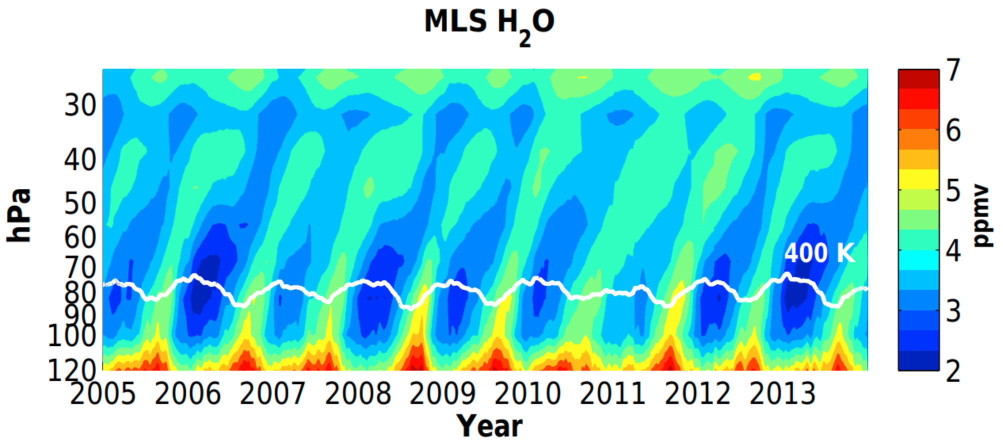
Quantifying turbulence in the tropical UTLS and its impact on transport using HVRR

Aurélien Podglajen[1*], **Rachel Atlas**[1], Richard Wilson[2]

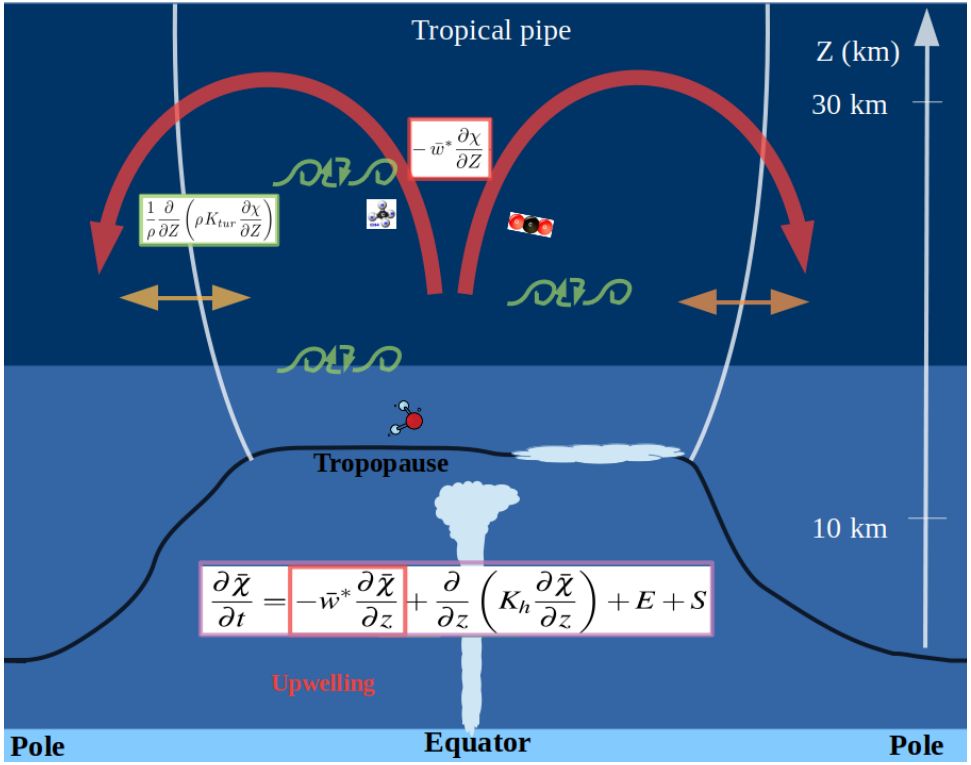
1 : LMD/IPSL, Paris, France
2 : LATMOS/IPSL, Paris, France
* : aurelien.podglajen@lmd.ipsl.fr

Motivation : Transport in the tropical UTLS



Mote et al., 1996 ; *Glanville and Birner*, 2017

- In the troposphere, convective transport (convective detrainment and radiative subsidence)
- In the UT and stratosphere (above the LZRH), slow, radiatively-driven upwelling associated with the Brewer-Dobson circulation
- Relative isolation from the extra tropics (tropical leaky pipe)
- The impact of turbulent mixing and diffusion is poorly constrained



Motivation : Transport in the tropical UTLS

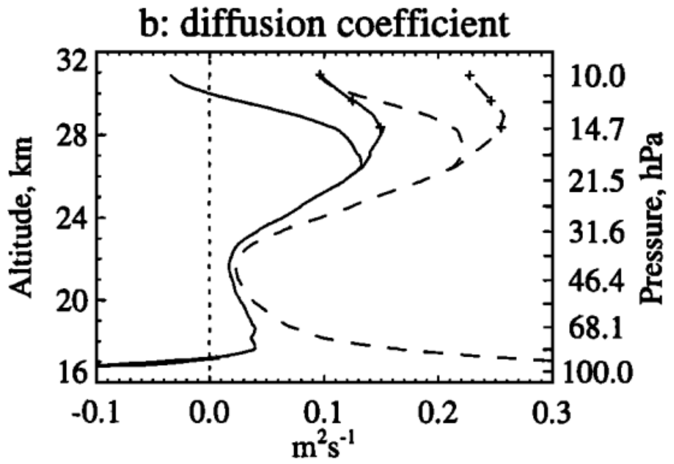
Zonal mean budget of a tracer in the tropical UTLS :

$$\frac{\partial \bar{\chi}}{\partial t} = -\bar{w}^* \frac{\partial \bar{\chi}}{\partial z} + \frac{\partial}{\partial z}\left(K_h \frac{\partial \bar{\chi}}{\partial z}\right) + E + S$$

Source term and ex the extra tropics

Advection term

Turbulent diffusion term;
K_h = vertical diffusivity (heat exchange coefficient)



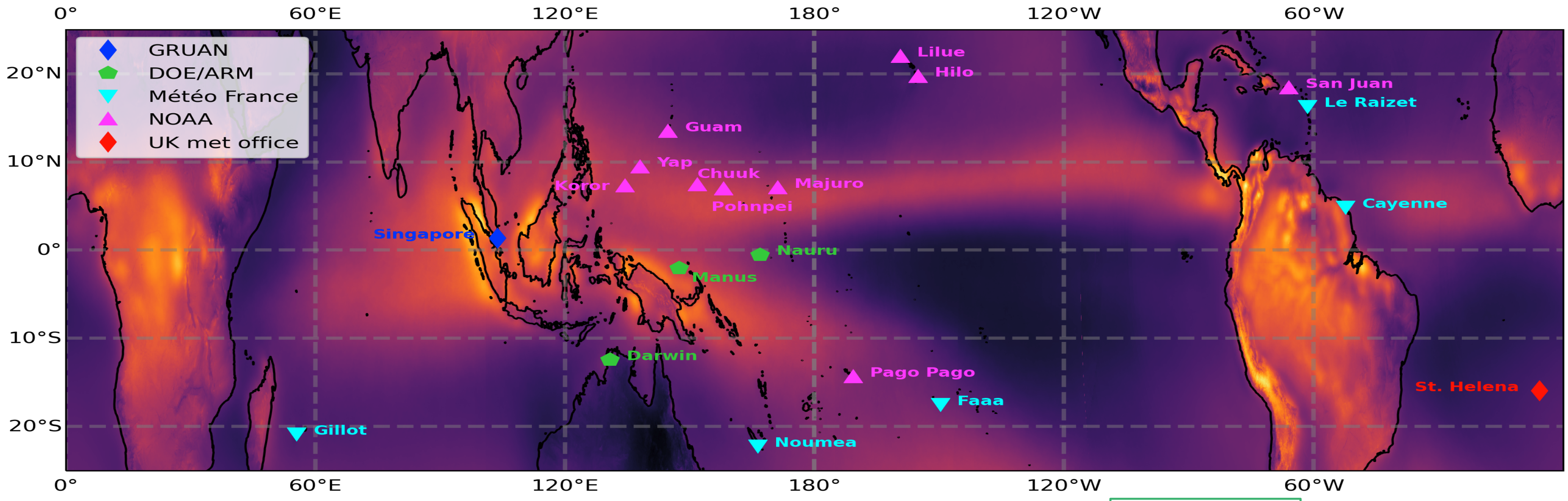
Mote et al., 1998

Study	*Mote et al.* (1998)	*Glanville and Birner* (2017)	*Dewan* (1980)	*Rao et al.* (2001)	*Sunilkumar et al.* (2015)	*Podglajen et al.* (2017)
K_h ($m^2 s^{-1}$)	0.02	4 x 0.02	0.2	~0.2	1-10	0.02 (top) to 0.2 (bottom)
Method	Tracer budget	Tracer budget	RaDAR	RaDAR	Thorpe	Aircraft

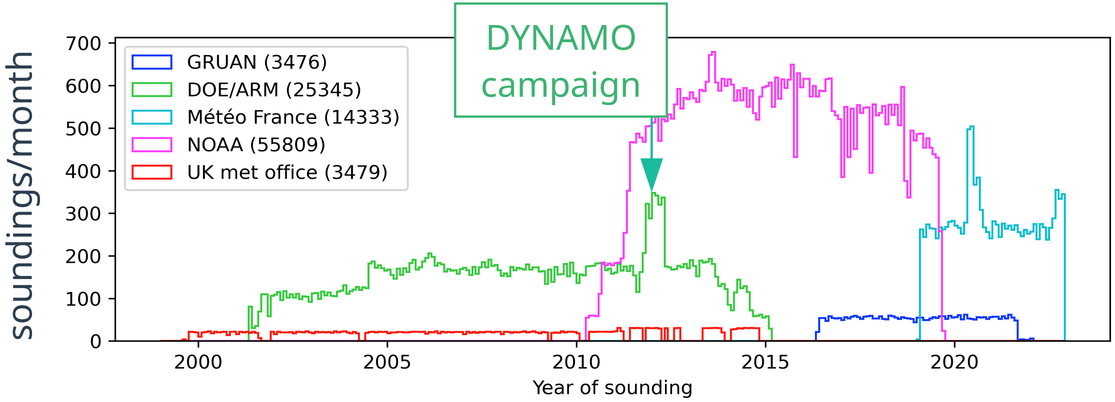
Outline

- **Inferring turbulence/small-scale mixing from tropical HVRR**
- Variability of ‘turbulent’ layers and relationship with tropical waves and convection
- Estimating the impact on transport (work in progress)

Selected HVRR in the tropical UTLS



- ~100,000 soundings in total between 2000 and 2023
- Generally reaching ~30 + km
- 1-2 s (5-10 m) resolution
- RS type: Modem (Météo-France), Väisälä (RS 80, 92 & RS 41, ARM), Lockheed Martin (NOAA)



Thorpe and Richardson number methods : advantages and caveats

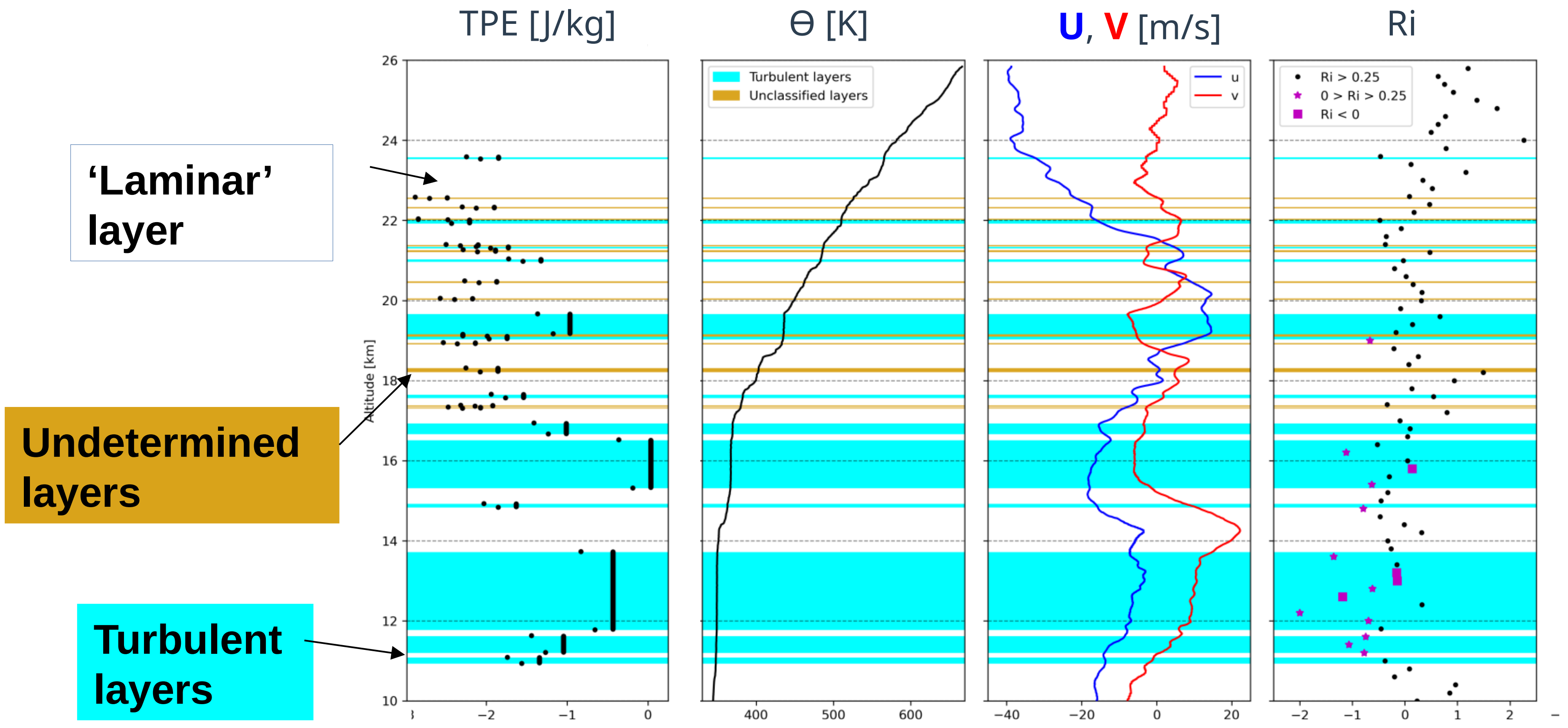
Thorpe

- **Only temperature (humidity), pressure and altitude profiles needed**
- **Sensitivity to noise of the temperature sensor**
  - Detection threshold depends on both resolution and noise level
  - Spurious (?) diurnal cycle
- **Size detection threshold : scales > 30 m**
- **Diagnostic of mixed layer (being mixed or previously mixed)**
- **Estimates of turbulent potential energy (TPE), its dissipation rate (ε_p), and heat diffusivity within the layer (K_h)**

Richardson number

- **Relies on temperature and horizontal wind (and altitude)**
- **Shear estime is sensitive to (chaotic) pendulum motions**
- **→ Effective resolution : 200 m (for N^2 and S^2)**
- **Ri< 0.25 (Ri<0) is a necessary condition for shear (convective) instability (Miles-Howard criterion)**
- **Diagnostic of ‘dynamically unstable layers’ (turbulent or likely to become turbulent)**

Estimating small-scale turbulent mixing from RS profiles



Thorpe diagnostic : *Wilson et al.*, 2011, 2013 method

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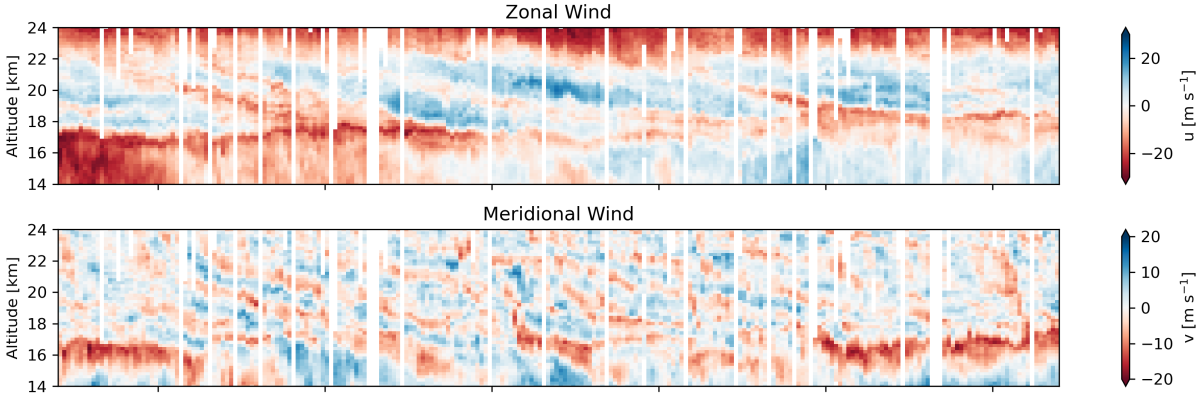
Case study

- **Intense observation period in Feb. 2012 (8 soundings per day)**
- **Hovmöller diagram of zonal wind reveal**
  - Downward propagating inertio-gravity waves in the lower stratosphere (+ QBO phase)
  - Lower frequency structures in the lower TTL

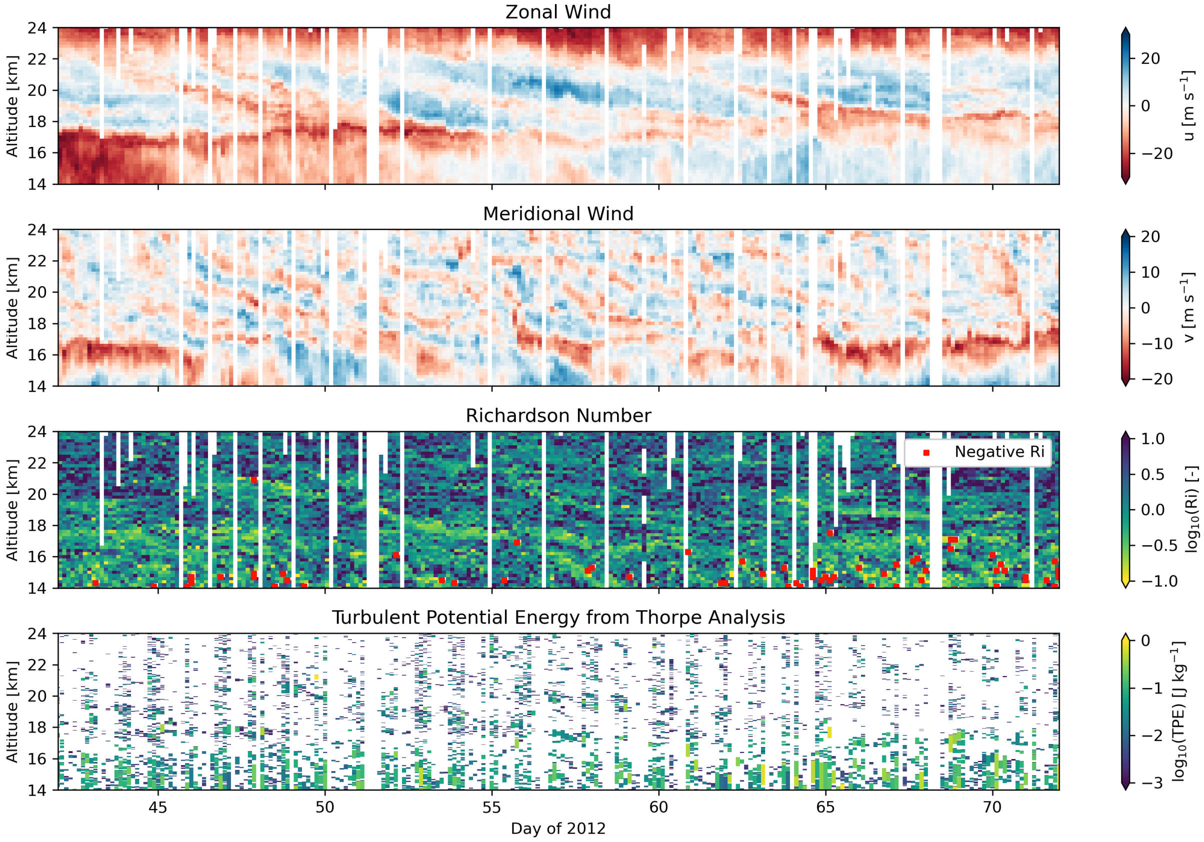
Manus (latitude= ~2°S) soundings during DYNAMO (2012)



Exemplary case study

- **Richardson number :**
  - downward propagating low Ri layers
  - Mostly shear-driven Ri<0.25 over 200 m
  - More frequent Ri<0 below the tropopause
- **Concomitent large turbulent potential energy (with strong diurnal cycle)**
  - Structured turbulent layers above CPT
- **For both :**
  - Clear signature of downward propagating inertio-gravity waves in the LS
  - More intermittent behavior in the UT
- **Suggests that different processes dominate in the T and S**

Manus (latitude= ~2°S) soundings during DYNAMO (2012)



Impact of (low-frequency) equatorial IGWs

- **Composite analysis around Ri<0.25 (n=417 in strat., n=4820 trop.) of the whole record**

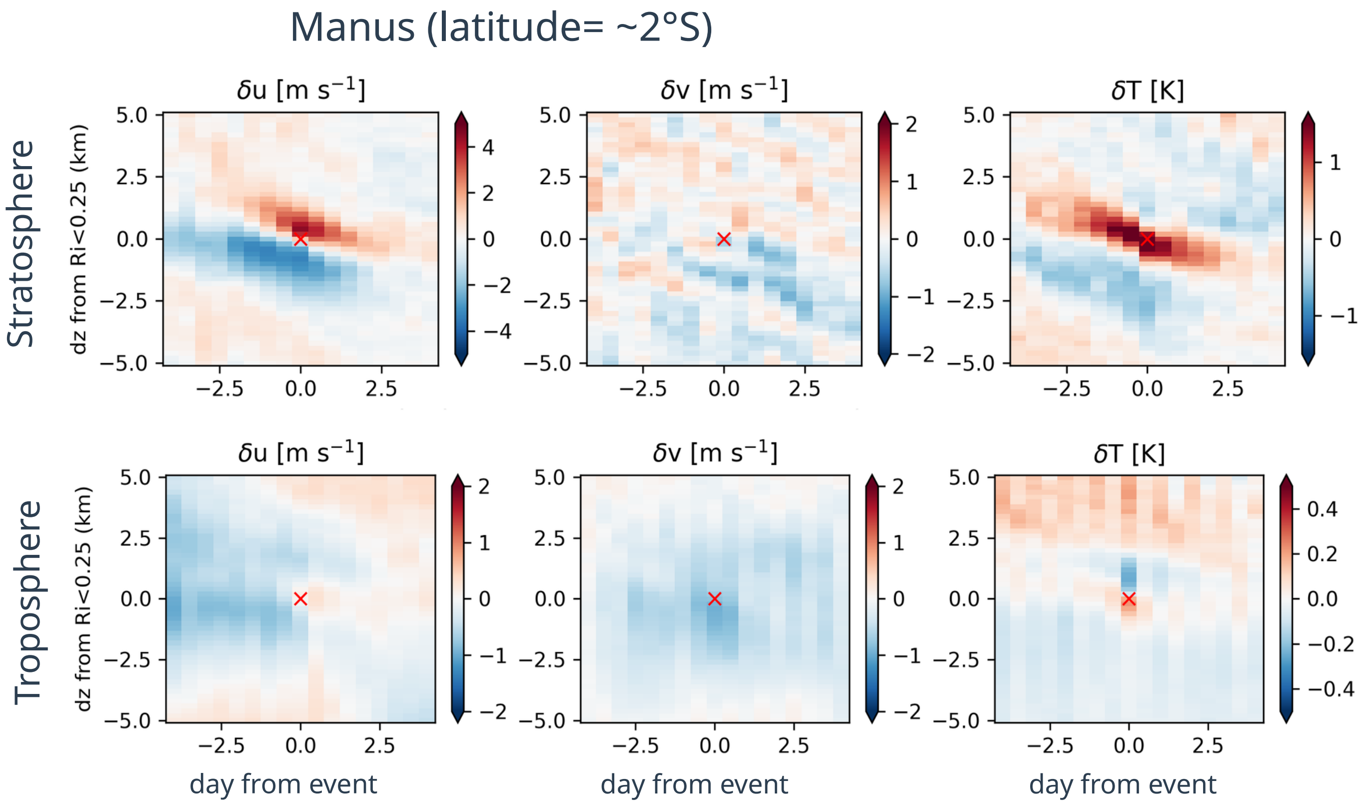
Manus (latitude= ~2°S)

Stratosphere

Troposphere

Impact of (low-frequency) equatorial IGWs

- **Composite analysis around Ri<0.25 (n=417 in strat., n=4820 trop.) of the whole record**
- **Stratosphere :**
  - Clear impact of (low-frequency) waves (Kelvin mostly ?)
  - Typical vertical wavelength (from T anomaly) : <~ 4 km
  - Typical period ~ 8 days
  - Shear dominates
- **Troposphere**
  - Weaker impact of waves

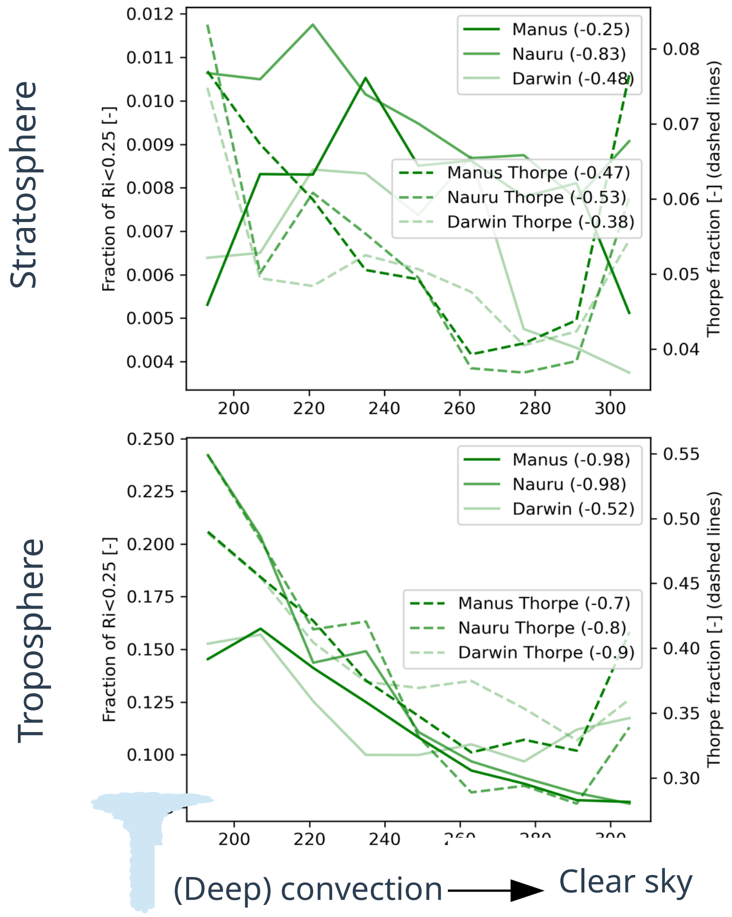


Relationship with convection

- **Turbulence from fraction of Ri<0.25 and Thorpe analysis**
- **Geostationnary window channel brightness temperature near site as a convective proxy**

- **Stratosphere :**
  - Weaker impact of convection in the vicinity of the sounding
- **Troposphere:**
  - Clear impact of convection

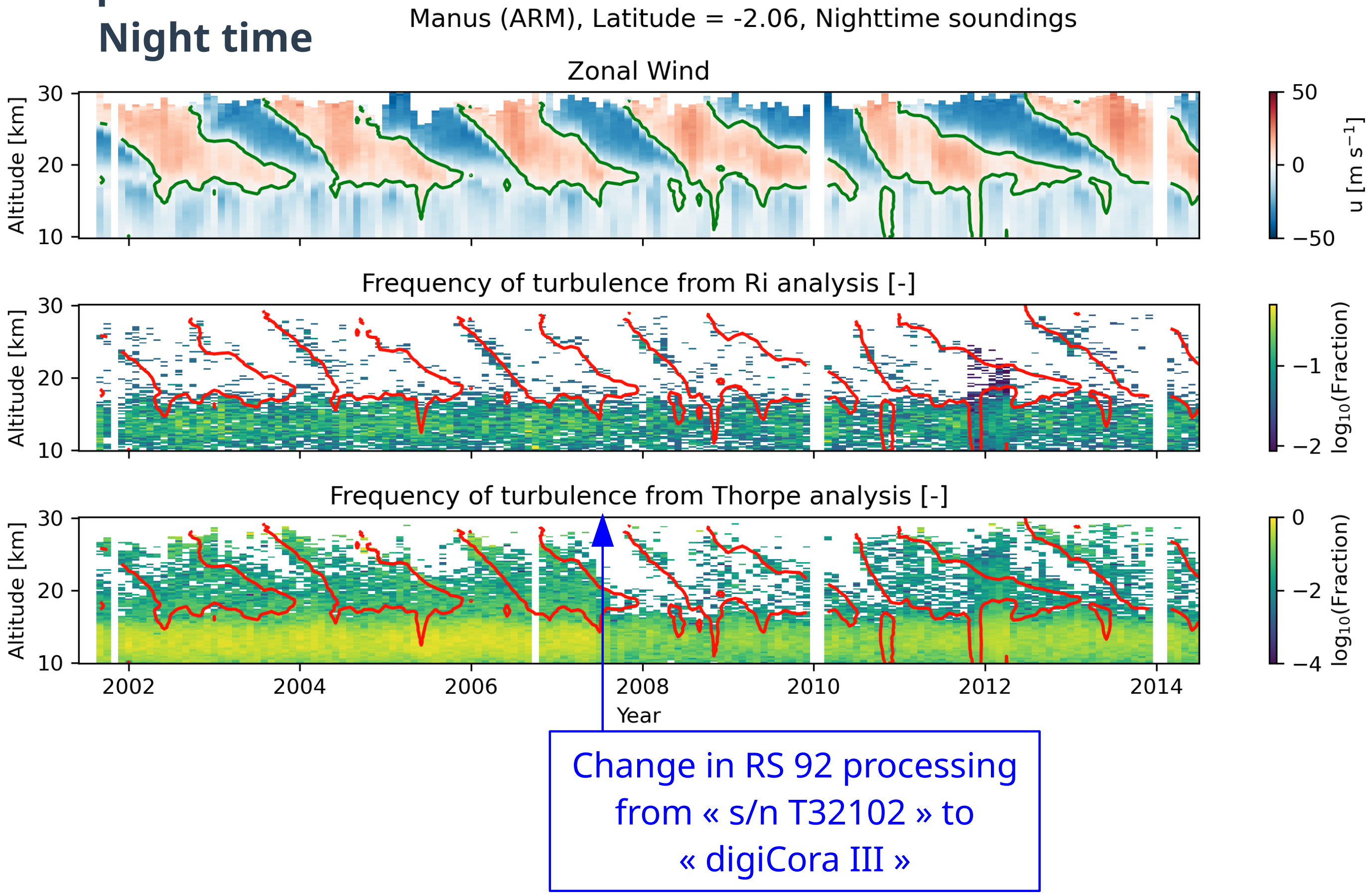
- **Contrast troposphere-stratosphere in the relationship with convection opposite to the impact of low-frequency waves**



Insight into annual and interannual variability

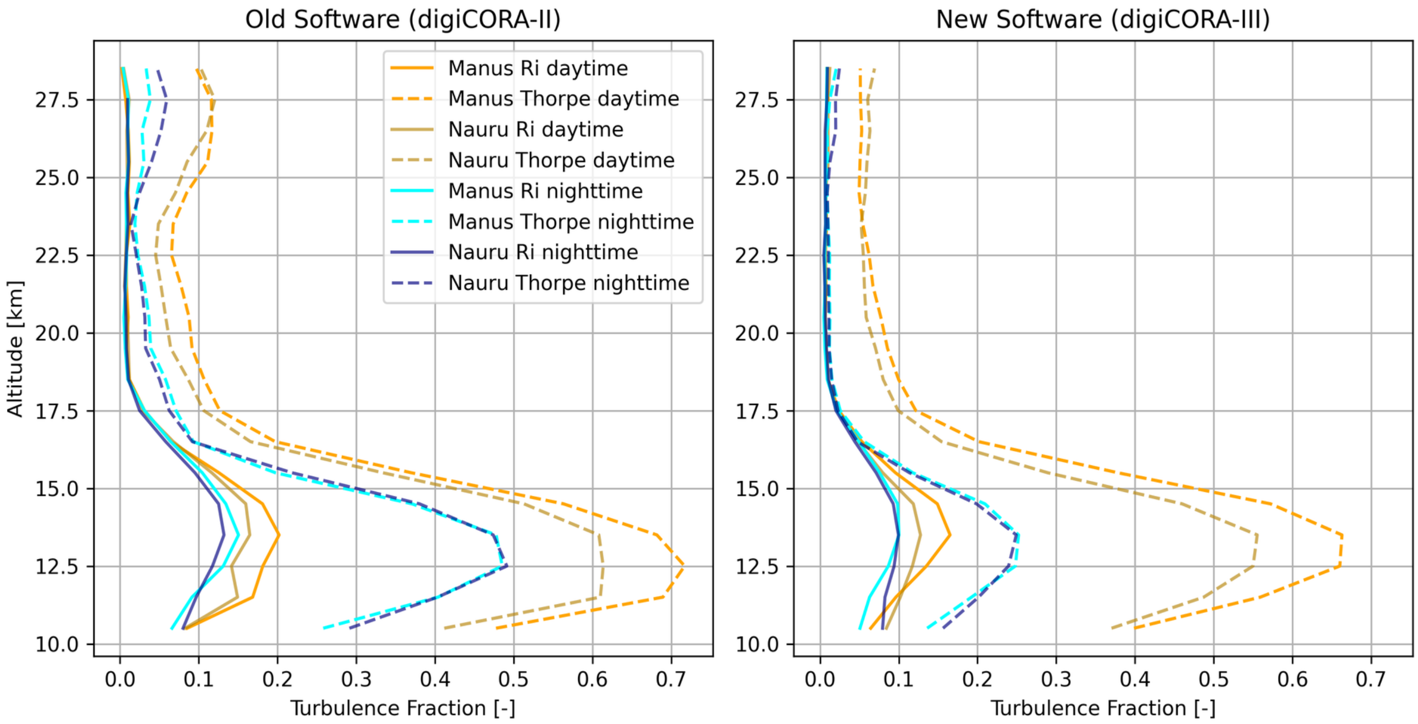
- **Stratosphere :**
  - Clear QBO signal : more frequent turbulence in shear zones
  - Westerly shear zones seem favored (Kelvin waves?)
  - Besides shear, asymmetry Westerly/Easterly with Thorpe
- **Troposphere:**
  - ENSO ?
  - Thorpe : sensitivity to processing (black box?)

Equatorial site
Night time



Insight into diurnal variability

- **Richardson**
  - Some diurnal variability: noise is unlikely to play a role (or is it ?)
- **Thorpe:**
  - Clear diurnal cycle : artifact due to noise (?)
- **Processing shows up more in nighttime measurements (disagrees with previous discussions)?**



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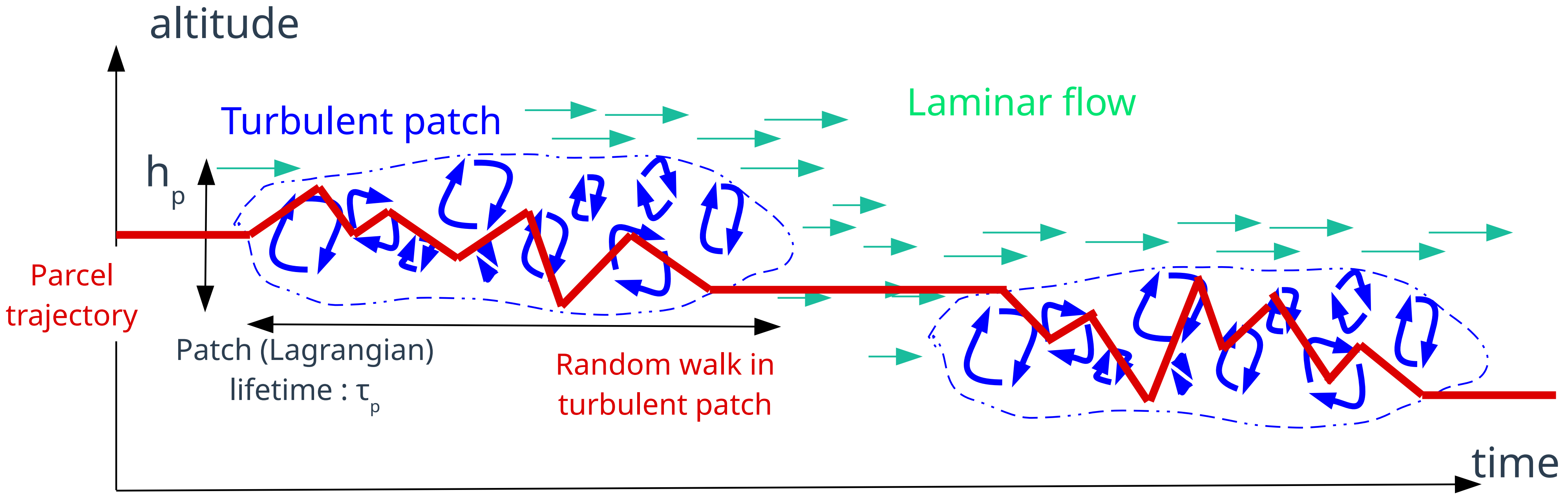
Back to vertical transport …

- **Principle of « effective » turbulent diffusivity : random walk in intermittent turbulent layers**



Dewan (1980) : perfectly mixed patches ; Alisse et al. (2001), Vanneste (2004) : imperfectly mixed patches

Also see Osman et al., 2016

Back to vertical transport …

- **Within each layer : first (1.5)-order closure and stationarity of the potential energy budget in a stratified medium enables to estimate local diffusivity:**

$$K_h = \frac{\varepsilon_p}{N^2}$$

- **If turbulent bursts occur randomly and INDEPENDENTLY (not an obvious assumption, especially in the stratosphere), then a formula can be derived as a function of :**
  - F_t : turbulent fraction
  - h_p : depth of the turbulent layer Thorpe overturn)
  - K_p : turbulent diffusivity within the layer
  - τ_p: lifetime of the turbulent layer

$$K_{\mathrm{eff}} = F_t \frac{\overline{h_p^3}}{12\overline{h_p \tau_p}}(1-c),$$

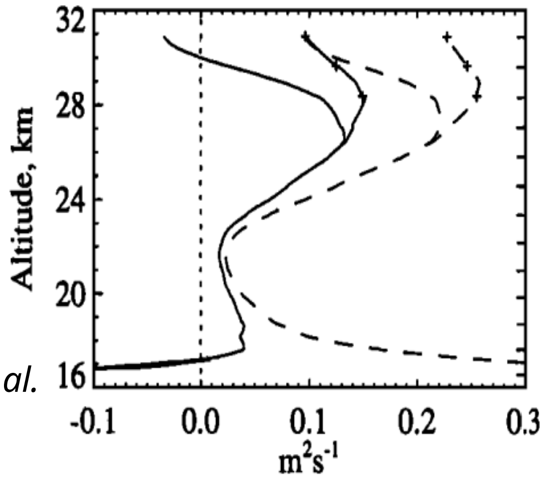
$$c = \frac{96}{\pi^4 \overline{h_p^3}} \sum_{n=0}^{\infty} \frac{\overline{h_p^3 \exp[-(2n+1)^2 \delta_p]}}{(2n+1)^4}$$

$$\delta_p \doteq \pi^2 K_p \tau_p / h_p^2$$

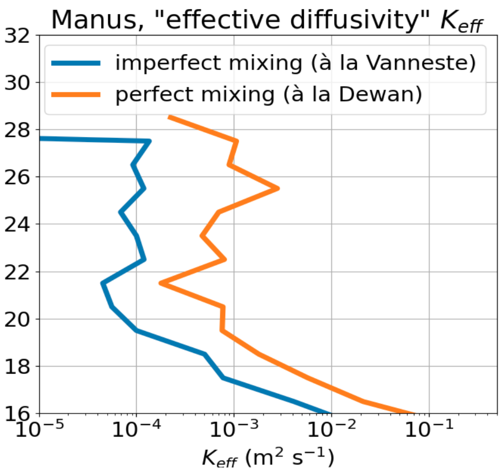
- **Need an assumption for the lifetime of turbulent patches : here a few hours, guidance from radar data: maybe new estimate from quasi-lagrangian Strateole 2 balloons (***Wilson et al.***, 2023)**

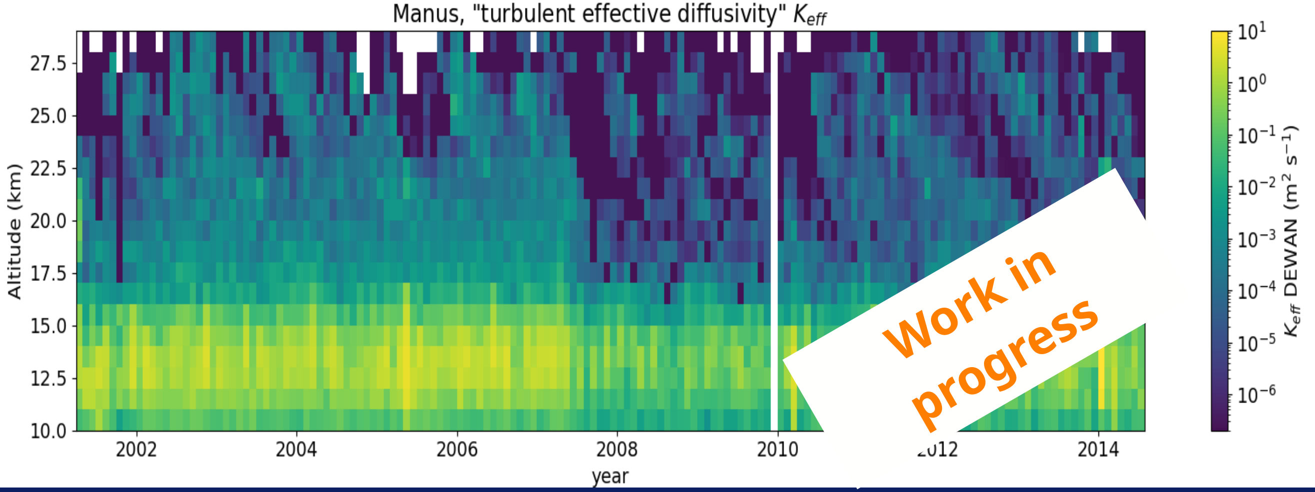
Dewan (1980) ; Alisse and Sidi (2001) ; Vanneste (2004)

Estimated « effective turbulent diffusivity »



Mote et al. (1998)





- **Average profile (mirroring Thorpe-estimated overturn fraction)**
- **Significant interannual variability**
- **Underestimation in the stratosphere**
  → detection issue ?
  → methodological issue ?
  → other processes ?
- **Results are sensitive to sonde processing changes – estimate sensitive to the results**

Summary

- **The contribution of turbulence/irreversible small-scale mixing to the tracer budget remains poorly constrained and estimates vary by order of magitude**

- **Thorpe and low Ri layers show relationship with equatorial waves (stronger in the stratosphere) and convection (stronger in the troposphere)**
- **The QBO seems to exert a strong control on stratospheric turbulence occurrence (Easterly shear phases)**

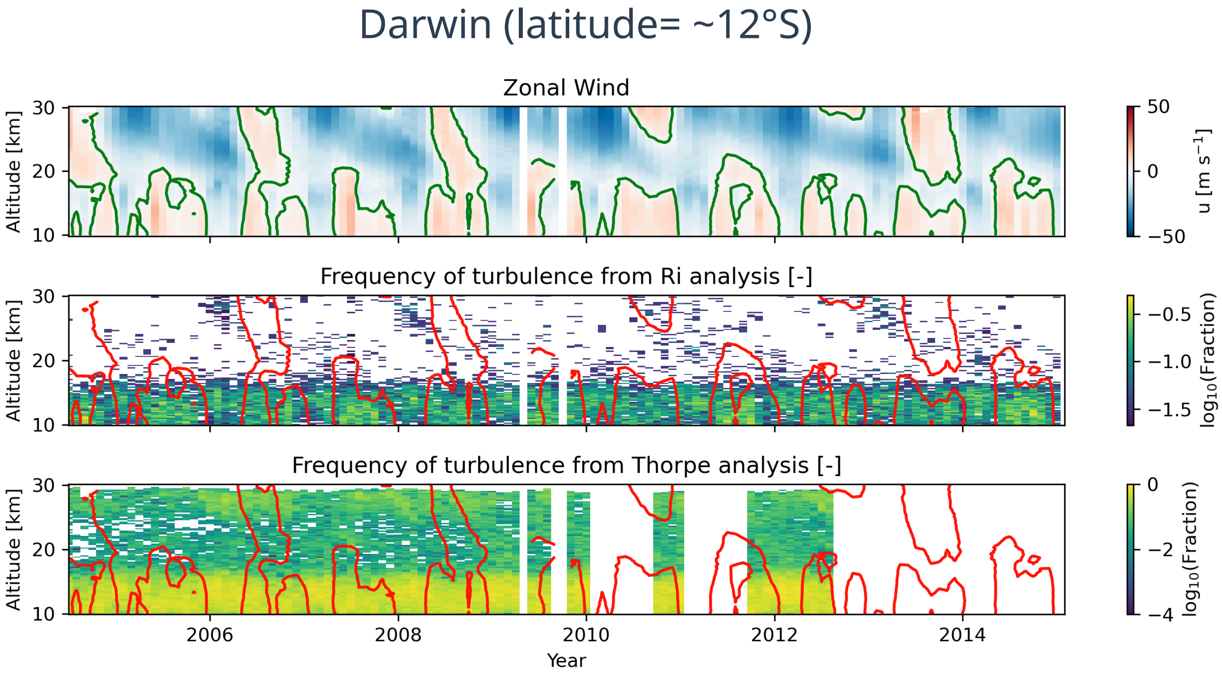
- **Preliminary diffusivity estimates from Thorpe analysis of radiosonde seem to disagree with tracer budget based estimates, strong sensitivity to processing, daytime noise to be clarified**
- **More information will be found in :** *Atlas et al., in prep. for JGR*

Thank you for your attention

Insight into annual and interannual variability

- **Stratosphere :**
  - Still a QBO signal :
  - Westerly shear zones seem favored (Kelvin waves?)
  - Besides shear, asymmetry Westerly/Easterly with Thorpe
- **Troposphere:**
  - ENSO ?
- **Thorpe : sensitivity to the processing (black box?)**

Tropical site



Robustness wrt to diurnal variability and processing

- **Robustness of interannual variability across diagnostics**