A method to estimate clear sky mesoscale vertical motion from geostationary satellite imagery

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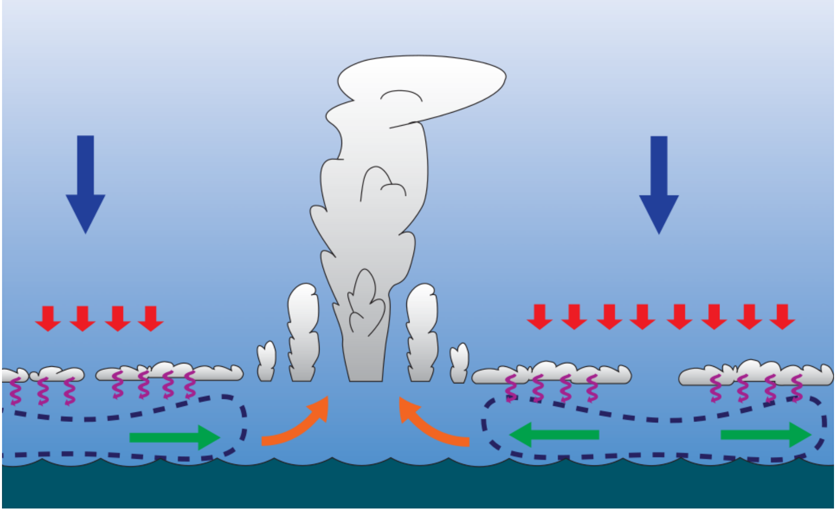
LMD Paris

February 2023

Motivations



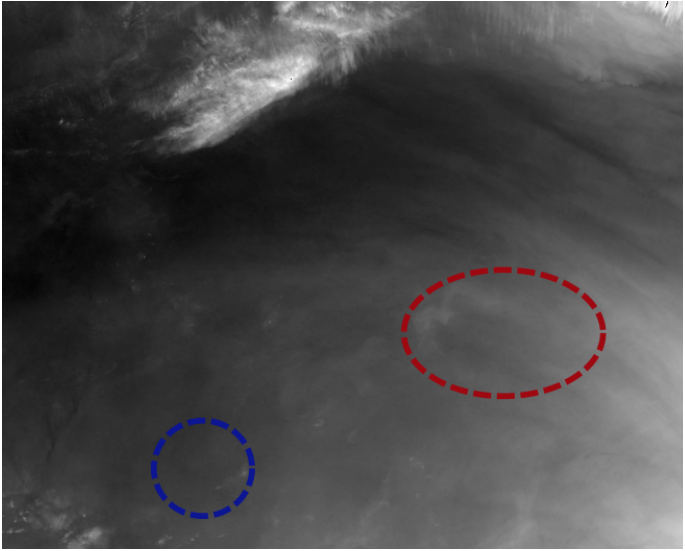
Coppin and Bony, 2015

- Importance of clear sky vertical motion in cloud organization and radiation-circulation coupling
- Sparsity and cost of in situ observations
- Currently no available satellite measurement
- Future satellite missions focus on assessing w within clouds

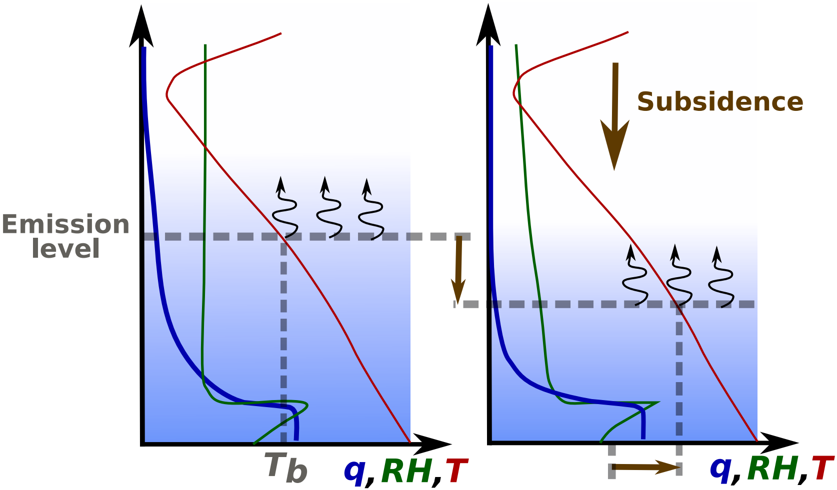
Outline

- Theory
- Implementation
- Evaluation
- Insights on possible causes of vertical motion

Main idea of the method



Main idea of the method



Subsidence dries the atmosphere and increases brilliance temperature

- (H1) At the wavelength considered **water vapor is the only significant absorber** and $e^{-\tau_s} << 1$
- (H2) **Relative humidity is vertically uniform in the vicinity of the emission level**
- (H3) The specific extinction coefficient κ is vertically uniform in the vicinity of the emission level
- (H4) Moist adiabatic lapse rate (WTG)
- (H5) **Hydrostatic approximation**
- (H6) Perfect gas
- (H7) No water vapour turbulent fluxes

Formula for optical thickness :

$$\tau = \int_{TOA}^{p} \frac{\kappa}{g} q \mathrm{d}p$$

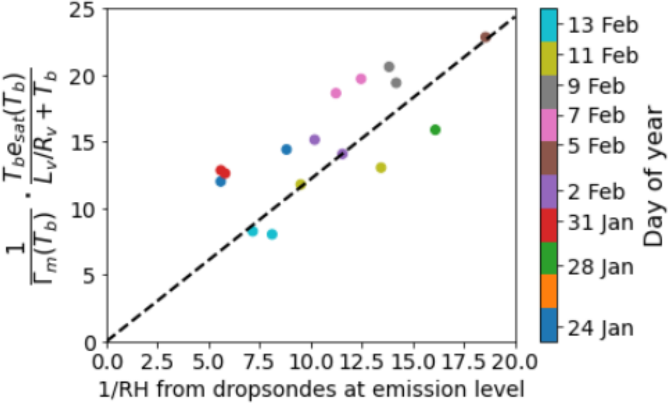
Integration done using :

- hydrostatic approximation
- perfect gas law
- Clausius Clapeyron law

Link between RH and temperature T^* at emission level

Result :

$$\frac{R_d \tau}{\epsilon \kappa} \times \frac{1}{RH} = \frac{1}{\Gamma_m(T^*)} \frac{T^* e_{sat}(T^*)}{L_v/R_v + T^*}$$



Link between relative humidity variations and vertical motion

Conservation of specific humidity :

$$q(p, t + \mathrm{d}t) = q(p - \omega \mathrm{d}t, t)$$

which implies a direct link between vertical velocity and relative humidity variations.

$$\frac{\mathrm{d}RH}{\mathrm{d}t} = -\frac{RH}{p}\left(\frac{L_s R_d \Gamma_m}{R_v g T} - 1\right) \times \omega$$

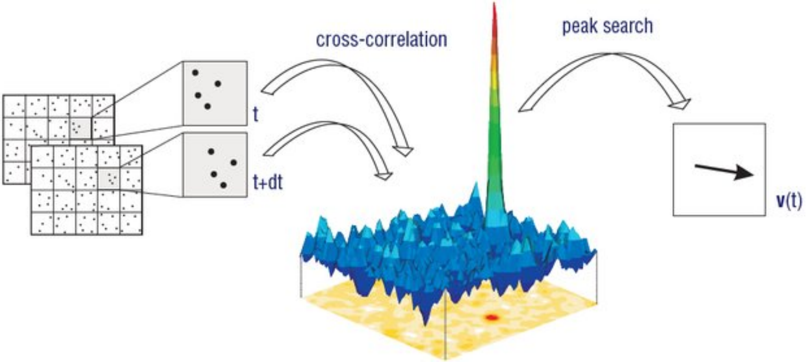
Direct link between vertical velocity ω and variations of temperature T^* at emission level :

$$\boxed{\omega = \frac{1}{\frac{L_s R_d \Gamma_m}{R_v g T^*} - 1} \frac{L_s p}{R_v T^{*2}} \frac{L_s/R_v + 2T^*}{L_s/R_v + T^*} \times \frac{\mathrm{d}T^*}{\mathrm{d}t}}$$

The relation is independent on spectroscopic properties !

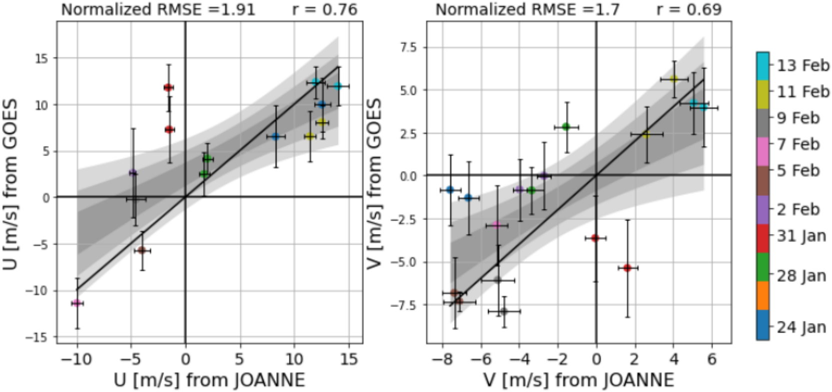
- Compute horizontal winds
- Compute temperature T^* from satellite radiances
- Compute Lagrangian derivative $\mathrm{d}T^*/\mathrm{d}t$
- Compute vertical velocity

Per-filtering to select water vapour filaments.

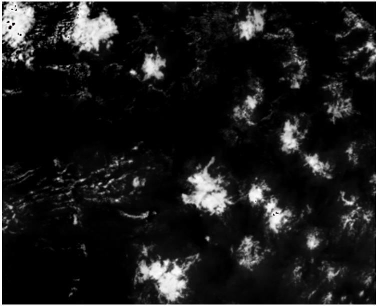


Wieneke, 2017

Determination of horizontal winds



Determination of temperature at $\tau = \tau^*$



Using these images we deduce :

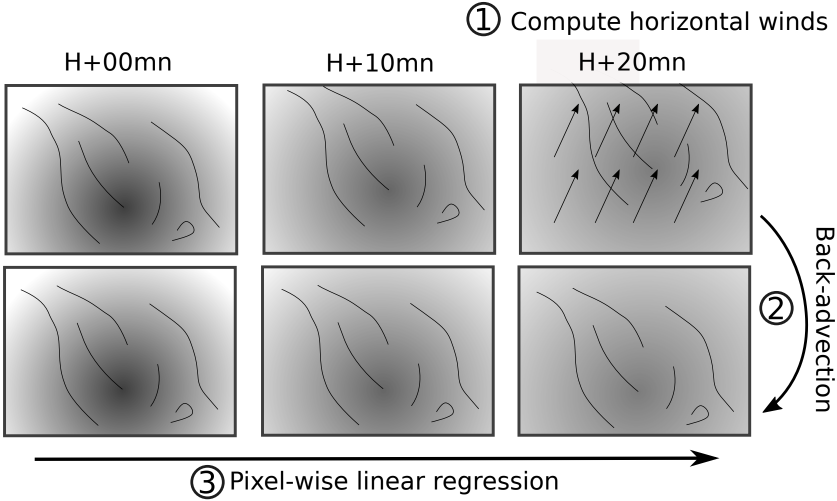
- Optical depth τ_s of the atmosphere at wavelength λ
- Sea Surface / Cloud Top Temperature T_{sfc}

Radiative transfer equation :

$$R_\lambda = \int_0^{\tau_s} B_\lambda(\tau) e^{-\tau} \mathrm{d}\tau + e^{-\tau_{sfc}} B_\lambda(T_{sfc})$$

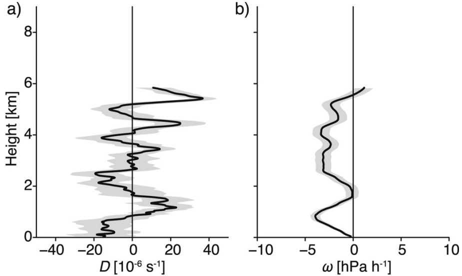
We invert this equation
$\rightarrow$ We can deduce temperature $T^* = f(R_\lambda, T_{sfc})$
$\rightarrow$ Correction from surface or cloud-top temperature inhomogeneities

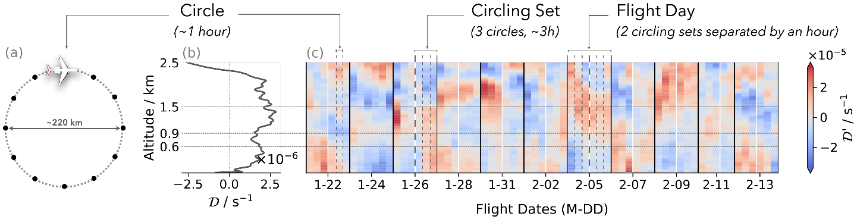
Determination of Lagrangian derivative of temperature $\mathrm{d}T^*/\mathrm{d}t$



Evaluation against JOANNE data

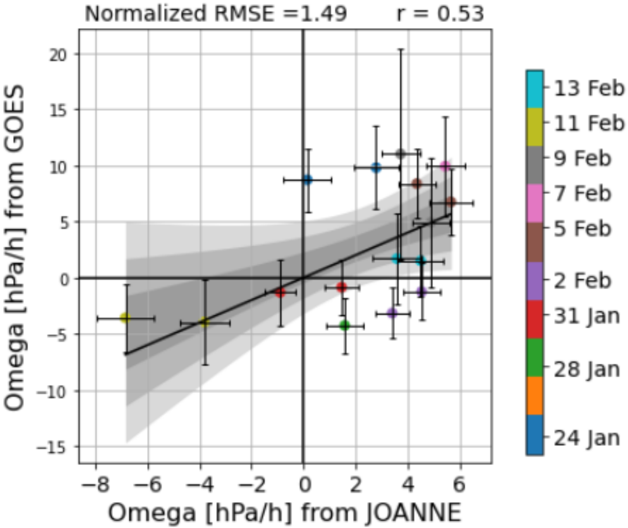
Joint dropsonde-Observations of the Atmosphere in North atlaNtic trade-wind Environments





Bony and Stevens 2019; George et al. 2021,2022

Evaluation against JOANNE data



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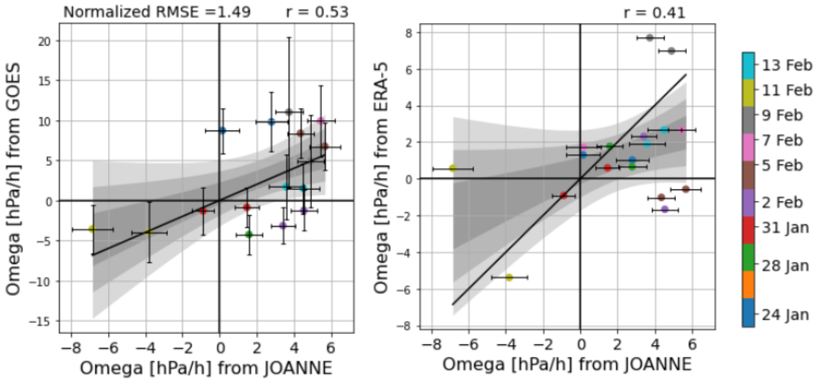
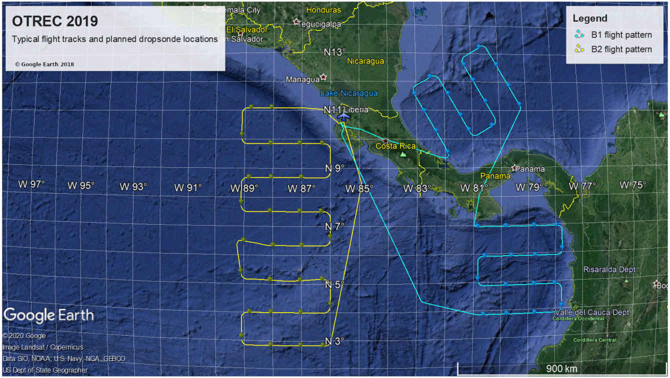


Grids of dropsondes in tropical Pacific during Aug-Oct 2019



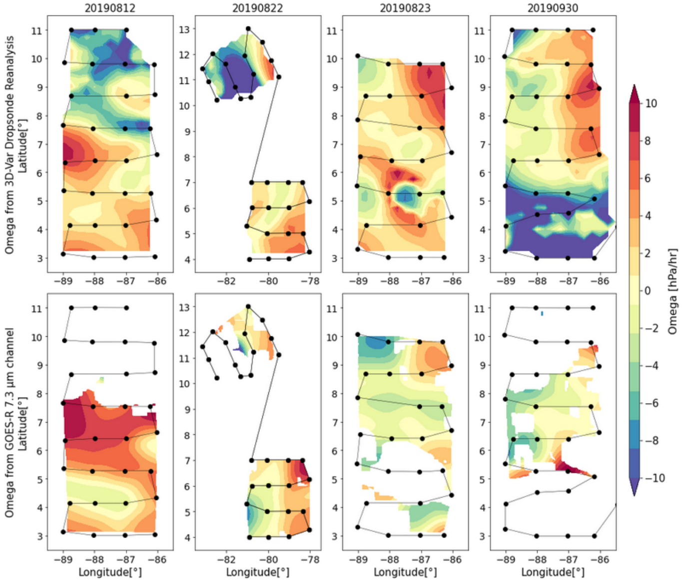
Vömel et al., 2021

- In regions of active deep convection
- Flight duration of 3-5h
- Dropsonde resolution 1 degree

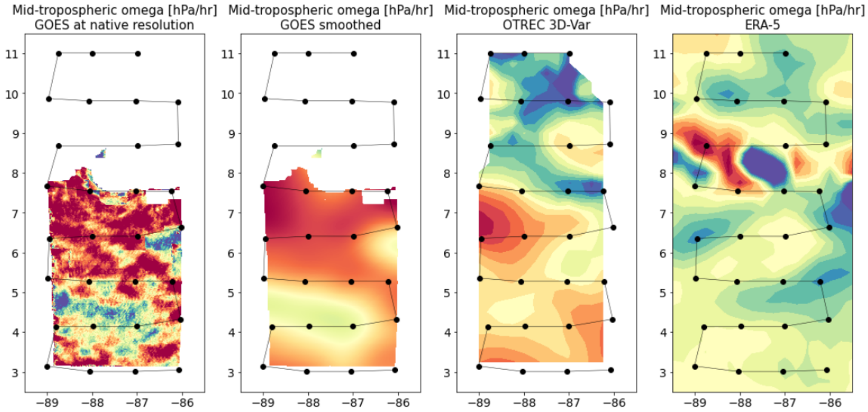
Vertical velocity computed from :

- Dropsondes using mass conservation *(Raymond & Fuchs-Stone, 2021)*
- GOES images for several hours, then interpolated onto flight track using the closest time from dropsonde launch

Evaluation against OTREC data



Evaluation against OTREC data

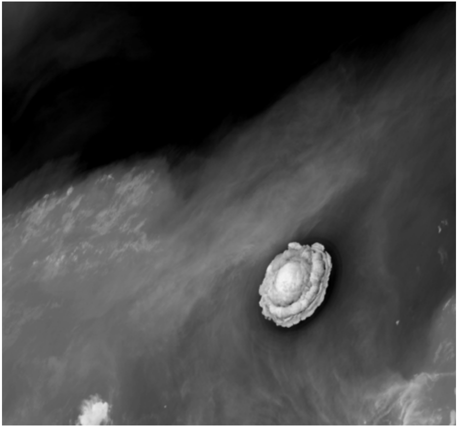


- 2.5km resolution in the Atlantic (500 $\times$ 2500km)
- NARVAL-1 : Winter trades (December 2013)
- NARVAL-2 : ITCZ edge (August 2016)
- Hourly output of 3D fields

Simulation of brilliance temperature of GOES-16 ABI Instrument using radiative transfer code RTTOV.

Simulated performances are similar to those during OTREC and EUREC4A.

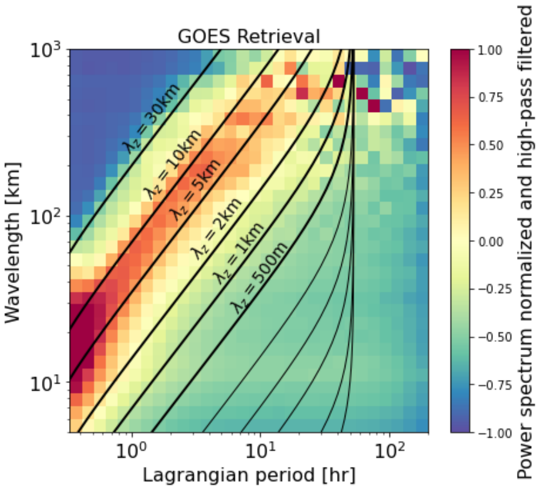
15 January 2022 : Hunga Tonga eruption triggered worldwide gravity waves



GOES-W image at 6.9µm

Evaluation at subhourly time scale

Gravity waves as a good candidate for mesoscale vertical motion



$$(\omega - \vec{u} \cdot \vec{k})^2 = N^2 \frac{\vec{k}^2}{\vec{k}^2 + m^2 + \frac{1}{4H^2}}$$ (inspired from *Wheeler&Kiladis 1999*)

Gravity waves as a good candidate for mesoscale vertical motion

- Ability to retrieve temporal and spatial variations of mesoscale vertical velocity
- Limited quantitative performance
- Measurements at high spatial (2km) and temporal (10mn) resolution over full geostationary disk
- First results seem to support the hypothesis for gravity waves (vs radiation) as a main cause for mesoscale vertical motion

Next steps :

- Evaluation of the method against VHF radar data ?
- Use of the tool to study convective aggregation

At what level τ^* do we measure $\frac{\mathrm{d}T^*}{\mathrm{d}t}$?

Simple possible hypothesis : $\tau^* = 1 \rightarrow T^* = T_b$

But actually we observe variations of temperature at the following level :

$$\tau^* = \langle \tau \rangle_{\frac{\delta T_b}{\delta T}} = 1 + \eta \approx 1.35$$

where $\eta = \frac{hcR_v}{\lambda L_s k_B}$ depends only on the channel wavelength.

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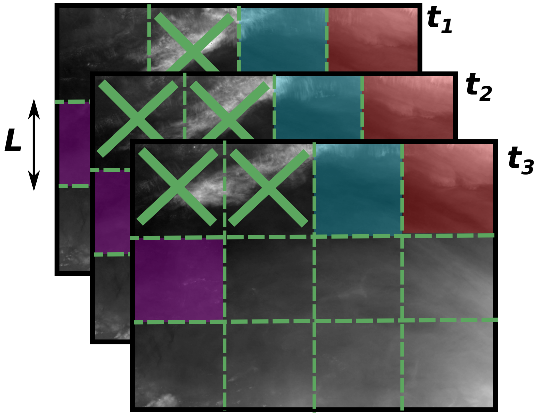
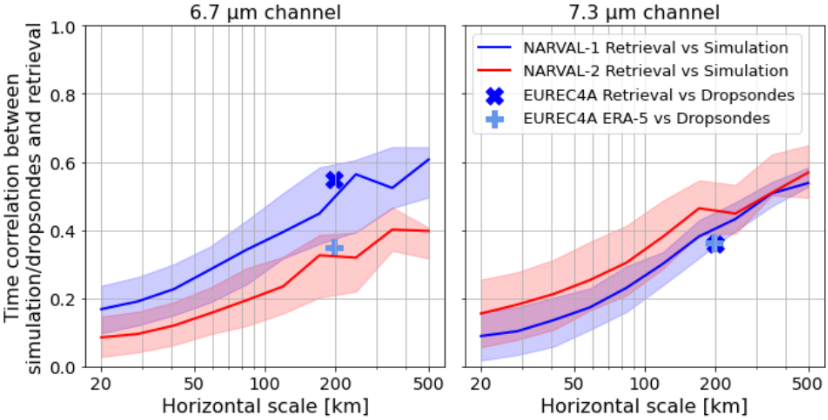
Simulation of brilliance temperature of GOES-16 ABI Instrument using radiative transfer code RTTOV.

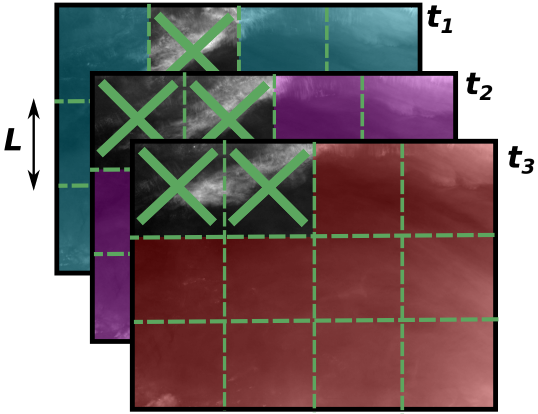
Because output is "only" hourly it is not possible to use a linear regression to compute $\mathrm{d}T_b/\mathrm{d}t$, only a difference between H and H$+$1 is done. $\rightarrow$ we expect a poorer performance of the retrieval



One time series of omega in the simulation and the retrieval for each colour → one correlation per block → mean correlation and uncertainty

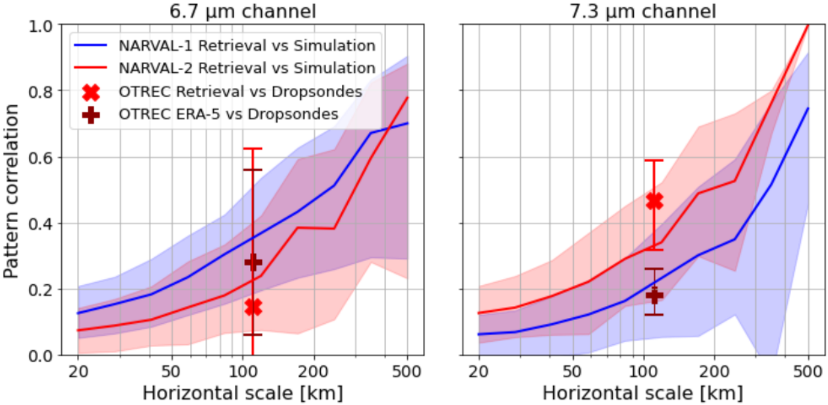
Evaluation in the NARVAL simulations





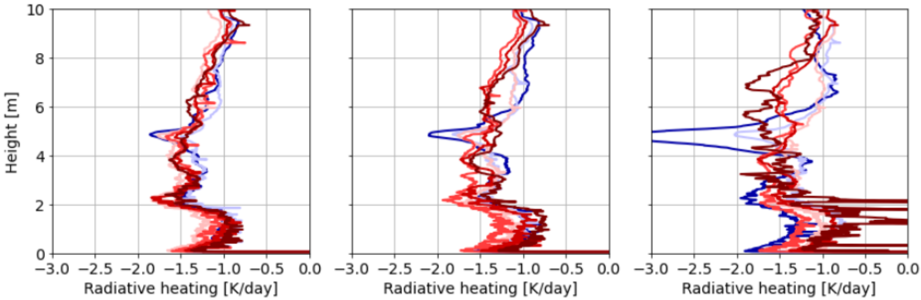
One series of omega in the simulation and the retrieval for each colour
→ one correlation per timestep → mean correlation and uncertainty

Evaluation in the NARVAL simulations



Gravity waves as a good candidate for mesoscale vertical motion

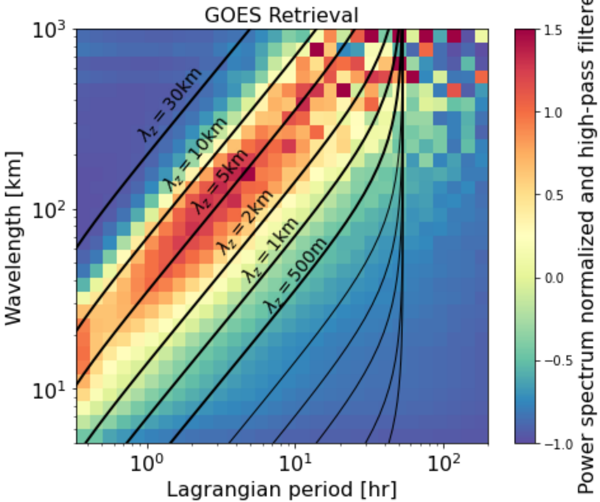
Small scale(10km) Mesoscale(100km) Large scale(500km)



Radiative cooling matters mostly for large scale circulations only in the free troposphere

But local impact of vertical velocity on PBL cooling

Gravity waves as a good candidate for mesoscale vertical motion



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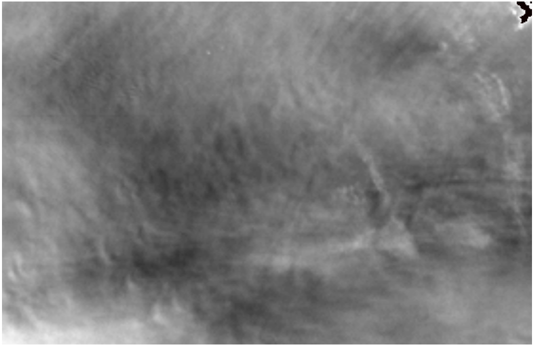
We invert this equation
$\rightarrow$ We can deduce temperature $T^* = f(R_\lambda, T_{sfc})$
$\rightarrow$ Correction from surface or cloud-top temperature inhomogeneities

$$T^* \approx B_\lambda^{-1}\left(\tau^{*\eta} \cdot \frac{R_\lambda - e^{-\tau_s} B_\lambda(T_s)}{\Gamma(1+\eta) - \tau_s^\eta e^{-\tau_s}\left(1 + \frac{\eta}{\tau_s}\right)}\right)$$

Determination of horizontal winds

- High pass filter to select small scale features (<30km)
- Band rejection filter at 10km to remove fast gravity waves



(ex : GOES-E 6.2µm channel over Barbados, 24 Jan 2020)