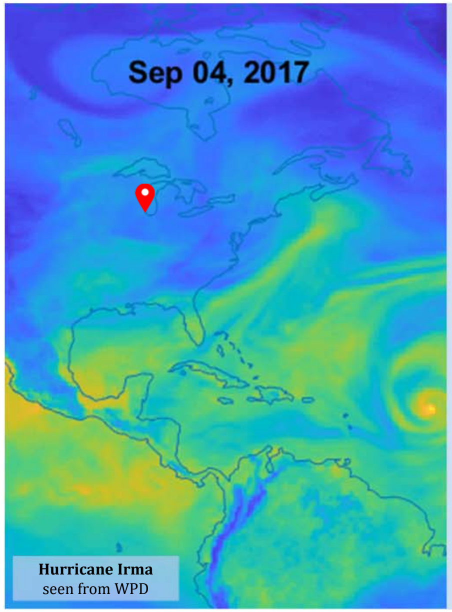

Modeling the vertical dependence of the Wet Path Delay: application in satellite altimetry over coastal and inland waters

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FCT Fundação para a Ciência e a Tecnologia
European Union European Social Fund

Outline

1. **W**et **P**ath **D**elay (**WPD**) for Satellite Altimetry
    - Limitations over **coastal** and **inland waters**
    - **Requirement for modeling** its altitude dependence

2. Modeling this altitude dependence using ERA5 data
    - Kouba (2008) formulation
    - **Development** of improved expressions (UP)
        - **Assessment** using ERA5 data (not used in the modeling)
        - **Validation** using radiosondes data

3. Conclusions

WPD for Satellite Altimetry

- WPD from **M**icro**w**ave **R**adiometers (**MWR**) → **invalid** over coastal and inland waters.
- Alternative sources:
  - ✓ **G**lobal **N**avigation **S**atellite **S**ystems (**GNSS**)
  - ✓ **N**umerical **W**eather **M**odels (**NWM**)
- **Problem!** WPD at different altitudes:

MWR	Sea level
GNSS	Station height
NWM	Orography height

Levels of interest
Coastal zones: sea level
Inland waters: water body height

An expression to reduce the various WPD is required.

Objective

- **The modeling of the WPD vertical dependence is a crucial step to combine the various WPD.**
- The only expression available (Kouba, 2008) has some limitations, since it considers the same altitude reduction, irrespective of geographic location and time.

Objective: modeling the WPD altitude dependence, aiming at developing improved expressions to account for its complex 4-D variation.

✓ Performed using **WPD vertical profiles** computed globally using **ERA5 data on pressure levels (PL):**

  - **temperature (T)**
  - **specific humidity (q)**.

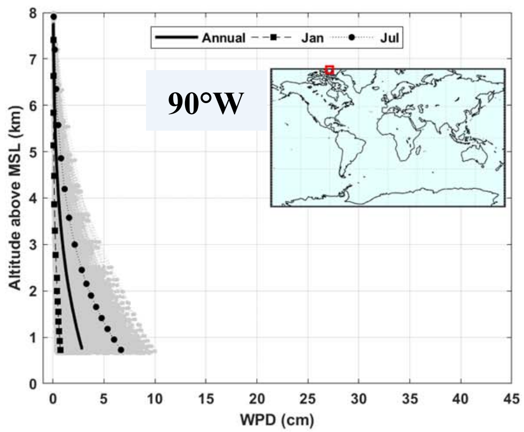
WPD computation from ERA5 data on PL

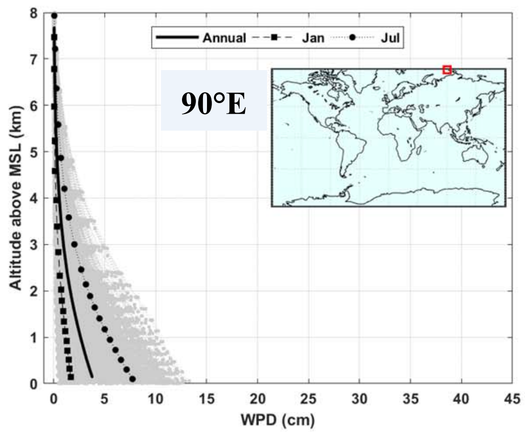
Ocean Surface Topography Science Team Meeting (OSTST)
21-25 October, 2019
Chicago, Illinois

- Using a numerical integration, from the highest level down to the lowest vertical level.

$$WPD = \left[1.116454 \times 10^{-3} \int_{P_{TOA}}^{P_{surf}} q\, dp + 17.66543928 \int_{P_{TOA}}^{P_{surf}} \frac{q}{T}\, dp\right] \times [1 + 0.0026 \cos 2\varphi]$$

(CLS, 2011)





← WPD vertical profiles computed using *T* and *q* from ERA5 on PL

Grey → profiles every 3-h over the year 2010
Solid line → annual mean profile
Squares, dashed line → January mean profile
Circles, dotted line → July mean profile

Kouba formulation

Kouba (2008) proposed the following expression:

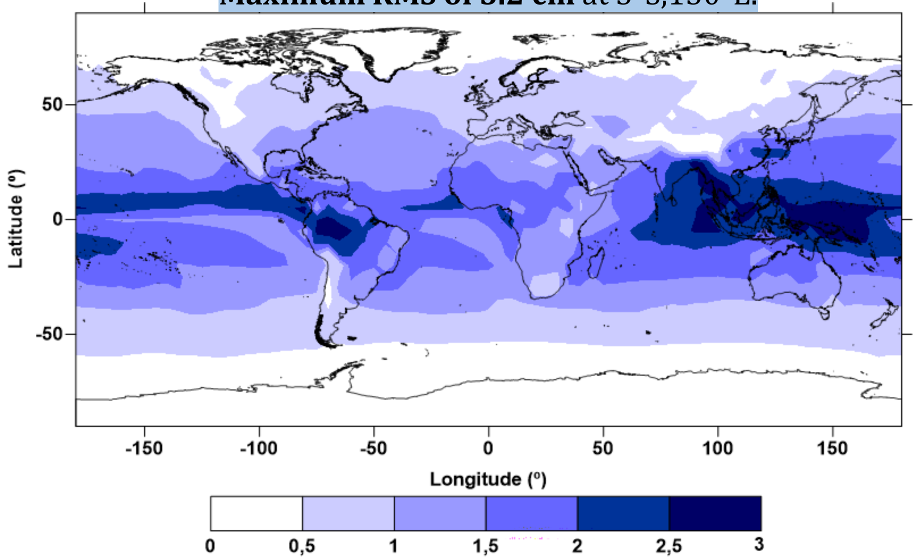
$$WPD_i = WPD_0 . e^{\frac{h_0 - h_i}{2000}}$$

Assessment of the Kouba expression using two WPD vertical profiles:

[3D] Computed from ERA5 data on PL

[2D+reduction] Computed at ERA5 orography level and then reduced to the PL using the **Kouba expression**.

Maximum RMS of 3.2 cm at 5°S,150°E.



RMS (cm) of the WPD differences between 3-D and 2-D with Kouba reduction, using profiles every 3-h in a grid 5°x5° over the year 2014.

UP modeling: spatial dependence

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$$\mathrm{WPD_i} = \mathrm{WPD_0} . e^{\frac{h_0 - h_i}{\alpha}}$$

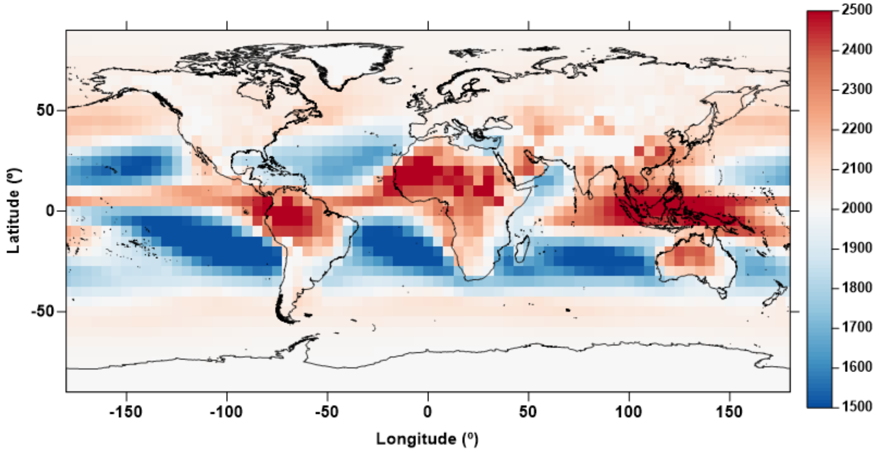
Invariable Kouba coefficient: $\boldsymbol{\alpha} = \mathbf{2000}$

α is computed using least squares at each location and for each WPD vertical profile.

4 years (2010-2013), 5°x5°, every 3-h

UP-01 modeling consists in a set of **α** coefficients, dependent on geographic location.

UP-01 coefficients: $\boldsymbol{\alpha}(\mathbf{lat}, \mathbf{lon}) = \cdots$



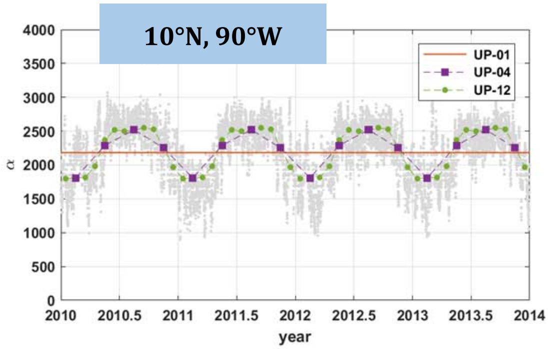
Spatial representation of the α, computed as the mean for each point (**UP-01**). Minimum and maximum coefficients are **1165** and **2705**, respectively.

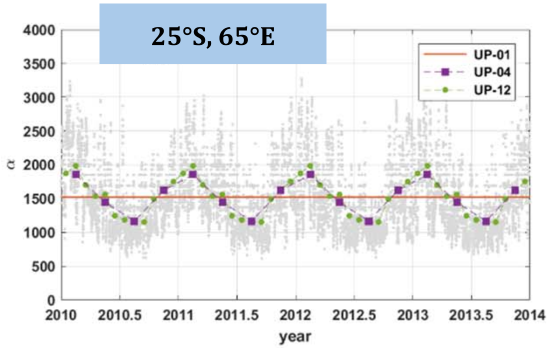
Impact of different coefficients:
For $\mathrm{WPD_0} = 30$ cm, $\mathrm{h_0} = 0$ m and $\mathrm{h_i} = 1000$ m

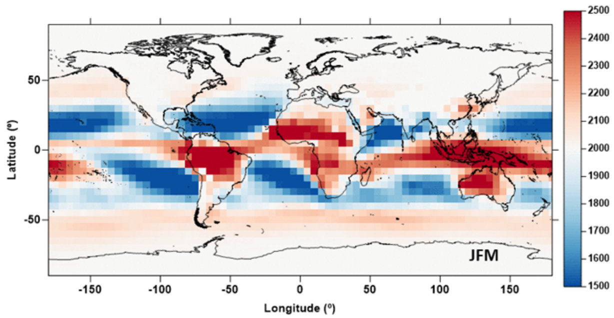
α	1500	2000	2500
$\mathrm{WPD_i}$ (cm)	**15.4**	**18.2**	**20.1**

UP modeling: temporal dependence

- The time evolution of α coefficients reveals regions with a clear annual signal.







Spatial representation of the α, computed as the seasonally-averaged for each point (**UP-04**).

UP-04 and **UP-12** modeling consists in a set of α coefficients, varying in space and **time**.

UP-01 → single coefficient for each point (non time dependent)

UP-04 → seasonally-averaged coefficients

UP-12 → monthly-averaged coefficients

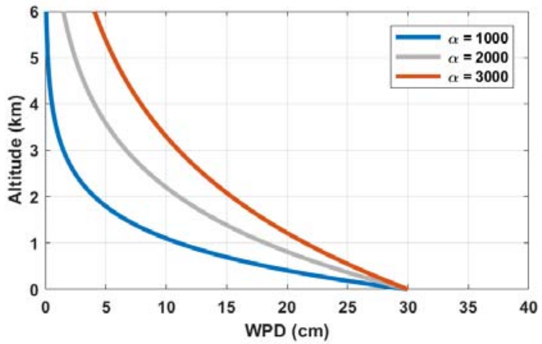
UP-01 coefficients: $\boldsymbol{\alpha}(\mathbf{lat}, \mathbf{lon}) = \cdots$

UP-04 coefficients: $\boldsymbol{\alpha}(\mathbf{lat}, \mathbf{lon}, \mathbf{season}) = \cdots$

UP-12 coefficients: $\boldsymbol{\alpha}(\mathbf{lat}, \mathbf{lon}, \mathbf{month}) = \cdots$

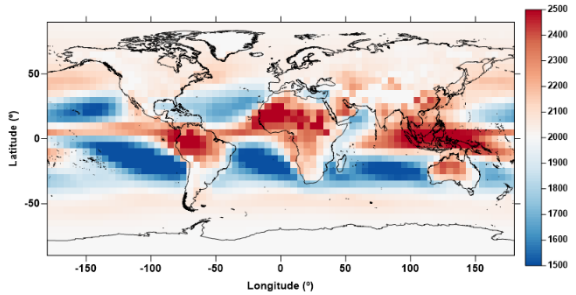
Physical meaning

- **small α** → WPD vanish more rapidly with altitude;
- **large α** → slower decrease.

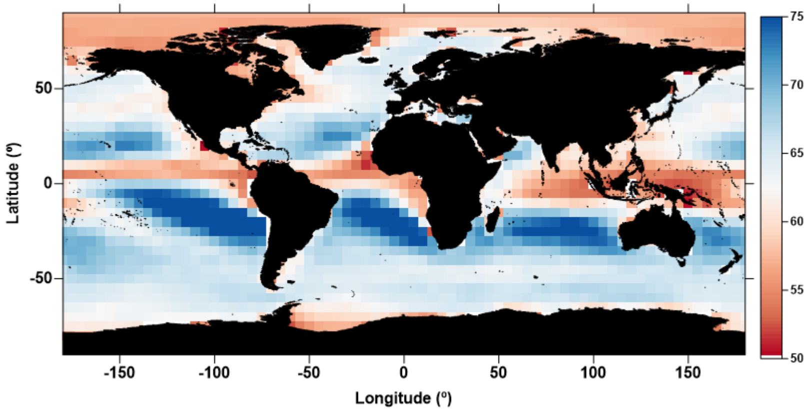


Blue regions have larger near-surface water vapor concentrations than red regions.

When compared with the total atmospheric column at each point, a **small α** indicates a larger near-surface water vapor concentration, than a **large α**.

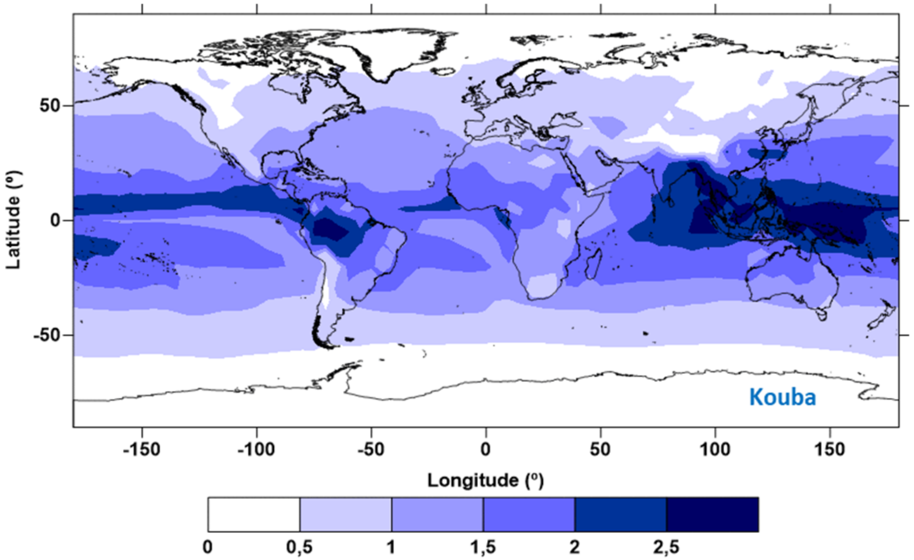


↑ **UP-01**



← **% of WPD up to 2 km**

Assessment with ERA5



RMS (cm) of the WPD differences between 3-D and 2-D with reduction to the PL using different modelings, using profiles every 3-h in a grid 5°x5° over the year 2014 (**not used in the UP modeling**).

Maximum RMS (cm)
Kouba (3.2), **UP-01 (2.5)**, **UP-04 (2.2)**, **UP-12 (2.1)**

Regions where UP modeling has the most significant impact (5°S,150°E)
Kouba → RMS of **3.2 cm**
UP-01, **UP-04** or **UP-12** → **1.2 cm**
RMS decrease: 2.0 cm
Temporal modeling has no impact
(UP-01 ~ UP-04 ~ UP-12)

Regions where temporal modeling has the most significant impact (25°N,90°E)
Kouba → RMS of **2.7 cm**
UP-01 → RMS of **2.5 cm** **RMS decrease: 0.2 cm**
UP-04 → RMS of **1.7 cm** **RMS decrease: 1.0 cm**
UP-12 → RMS of **1.4 cm** **RMS decrease: 1.3 cm**

Validation with radiosondes (RS)

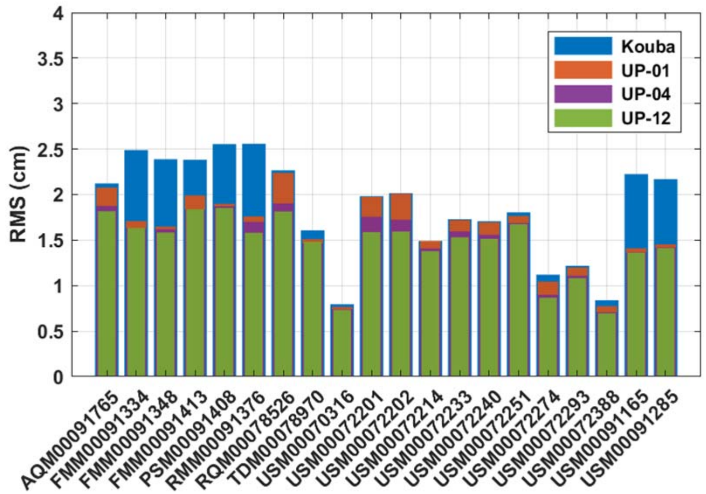
Using two WPD vertical profiles:

[RS] Computed from RS data on vertical levels

[RS + reduction] using the WPD at lowest level and then reduced to the upper levels using the **Kouba**, **UP-01**, **UP-04** and **UP-12** coefficients.

- The most significant RMS decrease is from **Kouba** to **UP-01** (**single coefficient** to **spatially-dependent coefficients**).
- In some regions, the modeling of the spatial and temporal dependence (**UP-04** and **UP-12**) has a significant impact, when compared with **UP-01**.

✓ RMS decrease using **UP** modeling, instead of **Kouba**, can be larger than **1 cm**.



RMS (cm) of the WPD differences between RS and lowest level with different reductions, using soundings every 12-h over the year 2014.

Conclusions

- The vertical distribution of the WPD is highly variable, becoming this modeling difficult.

- In some regions, an annual signal in the coefficients is clear.

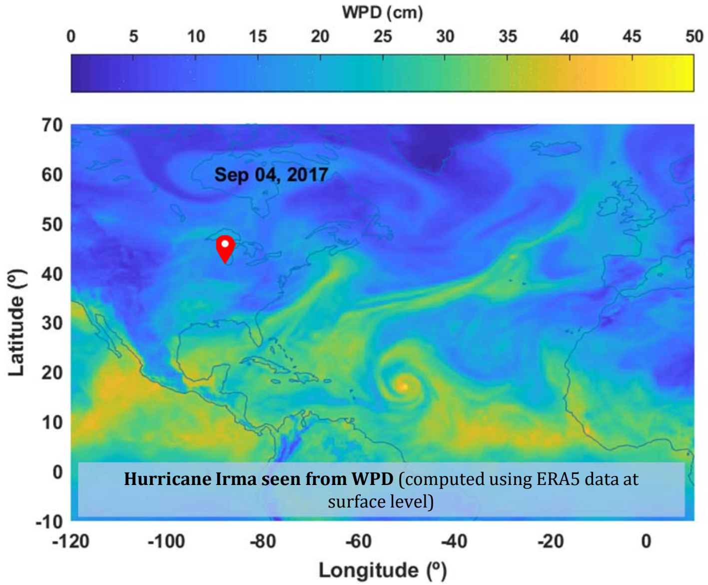
- This modeling consists in a set of coefficients, varying in space [**UP-01**] and time [**UP-04** (seasonally-averaged) and **UP-12** (monthly-averaged)].

- When compared with an invariable coefficient (**Kouba**), the most significant RMS decrease appears when only spatially-dependent coefficients (**UP-01**) are used.

- An assessment with ERA5 data (not used in modeling) shows that for the location where the **Kouba** coefficient has the maximum RMS of **3.2 cm**, this value is reduced to **1.2 cm** when **UP** coefficients are used.

- In some regions, the modeling of the spatial and temporal dependence (**UP-04** and **UP-12**) has a significant impact, when compared with **UP-01**.

- Independent comparisons with radiosondes show that the RMS decrease can be larger than **1 cm**, when **UP** coefficients are used, instead of **Kouba**.



Hurricane Irma seen from WPD (computed using ERA5 data at surface level)

Thank you!

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* Telmo Vieira is supported by the *Fundação para a Ciência e a Tecnologia (FCT)* through the fellowship **SFRH/BD/135671/2018**, funded by the European Social Fund and by *Ministério da Ciência, Tecnologia e Ensino Superior (MCTES)*.

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