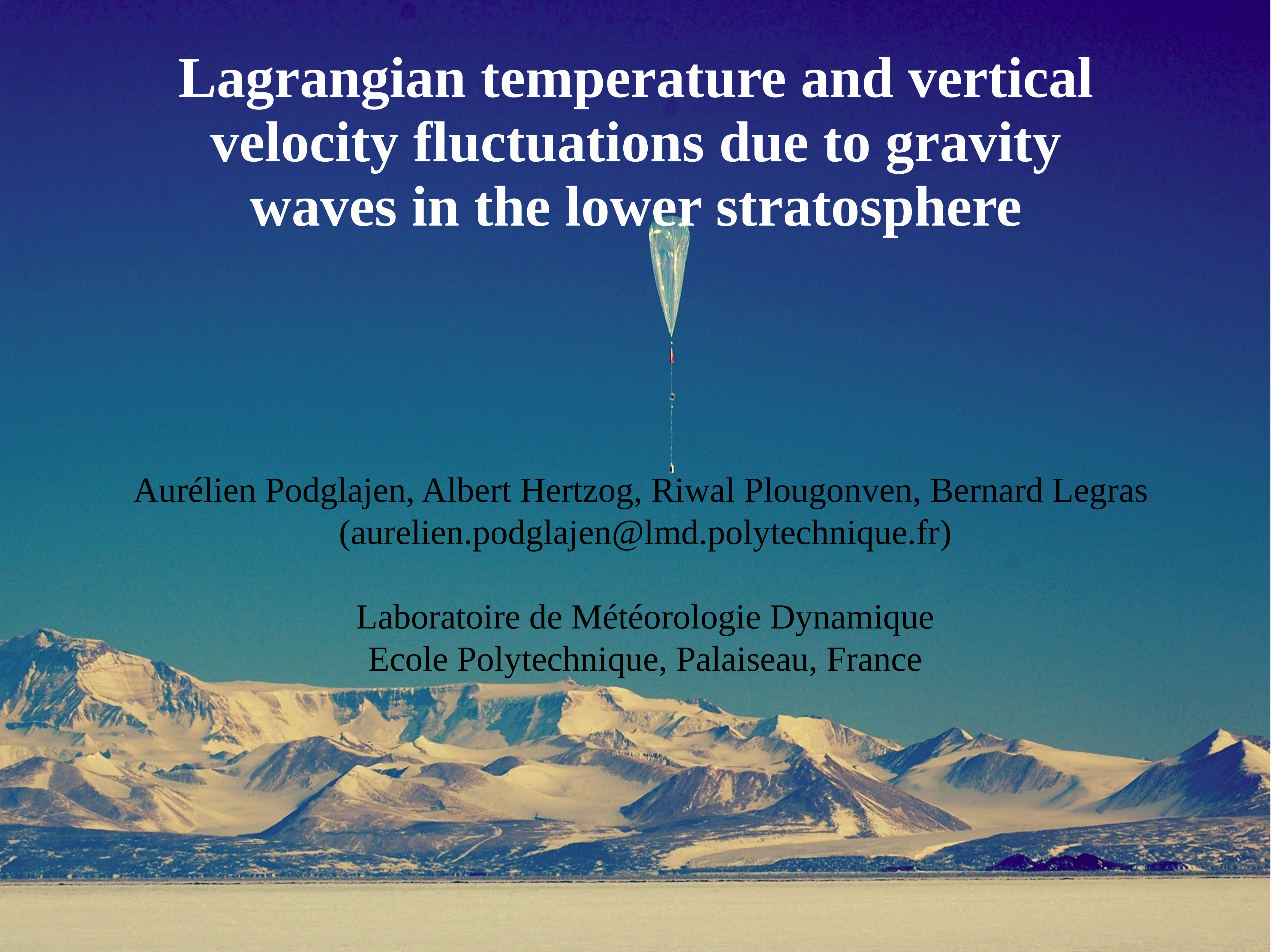


Lagrangian temperature and vertical velocity fluctuations due to gravity waves in the lower stratosphere

Aurélien Podglajen, Albert Hertzog, Riwal Plougonven, Bernard Legras
(aurelien.podglajen@lmd.polytechnique.fr)

Laboratoire de Météorologie Dynamique
Ecole Polytechnique, Palaiseau, France

Introduction

- Sensitivity of chemistry and microphysics to temperature-vertical velocity fluctuations (Polar Stratospheric Clouds, cirrus, aerosols)

Example of the impact the gravity wave “fast” temperature fluctuations on the microphysics : homogeneously nucleated ice crystal number concentration in cirrus clouds

- to constrain the temperature fluctuations undergone by air parcels, need of Lagrangian observation of the fluctuations

Superpressure Balloon campaigns provide a good and unbiased sampling over regions of interest

Superpressure balloon campaigns in 2010

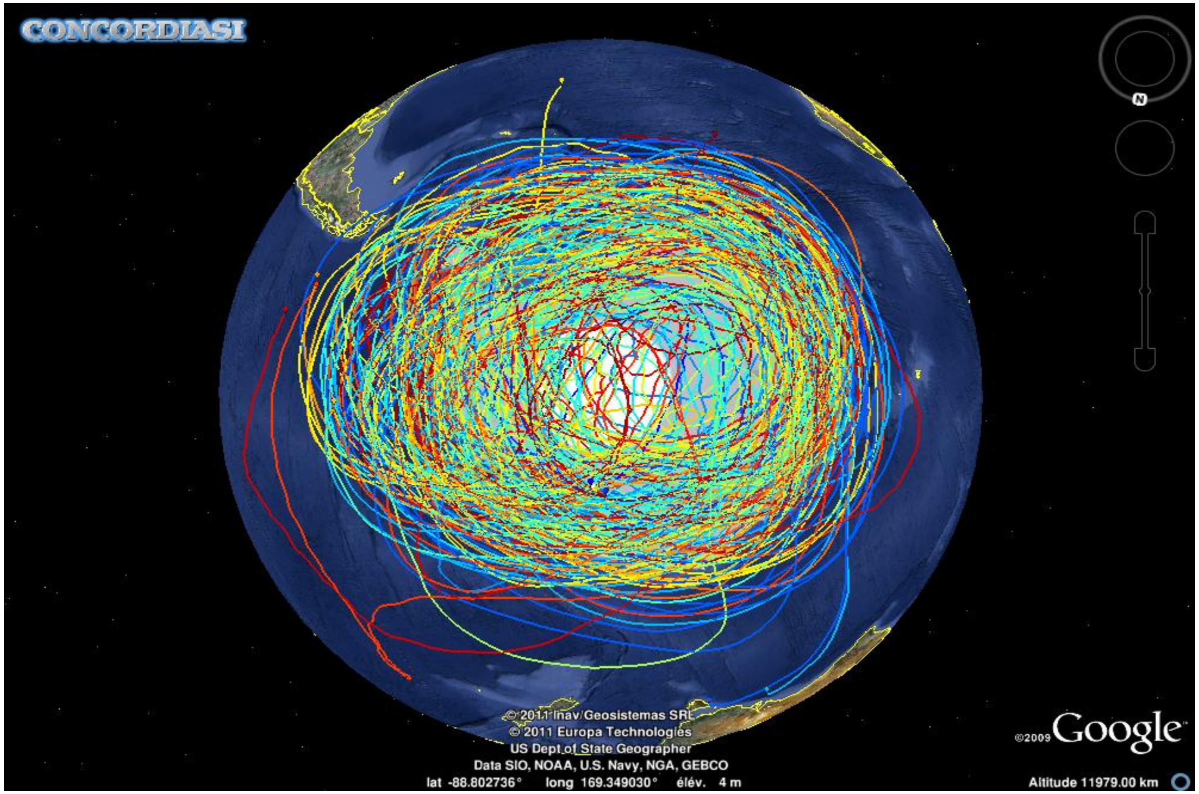
19 balloons over Antarctica (September-December, austral spring): **PSCs**

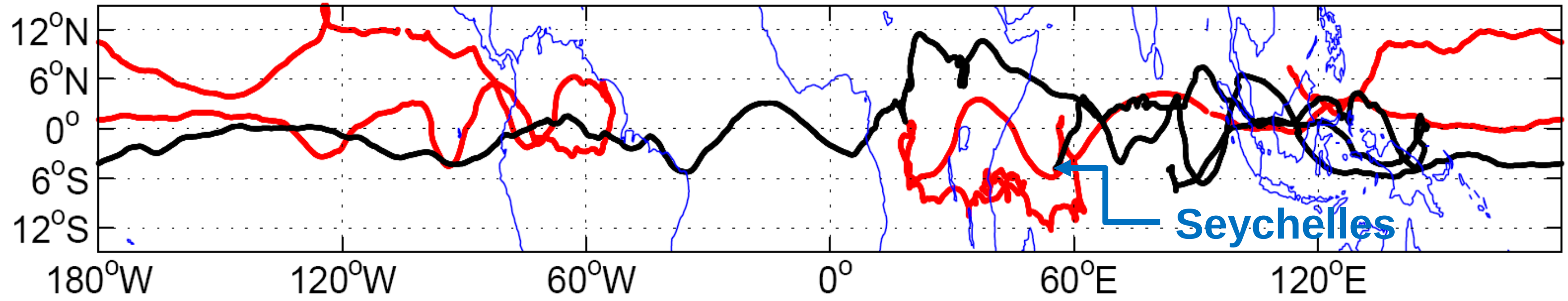
2 balloons in the tropics (March-May, boreal spring): **TTL cirrus**

~3 months flights

1 min sampling

Measurements of the balloon position, temperature, pressure



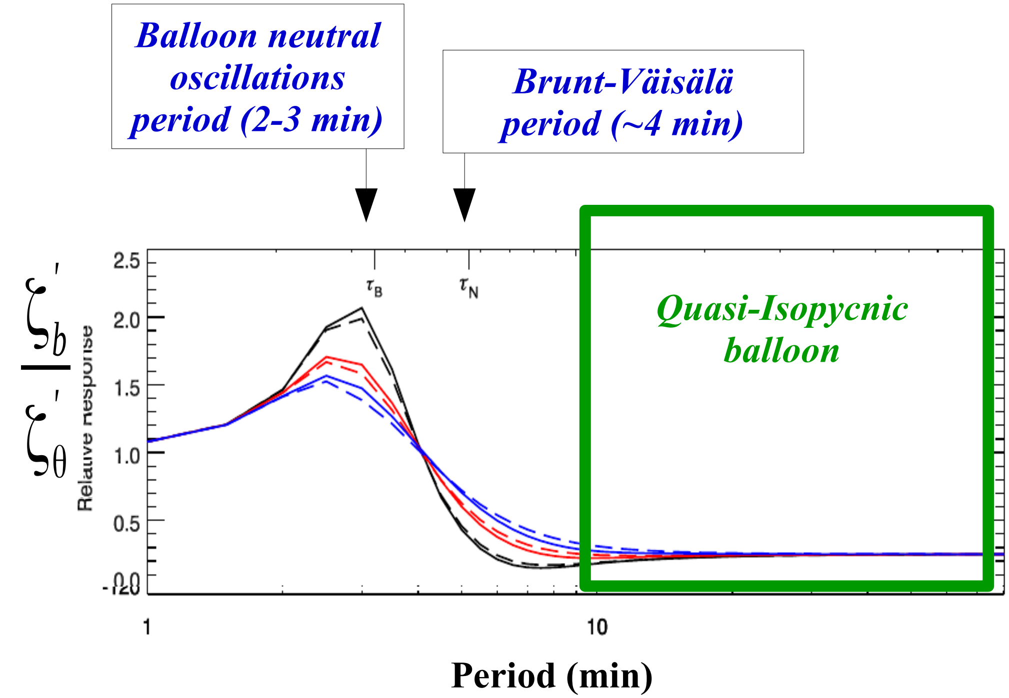


Superpressure Balloon flights allow to quantify Lagrangian Temperature and vertical velocity fluctuations

On the horizontal, the balloon follows the wind field :
quasi-Lagrangian measurements

On the vertical, we consider that the balloon follows **isopycnic (constant density) surfaces** (questionable at GW high frequencies)

The vertical displacement of (isentropic) air parcels ζ_θ is deduced from that of the isopycnic balloon ζ_ρ (deduced from pressure)



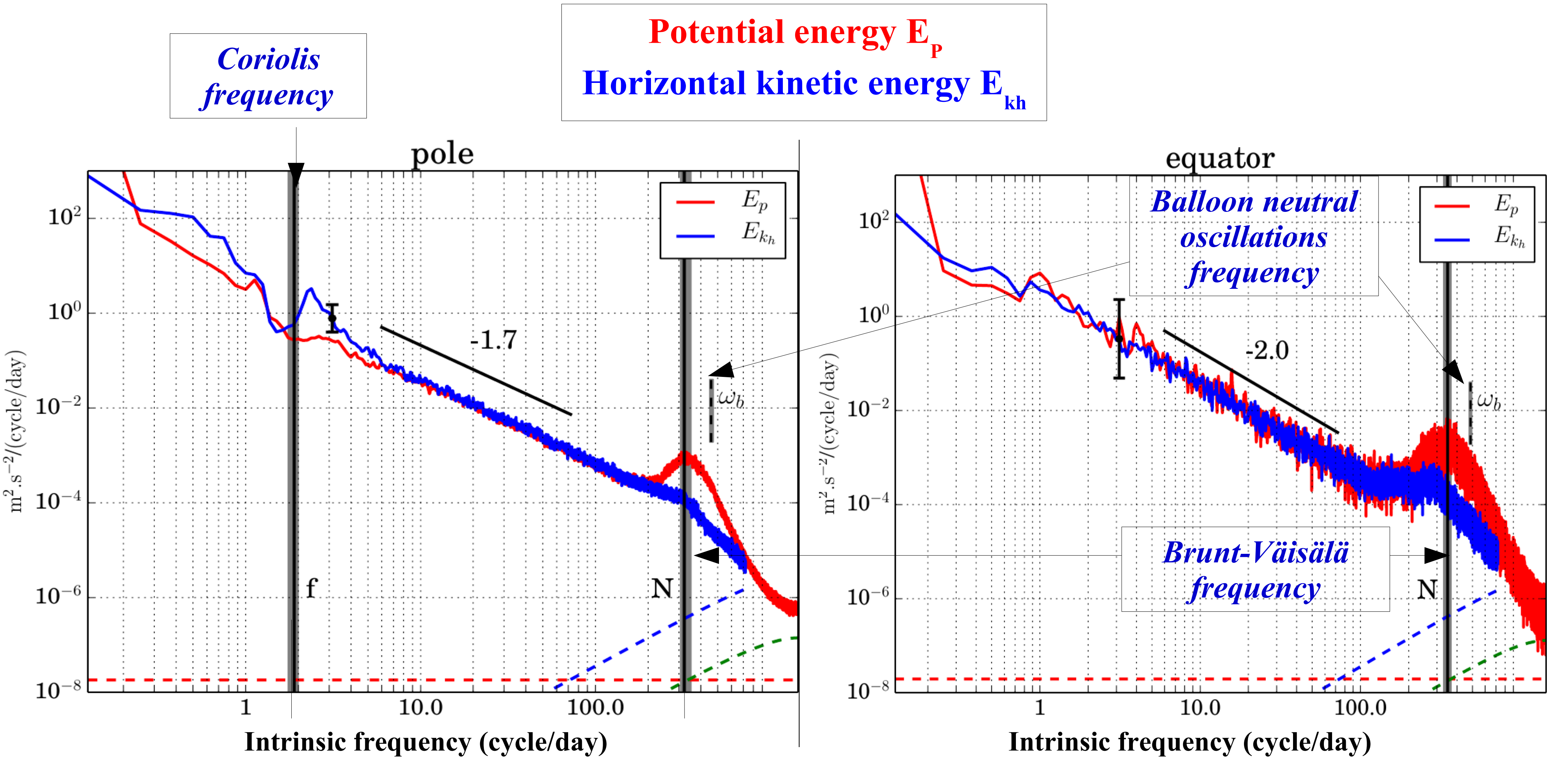
Vincent and Hertzog, 2014

$\zeta_\rho = \alpha\, \zeta_\theta$ where $\alpha \simeq 0.3$ in the lower stratosphere

Lagrangian temperature fluctuations T_l' are deduced from the estimated vertical displacement (dry adiabatic):

$$T_l' = -\frac{g}{C_p}\zeta_\theta'$$

Observed spectra of atmospheric motions show scaling behavior and exceptions in the GW range



Large-scale motions

Inertio-gravity waves (GWs)

Isotropic turbulence ?

$$E_{k_h} = \frac{1}{2}(u'^2 + v'^2)$$

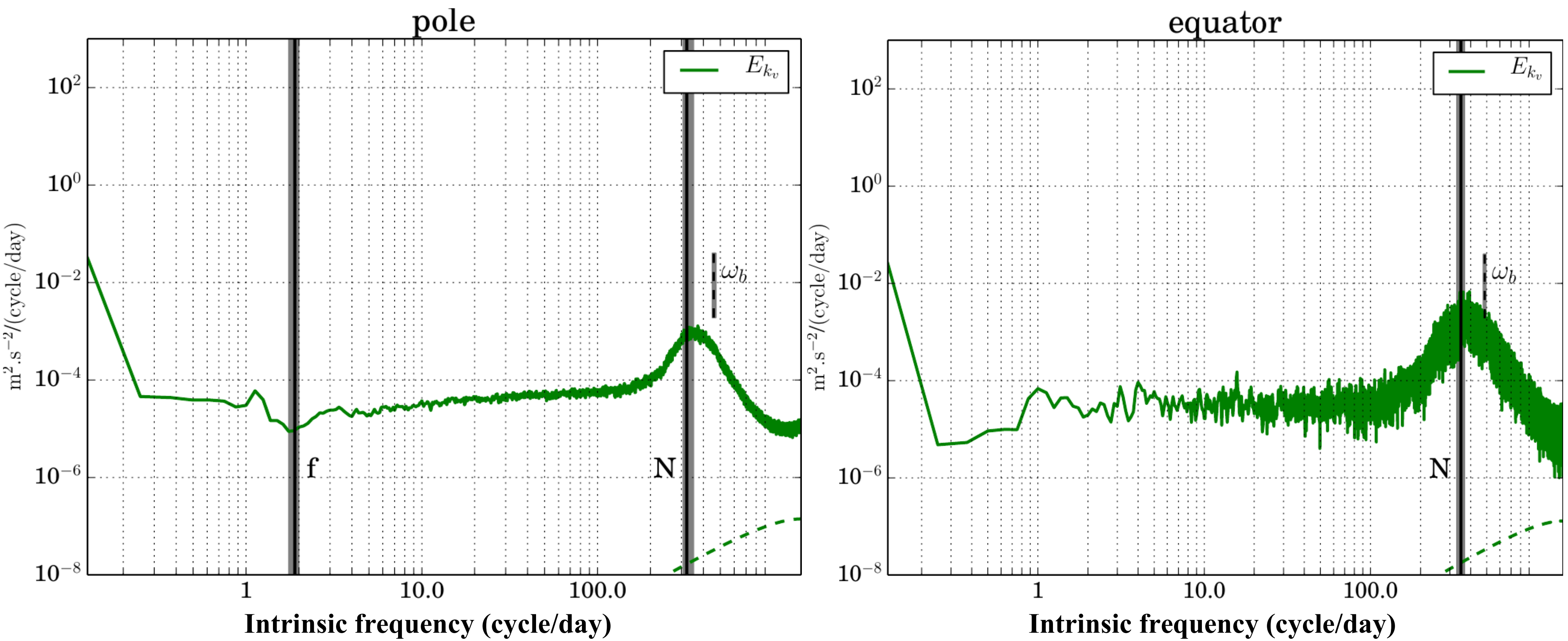
$$E_p = \frac{1}{2}N^2{\zeta'_\theta}^2$$

Exceptions to scaling behavior : peaks at **f** in E_{kh} and at **N** in E_p (pollution by non isopycnic behavior ?)

Podglajen et al., 2016, GRL

High frequency gravity waves dominate the vertical velocity

Vertical kinetic energy

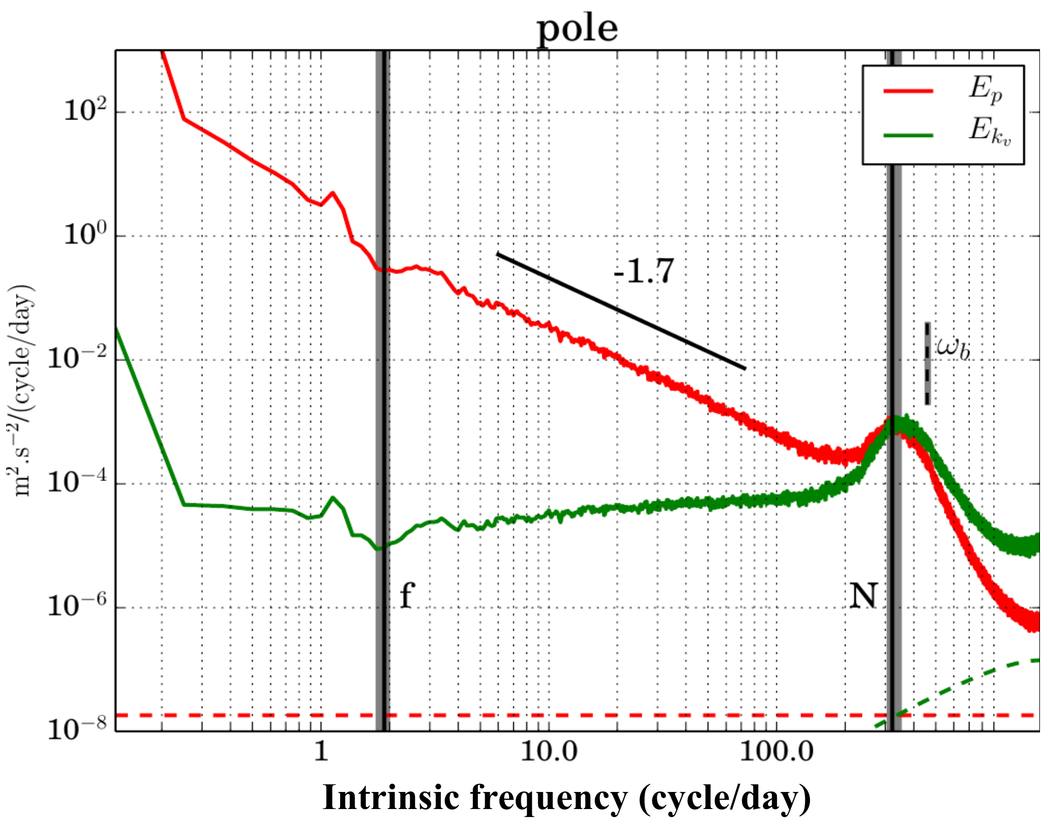


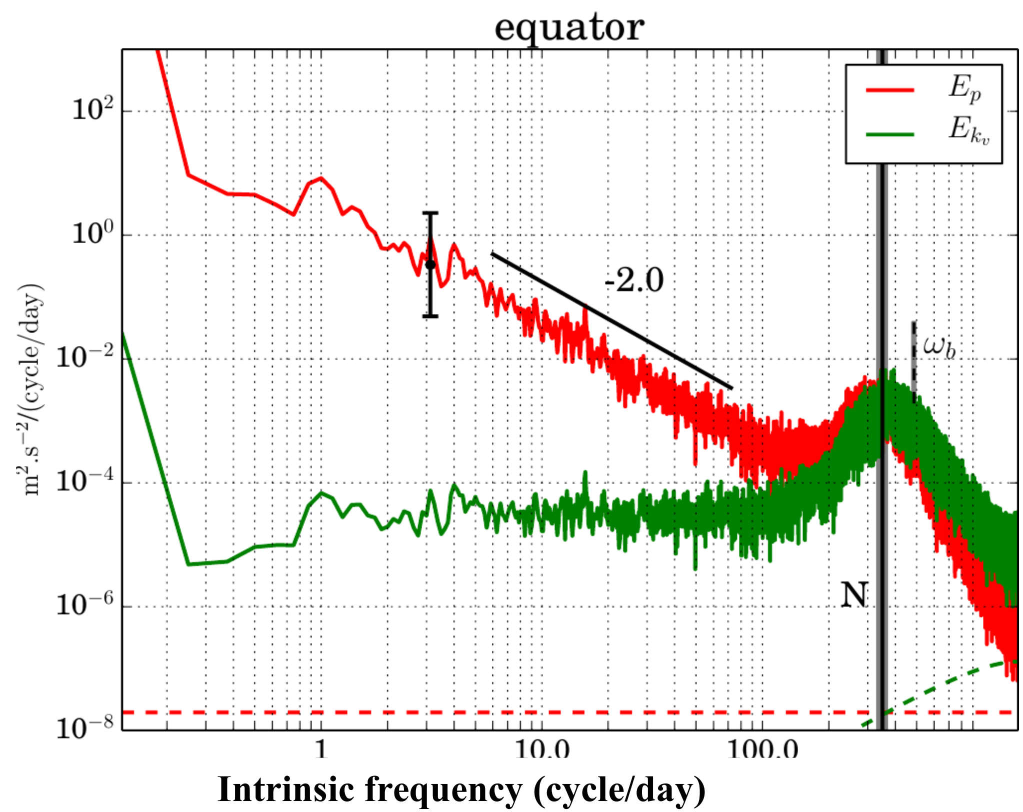
The spectrum of vertical velocity is approximately flat up to N/2 both in the tropics and the pole, then increases towards N. Potential effect of the balloon response at these high frequencies.

In any case, the **variance of vertical velocity** is mainly contained **in the high frequencies**; strong maxima in vertical velocity variance at the Brunt-Väisälä frequency.

How do microphysically relevant quantities relate to balloon observations ?

Lagrangian temperature fluctuation power spectrum
Lagrangian cooling rates power spectrum





Lagrangian Temperature fluctuations (deduced from the vertical displacement) :

$$T'_l = -\frac{g}{C_p}\zeta'_\theta$$

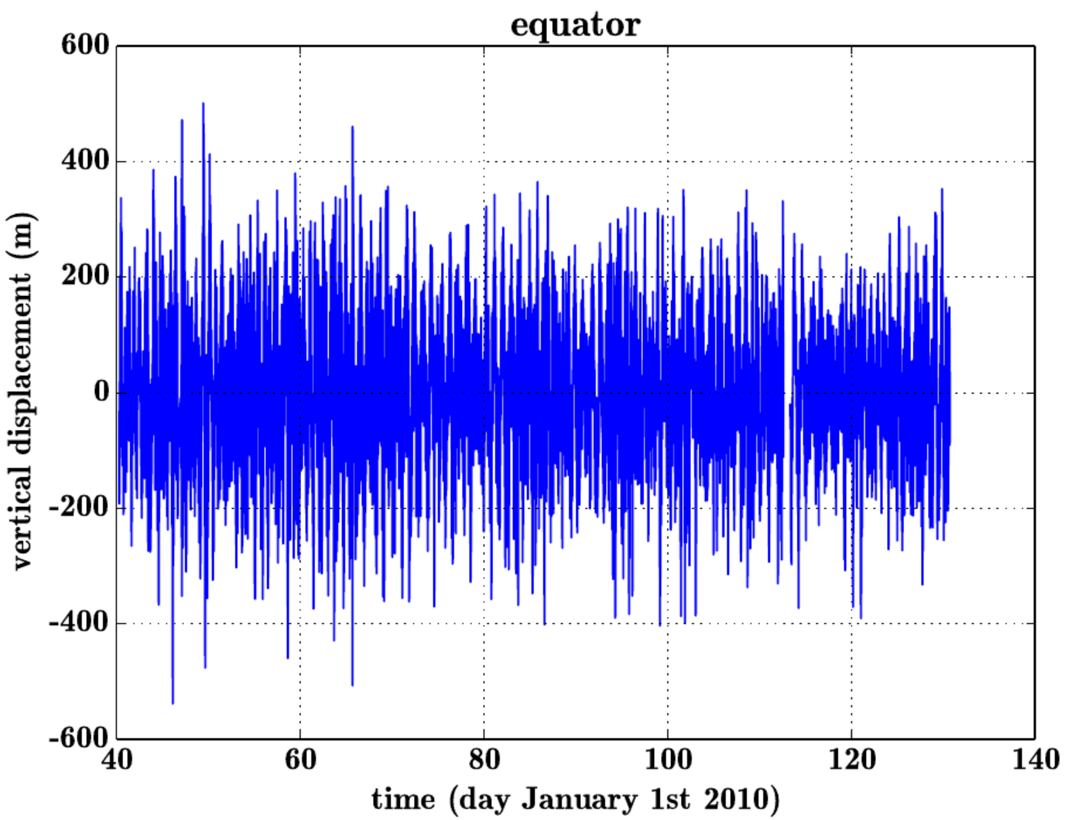
$$T'^2_l = 2\left(\frac{g}{C_p N}\right)^2 E_p$$

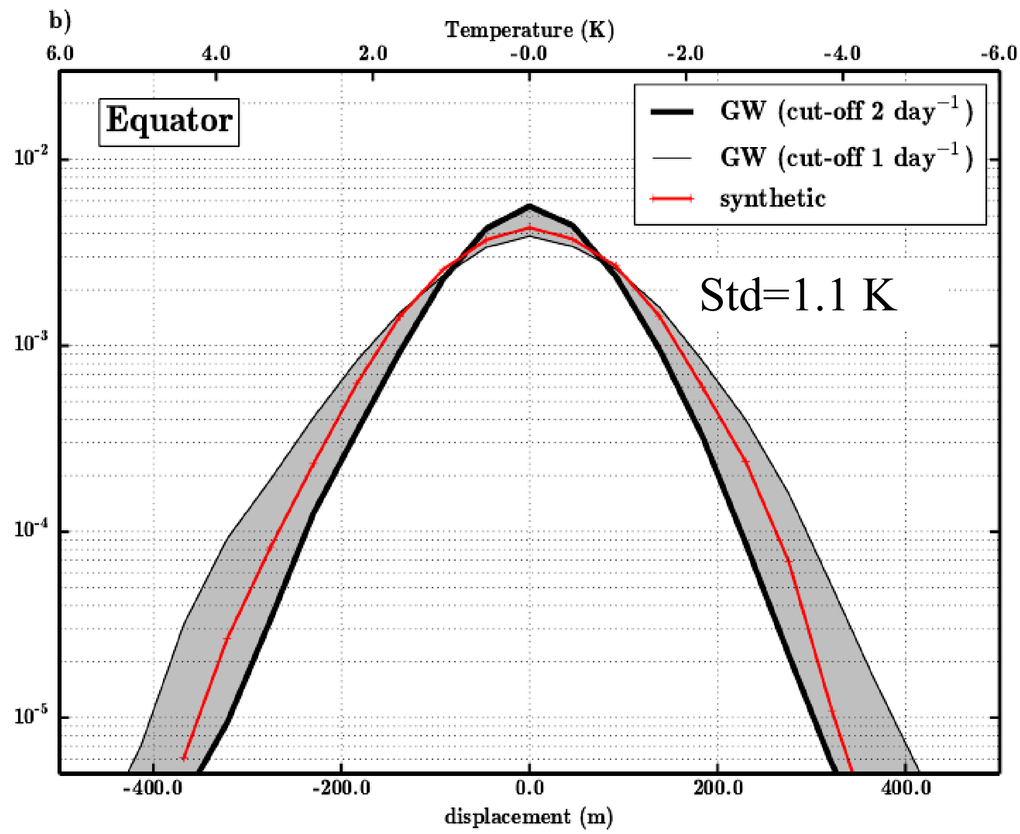
Lagrangian cooling rates :

$$\frac{DT'_l}{Dt} = -\frac{g}{C_p}w'$$

Temperature fluctuations in the equatorial LS are Gaussian, limited intermittency

Temperature PDF



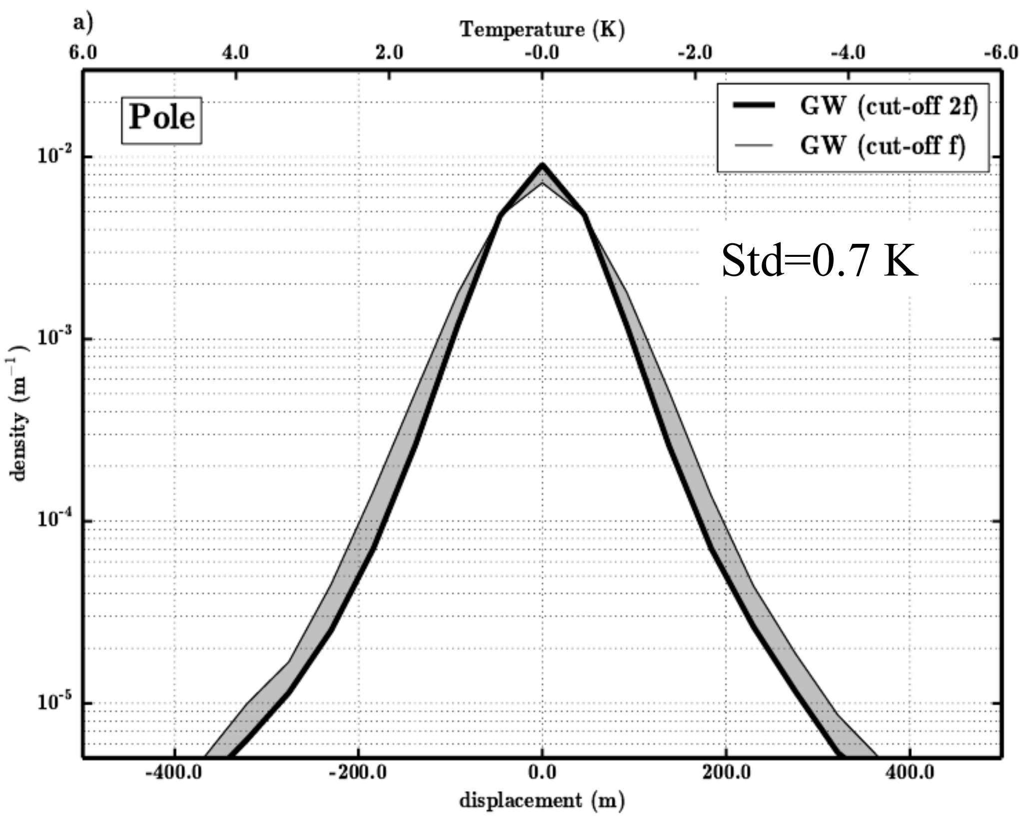


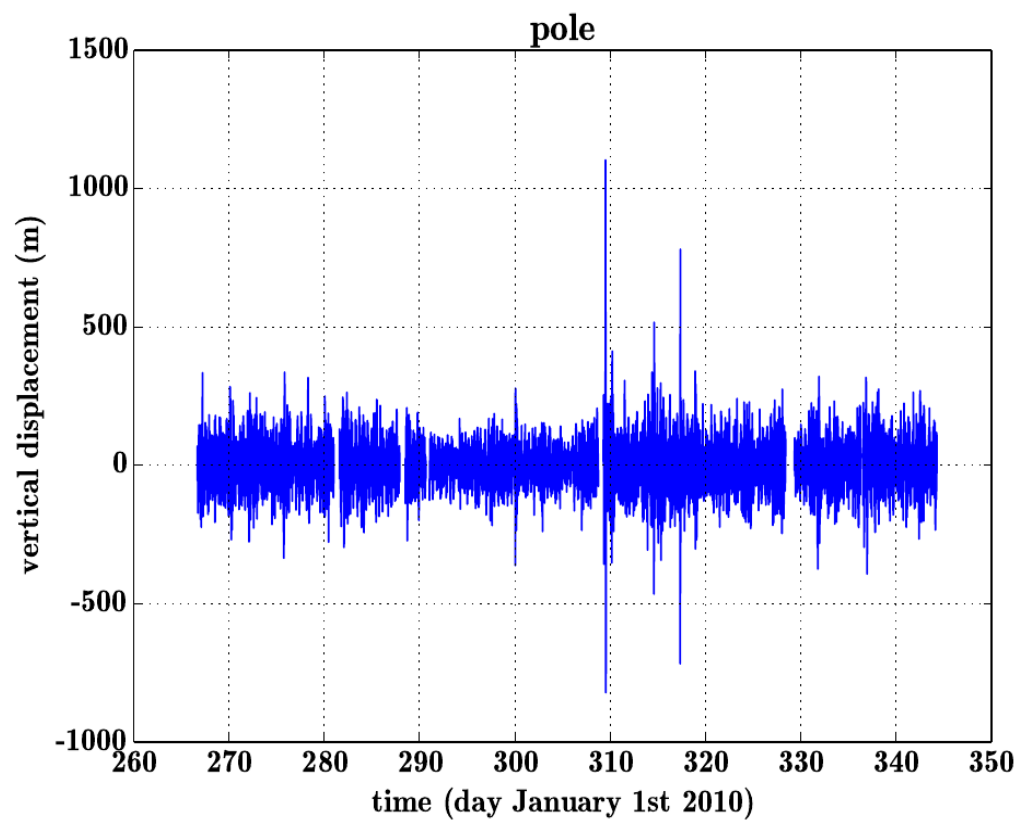
Important contribution of the gravity waves to the temperature variability

Gaussian PDF over the equator

Temperature fluctuations in the polar LS have large wings are more intermittent

Temperature PDF





Important contribution of the gravity waves to the temperature variability

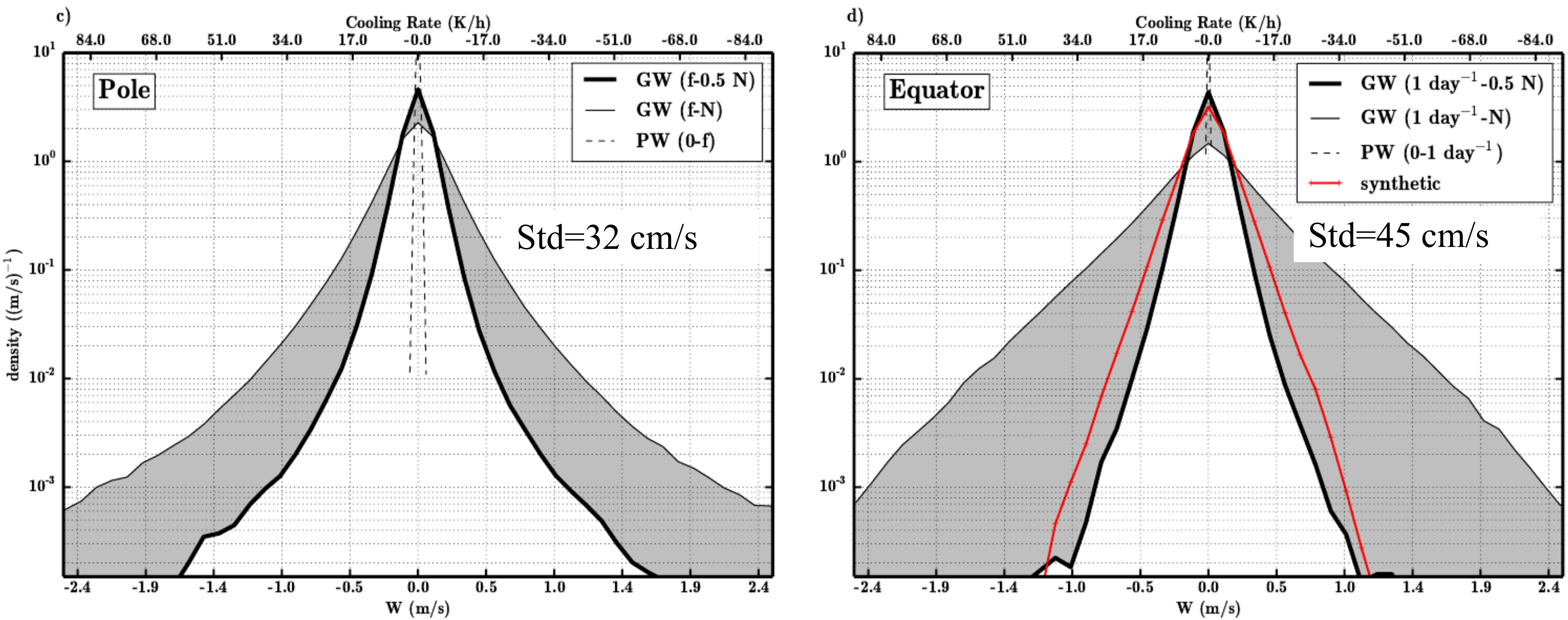
Gaussian PDF over the equator, non Gaussian PDF over the pole

Larger contribution of the wings to the variance in the polar flights.

Linked to intermittency in the GW field

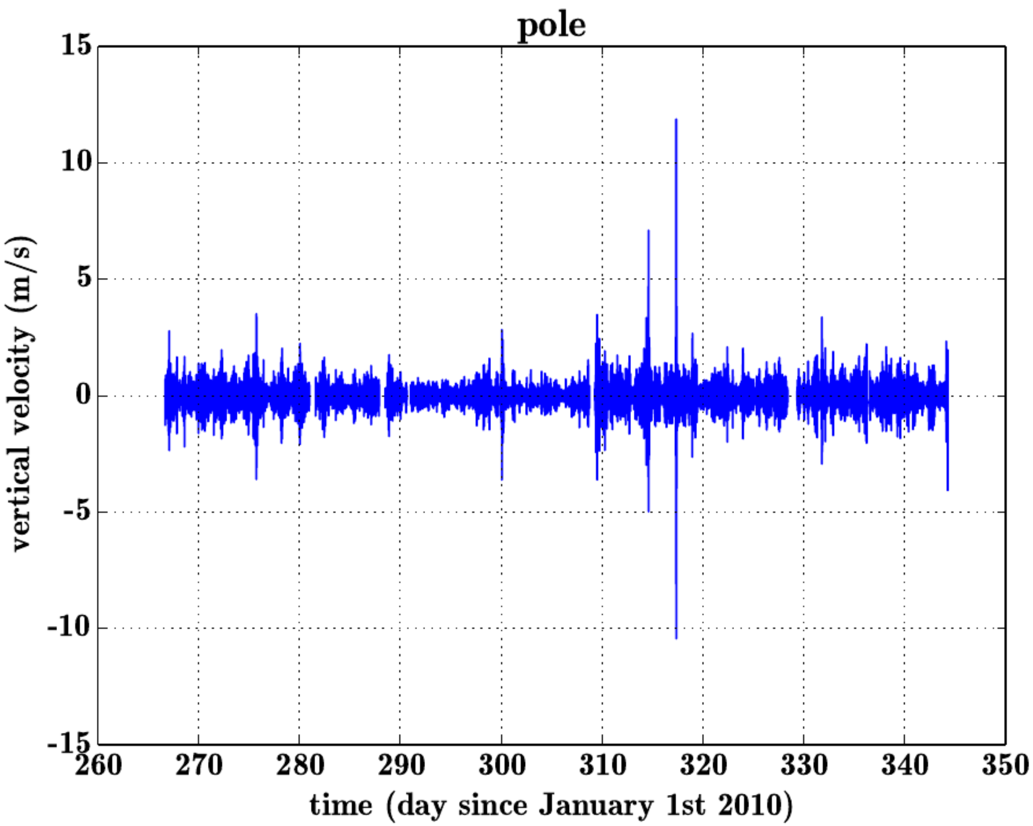
Vertical velocity/cooling rates are non Gaussian (intermittent)

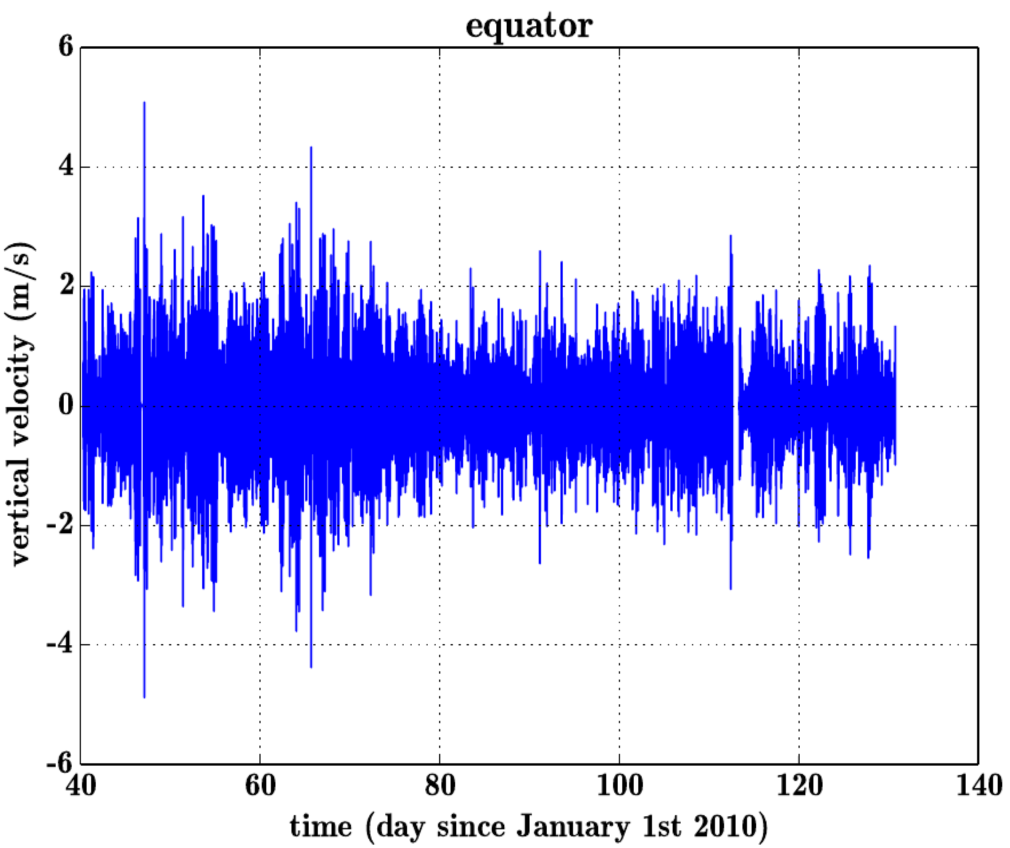
Vertical velocity/cooling rates PDF



Variability largely dominated by the (very) high frequencies (gravity waves >> planetary waves)
Non Gaussian PDFs both over the equator and the pole : intermittent field.
Larger contribution of the wings to the variance in the Southern Pole flights.

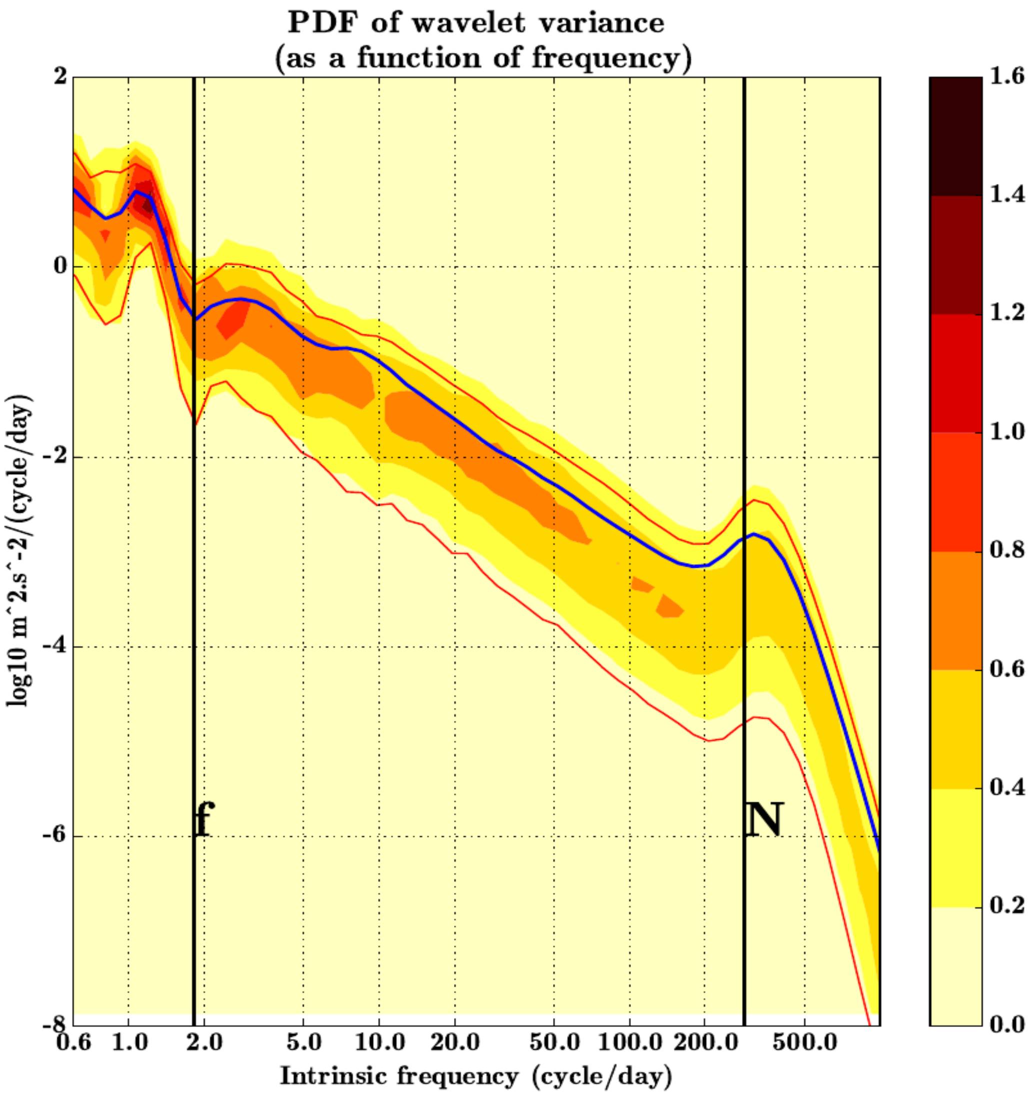
Intermittency in vertical velocity is weaker in the tropics, stronger over the pole



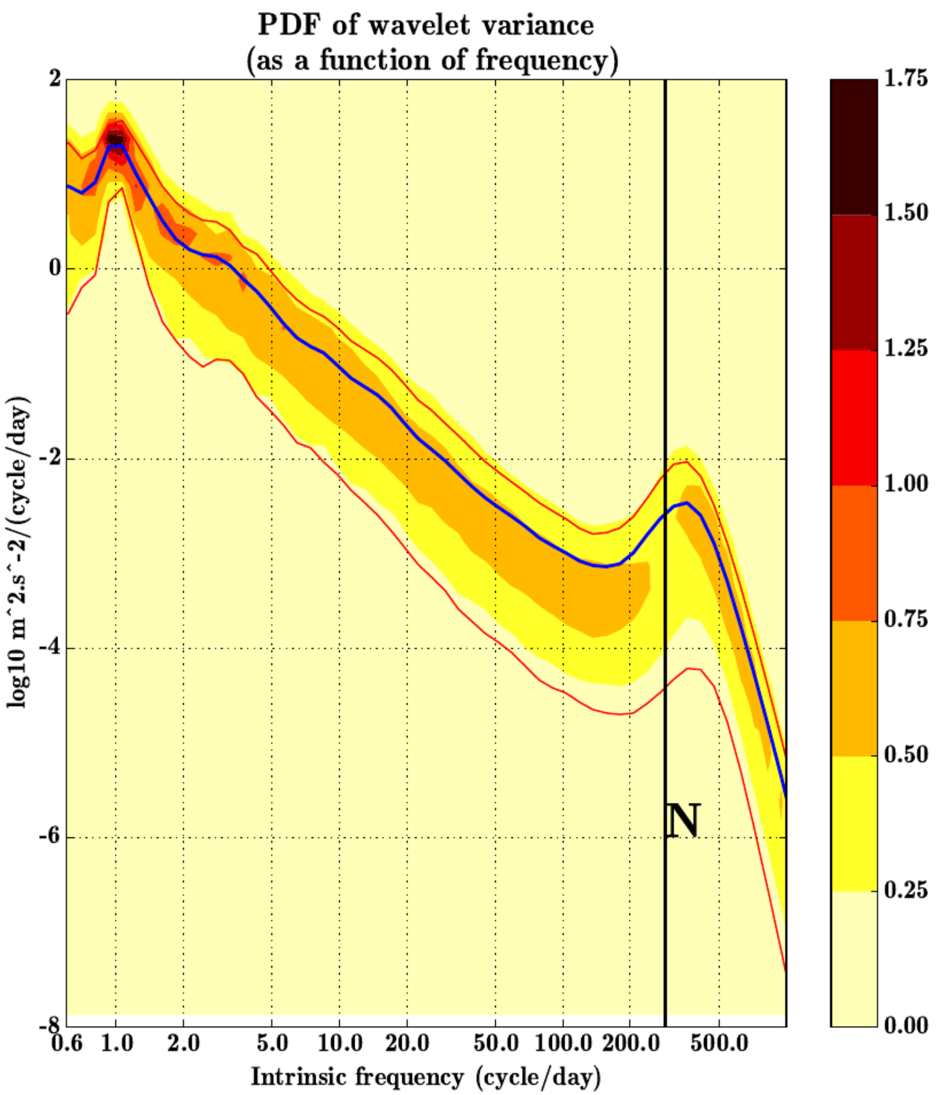


Intermittency of temperature fluctuations varies with frequency

Pole

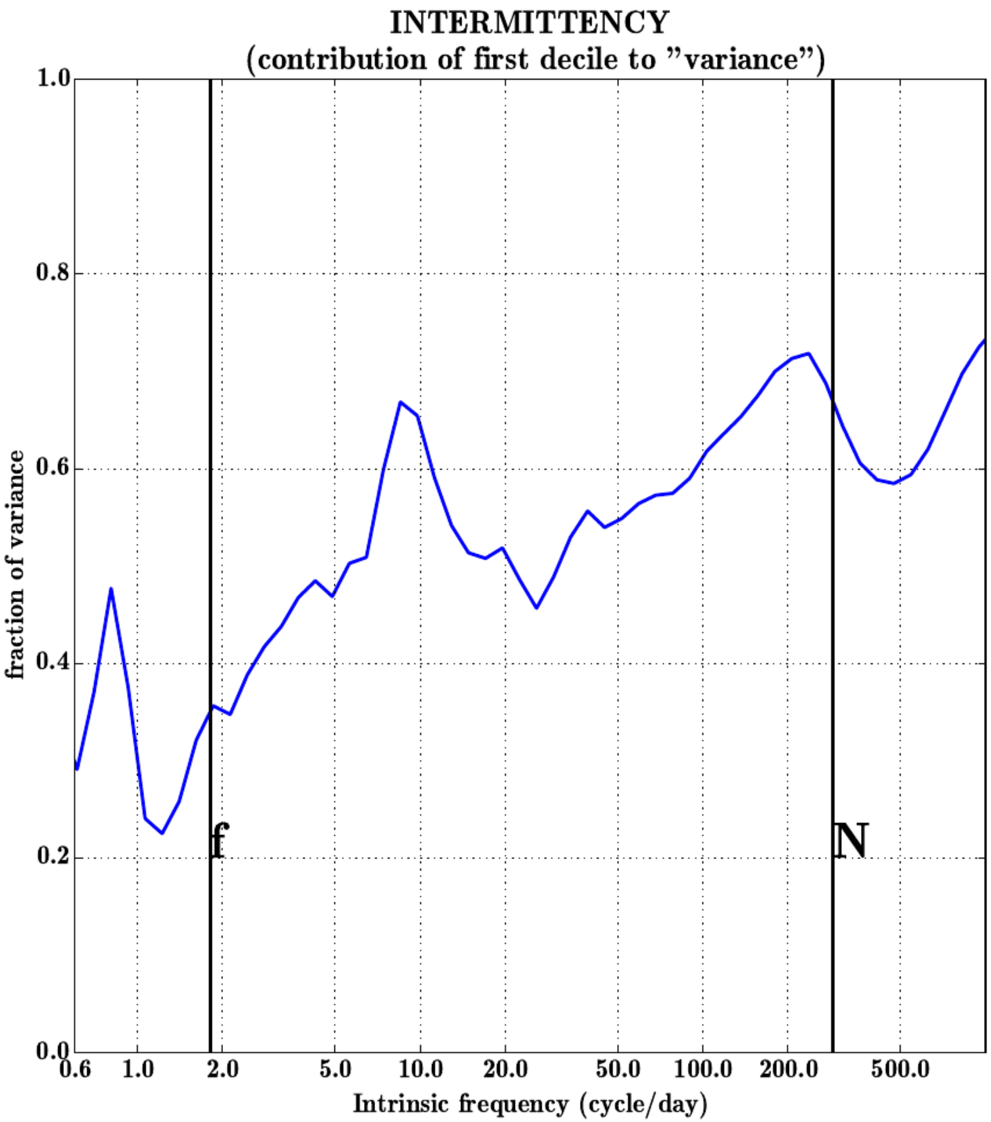


Equator

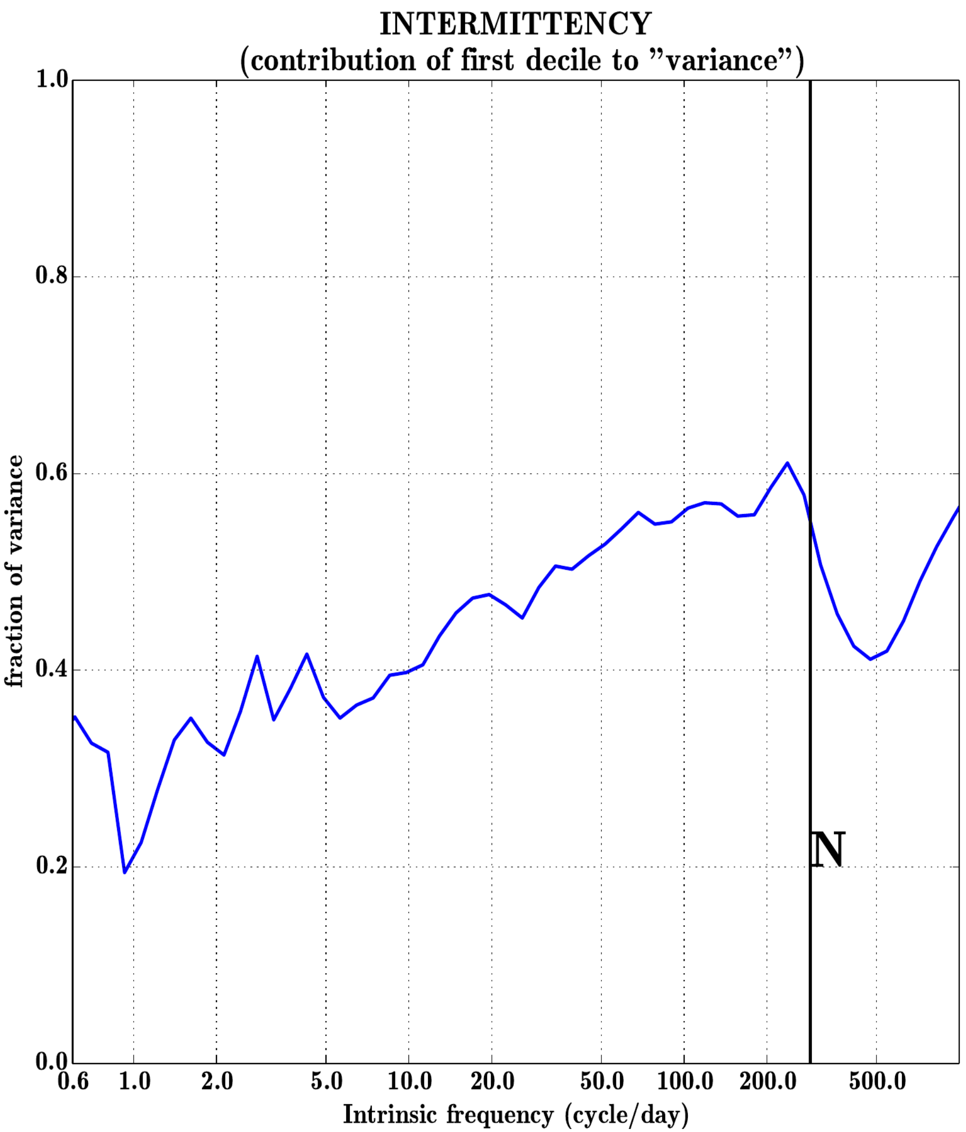


Intermittency increases with frequency

Pole

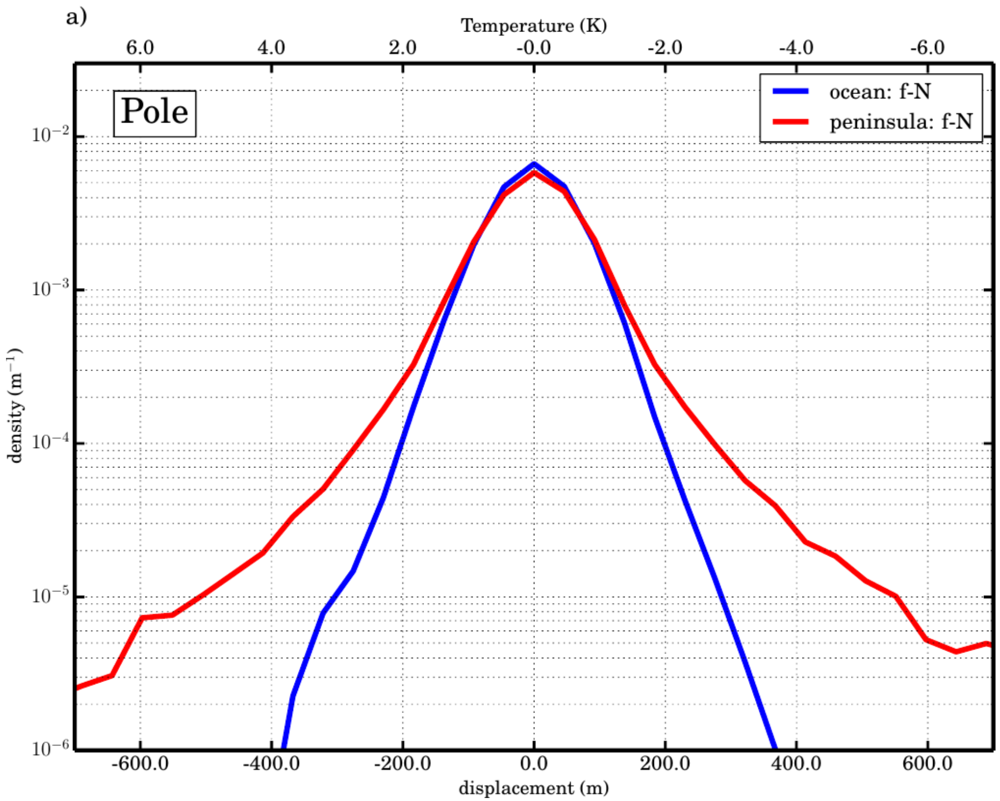


Equator

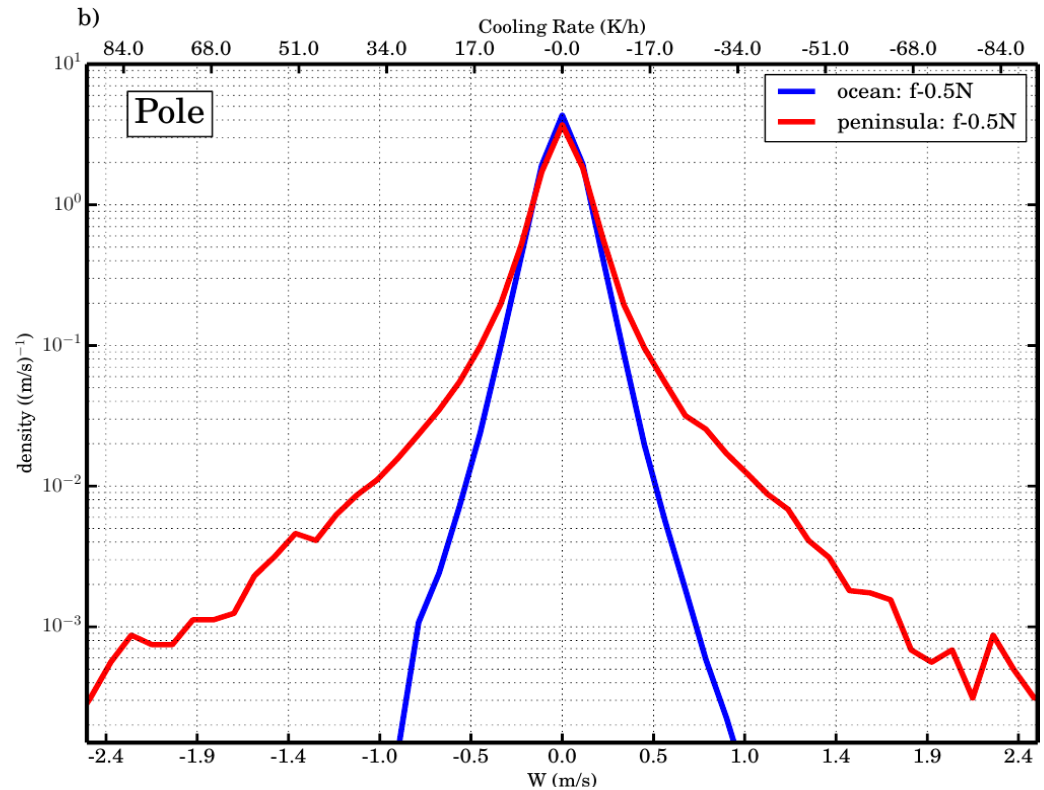


Large-intermittent T-W excursions over the pole are mainly tied to orography

Regional contributions over the pole



Temperature



Vertical velocity

Large wings over the pole are associated with **mountain waves** (regions of high topographic gradients : Antarctic peninsula versus ocean and the flat Antactic plateau), both for temperature and vertical velocity

Summary

- Superpressure balloon observations quantify Lagrangian temperature fluctuations

-Those observations confirm the scaling behavior in the mid-frequency range (T perturbations are the strongest at low frequencies, W fluctuations are the strongest at high frequencies)

- They suggest a peak of vertical velocity variance near the buoyancy frequency

-GW induced temperature fluctuations are close to gaussian in the tropics but not over the pole : large tails due to intermittency

-GW vertical velocity fluctuations are non gaussian in both regions

-Intermittency of T fluctuations increases with intrinsic frequency

-AR-1 process reproduce realistic temperature fluctuations in the tropics (simple parameterization)

Geophysical Research Letters

RESEARCH LETTER

10.1002/2016GL068148

Lagrangian temperature and vertical velocity fluctuations due to gravity waves in the lower stratosphere

Aurélien Podglajen[1], Albert Hertzog[2], Riwal Plougonven[1], and Bernard Legras[1]

[1]Laboratoire de Météorologie Dynamique, CNRS-UMR8539, Institut Pierre Simon Laplace, École Normale Supérieure, École polytechnique, Université Pierre et Marie Curie, Paris, France, [2]Laboratoire de Météorologie Dynamique/IPSL, UPMC Univ Paris 06, CNRS, Palaiseau, France

Key Points:

- Long-duration balloon observations are used to characterize Lagrangian temperature fluctuations
- Intrinsic frequency spectra and PDFs are derived for temperature and cooling rates

Backup slides

Balloon response to air motions

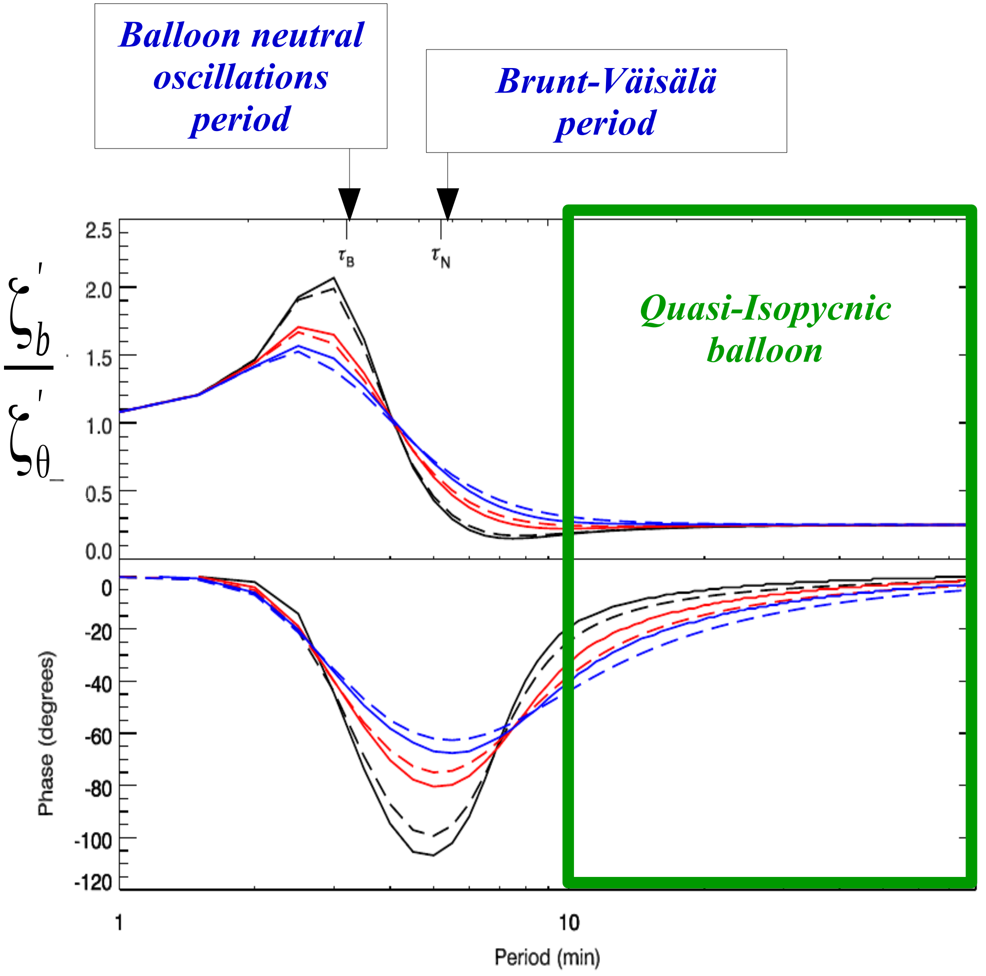
However, the balloon is no longer isopycnic at high frequencies, its vertical position ζ_b' evolves as :

$$\frac{\partial^2 \zeta_b'}{\partial t^2} = -\omega_B^2 \zeta_b' + \frac{2}{3} g R - A \left(\frac{\partial \zeta_b'}{\partial t} - w' \right) \left| \frac{\partial \zeta_b'}{\partial t} - w' \right| + \frac{\partial w'}{\partial t}$$

Numerical simulations of the balloon response to harmonic “atmospheric” oscillations :

Amplitude and phase response

Vincent and Hertzog, 2014

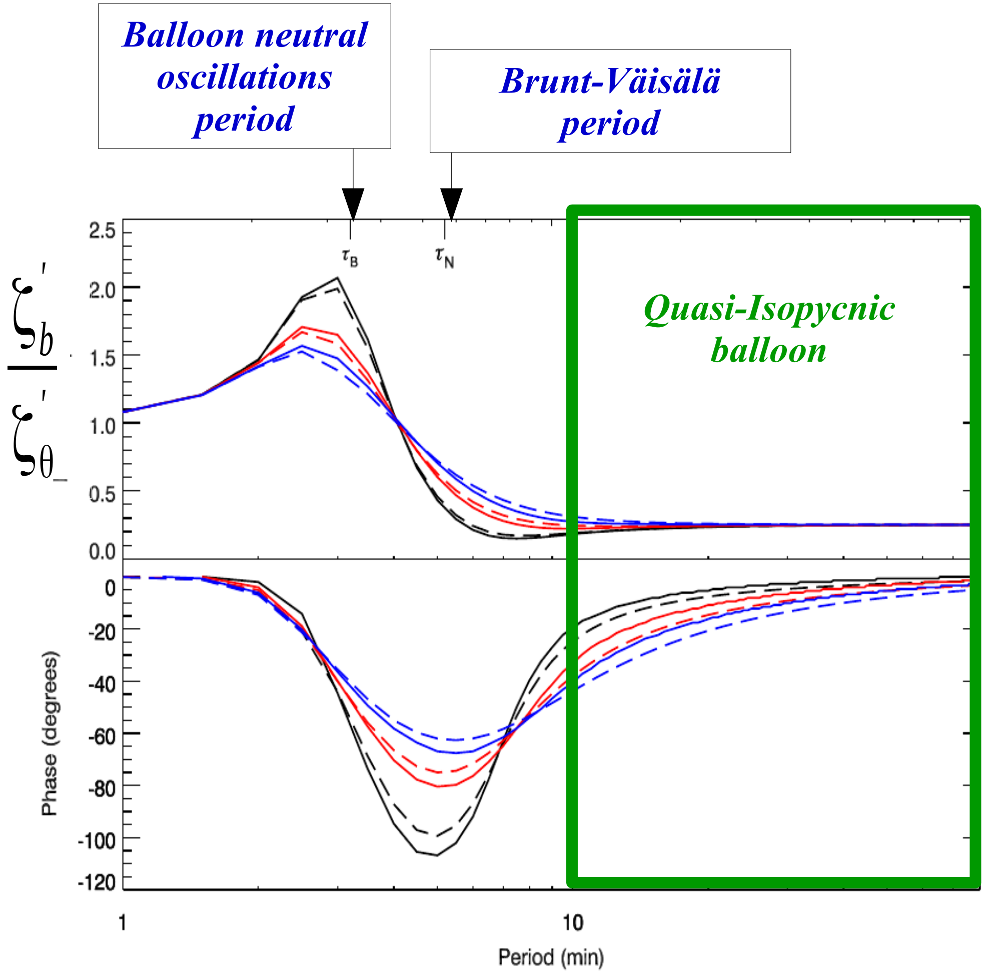


Balloon response to air motions

However, the balloon is no longer isopycnic at high frequencies, its vertical position ζ_b' evolves as :

$$\frac{\partial^2 \zeta_b'}{\partial t^2} = -\omega_{\mathrm{B}}^2 \zeta_b' + \frac{2}{3} g R - A \left(\frac{\partial \zeta_b'}{\partial t} - w' \right) \left| \frac{\partial \zeta_b'}{\partial t} - w' \right| + \frac{\partial w'}{\partial t}$$

Isopycnic behavior: $0 = -\omega_{\mathrm{B}}^2 \zeta_b' + \frac{2}{3} g R$

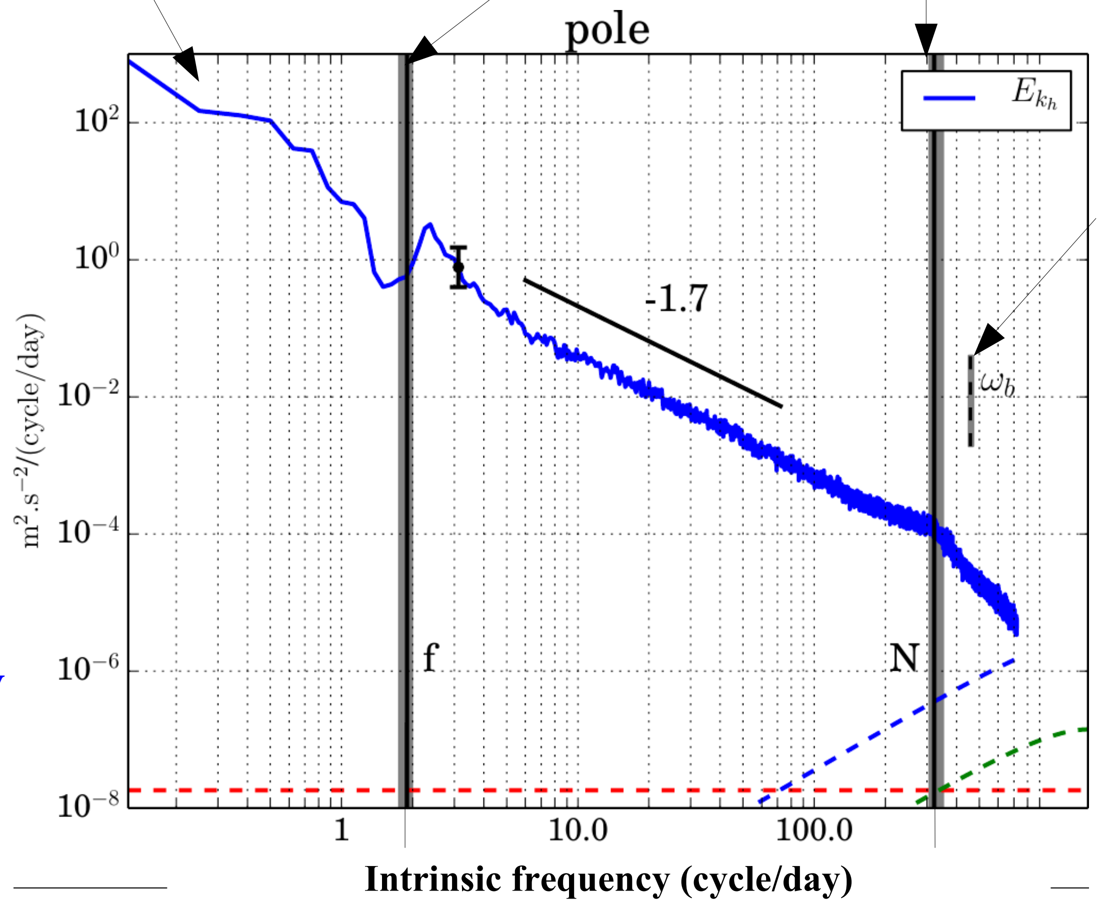


Balloon observations resolve the whole GW spectrum

Concordiasi and Pre-concordiasi observations resolve the intrinsic frequency spectra of atmospheric fluctuations

In particular, they resolve the whole gravity-wave subrange and include **horizontal kinetic energy spectra**

$$E_{k_h} = \frac{1}{2}(u'^2 + v'^2)$$



Podglajen et al., 2016, GRL

Variance at the Brunt-Väisälä

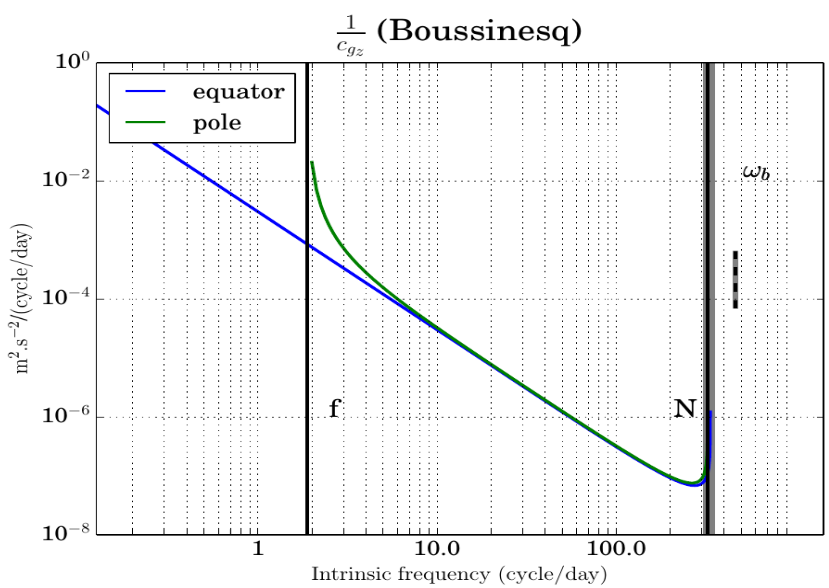
Strong enhancement in potential and vertical kinetic energy power spectra at the Brunt-Vaisala frequency (trapped-near reflection waves)

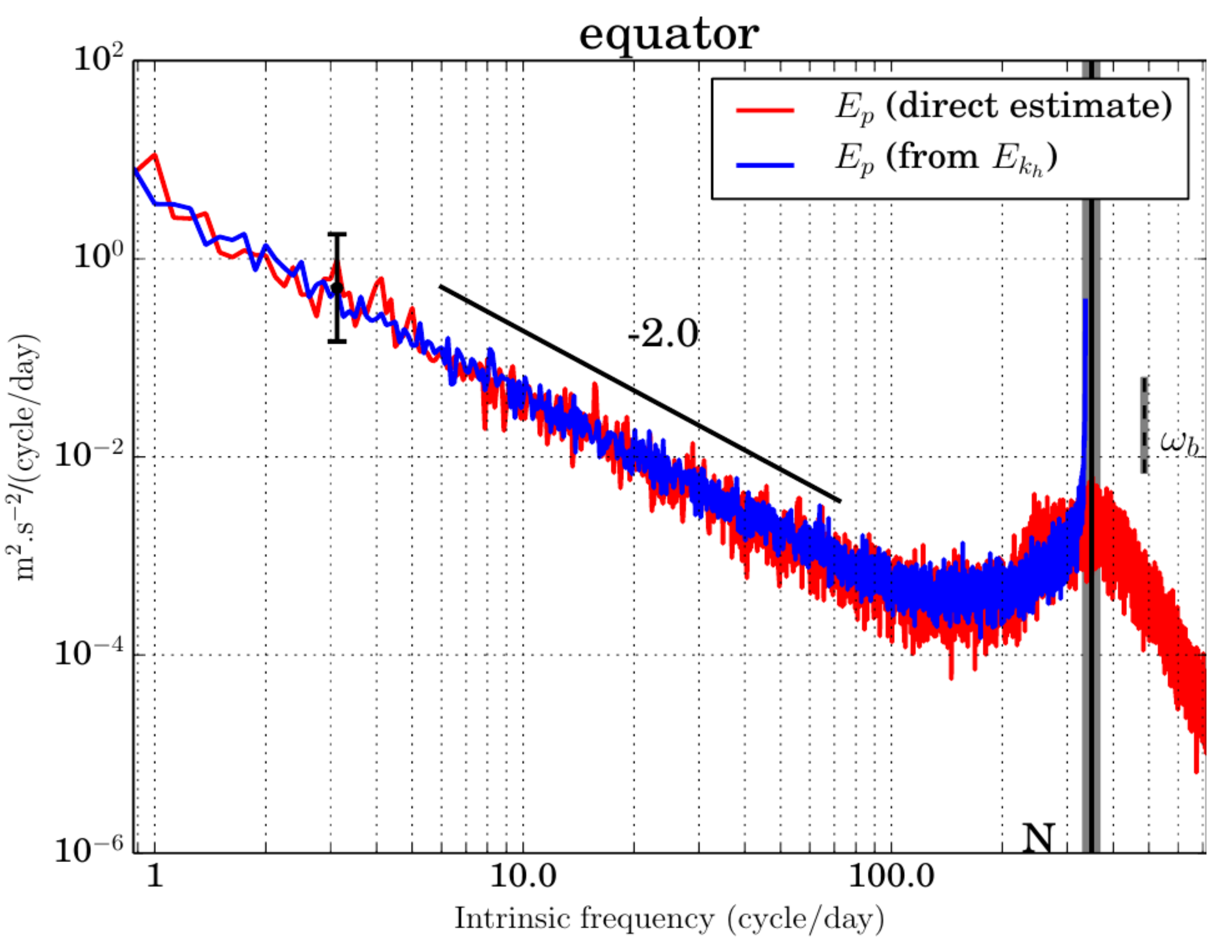
Artifact of balloon observations? (non isopycnic balloon response)? Maybe but

Potential energy

$$E_p = \left(\frac{N^2}{N^2 - \hat{\omega}^2}\right)\left(\frac{\hat{\omega}^2 - f^2}{\hat{\omega}^2 + f^2}\right) E_{k_h}$$

Horizontal kinetic energy

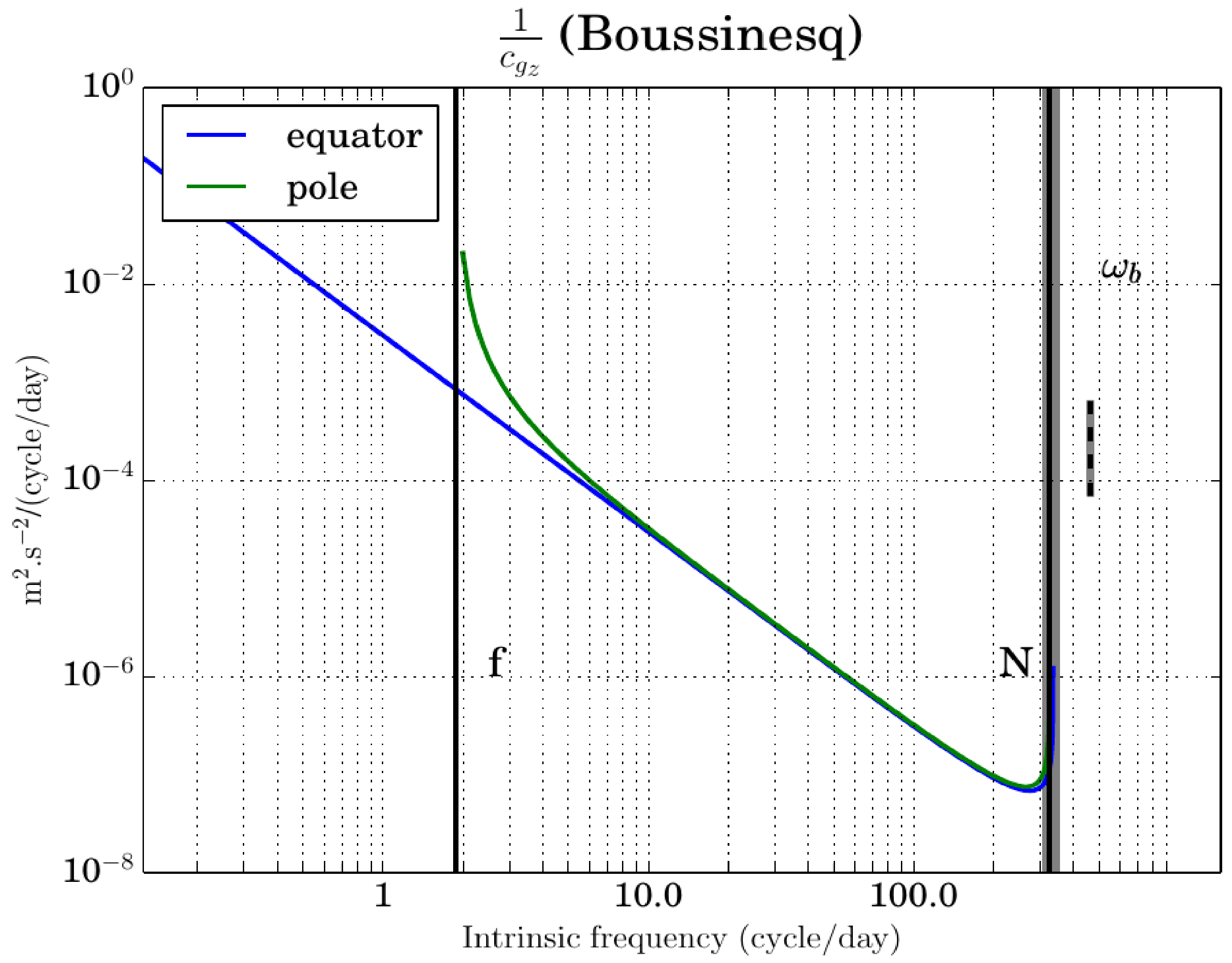




Variance at the Brunt-Väisälä

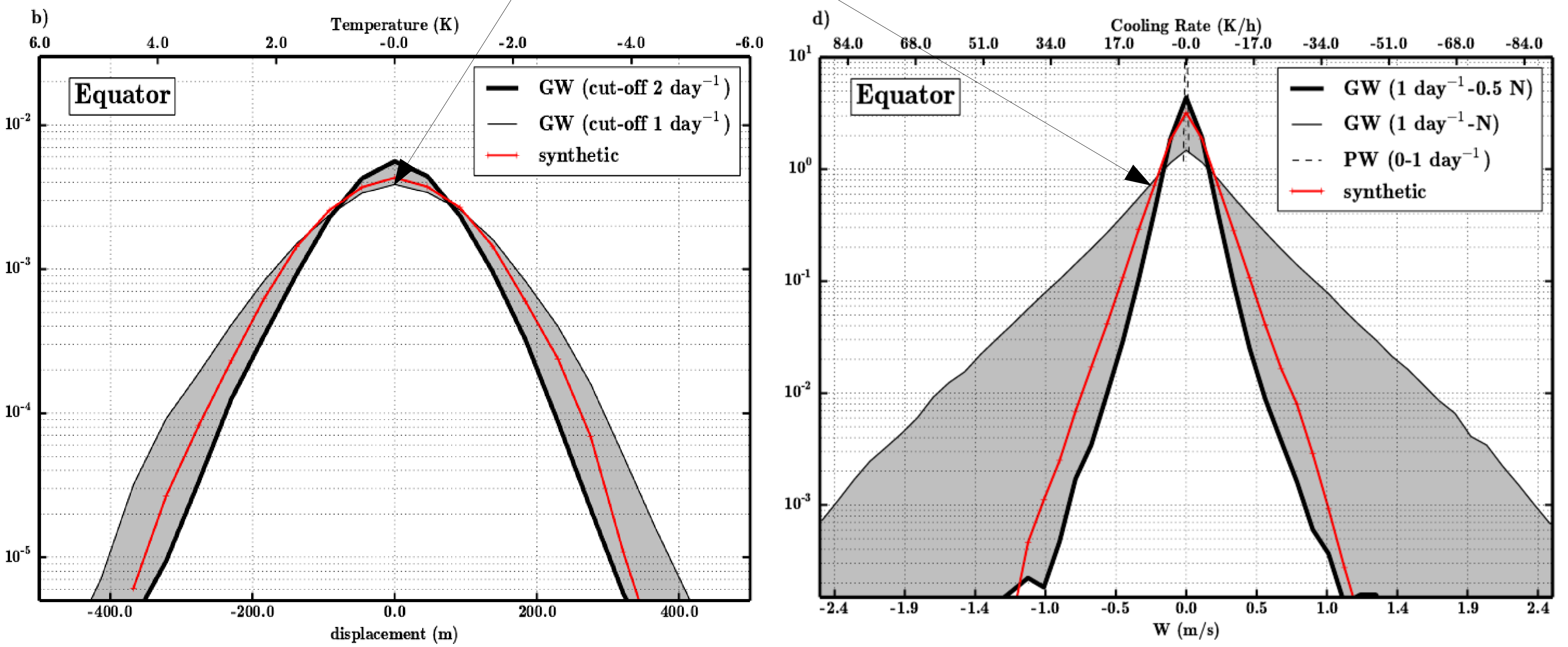
Strong enhancement in potential and vertical kinetic energy power spectra at the Brunt-Vaisala frequency (trapped-near reflection waves)

Artifact of balloon observations? (non isopycnic balloon response)? Maybe but



Synthetic Lagrangian temperature time series

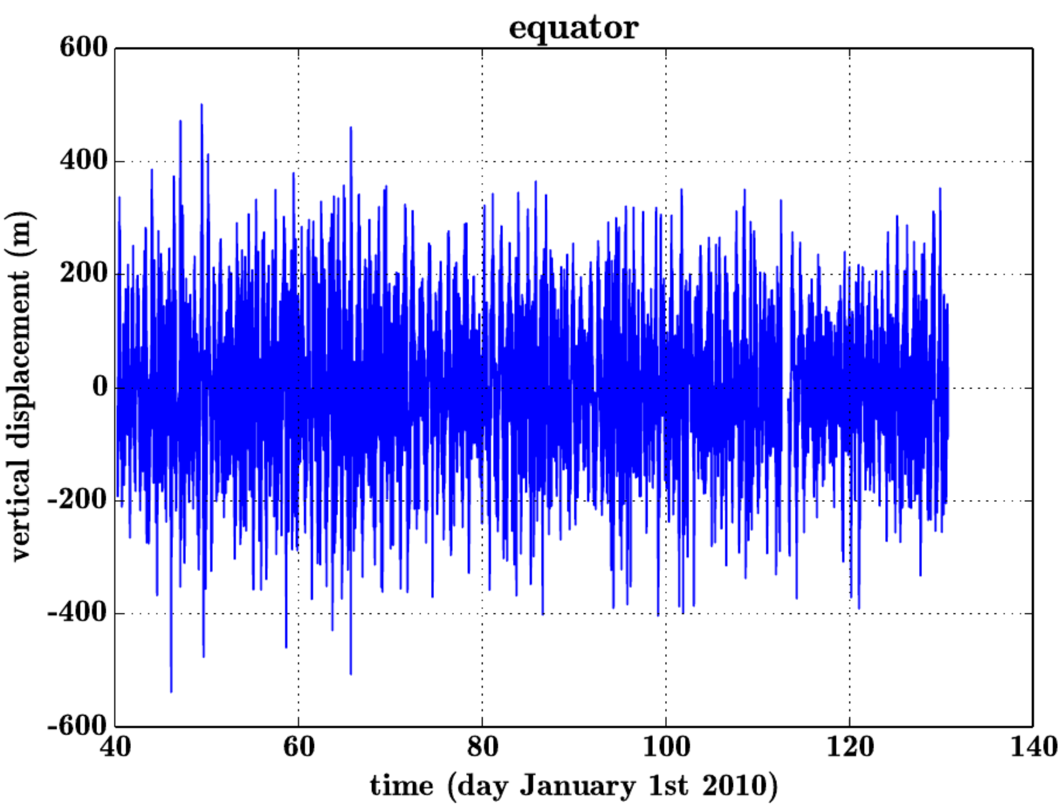
PDF of synthetic temperature and cooling rates time series

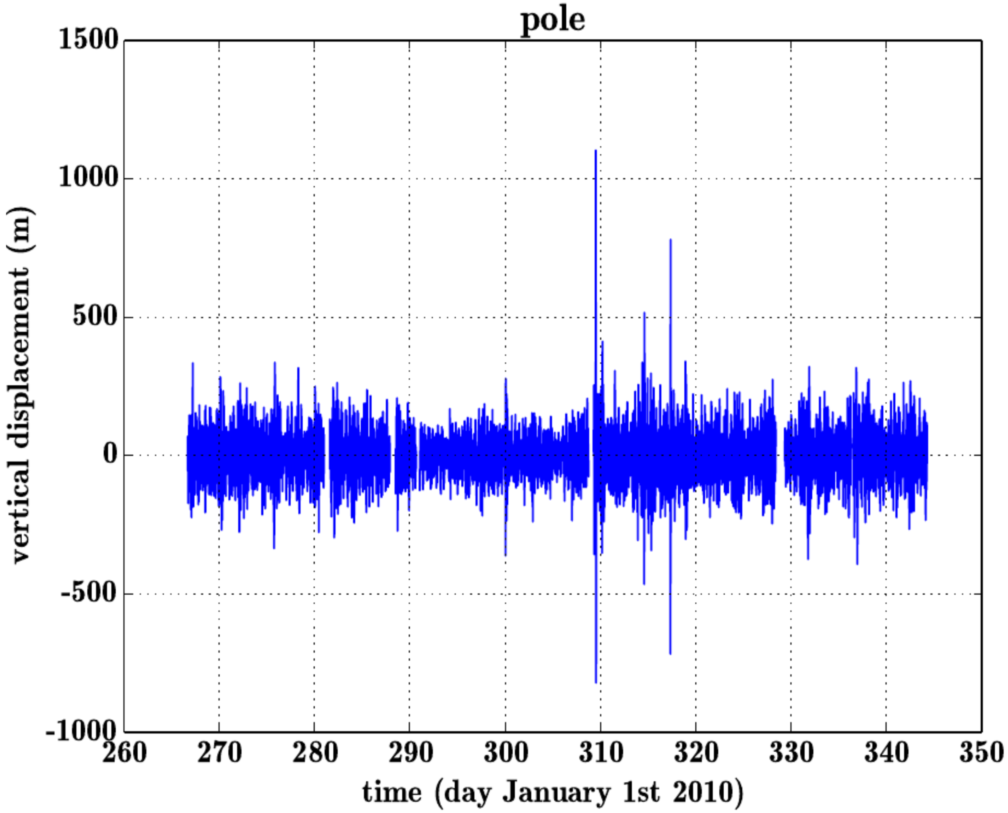


Podglajen et al., accepted GRL

Temperature fluctuations : Equator vs pole

Temperature PDF





Vertical displacement

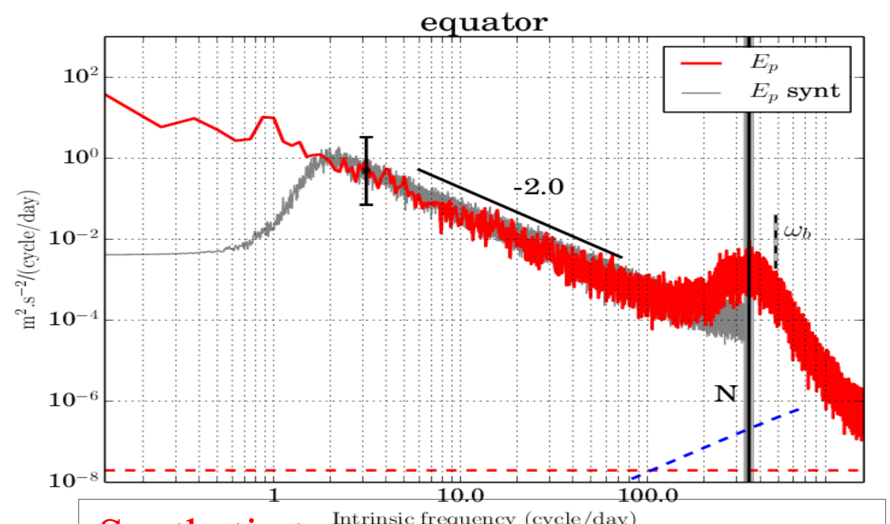
Important contribution of the gravity waves to the temperature variability

Gaussian PDF over the equator, non Gaussian PDF over the pole

Larger contribution of the wings to the variance in the polar flights.

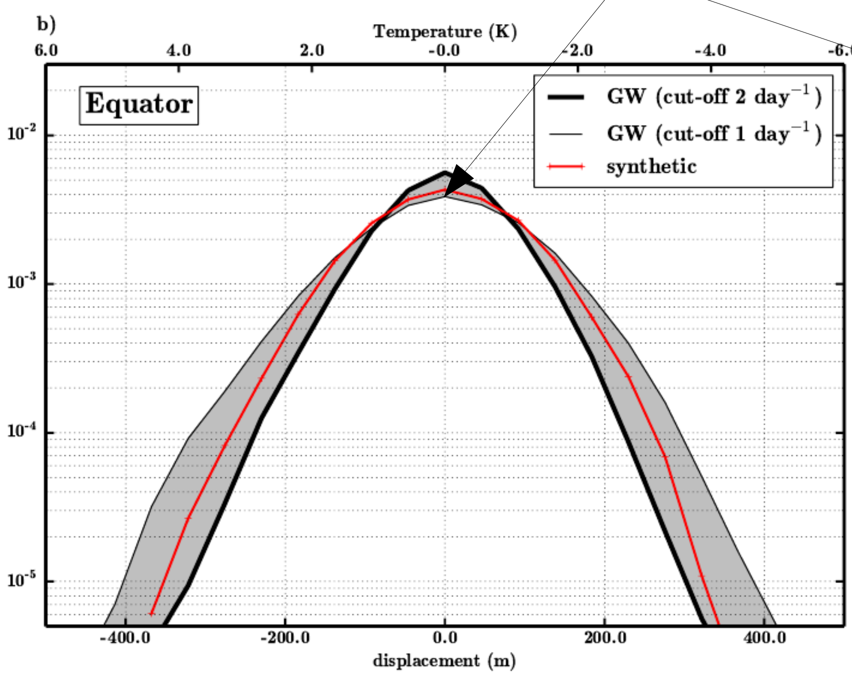
Synthetic AR-1 processes allow to reproduce realistic time series of Lagrangian T-fluctuations

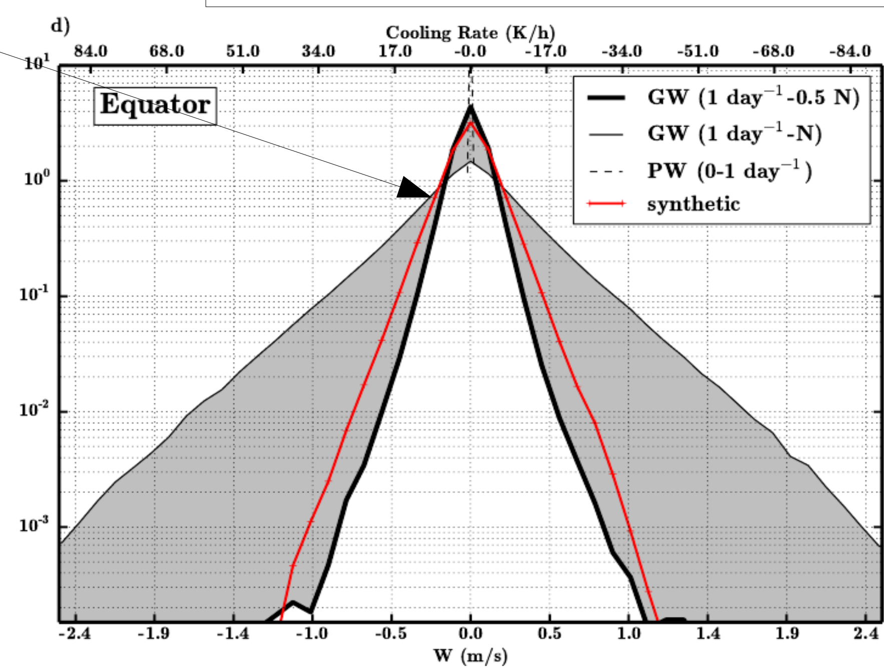
$$\zeta'_{t+dt} = \zeta'_t + W \cdot dt$$



Synthetic temperature spectrum

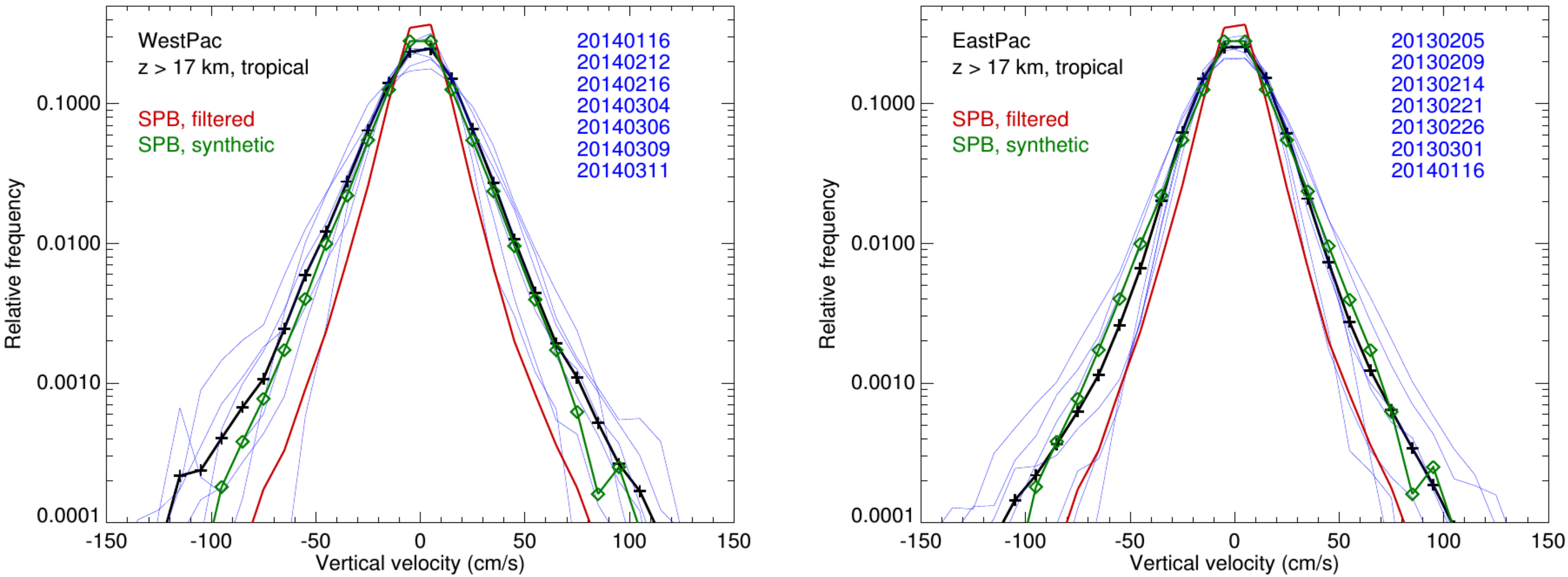
PDF of synthetic temperature and cooling rates time series





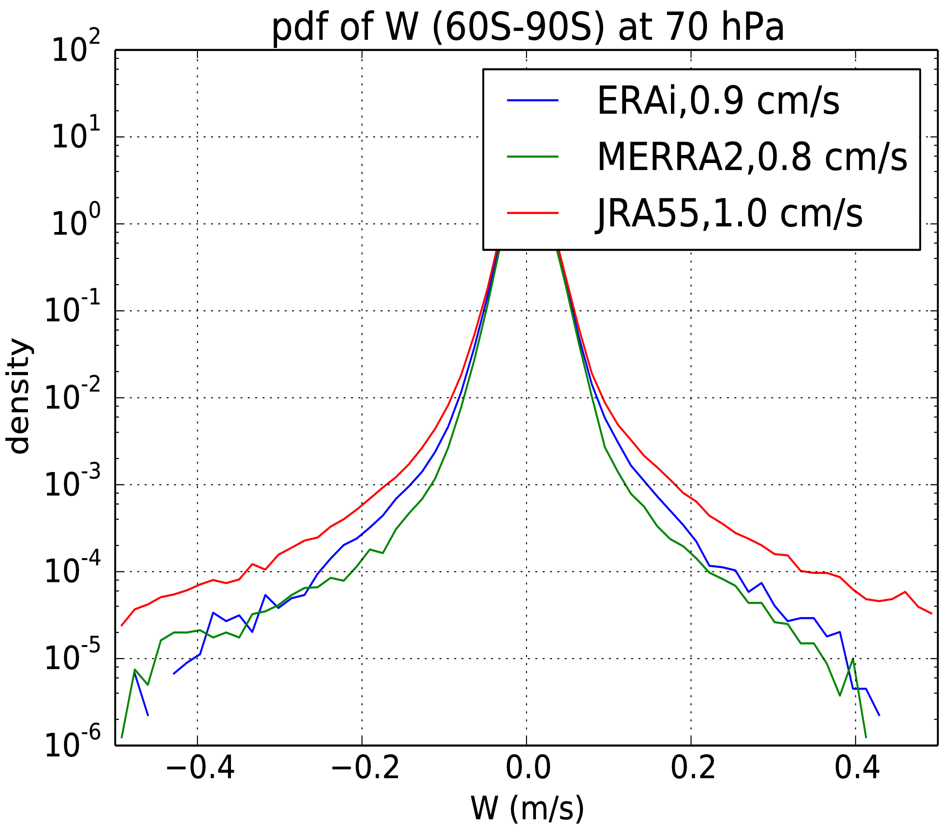
Synthetic Lagrangian temperature time series

Satisfactory agreement with ATTREX MMS data for the deep tropics

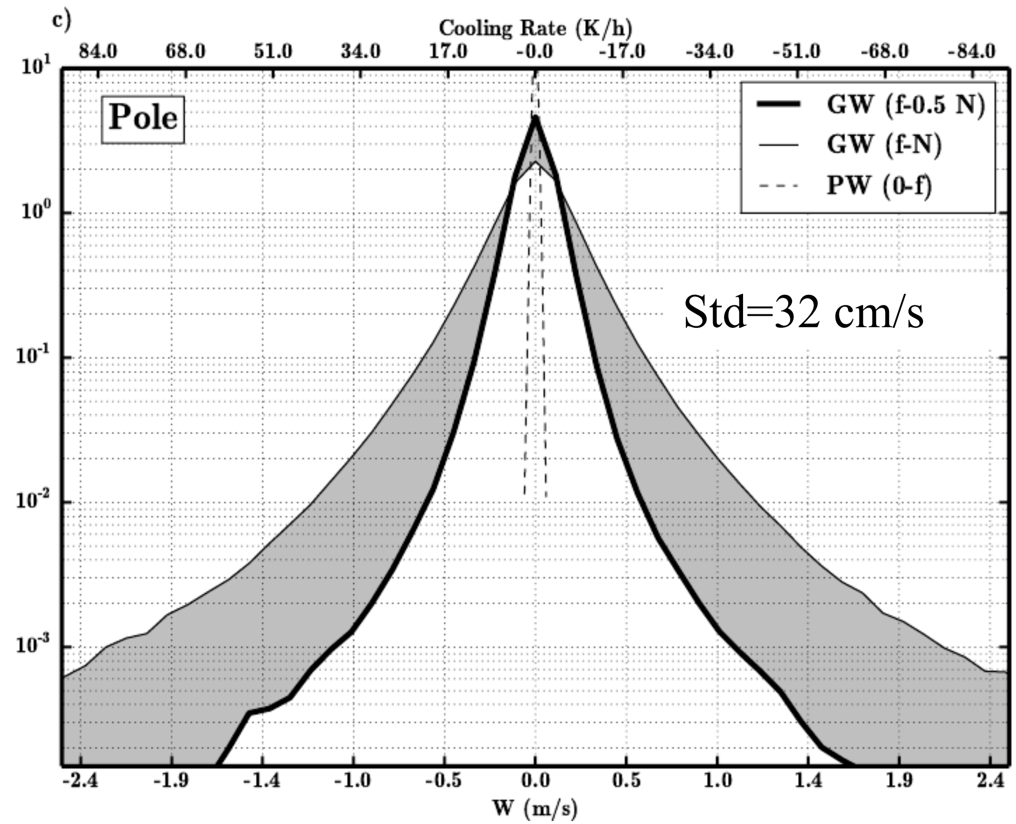


Jensen et al. , submitted to GRL

Vertical velocity in reanalyses



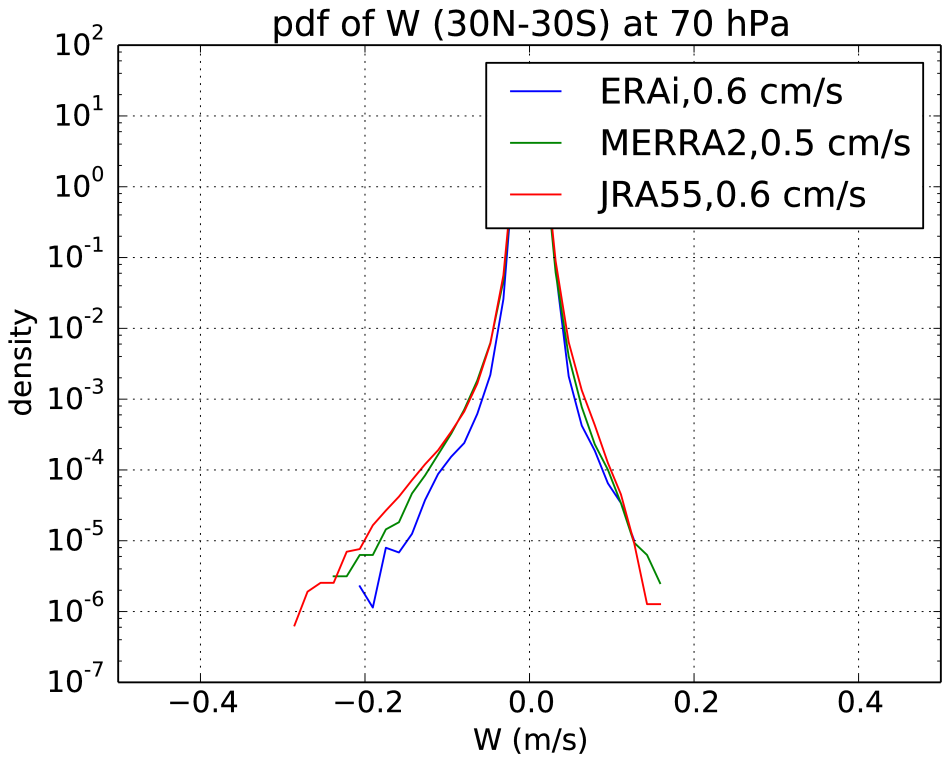
Reanalyses



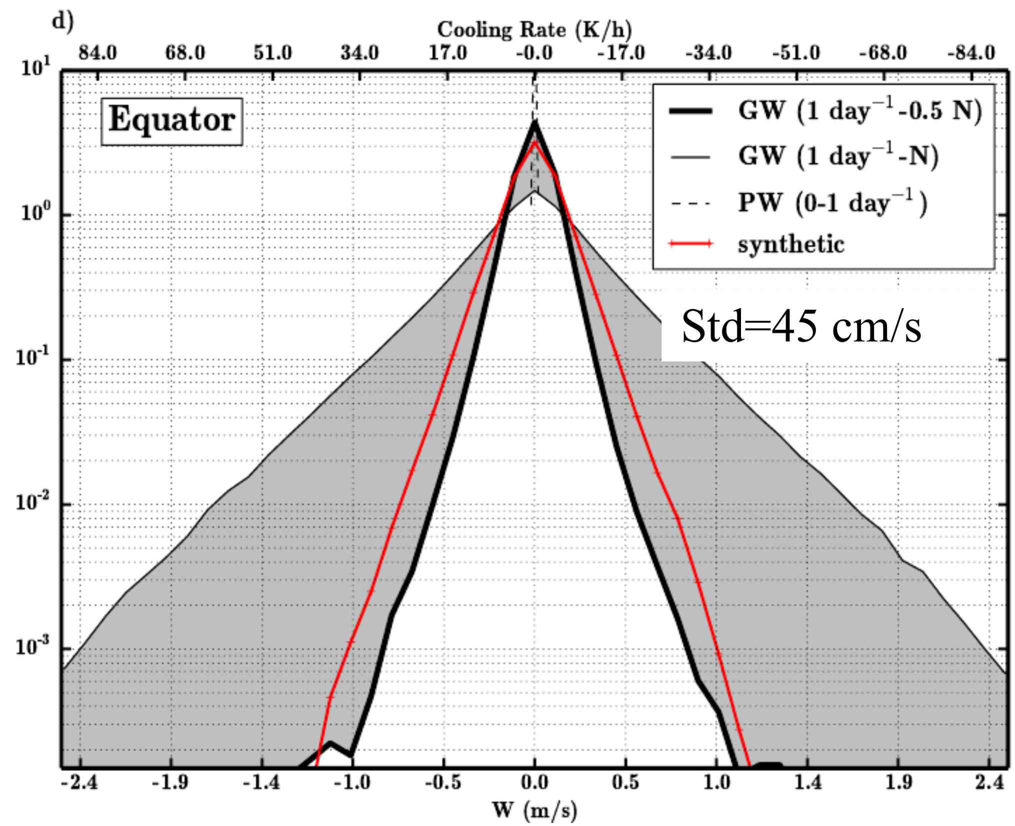
Balloon observations

Strong underestimation of the vertical velocity in the tropics in modern reanalyses, comparable shapes

Vertical velocity in reanalyses



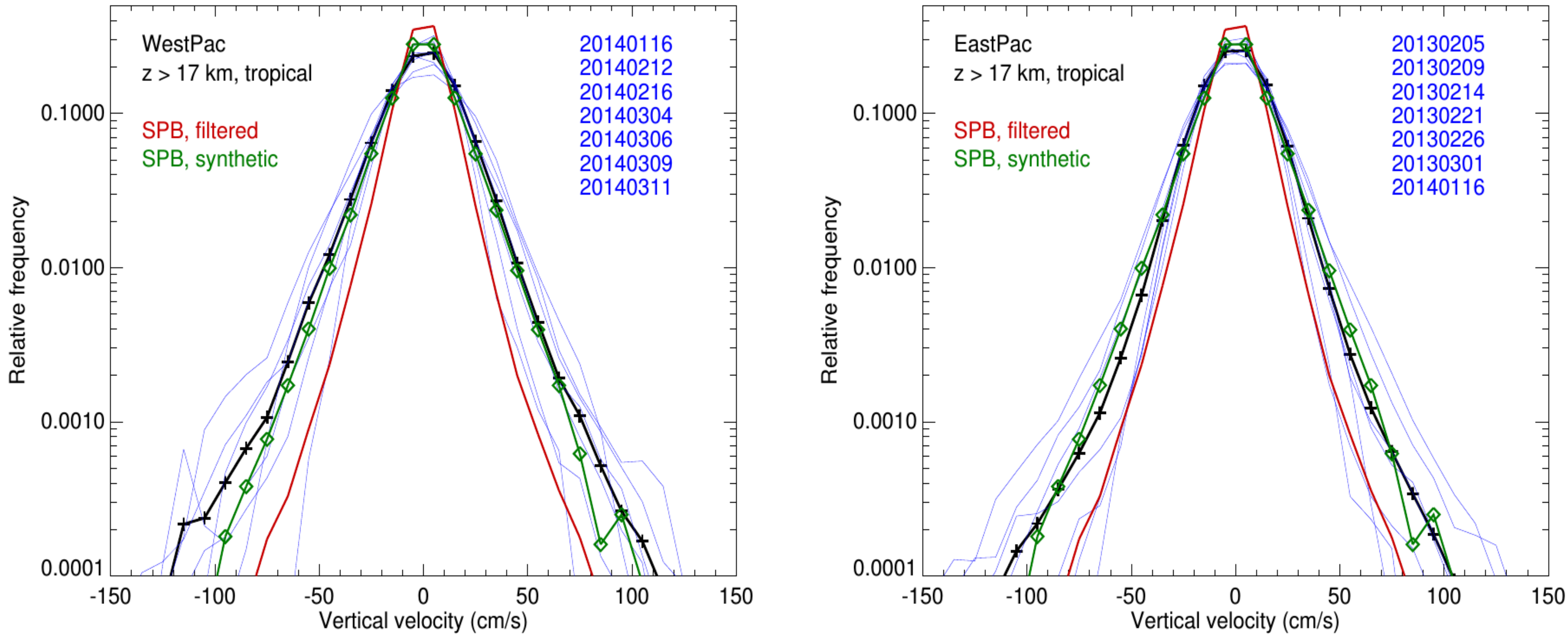
Reanalyses



Balloon observations

Strong underestimation of the vertical velocity in the tropics in modern reanalyses, comparable shapes

The distribution of vertical velocity in the tropical lower stratosphere agrees between the balloon and aircraft observations



Jensen et al. , in revision for GRL

Lagrangian temperature vs Eulerian temperature fluctuations

Eulerian and Lagrangian temperature fluctuations are both due to the vertical displacement ζ_θ of air parcels, for different reasons:

The Lagrangian temperature fluctuations are mainly due to adiabatic expansion :

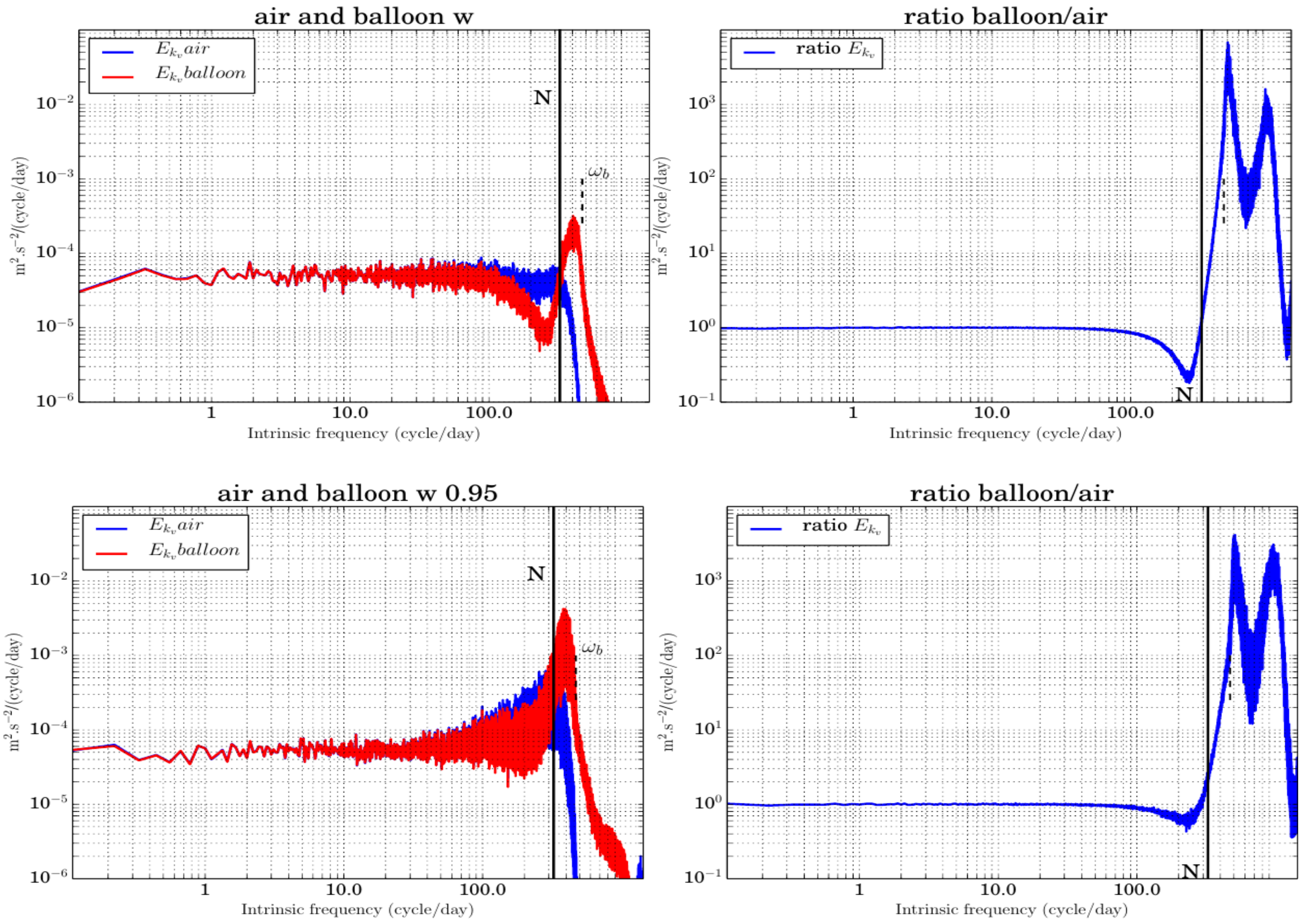
$$T_l' = -\frac{g}{C_P}\zeta_\theta$$

While the Eulerian ones are due to vertical advection in a stable (non isentropic, $N^2>0$)

$$T_l' = T' + \zeta_\theta \frac{d\bar{T}}{dz}$$

$$T' = -\zeta_\theta \left(\frac{g}{C_P} + \frac{d\bar{T}}{dz}\right) = \frac{C_P}{g^2}\bar{T}N^2 T_l'$$

Balloon response to air motions and variance at the Brunt Vaisala frequency

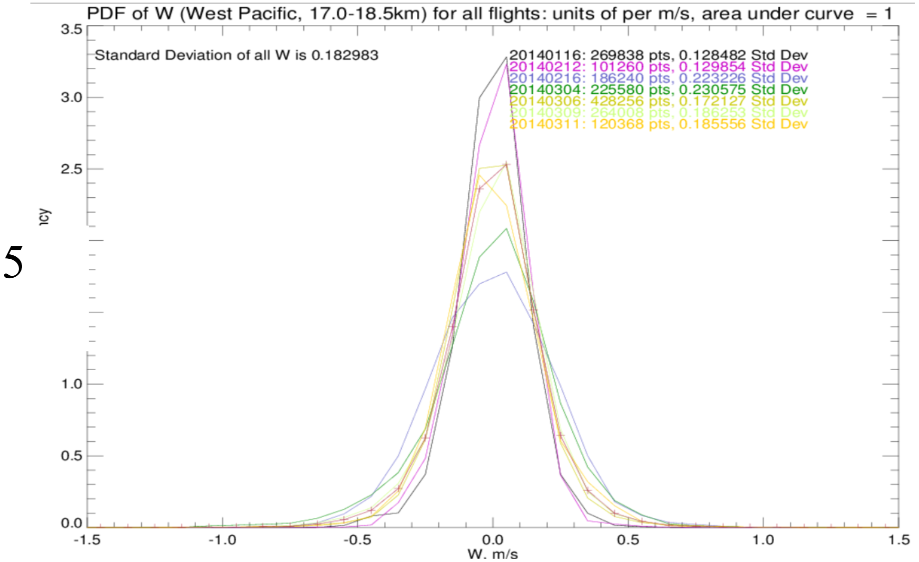


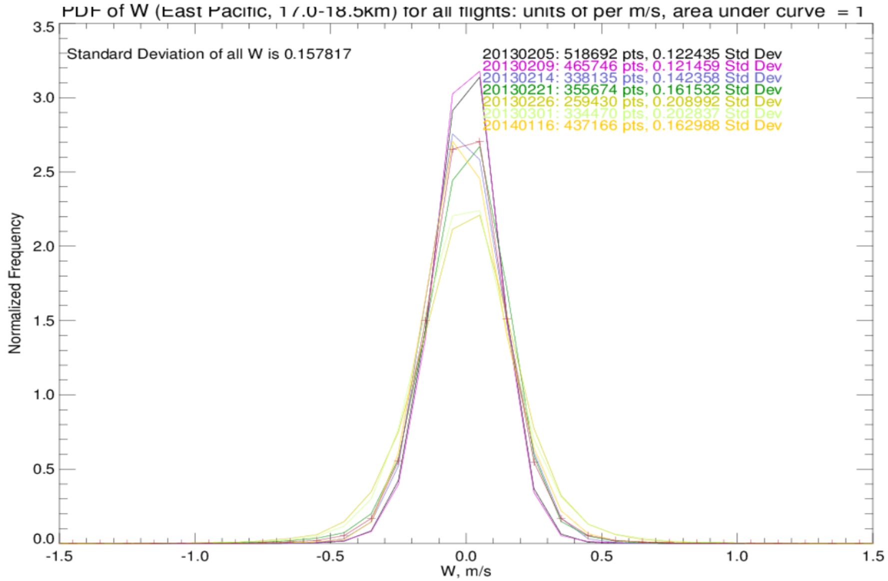
Altitude correction for Lagrangian temperature perturbations

ATTREX Western Pacific

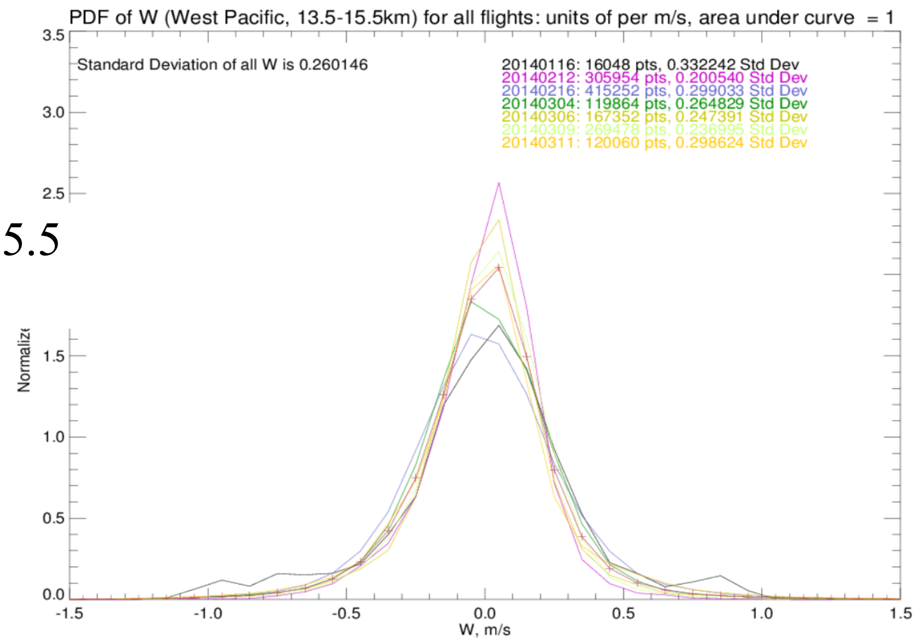
ATTREX Eastern Pacific

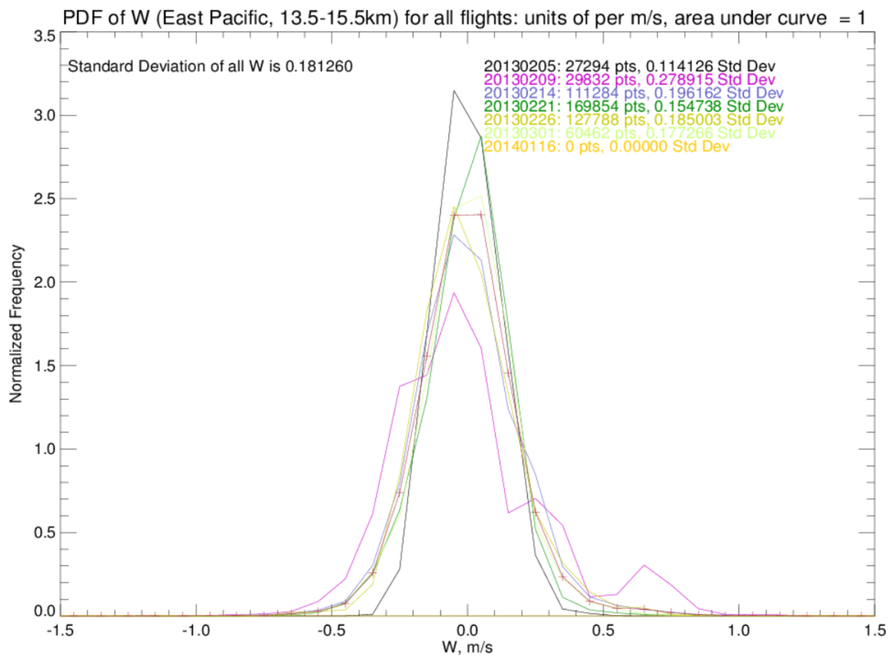
17-18.5 km





13.5-15.5 km





Courtesy of L. Pfister

Lagrangian temperature vs Eulerian temperature perturbations

Eulerian and Lagrangian temperature fluctuations are both due to the vertical displacement ζ_θ of air parcels, for different reasons:

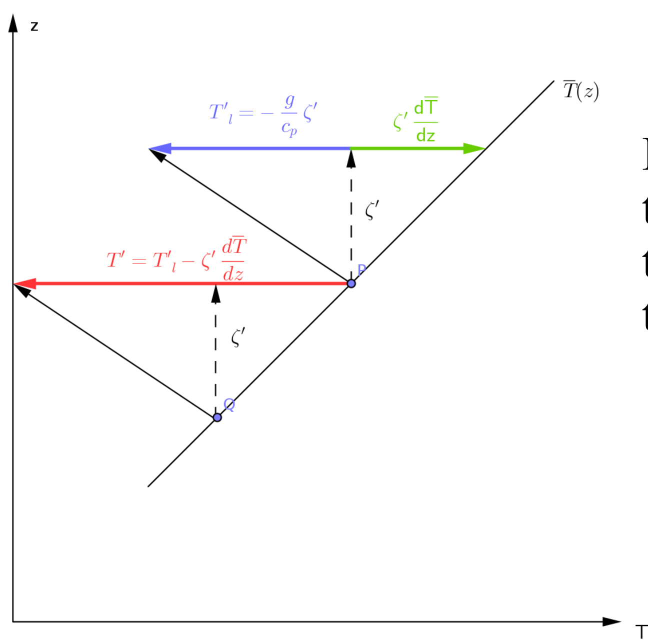
The Lagrangian temperature fluctuations are mainly due to adiabatic expansion :

$$T_l' = -\frac{g}{C_P}\zeta_\theta$$

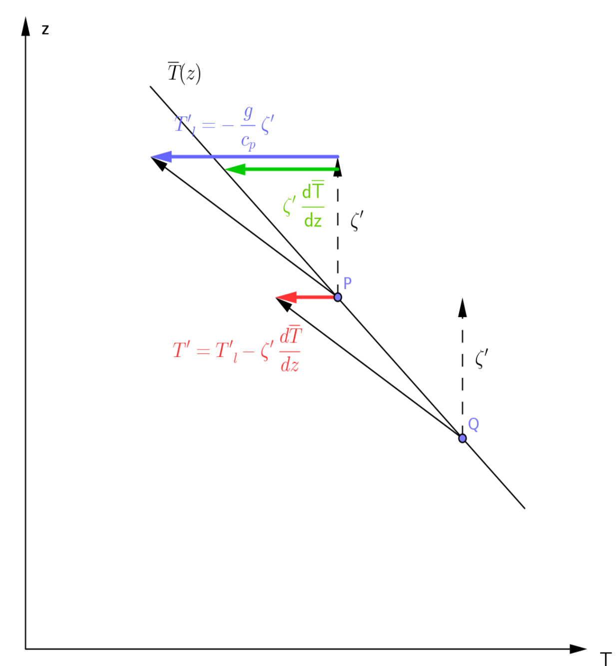
While the Eulerian ones are due to vertical advection in a stable (non isentropic, $N^2>0$)

$$T_l' = T' + \zeta_\theta \frac{d\bar{T}}{dz}$$

$$T' = -\zeta_\theta\left(\frac{g}{C_P} + \frac{d\bar{T}}{dz}\right) = \frac{C_P}{g^2}\bar{T}N^2T_l'$$

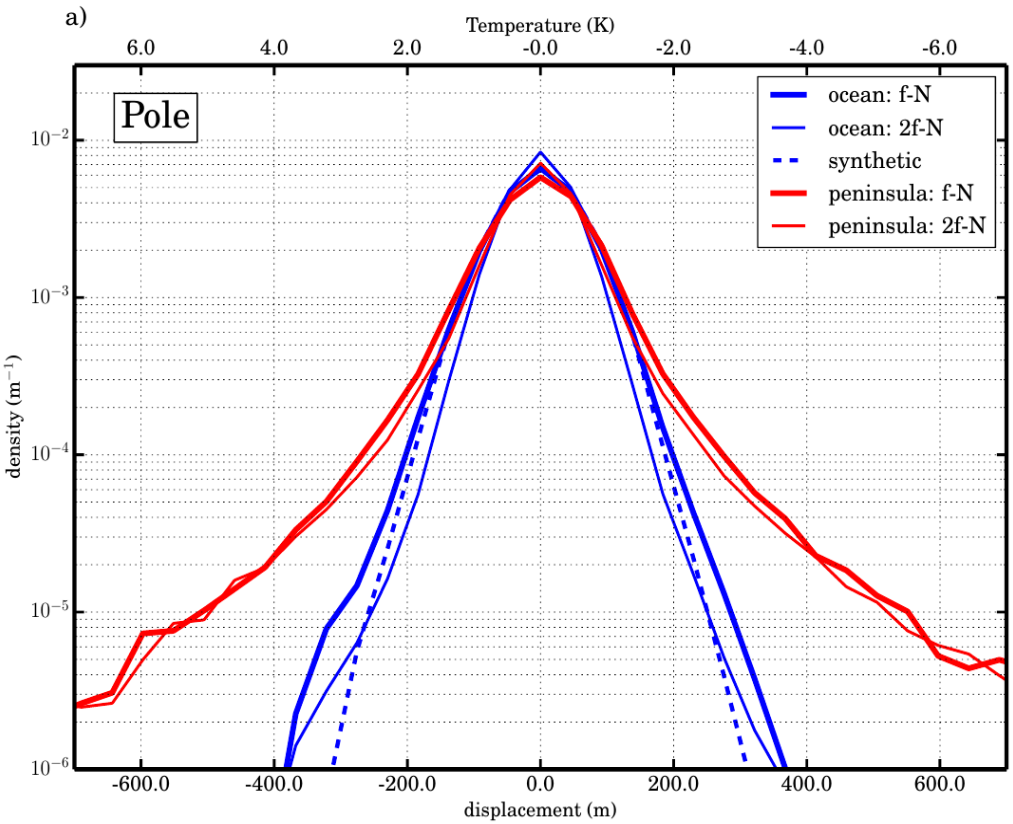


Eulerian vs Lagrangian temperature perturbation in the stratosphere (left) and troposphere (right)

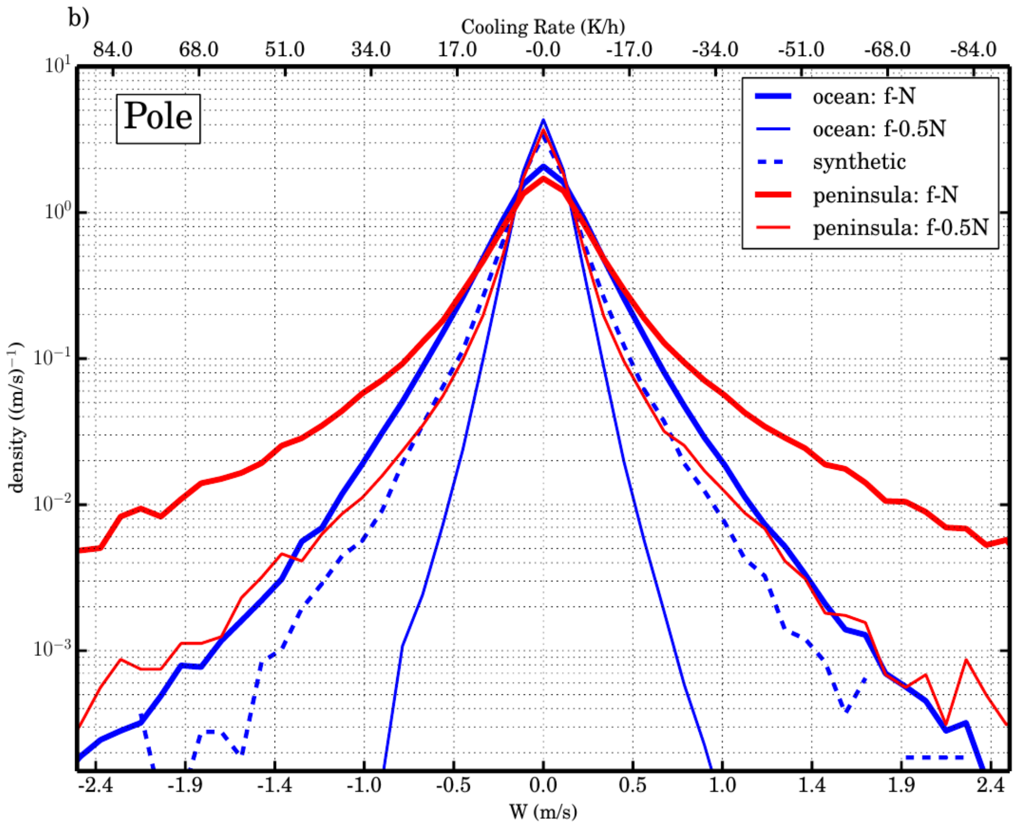


Observed vertical velocities

Regional contributions over the pole



Temperature



Vertical velocity

Large wings over the pole are associated with **mountain waves** (regions of high topographic gradients : Antarctic peninsula versus ocean and the flat Antactic plateau), both for temperature and vertical velocity