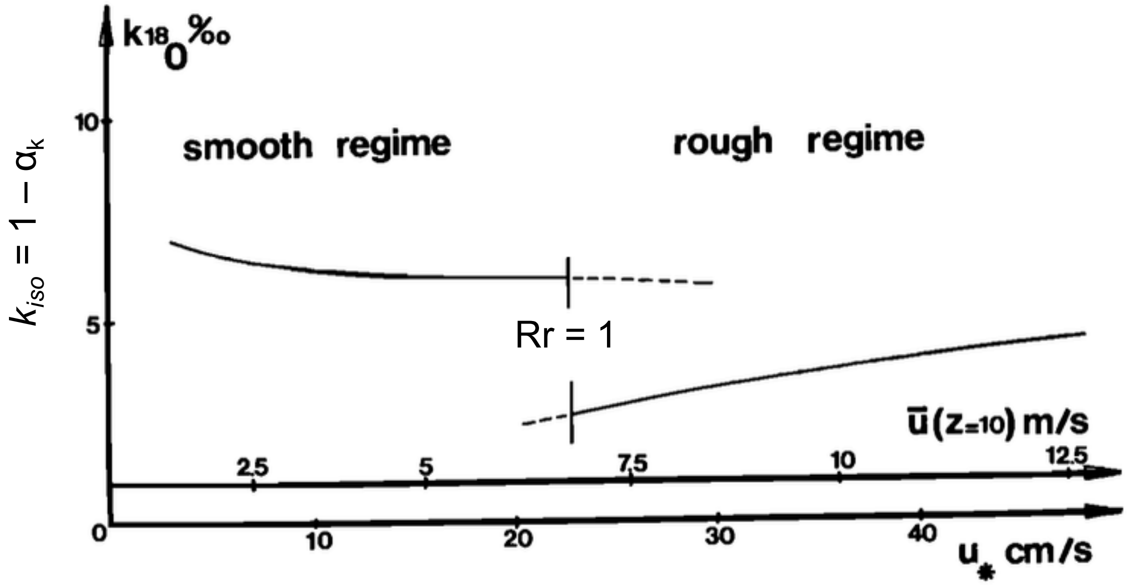
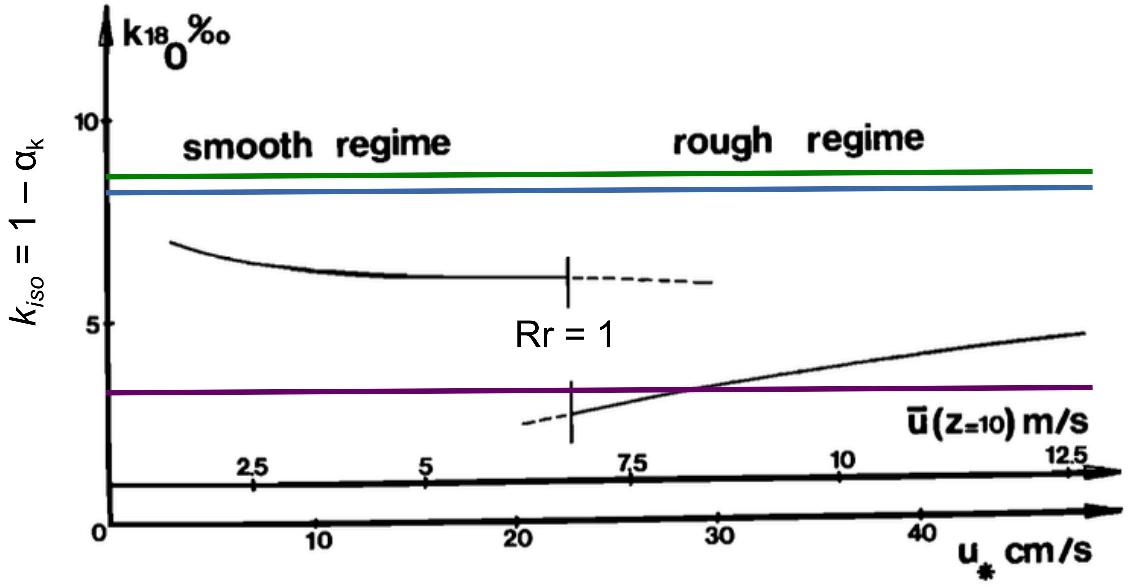


Fig. 2. Variation of the kinetic fractionation factor for oxygen 18, $k_{^{18}O}$, with the friction velocity or the mean wind speed at $z = 10$ m.

Merlivat & Jouzel (1979)

# Wind-speed dependent parameterization of $k_{iso}$ (and especially the discontinuity) is not in line with observations



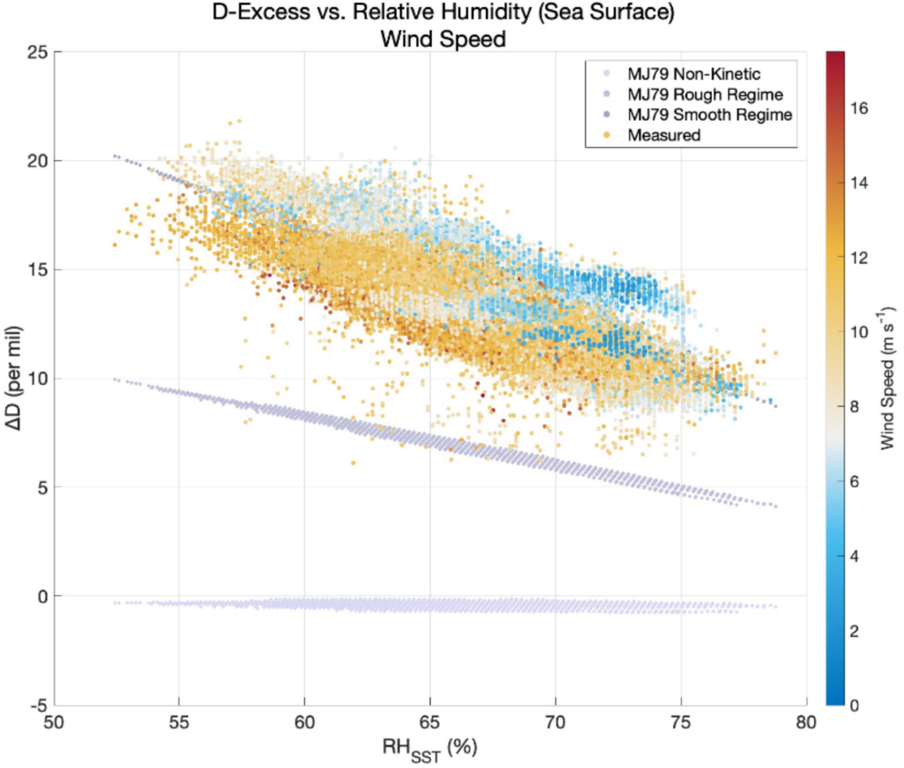
$k_{H218O}$ = 7.9‰ (Uemura et al., 2010)
$k_{H218O}$ = 7.5‰ (Pfahl & Wernli, 2009)

$k_{H218O}$ = 3.4‰ (Bonne et al., 2019)

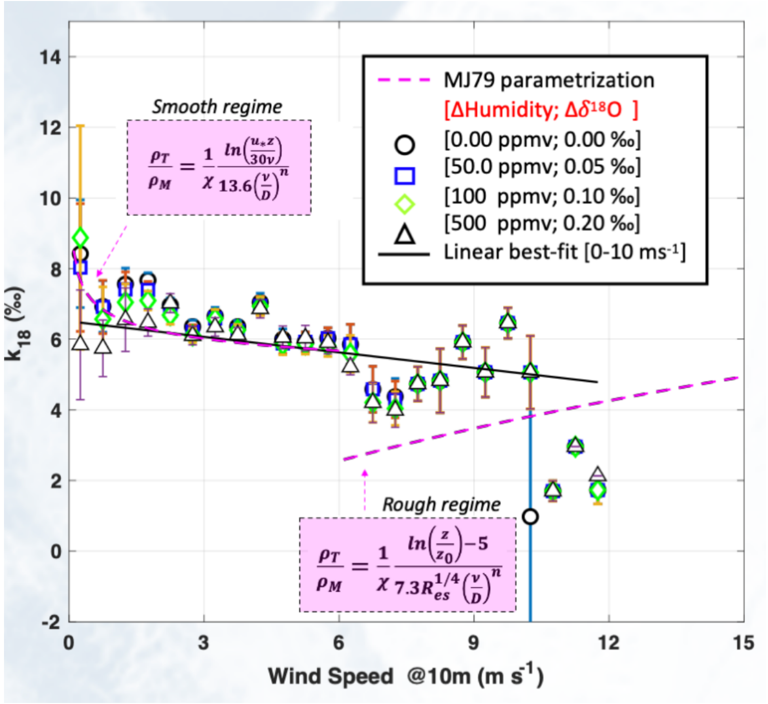
Fig. 2. Variation of the kinetic fractionation factor for oxygen 18, $k_{^{18}O}$, with the friction velocity or the mean wind speed at $z = 10$ m.

Merlivat & Jouzel (1979)

# Measured vapor isotopes match better with smooth regime parameterization



Tuesday Poster by Sebastian Los (Poster #7)



Wednesday Poster by Daniele Zannoni (Poster #9)

# A new theoretical framework for parameterizing $k_{iso}$

Steps:

1) Deduce the friction velocity based on wind speed
2) Use the momentum flux equation to derive the eddy viscosity profile and the fraction of momentum flux carried by waves at the surface
3) Use the resulting eddy diffusivity profile in the scalar flux equation, along with a component of the scalar flux associated with waves
4) Use this equation to derive the scalar transfer coefficient $C_x$ ,which depends explicitly on the scalar diffusivity.

# Momentum flux equation over a wall

kinematic viscosity

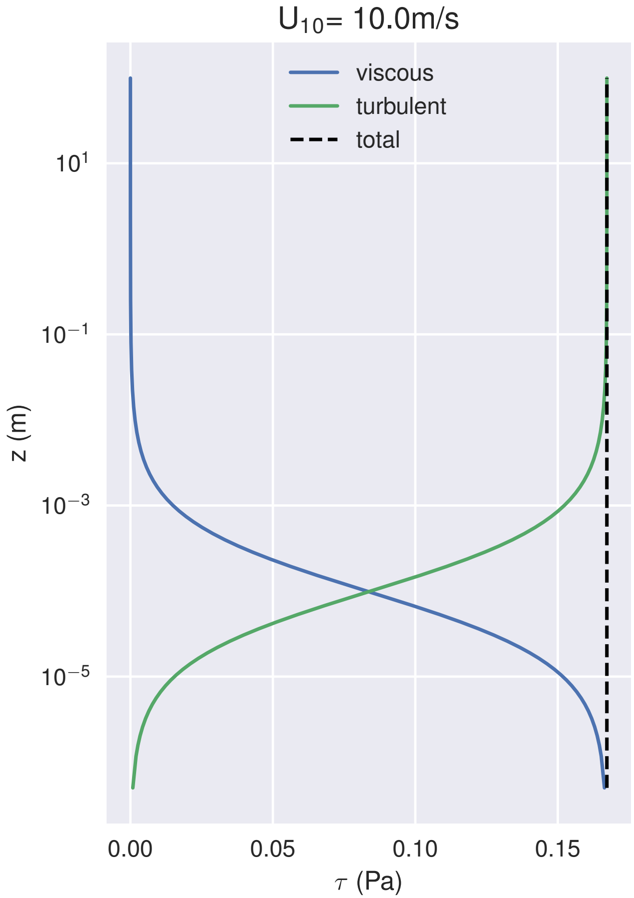
$$\overline{u'w'} = u_*^2 = \nu \frac{\partial U}{\partial z} + K_m \frac{\partial U}{\partial z}$$

friction velocity    eddy viscosity

$$K_m = \kappa u_* z$$

von Karman constant ($\kappa$=0.4)

$$\rightarrow \quad \frac{\partial U}{\partial z} = \frac{u_*^2}{\nu + K_m}$$



# Momentum flux equation with wave component

Cifuentes-Lorenzen et al. (2018)

momentum carried by waves

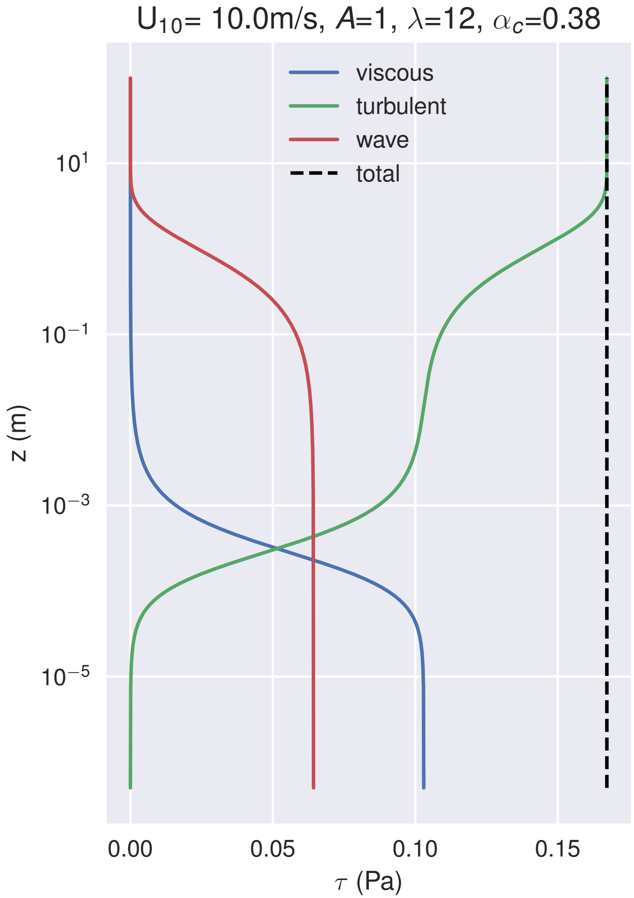
$$\overline{u'w'} = u_*^2 = \nu \frac{\partial U}{\partial z} + K_m \frac{\partial U}{\partial z} + \alpha_c u_*^2 e^{-Az}$$

$$K_m = \frac{\kappa u_* z \sqrt{1 - \alpha_c e^{-Az}}}{1 + (\delta/z)^m}$$

loss of friction velocity due to waves

falloff of turbulence close to the surface

$$\rightarrow \quad \frac{\partial U}{\partial z} = \frac{u_*^2 (1 - \alpha_c e^{-Az})}{\nu + K_m}$$


$U_{10}$= 10.0m/s, $A$=1, $\lambda$=12, $\alpha_c$=0.38

$A$ [m$^{-1}$]
inverse wave height

$\lambda$
sublayer height
$(\delta = \lambda\nu/u_*)$

$\alpha_c$
fraction of momentum carried by waves

# Momentum flux equation with wave component

Cifuentes-Lorenzen et al. (2018)

momentum carried by waves

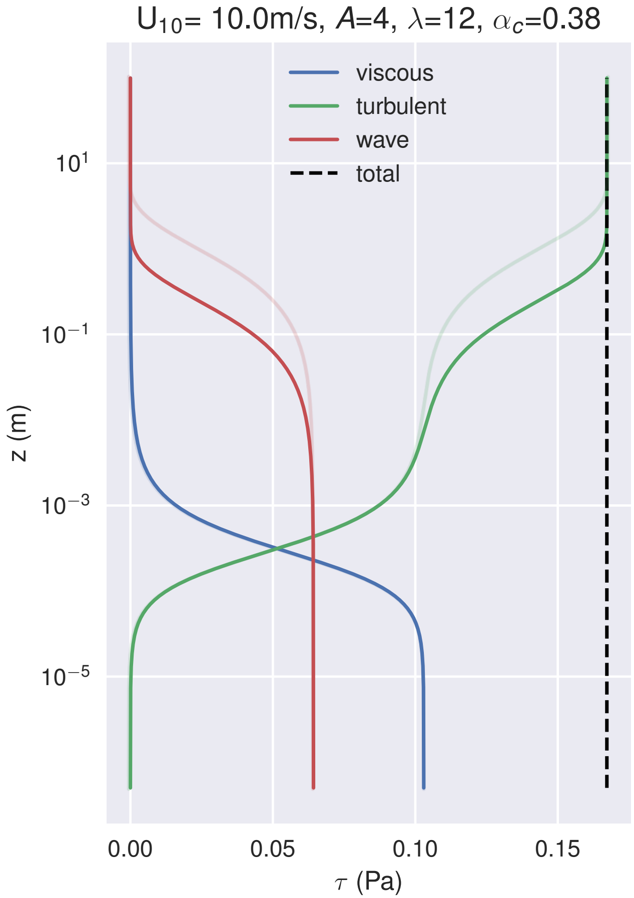
$$\overline{u'w'} = u_*^2 = \nu \frac{\partial U}{\partial z} + K_m \frac{\partial U}{\partial z} + \alpha_c u_*^2 e^{-Az}$$

$$K_m = \frac{\kappa u_* z \sqrt{1 - \alpha_c e^{-Az}}}{1 + (\delta/z)^m}$$

loss of friction velocity due to waves

falloff of turbulence close to the surface

$$\rightarrow \quad \frac{\partial U}{\partial z} = \frac{u_*^2 (1 - \alpha_c e^{-Az})}{\nu + K_m}$$



**$A$ [m$^{-1}$]**
**inverse wave height**

$\lambda$
sublayer height
$(\delta = \lambda \nu / u_*)$

$\alpha_c$
fraction of momentum carried by waves

# Momentum flux equation with wave component

Cifuentes-Lorenzen et al. (2018)

momentum carried by waves

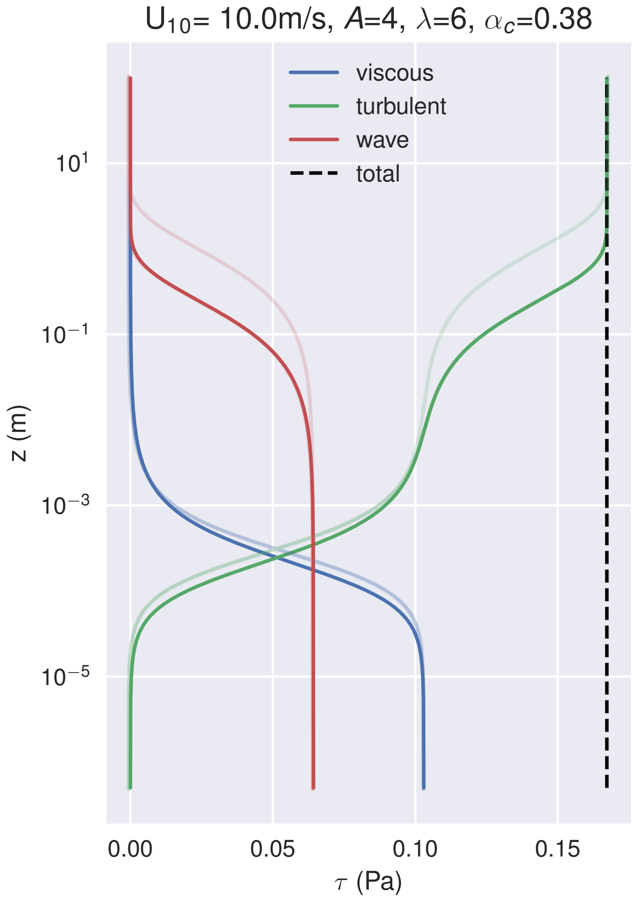
$$\overline{u'w'} = u_*^2 = \nu\frac{\partial U}{\partial z} + K_m\frac{\partial U}{\partial z} + \alpha_c u_*^2 e^{-Az}$$

$$K_m = \frac{\kappa u_* z\sqrt{1-\alpha_c e^{-Az}}}{1+(\delta/z)^m} \leftarrow$$

loss of friction velocity due to waves

falloff of turbulence close to the surface

$$\rightarrow \quad \frac{\partial U}{\partial z} = \frac{u_*^2(1-\alpha_c e^{-Az})}{\nu + K_m}$$



$A$ [m$^{-1}$]
inverse wave height

**$\lambda$**
**sublayer height**
**($\delta = \lambda\nu/u_*$)**

$\alpha_c$
fraction of momentum carried by waves

# Momentum flux equation with wave component

Cifuentes-Lorenzen et al. (2018)

momentum carried by waves

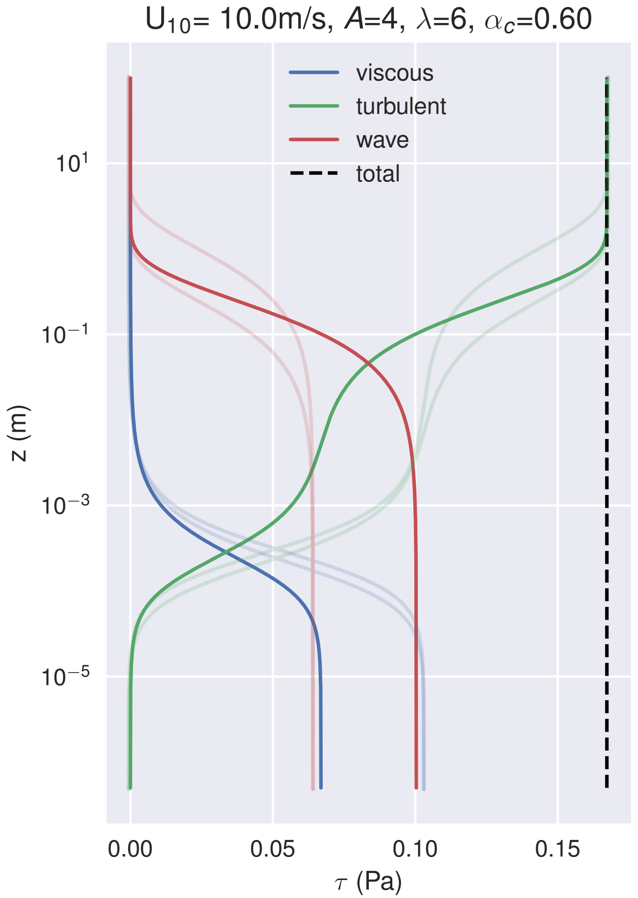
$$\overline{u'w'} = u_*^2 = \nu\frac{\partial U}{\partial z} + K_m\frac{\partial U}{\partial z} + \alpha_c u_*^2 e^{-Az}$$

$$K_m = \frac{\kappa u_* z\sqrt{1-\alpha_c e^{-Az}}}{1+(\delta/z)^m}$$

← loss of friction velocity due to waves

falloff of turbulence close to the surface

$$\rightarrow \quad \frac{\partial U}{\partial z} = \frac{u_*^2(1-\alpha_c e^{-Az})}{\nu + K_m}$$



$A$ [m$^{-1}$]
inverse wave height

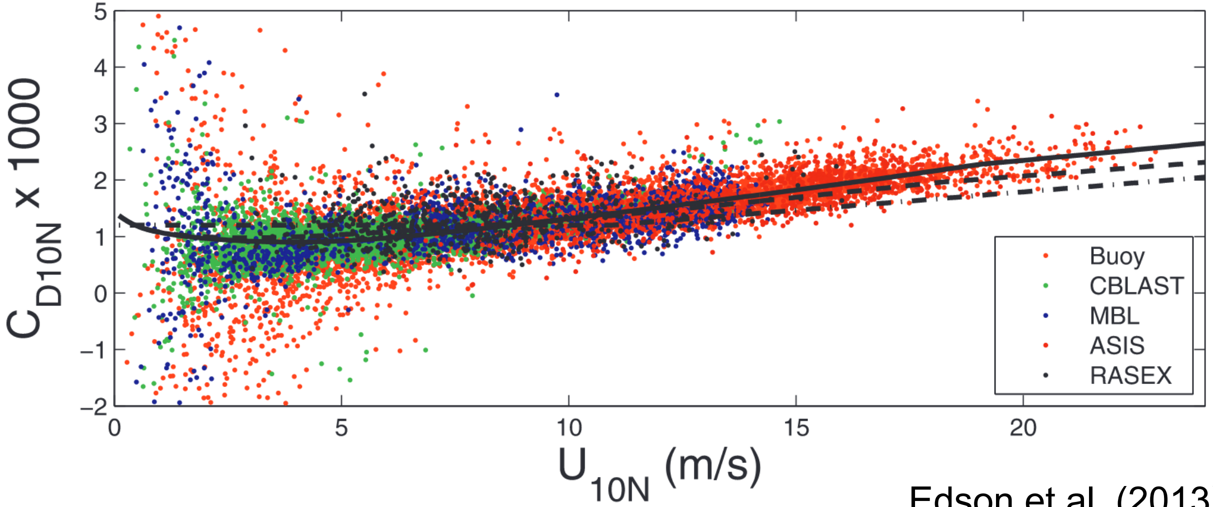
$\lambda$
sublayer height
$(\delta = \lambda\nu/u_*)$

$\boldsymbol{\alpha_c}$
**fraction of momentum carried by waves**

# Assumptions

- $\lambda = 12$ (Reichhardt, 1951)
- $A = 1m^{-1}$
- $m = 1$

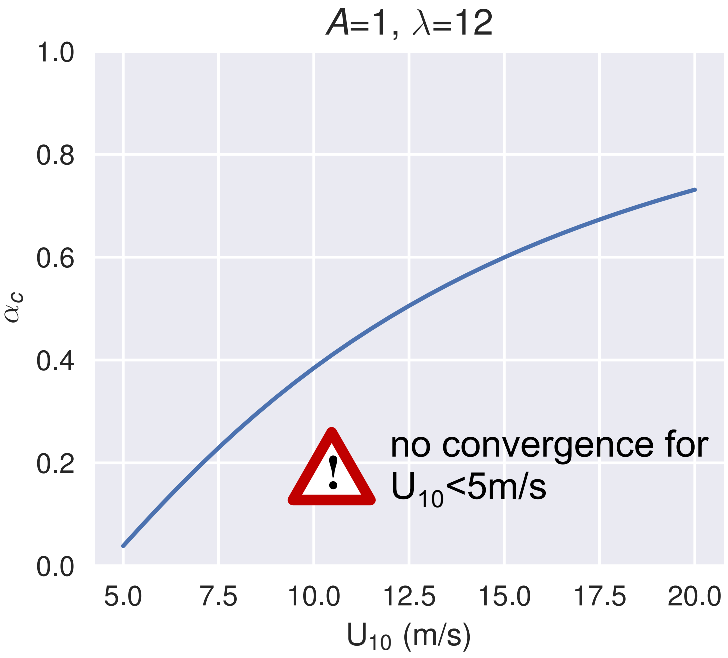
- $C_D = \frac{1.03 \cdot 10^{-3} + 0.04 \cdot 10^{-3} \cdot {U_{10}}^{1.48}}{{U_{10}}^{0.21}}$ → $u_* = \sqrt{C_D} \cdot U_{10}$



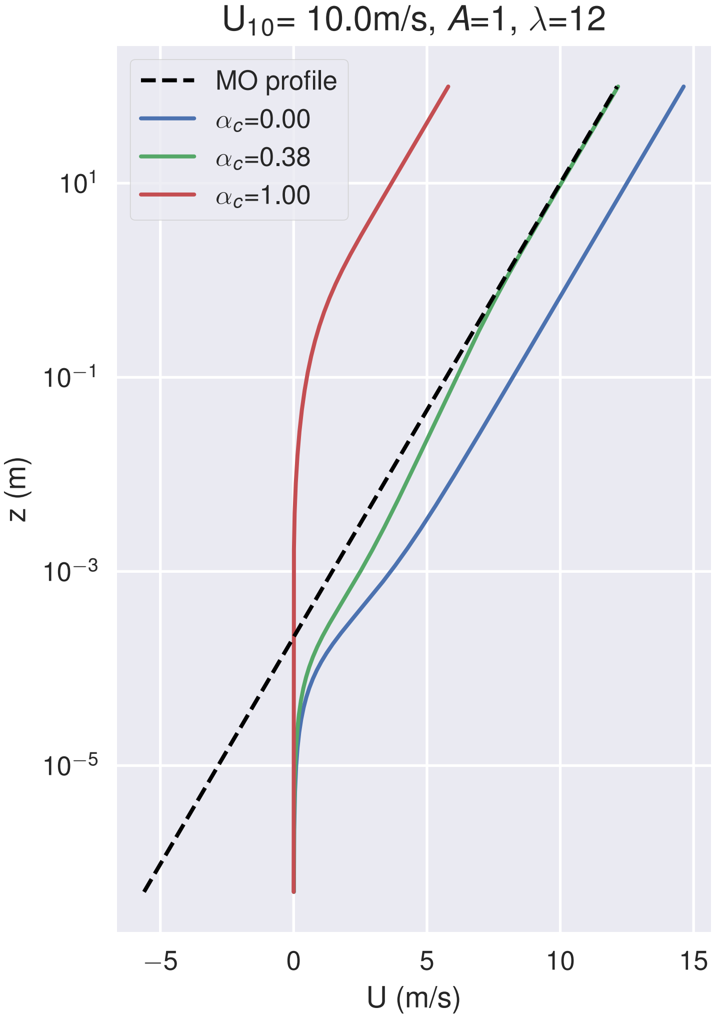
Edson et al. (2013)

# Finding $\alpha_c$

- Solve root-finding problem to determine $\alpha_c$ for which $U(z=10m) = U_{10}$
- Result: $\alpha_c$ increases with wind speed



no convergence for $U_{10}$<5m/s



# Scalar (/water isotope) flux equation

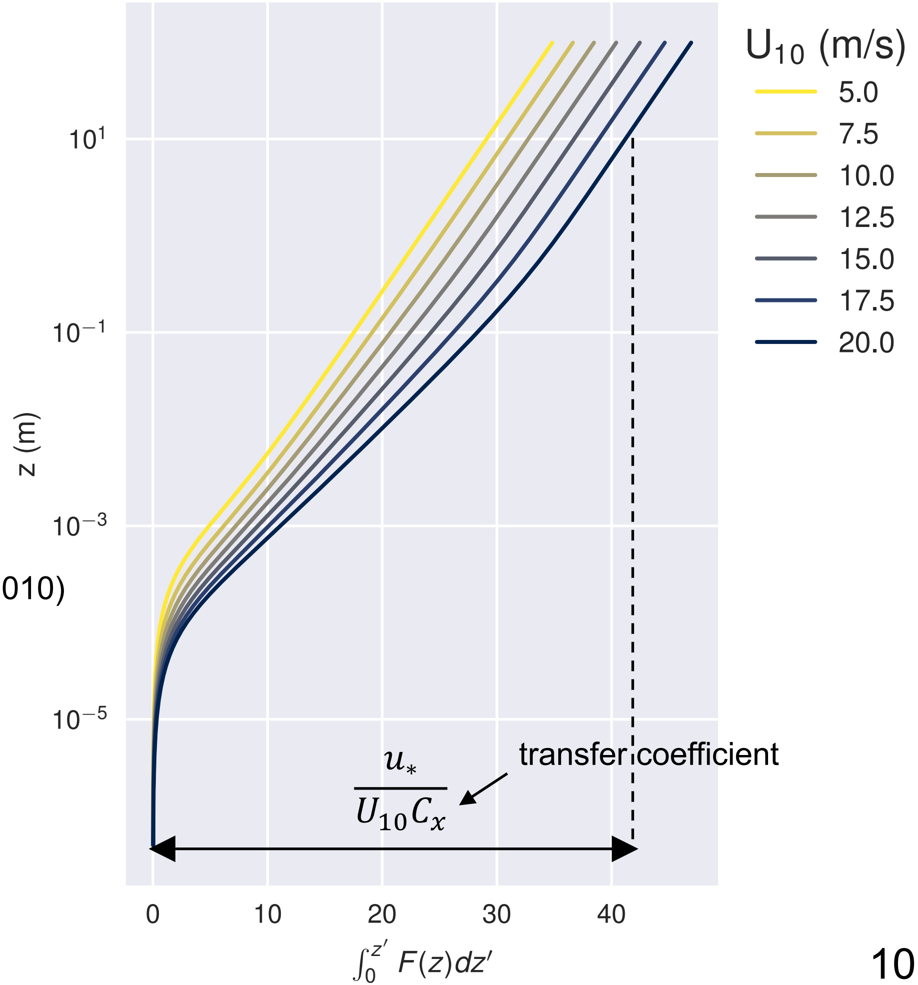
$$\overline{w'x'} = -u_* x_* = -\frac{\nu}{S_x}\frac{\partial X}{\partial z} - \frac{K_m}{S_t}\frac{\partial X}{\partial z} - \alpha_h u_* x_* e^{-Az}$$

turbulent Schmidt number ($S_t = 1$)

molecular Schmidt number ($S_x = \nu/D$)

$\alpha_h = 0.3 \cdot \alpha_c$ wave-coherent scalar flux (Mueller and Veron, 2010)

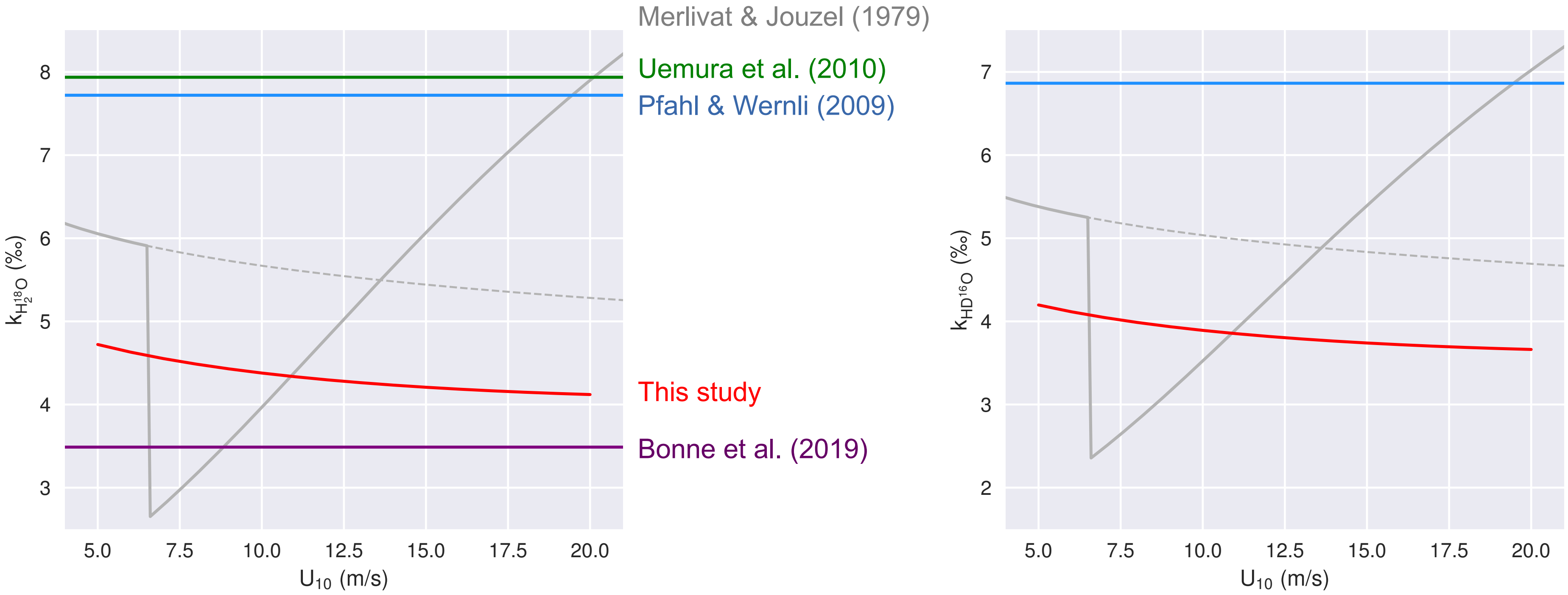
→ $$\frac{\partial X}{\partial z} = \frac{u_* x_* \left(1 - \alpha_h e^{-Az}\right)}{\nu/S_x + K_m/S_t} = x_* F(z)$$



# Result: weak dependence of $k_{iso}$ on wind speed

$$k_{\mathrm{H_2^{18}O}} = 1 - \frac{C_{\mathrm{H_2^{18}O}}}{C_{\mathrm{H_2^{16}O}}}$$

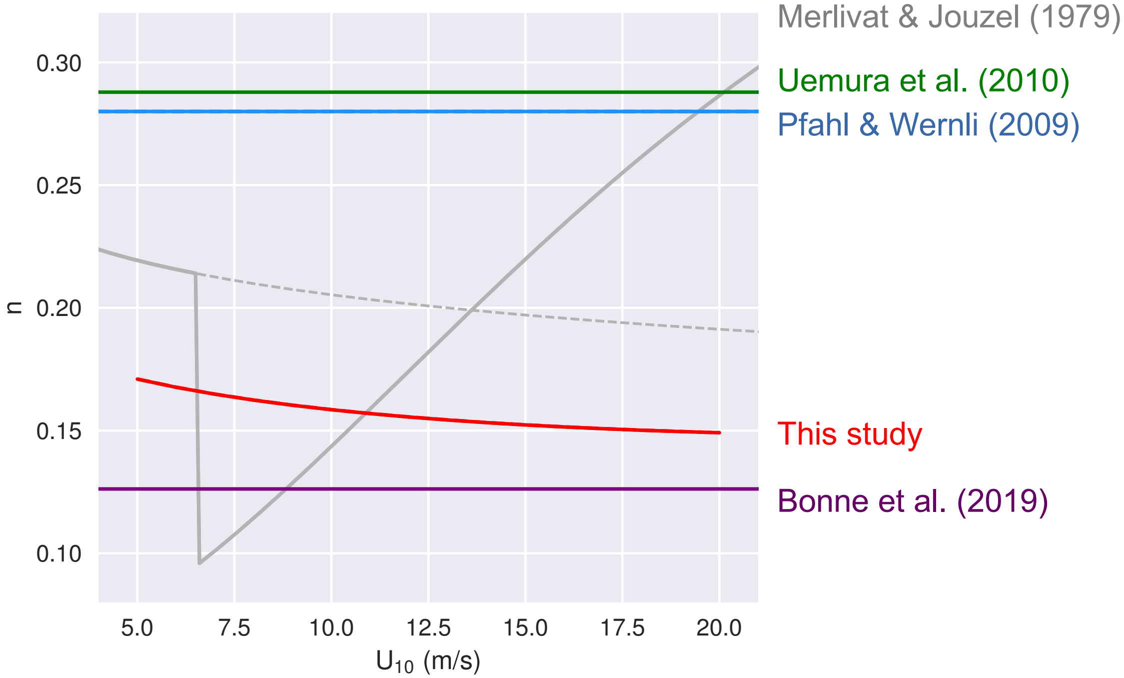
$$k_{\mathrm{HD^{16}O}} = 1 - \frac{C_{\mathrm{HD^{16}O}}}{C_{\mathrm{H_2^{16}O}}}$$



Diffusivities from Merlivat (1978)

# Result: weak dependence of *n* on wind speed

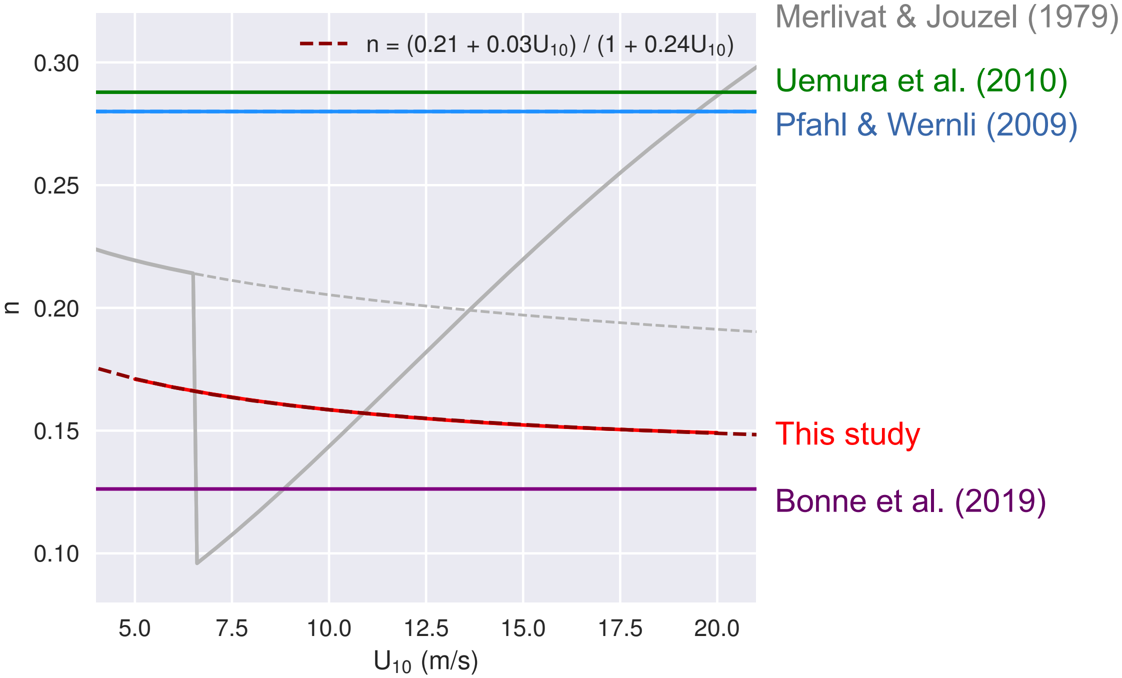
$$1 - k_{iso} = \left(\frac{D_{iso}}{D_{H_2^{16}O}}\right)^n$$



Diffusivities from Merlivat (1978)

# Result: weak dependence of *n* on wind speed

$$1 - k_{iso} = \left( \frac{D_{iso}}{D_{\mathrm{H}_2^{16}\mathrm{O}}} \right)^n$$



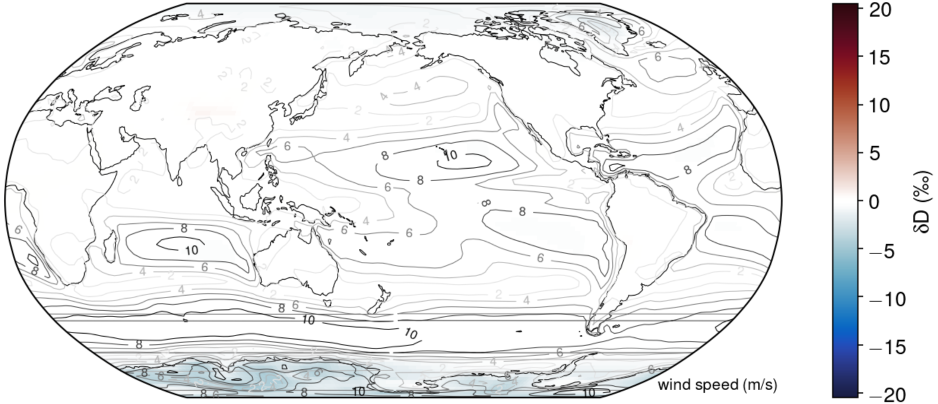
Diffusivities from Merlivat (1978)

# iCAM5 simulations

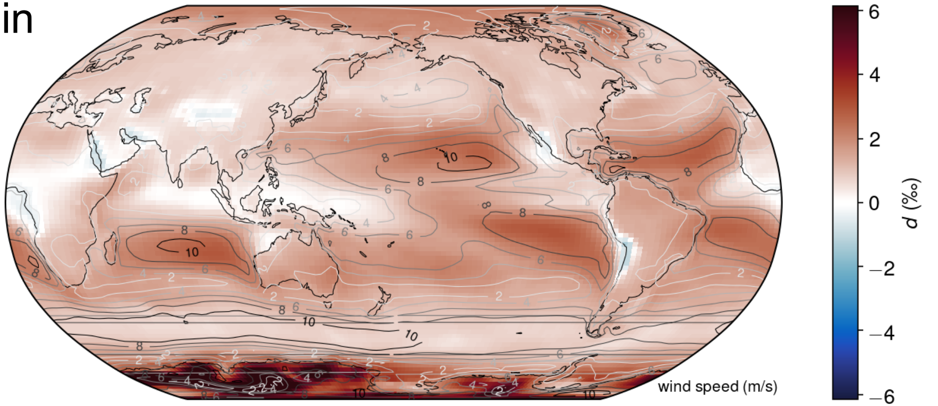
Nusbaumer et al. (2017)

- 2 year free-running simulations (1 year spin-up)
- 2.5°x1.9° horizontal resolution
- 30 vertical levels

Vapor isotope ratios at lowest model level (wave – control)



Higher d-excess in simulation with new scheme



Next step: nudged simulations

# Summary

- We developed a new framework for parameterizing nonequilibrium fractionation during evaporation from the ocean, which explicitly accounts for waves.

- The new scheme simulates a slight decrease in the strength of nonequilibrium fractionation with wind speed, similar to the smooth regime parameterization by Merlivat & Jouzel (1979).

- This is in line with measurements of vapor isotopes in the near-surface boundary layer (e.g., Pfahl & Wernli, 2009; Uemura et al., 2010; Steen-Larsen et al., 2014; Bonne et al., 2019; Posters by Sebastian Los and Daniele Zannoni).